Copyeditor: Mary Grace Trillana

Identification of Temporal Pathomechanical Factors during the Tennis Serve

CAROLINE MARTIN[1], RICHARD KULPA[1], MICKAËL ROPARS[1,2], PAUL DELAMARCHE[1], and BENOIT BIDEAU[1]

[1]*M2S Laboratory, UFR APS, University of Rennes 2, ENS Cachan, Bruz, FRANCE; and* [2]*Upper Limb Orthopaedic Surgery Unit, Pontchaillou University Hospital, Rennes, FRANCE*

ABSTRACT

MARTIN, C., R. KULPA, M. ROPARS, P. DELAMARCHE, and B. BIDEAU. Identification of Temporal Pathomechanical Factors during the Tennis Serve. *Med. Sci. Sports Exerc.*, Vol. 45, No. 11, pp. 00–00, 2013. **Purpose**: The purpose of this study was twofold: (a) to measure the effects of temporal parameters on both ball velocity and upper limb joint kinetics to identify pathomechanical factors during the tennis serve and (b) to validate these pathomechanical factors by comparing injured and noninjured players. **Methods**: The serves of expert tennis players were recorded with an optoelectronic motion capture system. These experts were then followed during two seasons to identify overuse injuries of the upper limb. Correlation coefficients assessed the relationships between temporal parameters, ball velocity, and peaks of upper limb joint kinetics to identify pathomechanical factors. Temporal parameters and ball velocity were compared between injured and noninjured groups. **Results**: Temporal pathomechanical factors were identified. The timings of peak angular velocities of pelvis longitudinal rotation, upper torso longitudinal rotation, trunk sagittal rotation, and trunk transverse rotation and the duration between instants of shoulder horizontal adduction and external rotation were significantly related to upper limb joint kinetics and ball velocity. Injured players demonstrated later timings of trunk rotations, improper differences in time between instants of shoulder horizontal adduction and external rotation, lower ball velocities, and higher joint kinetics. **Conclusions**: The findings of this study imply that improper temporal mechanics during the tennis serve can decrease ball velocity, increase upper limb joint kinetics, and thus possibly increase overuse injuries of the upper limb. **Key Words:** BIOMECHANICS, KINETICS, SHOULDER, ELBOW, INJURY

If you ask tennis coaches what their main priorities are when teaching tennis serve, their responses could be "improving performance, especially ball velocity" and "preventing injury." Indeed, the ability for tennis players to produce high ball velocity during the serve is a key element of a successful play because it puts the opponent under stress and may hinder its return. However, epidemiological studies have associated the serve with overuse injuries in the upper limb joints (5,15,31), which are a common medical problem in all competitive levels in tennis (17,30). The etiology of these injuries is assumed to be multifactorial. Among all the risk factors, excessive joint kinetics, linked with poor technique and/or overuse, are commonly cited as causes of these problems (10,11,19–21,38). Any kinematic or temporal pattern that significantly increases joint kinetic values without increasing ball velocity is thus considered as "pathomechanical" (13). Indeed, even minor technical and temporal errors, which are continually repeated throughout a match, a competitive season, or a career, may affect the performance, increase joint kinetics, and consequently cause tendon overuse microinstability problems (19,21). Conversely, it has been suggested that proper temporal mechanics may enable athletes to achieve maximum performance with minimum chances of injury (15). For example, in baseball, it is believed that the safest and most efficient pitching depends on the correct timing and sequence of motions as much as the quality of the motions themselves (7). In such a sequence of motions, the timing of trunk rotations seems to be crucial because the trunk is a link that considerably contributes to the body angular momentum and can affect tennis performance (25,26). Consequently, research has focused on the effects of trunk rotation timing on upper limb joint kinetics during the baseball pitching (1,38). However, there is a lack of similar studies on tennis serve. In a tennis serve, the arm moves from horizontal abduction to adduction and to extreme angles of the shoulder's external rotation during the cocking and acceleration phases. The difference in time between the instant when shoulder begins horizontal adduction and the instant when the shoulder external rotation exceeds 90° represents the shoulder hyperangulation phenomenon (18,28). It is responsible for main shoulder injuries recorded for tennis players, such as anterior microinstability or impingement syndromes (18,28). Indeed, it has been suggested that a delayed shoulder horizontal abduction and an early external rotation may lead to the arm being "late" behind the trunk in

Address for correspondence: Caroline Martin, M.Sc., M2S laboratory, Rennes 2 University, ENS Cachan, Avenue Robert Schuman, Bruz, France; E-mail: caromartin@numericable.fr.
Submitted for publication December 2012.
Accepted for publication April 2013.

