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Upper limb joint kinetic analysis during tennis serve: Assessment of competitive level on efficiency and injury risks

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The aim of this work was to compare the joint kinetics and stroke production efficiency for the shoulder, elbow, and wrist during the serve between professionals and advanced tennis players and to discuss their potential relationship with given overuse injuries. Eleven professional and seven advanced tennis players were studied with an optoelectronic motion analysis system while performing serves. Normalized peak kinetic values of the shoulder, elbow, and wrist joints were calculated using inverse dynamics. To measure serve efficiency, all normalized peak kinetic values were divided by ball velocity. *t*-tests were used to determine significant differences between the resultant joint kinetics and efficiency values in both groups (advanced vs professional). Shoulder inferior force, shoulder anterior force, shoulder horizontal abduction torque, and elbow medial force were significantly higher in advanced players. Professional players were more efficient than advanced players, as they maximize ball velocity with lower joint kinetics. Since advanced players are subjected to higher joint kinetics, the results suggest that they appeared more susceptible to high risk of shoulder and elbow injuries than professionals, especially during the cocking and deceleration phases of the serve.

Overuse injuries in sport can result from a complex interaction between various risk factors such as age, gender, muscle weakness and imbalance, poor equipment, number of repetitions during trainings and competitions, and excessive joint loadings (Kannus, 1997). Among all the risk factors in overhand throwing and striking activities, excessive joint loadings (forces and torques) are known to be a crucial risk factor causing repetitive microtrauma that are responsible for overuse upper limb joint injuries (Kibler, 1995; Kannus, 1997; Lintner et al., 2008; Anderson & Alford, 2010). Indeed, it appears logical that players subjected to higher loadings might be more likely to sustain joint overuse injury (Reid et al., 2007). This long-held theory about the relation between joint loadings and incidence of overuse injuries has been recently confirmed for overhand skill (Anz et al., 2010). Indeed, in a professional baseball pitcher population, it has been reported that increased shoulder and elbow loadings were associated with increased elbow injury (Anz et al., 2010). Concerning tennis, the serve has been reported to be a traumatic skill, as it causes high loads on the shoulder and elbow joints in professional tennis players (Elliott et al., 2003; Reid et al., 2007), almost identical to those reported for baseball pitchers (Fleisig et al., 1995). The traumatic effect of the tennis activity is also linked to the repetitive nature of the serve movement throughout the player's competitive career. Interestingly, tennis players hit between 50 and 150 serves during a match. This result is increased by the number of single matches played by the players during a competitive season (around 60 matches), without considering double matches and training sessions (Reid et al., 2008). This repetition of serves inflicted on the upper limb joints in competitive tennis players may explain why overuse injuries of the upper limb joints are a common medical problem in all competitive levels in tennis (Marx et al., 2001; Ellenbecker et al., 2009; Abrams et al., 2012; Hjelm et al., 2012). Indeed, theses overuse injuries concern not only professional tennis players but also recreational and advanced competitive players (Jayanthi et al., 2005; Pluim et al., 2006; Abrams et al., 2012). Tennis is a world-class competitive sport attracting tens of millions of players all around the world, and the majority of them is presumed to be recreational or advanced rather than elite. However, serving loads at various competitive levels and their implications for given types of potential injuries have not been documented, as all previous studies have been limited to professional players (Elliott et al., 2003; Reid et al., 2008).

Moreover, it has been suggested that an improved technique while performing the serve may lead to fewer injuries (Elliott et al., 2003; Aguinaldo et al., 2007) and higher efficiency (Aguinaldo & Chambers, 2009). In fact, a highly efficient server is one who can maximize output (ball velocity) with the least joint load (Aguinaldo & Chambers, 2009). It is still unknown if an advanced tennis player produces a less-efficient serve technique compared to a professional. Kinetic differences between competitive levels may be insightful for understanding injury potential.

The aim of this work was to compare the joint kinetics and stroke production efficiency for the shoulder, elbow, and wrist during the serve between professionals and advanced tennis players and to discuss their potential relationship with given overuse injuries.