0195-9131/13/4511-0000/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e318299ae3b

a traumatic hyperangulation position during the overhand motion (7). Consequently, incorrect difference in time between shoulder horizontal abduction/adduction and external rotation could affect shoulder structures (28,37) and generate rotator cuff injuries and labral tears (18). It has been reported that a poor leg drive decreases ball velocity (14) and increases shoulder and elbow kinetics during the tennis serve (9). However, no study has identified pathomechanical factors by analyzing the effect of temporal patterns on the joint kinetics and ball velocity. Determining the temporal patterns that overload upper limb joints may help tennis players to avoid pathomechanical errors when serving, errors that may lead to overuse injuries and/or reduce ball velocity. As a consequence, the purposes of this study were twofold: (a) to measure the effect of temporal parameters on ball velocity and upper limb joint kinetics to identify pathomechanical factors during tennis serve and (b) to validate these pathomechanical factors by comparing injured and noninjured players.

MATERIALS AND METHODS

Subjects. Twenty male expert tennis players (mean ± SD; age = 24.7 ± 5.6 yr, height = 1.85 ± 0.08 m, mass = 76.8 ± 9.0 kg) with an International Tennis Number between 4 and 1 volunteered in this study (16). Among them, 13 participants were professional players holding a single (17th, 88th, 118th, 147th, 326th, 522nd, 921st, 998th, and 1421st) or a double ATP ranking (35th, 36th, 48th, and 210th). The others were national or regional tennis players. Before 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 ethics committee and conducted in accordance with the 1975 Declaration of Helsinki.

Experimental protocol. Before this 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 (stretching and serves with low ball velocity), 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. The subjects were asked to serve with maximum ball velocity 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. Players were equipped with 38 retroreflective markers placed on anatomical landmarks determined in agreement with previously published data (23,32). 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 three-dimensional (3-D) landmarks trajectories. It was composed of 12 high-resolution cameras (4 megapixels) operating at a nominal frame rate of 300 Hz. Participants only wore shorts to limit any movement of the markers from their anatomical landmarks. After the capture, 3-D coordinates of the landmarks were reconstructed with ViconIQ software (IQ; Vicon, Oxford, UK) with a residual error less than 1 mm. The 3-D motions of each player were expressed in a right-handed inertial reference frame R1 whose origin was at the center of the baseline. X represented the baseline, Y pointed forward, and Z was vertical and pointed upward. The 3-D coordinate data of the markers were smoothed with a Butterworth low-pass filter with a cutoff frequency of 15 Hz, determined by residual analysis (40).

Postimpact ball velocity. Postimpact ball velocity was measured for each trial by using a radar (Stalker Professional Sports Radar, Applied Concepts, Texas; accuracy = ±1 mph, frequency = 34.7 GHz, 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.

Kinetic values. An inverse dynamics approach was used to calculate the peak of joint forces and torques. The serving arm was modeled as a three-link kinetic chain composed of the racket/hand segment, forearm, and upper arm. For the purpose of the study, shoulder anterior and inferior forces, shoulder horizontal abduction and internal rotation torques, elbow medial force, elbow varus torque and flexion torques, wrist flexion, and radial deviation torques were analyzed. The joint forces and torques obtained were first computed in the reference frame R1 and were later transformed to a series of anatomically relevant, right-handed orthogonal local reference frames at each joint. Kinetic peaks were normalized: forces were divided by body mass, and torques were divided by the product of body mass by height (7). The moment of inertia of the racket about its mediolateral axis was computed using the parallel axis theorem and published racket "swing weight" data (36), as suggested by Elliott et al. (9). Racket moment of inertia about the long axis was calculated as reported in the literature (3):

$$\text{moment of inertia}(\text{kg}\bullet\text{m}^{-2}) = (\text{mass} \times \text{head width}^2)/17.75$$

Racket moment of inertia about its anteroposterior axis was defined as the sum of the racket's other two principal moments of inertia (3). Segmental masses and moments of inertia used in the inverse dynamics computations were obtained from previously published data (8). All the kinetic values were calculated by Matlab software 6.5 (Mathworks, Natick, MA).

Temporal parameters. We have extracted four temporal parameters: peak angular velocity of pelvis longitudinal rotation, upper torso longitudinal rotation, trunk sagittal rotation, and transverse rotations. These parameters were selected because they delimit a sequence of proximal-to-distal body motions during which the transfer of energy and momentum from the lower limbs to the upper limb occurs when performing overhand motions (34). During the cocking and acceleration phases of tennis serve, the arm moves from horizontal abduction to adduction and then to extreme angles of the shoulder's external rotation. Therefore, the difference in time between the instant of shoulder's horizontal adduction and the instant the shoulder exceeds an external rotation of 90° is relevant, as it models the shoulder hyperangulation phenomenon (38). A positive value indicates that the instant of shoulder horizontal adduction occurred after the instant the shoulder exceeded 90° of external rotation (Fig. 1A). A negative value indicates that the instant of shoulder horizontal adduction occurred before the instant the shoulder exceeded 90° of external rotation (Fig. 1B). To evaluate the temporal patterns across all participants, the temporal parameters were expressed as a percentage of the normalized serving cycle, defined from ball toss (0%) to ball impact (100%). Ball toss and ball impact were determined by direct observation of the recorded data. Shoulder horizontal adduction and shoulder external rotation were defined and calculated as proposed by Fleisig et al. (12).

Injury data and questionnaire. To establish the relationship between a particular movement pattern measured by a laboratory analysis and a risk of injury, we propose to couple motion analysis techniques with a prospective registration of injuries (22). Consequently, we designed a questionnaire to prospectively determine all injuries related to tennis for a given player during a two-season period after the motion capture session. The players were first asked the following question: "Did you have any injuries that prevented you from playing at 100% of your capacities?" Then the players were asked to report the number of injuries, the name of the injuries, the type of injuries (traumatic or overuse), the location of injuries, their severity, and the tennis strokes affected by these injuries. The players received written information about the definition of an injury and the injury reporting procedure. To overcome limitations of the questionnaire approach (22) and to verify injury data reported by players, coaches and physiotherapists of the ATP Tour were contacted. Moreover, www.tennisinsight.com (a Web site that gathers data on the location of injuries and withdrawal of each player during international tournaments) was also consulted. Among all the injuries reported by the players, only the overuse injuries directly related to the dominant upper limb joints (shoulder, elbow and wrist) and registered pain during the serve were considered to be meaningful and were included in the analysis. Additional confounding factors possibly contributing to injury, including demographic information (age, height, mass, and body mass index), were also reported (2).

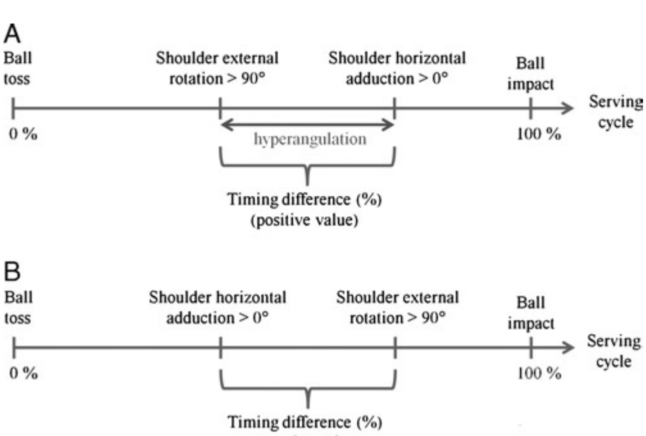

FIGURE 1—Schematic representation of timing difference between shoulder horizontal adduction and shoulder external rotation.

Injury definition. In the present study, an injury was defined as any physical complaint or manifestation sustained by a player, which results from a tennis match or tennis training, irrespective of the need for medical attention or time loss from tennis activities (29). Definitions of injury location, type of injury, and severity were based on the previous consensus statement of Pluim et al. (29). The severity of an injury was defined as the number of days elapsed between the date of the injury and the date of the player's return to full participation in tennis training and availability for matches (29). A traumatic injury was defined as an injury caused by a trauma related to tennis practice, whereas an overuse injury was defined as an injury with a gradual onset and not caused by any trauma (35).