Materials and methods

Subjects

Eleven male professional tennis players [mean ± standard deviation (SD): age 25.5 ± 4.3 years; height 1.88 ± 0.07 m; weight 80.4 ± 7.7 kg, International Tennis Number (ITN) 1] and seven advanced tennis players (mean ± SD: age 25.3 ± 7.3 years; height 1.81 ± 0.04 m; weight 70.1 ± 6.2 kg, ITN 3 or 4) have participated voluntarily in this study. The professional players involved in the present study had a singles (17th, 88th, 118th, 147th, 287th, 522th, 921th) or a doubles Association of Tennis Professionals (ATP) ranking (35th, 36th, 48th, 210th). According to the International Tennis Federation (2009), "the players with an ITN 4 ranking master the use of power and spins and are beginning to handle pace, have sound footwork, can control depth of shots, and are beginning to vary plan game according to opponents";"The players with an ITN 3 ranking have good shot anticipation and frequently have outstanding shot or attribute around which one may be structured." ITN 1 ranking corresponds to professional players. Prior to experimentation, the participants underwent a medical examination and were fully informed of the experimental procedures. All players were considered healthy, with no significant bodily injury at the time of testing or previous history of pain or surgery on the dominant arm. Informed consent was obtained for each player. The study was approved by the local ethical committee and conducted in accordance with the 1975 Declaration of Helsinki.

Experimental protocol

Prior to experiment, participants had as much time as needed to familiarize themselves with the testing environment and the landmarks set. After a warm-up of 10 min, each player performed five 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 (Fig. 1). The subjects were asked to serve at their best level as in an official tournament. A 30-s rest period was allowed between trials.

In situ motion capture

The experiment took place in an indoor tennis court during an ATP professional tournament. Players were equipped with 38 retro-reflective markers placed on anatomical landmarks determined in agreement with previously published data (Zatsiorsky et al., 1990; Leardini et al., 1999; Reed et al., 1999). Five additional landmarks were positioned on the racket. Participants used their own racket during motion capture to ensure they felt as comfortable as possible during their serves. A Vicon MX-40 motion capture system (Oxford Metrics Inc., Oxford, UK) was used to record the 3D landmarks' trajectories. It was composed of 12 high-resolution cameras (4 megapixels) operating at a nominal frame rate of 300 Hz and positioned as shown in Fig. 1. Despite accurate marker placement and although participants wore only shorts (Fig. 2) to limit movement of the markers from their anatomical landmarks, authors were aware that skin-attached markers can produce errors because of thickness of soft tissue, and movement of the skin and muscle. After the capture, 3D coordinates of the landmarks were reconstructed with ViconIQ software (IQ, Vicon, Oxford, UK) with a residual error less than 1 mm. The 3D motions of each player expressed in a right-handed inertial reference frame R1, where the origin was at the center of the baseline. *X* represented the parallel direction to the baseline, *Y* pointed forward, and *Z* was

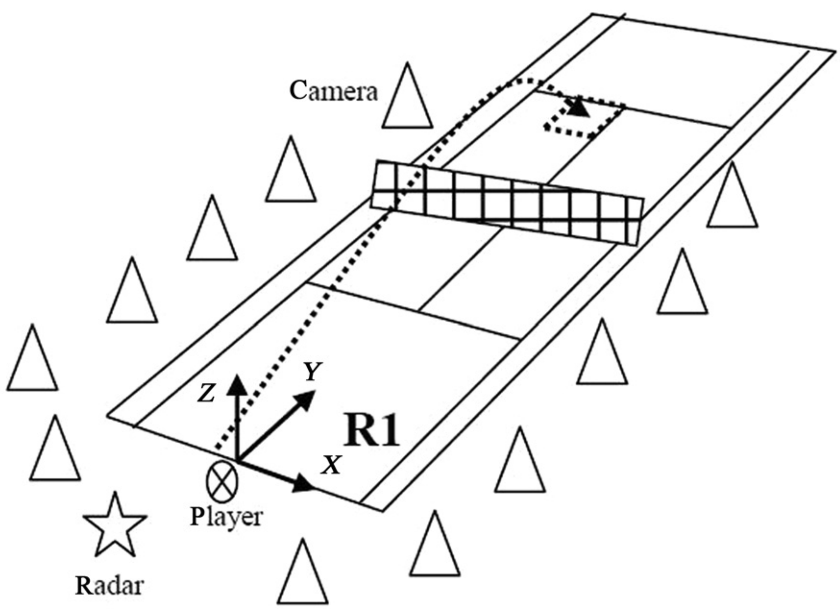

Fig. 1. The filming setup. R1: right-handed inertial reference frame.