Statistical analysis. Mean and SD values (five trials for each player) were computed for all parameters. Unpaired Student's *t*-tests were used to compare demographic data, ball velocity, and temporal parameters between the injured and the noninjured groups. Pearson and Spearman correlation coefficients were used to assess the relationships between temporal parameters, ball velocity, and peak upper limb joint kinetics (SigmaStat 3.1; Jandel Corporation, San Rafael, CA). In accordance with the definition of Fortenbaugh et al. (13), the parameters that both showed significant positive correlations with joint kinetics and significant negative correlation with ball velocity are considered as "pathomechanical" and are discussed in this study. Statistical significance was defined as $P < 0.05$. 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 $r > 0.5$ (6). Statistical power analysis with $\alpha = 0.05$ and $\beta = 0.2$ revealed that, for the shoulder anterior force, $n = 10$ tennis players were needed to detect a large effect between the two groups.

RESULTS

Overuse injuries data. Eleven players reported upper limb overuse joint injuries, including six players with a shoulder tendinopathy, five players with an elbow tendinopathy, and one player with a wrist tendinopathy (Table 1). Concerning shoulder injuries, symptoms reported by players were clinically related to rotator cuff tendinopathies, labral tears, or type 2 SLAP lesions. Demographic data revealed no

TABLE 1. Demographics of injured group (n = 11).

Player No.	Age	Height (m)	Mass (kg)	BMI (kg·m^{-2})	Ranking	Injury	Location	Severity
1	28	1.81	71	21.6	ITN 4	Type 2 SLAP lesions	Shoulder	Severe
2	22	1.85	72	21.0	ITN 4	RC tendinopathy	Shoulder	Severe
3	23	1.92	91	24.7	ITN 1	RC tendinopathy	Shoulder	Severe
4	30	1.85	84	24.5	ITN 1	Labral tears	Shoulder	Severe
5	29	1.83	80	23.9	ITN 3	RC tendinopathy	Shoulder	Moderate
6	23	1.82	70	21.1	ITN 1	RC tendinopathy	Shoulder	Severe
						Tendinopathy	Elbow	Severe
7	20	1.79	61	19.0	ITN 4	Tendinopathy	Elbow	Moderate
8	22	1.87	74	21.2	ITN 4	Tendinopathy	Elbow	Moderate
9	19	1.92	93	25.2	ITN 1	Tendinopathy	Elbow	Moderate
10	41	1.76	65	19.1	ITN 4	Tendinopathy	Elbow	Moderate
11	18	1.70	68	23.5	ITN 1	Tendinopathy	Wrist	Severe
Mean ± SD	25 ± 7	1.83 ± 0.06	75.4 ± 10.4	22.2 ± 2.2	/	/	/	/

Demographic data obtained at the time of motion capture.
BMI, body mass index; RC tendinopathy, rotator cuff tendinopathy.

statistically significant difference between the injured and the noninjured groups (Table 2).

Relationships between temporal parameters, ball velocity, and peak joint kinetics. Table 3 summarizes the relationships between temporal parameters, ball velocity, and peak upper limb joint kinetics. Significant relations were detected between the timing of peak angular velocity of trunk transverse rotation and the ball velocity, the shoulder anterior force, the shoulder inferior force, the shoulder horizontal abduction torque, the shoulder internal rotation torque, the elbow medial force, the elbow varus torque, the elbow flexion torque, the wrist flexion torque, and the wrist radial deviation torque. These results indicate that a later timing of the peak angular velocity of trunk sagittal rotation is associated with lower ball velocity and greater peak values for these joint kinetics. A later timing of the peak angular velocity of trunk sagittal rotation was significantly correlated with lower ball velocity, higher shoulder anterior force, shoulder inferior force, shoulder horizontal abduction torque, elbow flexion torque, wrist flexion torque, and wrist radial deviation torque. Significant relationships were identified between the timing of upper torso longitudinal rotation and the ball velocity, the shoulder inferior force, the shoulder horizontal abduction torque, the elbow medial force, the elbow flexion torque, the wrist flexion torque, and the wrist radial deviation torque. Significant relations were identified between the timing of pelvis longitudinal rotation and the ball velocity, the shoulder anterior force, the shoulder inferior force, the elbow medial force, the elbow flexion torque, the wrist flexion torque, and the wrist radial deviation torque. Furthermore, the results demonstrate that the more the instant of shoulder external rotation precedes the instant of shoulder horizontal adduction, the more the shoulder anterior force and horizontal abduction torque increase and the more the ball velocity decreases.

Comparisons of peak joint kinetics between the injured and the noninjured groups. The results shown in Table 4 reveal that seven of the nine peaks of joint kinetics analyzed during the serve were significantly different between the injured and the noninjured groups. Indeed, shoulder inferior force, shoulder anterior force, shoulder horizontal abduction torque, elbow medial force, elbow flexion torque, wrist flexion torque, and wrist radial deviation torque were significantly higher in injured players. No statistical difference was found between the injured and the noninjured groups concerning the peaks of shoulder internal rotation torque and elbow varus torque. Moreover, ball velocity was significantly higher in noninjured players than that in injured players.

Comparisons of temporal parameters between the injured and the noninjured groups. The results presented in Table 5 show that the timing of peak angular velocity of trunk sagittal and transverse rotations, pelvis longitudinal rotation, and upper torso longitudinal rotation occurred later in the injured players. The difference in time between the shoulder horizontal adduction and the external rotation was significantly longer for injured players than for noninjured players. The results show that the instant of shoulder external rotation occurred before the instant of shoulder horizontal adduction in injured players. Conversely, noninjured players were able to achieve shoulder horizontal adduction just before extreme positions of external rotation.

DISCUSSION

The purposes of this study were (a) to measure the effects of temporal parameters on ball velocity and on upper limb joint kinetics to identify pathomechanical factors during the

TABLE 2. Demographics of noninjured group with P values of Student's t-test (n = 9).

Player No.	Age	Height (m)	Mass (kg)	BMI (kg·m^{-2})	Ranking
12	18	1.81	76	23.2	ITN 1
13	22	1.77	66	21.1	ITN 3
14	28	1.80	76	23.5	ITN 1
15	25	1.96	78	20.3	ITN 1
16	26	2.02	90	22.1	ITN 1
17	28	1.81	76	23.2	ITN 1
18	30	1.80	79	24.4	ITN 1
19	18	1.89	75	21.0	ITN 1
20	31	1.93	90	24.2	ITN 1
Mean ± SD	25 ± 5	1.87 ± 0.09	78.7 ± 7.1	22.4 ± 1.5	/
P values	0.967	0.282	0.429	0.838	/

P values represent statistical significant analysis between injured and noninjured group data based on unpaired Student's t-test analysis.
BMI, body mass index.

TABLE 3. Correlation coefficients between temporal parameters, ball velocity, and upper limb peak joint kinetics.

Temporal Parameters	Ball Velocity	Shoulder Anterior Force	Shoulder Inferior Force	Shoulder Horizontal Abduction Torque	Shoulder Internal Rotation Torque	Elbow Medial Force	Elbow Varus Torque	Elbow Flexion Torque	Wrist Flexion Torque	Wrist Radial Deviation Torque
Timings of maximal angular velocities										
Trunk transverse rotation	−0.22*	0.43***	0.53***	0.23*	0.22*	0.42***	0.26*	0.28**	0.45***	0.46***
Trunk sagittal rotation	−0.35***	0.36***	0.53***	0.37***	NS	NS	NS	0.34***	0.65***	0.56***
Upper torso longitudinal rotation	−0.35***	NS	0.57***	0.27**	NS	0.21*	NS	0.26*	0.41***	0.54***
Pelvis longitudinal rotation	−0.58***	0.23*	0.54***	NS	NS	0.22*	NS	0.30**	0.41***	0.38***
Timing between the shoulder horizontal adduction and the external rotation	−0.26*	0.40***	NS	0.40***	NS	NS	NS	NS	NS	NS

* $P < 0.05$,
** $P < 0.01$,
*** $P < 0.001$.
NS, nonsignificant.

tennis serve and (b) to validate these pathomechanical factors by comparing injured and noninjured players.