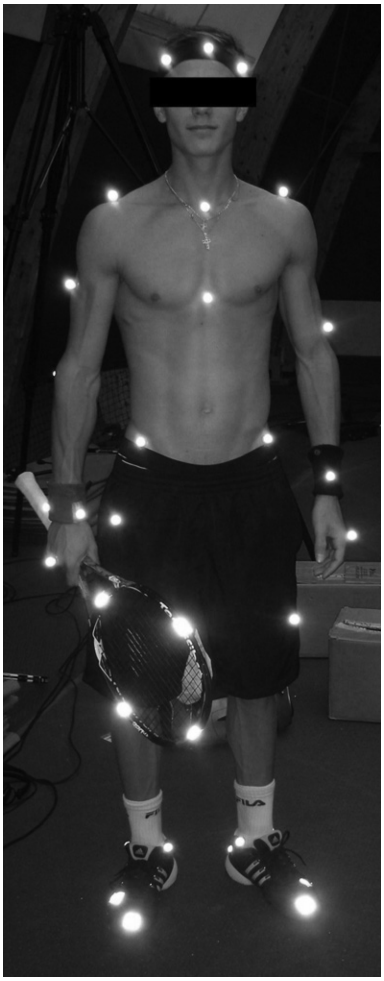

Fig. 2. The positions of the landmarks.

vertical and pointed upward (Fig. 1). The 3D coordinate data of the markers were smoothed with a Butterworth low-pass filter with a cutoff frequency of 15 Hz, determined by residual analysis (Winter, 1990).

Post-impact ball velocity

Post-impact ball velocity (V_{ball}) was measured for each trial by using a radar (Stalker Professional Sports Radar, Applied Concepts, Plano, Texas, USA, accuracy: ± 1 mph, frequency: 34.7 GHz, Target Acquisition Time: 0.01 s) fixed on a 2.5-m height tripod, 2 m behind the players in the direction of the serve.

Kinetic values

Sixteen peak joint kinetics of the shoulder, elbow, and wrist joints were calculated. These kinetics have been chosen because they are thought to be indicative of injury potential during overhand sport movements (Fleisig et al., 1995, 1999; Elliott et al., 2003).The serving arm was modelled as a three-link kinetic chain composed of the racket/hand segment, forearm, and upper arm. The inverse dynamic approach was used to calculate the joint forces and torques. The joint forces and torques obtained were first computed in terms of reference frame R1 and were later transformed to a series of non-inertial, anatomically relevant, right-handed orthogonal references frames at each joint. Moment of inertia of the racket about its medial-lateral axis was computed using the parallel axis theorem and published racket "swingweight" data (USRSA, 2010), as suggested by Elliott et al. (2003).

Racket moment of inertia about the long-axis was calculated as reported in the literature (Brody, 1985):

$$\textit{Moment of inertia}\ \left(kg/m^2\right) = \left(mass \times head\ width^2\right)/17.75$$

Racket moment of inertia about its anterior-posterior axis was the sum of the racket's other two principal moments of inertia (Brody, 1985). Segmental masses and moments of inertia used in the inverse dynamics calculations were obtained from previously published data (De Leva, 1996).

All the kinetic values were calculated by Matlab software 6.5 (Mathworks, Natick, Massachussetts, USA). To facilitate the comparison between groups, kinetics peaks were normalized. Forces were divided by body weight (BW). Torques were divided by the product of BW by height (H) and then multiplied by 100 (Davis et al., 2009). Finally, normalized joint kinetics were divided by ball velocity to measure serve efficiency. These ratios indicate how much loads the upper limb joints (shoulder, elbow, and wrist) are experiencing per kilometer per hour, as generated in ball velocity (Davis et al., 2009).

To simplify interpretation of kinetic data, the serve motion was divided into phases (Fig. 3). The wind-up phase began when the server initiated his first movement (IFM); it ended with the ball toss (BT). Next was the cocking phase, from the BT to the maximal external rotation of the shoulder (MER). The arm acceleration phase followed, ending with ball impact (IMP). The time from ball impact (IMP) until the arm reached maximum internal rotation (MIR) was defined as the arm deceleration phase. The final phase was follow-through; it started at the time of maximum internal rotation and ended when the server had reached his balanced position (END).

Statistical Analyses

Means and standard deviations (five trials for each player) were calculated for all variables. Mann–Whitney tests (advanced vs. professional) were used to compare resultant joint forces data. The level of significance was established at $P < 0.05$ (SigmaStat 3.1, Jandel Corporation, San Rafael, California, USA). 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). Statistical power analysis with $\alpha = 0.05$ and $\beta = 0.1$ revealed that for the shoulder anterior force, $N = 18$ (11 professionals and seven advanced tennis players) have to be investigated to detect a large effect, between the two groups.

Results

Normalized joint kinetics

The peak values of normalized joint kinetics are presented in Table 1. The results reveal that five of the 16 parameters analysed during the serve were significantly different between competition levels. Indeed, shoulder inferior force, shoulder anterior force, shoulder horizontal abduction torque, and elbow medial force were significantly higher in advanced players and almost everyone showed medium or large effect sizes. The effect size for elbow medial force is small ($r = 0.274$). Elbow proximal force was significantly higher in professional players (5.5 ± 1.2 N/BW) than in advanced players (5.3 ± 0.9 N/BW; $P = 0.011$). However, this last result must be treated with caution since a very small

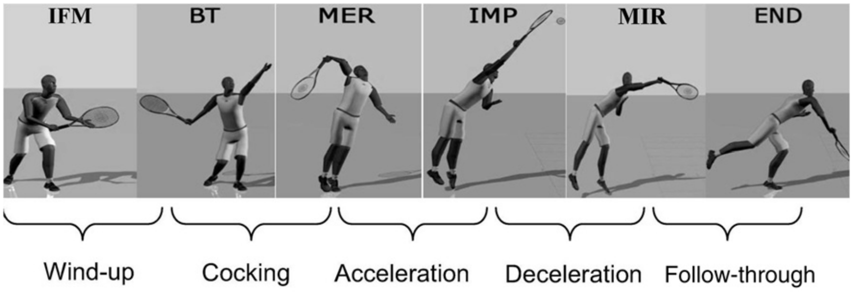

Fig. 3. The phases of the tennis serve.

Table 1. Normalized peak joint kinetic parameters (mean ± SD)

	Peak value phase	Professional ($n = 11$)	Advanced ($n = 7$)	P-value	Effect size
Shoulder forces (N/BW)					
Shoulder inferior force	Deceleration	2.9 ± 0.6	4.0 ± 0.8***	<0.001	0.643
Shoulder anterior force	Cocking	2.8 ± 0.8	3.2 ± 0.6**	0.003	0.336
Shoulder proximal force	Acceleration	5.4 ± 0.9	5.2 ± 1.0	0.206	0.103
Shoulder torques (Nm/BW × H)					
Shoulder internal rotation torque	Cocking	34.3 ± 7.4	33.1 ± 7.7	0.465	0.077
Shoulder horizontal adduction torque	Cocking	54.5 ± 11.8	54.0 ± 12.5	0.907	0.020
Shoulder horizontal abduction torque	Deceleration	19.7 ± 6.2	22.8 ± 5.6**	0.007	0.344
Elbow forces (N/BW)					
Elbow anterior force	Acceleration	1.7 ± 0.3	1.7 ± 0.5	0.301	0.028
Elbow medial force	Cocking	2.4 ± 0.5	2.7 ± 0.5**	0.010	0.274
Elbow proximal force	Deceleration	5.5 ± 1.2*	5.3 ± 0.9	0.011	0.074
Elbow torques (Nm/BW × H)					
Elbow flexion torque	Acceleration	19.8 ± 5.5	19.7 ± 5.2	0.399	0.004
Elbow varus torque	Cocking	36.1 ± 8.0	34.8 ± 7.7	0.293	0.084
Wrist forces (N/BW)					
Wrist anterior force	Acceleration	2.3 ± 0.6	2.5 ± 0.4	0.224	0.162
Wrist proximal force	Deceleration	0.9 ± 0.2	1.0 ± 0.3	0.248	0.174
Wrist medial force	Acceleration	3.4 ± 0.7	3.6 ± 0.6	0.675	0.249
Wrist torques (Nm/BW × H)					
Wrist flexion torque	Cocking	14.8 ± 2.7	15.3 ± 2.1	0.224	0.102
Wrist radial deviation torque	Acceleration	12.6 ± 3.7	13.8 ± 3.7	0.613	0.159

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.
BW, body weight; H, height.

effect size ($r = 0.074$) was calculated for this joint kinetic. Peak values of shoulder proximal force, shoulder internal rotation torque, shoulder horizontal adduction torque, elbow anterior force, elbow flexion torque, wrist anterior torque, wrist medial torque, wrist proximal force, wrist flexion torque, and wrist radial deviation torque did not differ between the two groups of tennis players ($P > 0.05$).

Serve efficiency

V_{ball} was significantly faster for the professional players (177.8 ± 17.3 km/h) compared to the advanced players (143.3 ± 14.4 km/h; $P < 0.001$; $r = 0.730$). All the parameters of serve efficiency analysed during the tennis serve were significantly lower for professional players than for advanced players ($P < 0.001$, Table 2). The upper limb joints of professional players experienced lower amounts of stress per meter per second of ball velocity generated during the serve. These results reveal that the professional players were more efficient than the advanced players. These results were noted to have large and medium effect sizes.

Discussion

The aim of this work was to compare the joint kinetics and stroke production efficiency for the shoulder, elbow, and wrist during the serve between professionals and advanced tennis players and to discuss their potential relationship with given overuse injuries. The results of this study are insightful since in the literature, kinetics during sport motion are used to predict potentially injurious behavior by associating joint kinetic peaks and overuse injuries (Atwater, 1979; Fleisig et al., 1995, 1996). Since advanced tennis players are subjected to higher loadings, which are known to be a risk factor of injury, our results surprisingly suggest that their serve technique put them at higher risks of shoulder overuse injuries and, at a lesser degree, of elbow lesions than

Table 2. Parameters of serve efficiency

	Professional ($n = 11$)	Advanced ($n = 7$)	P-value	Effect size
Shoulder forces/ball velocity (efficiency)				
Shoulder inferior force	0.015 ± 0.00	0.028 ± 0.01***	<0.001	0.813
Shoulder anterior force	0.016 ± 0.00	0.022 ± 0.00***	<0.001	0.710
Shoulder proximal force	0.032 ± 0.05	0.036 ± 0.01***	<0.001	0.567
Shoulder torques/ball velocity (efficiency)				
Shoulder internal rotation torque	0.192 ± 0.05	0.232 ± 0.05***	<0.001	0.427
Shoulder horizontal adduction torque	0.305 ± 0.05	0.378 ± 0.08***	<0.001	0.495
Shoulder horizontal abduction torque	0.111 ± 0.03	0.159 ± 0,04***	<0.001	0.574
Elbow forces/ball velocity (efficiency)				
Elbow anterior force	0.009 ± 0.00	0.012 ± 0.00***	<0.001	0.438
Elbow medial force	0.014 ± 0.00	0.019 ± 0.00***	<0.001	0.677
Elbow proximal force	0.030 ± 0.01	0.037 ± 0.01***	<0.001	0.503
Elbow torques/ball velocity (efficiency)				
Elbow flexion torque	0.110 ± 0.03	0.138 ± 0.03***	<0.001	0.449
Elbow varus torque	0.202 ± 0.05	0.244 ± 0.05***	<0.001	0.433
Wrist forces/ball velocity (efficiency)				
Wrist anterior force	0.013 ± 0.00	0.018 ± 0.00***	<0.001	0.569
Wrist proximal force	0.019 ± 0.00	0.025 ± 0.00***	<0.001	0.676
Wrist medial force	0.005 ± 0.00	0.007 ± 0.00***	<0.001	0.603
Wrist torques/ball velocity (efficiency)				
Wrist flexion torque	0.084 ± 0.02	0.108 ± 0.02***	<0.001	0.586
Wrist radial deviation torque	0.071 ± 0.03	0.098 ± 0.03***	<0.001	0.467

***$P < 0.001$.

professional ones, regardless of the number of repetitions during competitions and training sessions. According to the results, advanced players have similar risks of wrist injuries than professional players.

It has been reported that an increase in the amount of shoulder anterior force during the arm cocking phase is directly associated with pathology at the ligamentous restraints (Whiteley, 2007). Indeed, repetitive shoulder anterior forces during overhand activities are responsible for acquired laxity of the shoulder, corresponding to the excessive humeral head translation and an excessive external rotation, associated with pain and discomfort during the arm cocking phase (Braun et al., 2009), and sometimes leading to an unstable painful shoulder (Boileau et al., 2011). In tennis players, the shear forces that occur during overhead movement favor particularly the development of postero-superior impingement (Fleisig et al., 1995; Sonnery-Cottet et al., 2002). Thus, one may assume that the risks of “pathologic laxity” and glenoid labrum injury could be increased for advanced players compared to professional players since they produced higher shoulder anterior force during the cocking phase. Moreover, McLeod and Andrews (1986) have described the “shoulder grinding factor” that causes degeneration of the labrum. The translation of the humeral head induced by anterior shoulder force added to the internal rotation and proximal shoulder force acting on the humerus can cause forceful entrapment of the labrum between the humeral head and the glenoid rim, resulting in labral tearing (Andrews et al., 1991). Advanced tennis players may have a greater risk of this “grinding” injury since they showed greater shoulder anterior force during the cocking phase and similar proximal force (Table 1). Rotator cuff injury often results from tensile failure, as the rotator cuff muscles contract to resist distraction, horizontal adduction, and internal rotation of the shoulder during arm deceleration (Fleisig et al., 1999). Since the advanced players produced similar shoulder proximal force but higher shoulder horizontal abduction torque during the arm deceleration phase (Table 1), they may have a greater risk of rotator cuff injury, sometimes also associated to postero-superior impingement. According to the results, the cocking and deceleration phases during which advanced players are submitted to higher shoulder kinetics, are crucial periods that require particular attention from tennis coaches for avoiding shoulder injuries that seem relatively frequent in club players (15–17.4%; Chard & Lachmann, 1987; Jayanthi et al., 2005).

The similar peak of elbow varus torque generated during the cocking phase by advanced and professional players (Table 1) may imply that these two groups are at the same risk for elbow tension injuries, such as ulnar collateral ligament injury, as well as lateral compression pathologies, such as capitellar osteochondral lesions (Eygendaal et al., 2007). Moreover, the combination of varus torque and elbow extension during the tennis serve may produce the “valgus extension syndrome” in advanced and professional players (Wilson et al., 1983; Eygendaal et al., 2007). This syndrome may produce osteophyte at the posterior and posteromedial aspect of the olecranon tip, causing chondromalacia or loose body formation (Atwater, 1979). The significant difference concerning elbow medial force between advanced and professional players should be interpreted with care since the effect size was small and combined with relative high P-value ($P = 0.01$). The increased elbow medial force in advanced players during the cocking phase may induce a greater risk of ulna-humeral injury than in professional players. Indeed, their oleocranon may tend to impact or impinge against the posteromedial trochlea and oleocranon fossa of the humerus, producing chondral loss, posteromedial osteophytes, and oleocranon stress fractures (Cain et al., 2003; Anderson & Alford, 2010). These results must be related to relevant articles about tennis injuries. Interestingly, Kamien (1988) reported a relatively high prevalence of medial elbow pain (30%) in Australian club-level players. Moreover, the proportion of players that reported having suffered elbow pain during their career ranged from 20% to 47% in the studies involving adult club players (Priest et al., 1977; Chard & Lachmann, 1987; Jayanthi et al., 2005) while it seems lower in the studies including elite and professional players (10.9%; Winge et al., 1989). Concerning professional players, the higher proximal forces they generated along the radial aspect of the elbow during the deceleration phase might lead to the development of osteochondral lesions or osteochondritis dissecans in the capitellum (Anderson & Alford, 2010). However, the interpretation of this last result should be treated with extreme care since the effect size was very small. As a consequence, next research should be focused on further exploration of our possible findings regarding the mechanics of the elbow. If the present results about elbow kinetics are confirmed, further studies should be attentive to the mechanics of the elbow in a different way according to the level of their players. Indeed, a particular attention may be focused on the deceleration phase after the ball impact to identify pathomechanical factors that cause excessive high proximal force at the elbow in professional players. Conversely, in advanced players, researchers must pay attention to the cocking phase for determining the pathomechanical factors that increase the medial component of the elbow force.

This study is the first that provides data about wrist kinetics during the tennis serve. The values of wrist forces and torques in this study are higher than those reported for the tennis forehand (Bahamonde & Knudson, 2003) and suggest that the tennis serve is a skill at risk for the wrist. Indeed, most wrist pains occur because of repetitive overuse loading in tennis induced by shear, proximal forces, and rotational stress (Rettig, 1994). The results suggest that advanced players have a similar risk of tenosynovitis, triangular fibrocartilage complex lesions, and ulnar carpal impingement than professional players since they showed no significant difference of wrist forces and torques compared to professional players. These results are in accordance with epidemiological studies revealing close percents of wrist injuries in elite players (10%; Winge et al., 1989) and in advanced players (6–7%; Chard & Lachmann, 1987; Jayanthi et al., 2005).

Overuse injuries are not only caused by excessive joint kinetics but may be generated by the interaction between joint kinetics and several factors such as the number of repetitions (training and competitions; Kannus, 1997; Hjelm et al., 2012). Although the results of this study confirm that professional tennis players have a better serve technique by demonstrating similar or lower joint kinetics and therefore a theoretically decreased risk of overuse joint injury, their increased volume of play as compared with the advanced ones may account for the similarity in injury rates between the two groups (Abrams et al., 2012).

It has been proposed that efficient serving mechanisms may enable a player to maximize V_{ball} at the least cost (joint load) and the minimum chance of injury (Aguinaldo & Chambers, 2009; Ellenbecker et al., 2009). The results of the current study show that advanced tennis players are less “efficient” since they overload both their shoulder and elbow compared to professional players without reaching higher V_{ball}. One may assume that the low efficiency measured in advanced players could be related to improper mechanics of the kinetic chain for advanced players. It has been indicated that any disruption to the kinetic chain caused by improper mechanics could result in increased loading of upper limb joints in the sequence of movements (Kibler, 1995). As a consequence, it can be supposed that advanced players tried to compensate for the kinetic chain disruption caused by improper serve mechanics by increasing segment activation and loading (Lintner et al., 2008). Different hypotheses about improper tennis serve mechanics could explain higher shoulder and elbow kinetics in advanced players. Indeed, it has been shown that a poor leg drive during the tennis serve induces low ball velocity (Girard et al., 2005, 2007) but increases shoulder and elbow loadings (Elliott et al., 2003). Moreover, it has been reported that an abbreviated backswing produces higher shoulder anterior force during the cocking phase of the tennis serve (Elliott et al., 2003). As a consequence, to prevent overuse shoulder and elbow injuries incurred by advanced players, tennis coaches should be attentive to teach them an efficient lower limb activity and a full backswing. However, all the pathomechanical factors are not well known for the tennis serve. Yet, it has been shown that slight changes in timing and in kinematics have been reported to reduce performance of overhand skill with increased risks of overuse injury (Whiteley, 2007; Fortenbaugh et al., 2009). Most of these results obtained for the baseball pitching could be verified for the tennis serve. As a consequence, further research that tests relationships between kinematics, kinetics, and ball velocity are necessary to understand “where” and “when” failings are located in the tennis serve technique of advanced players compared to professional players.

Perspective

In summary, this study is the first to compare upper limb joint forces of competitive tennis players of different levels. Advanced players demonstrated lower ball velocity but similar or higher normalized upper limb joint kinetics than professional players. As a consequence, the results suggest that they appeared susceptible to high risk of shoulder overuse injuries and at a lesser degree, elbow overuse injuries, regardless of the number of repetitions (competitive and training sessions). The cocking and deceleration phases, during which advanced players are submitted to higher kinetics, are crucial periods that require particular attention from tennis coaches for avoiding shoulder and elbow injuries that are relatively frequent in these players (Chard & Lachmann, 1987; Jayanthi et al., 2005). The lower efficiency of advanced players compared to professional players could be explained by the fact that advanced tennis players may use improper serve technique that could overload their joints. Further research is needed to clearly identify the technical failings in advanced players.

Key words: biomechanics, loadings, shoulder, elbow.

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