The results of this study are insightful because five pathomechanical factors have been identified during the tennis serve. Indeed, the timings of peak angular velocities of the pelvis longitudinal rotation, upper torso longitudinal rotation, trunk transverse rotation, and sagittal rotation and the difference in time between shoulder horizontal adduction and external rotation were significantly related to upper limb joint kinetics and ball velocity (Table 3). Moreover, the "pathomechanical potential" of these temporal parameters was established in concrete terms by the comparison of their values between the injured and the noninjured groups (Table 5).

The findings of this study lead one to wonder how these temporal parameters increase joint kinetics in the upper extremity and decrease ball velocity and then lead to overuse injuries. Four of the pathomechanical parameters identified in this study concern the timings of the maximum trunk angular velocities (trunk transverse rotation, sagittal rotation, upper torso rotation, and pelvis longitudinal). Indeed, the correlation analyses show that the later the peak angular velocities of these rotations occur, the more upper limb joint kinetics increase and the more ball velocity decreases. Our results are in accordance with a previous study about baseball pitching (39), reporting that the "late trunk rotator" pitchers experienced higher shoulder and elbow kinetics than "early trunk rotators." Moreover, the current study demonstrates that noninjured players whose peak angular velocities of the trunk occurred earlier during the serve exhibited less joint kinetics. These findings can be explained in the light of energy transfer concept, described for the tennis serve (24,37). The serve is often called a "kinetic chain," from the lower limb actions toward the trunk and the upper limb, that would allow the generation, the summation, and the transfer of energy (20,37). The safest and most efficient (decreasing kinetics and increasing ball velocity) transfer of energy from the lower extremity to the upper extremity would depend on the correct timing of peak trunk angular velocities (20,37). Our results suggest that noninjured players were able to maximize ball velocity and reduce upper limb joint kinetics by rotating their trunk at maximal velocities earlier than injured players, allowing the energy to pass from the trunk to the shoulder at precisely the right timing within the correct sequence of movements. However, the exact instants for these optimum peak trunk angular velocities have yet to be determined and need to be addressed in future investigations. Conversely, it has been hypothesized that a breakage of a link in the proximal part of the kinetic chain caused by an incorrect timing would lead to a higher load on the most distal joints (shoulder, elbow, and wrist) and a decrease of ball velocity (37). Thus, improper and later timings of peak trunk, pelvis, and upper torso angular velocities can result in a loss of energy, nontransferred to the serving arm. This loss of energy would force the players to increase joint kinetics as compensation and consequently expose them to a greater risk of upper limb

TABLE 4. Mean ± SD values of normalized peak joint kinetics and ball velocity and comparisons between the injured and the noninjured groups (mean ± SD).

Peak Joint Kinetics and Ball Velocity	Whole Group (*N* = 20)	Noninjured Group (*n* = 9)	Injured Group (*n* = 11)	*P*	Effect Size *r*
Shoulder anterior force (BM)	2.9 ± 0.6	2.7 ± 0.5	3.1 ± 0.6*	0.004	0.293
Shoulder inferior force (BM)	3.3 ± 0.9	2.7 ± 0.5	3.8 ± 0.8*	<0.001	0.663
Shoulder hor. abduction torque (BM × H)	0.23 ± 0.01	0.19 ± 0.06	0.26 ± 0.13*	<0.001	0.354
Shoulder internal rotation torque (BM × H)	0.35 ± 0.08	0.35 ± 0.07	34.7 ± 0.09	0.863	0.018
Elbow medial force (BM)	2.5 ± 0.5	2.3 ± 0.5	2.7 ± 0.4*	<0.001	0.383
Elbow varus torque (BM × H)	0.37 ± 0.09	0.37 ± 0.08	0.37 ± 0.09	0.932	0.009
Elbow flexion torque (BM × H)	0.21 ± 0.05	0.19 ± 0.06	0.22 ± 0.04*	0.011	0.250
Wrist flexion torque (BM × H)	0.17 ± 0.04	0.15 ± 0.03	0.18 ± 0.04*	<0.001	0.391
Wrist radial deviation torque (BM × H)	0.15 ± 0.05	0.13 ± 0.05	0.17 ± 0.05*	<0.001	0.356
Ball velocity ($m \cdot s^{-1}$)	45.9 ± 6.3	47.5 ± 5.4	44.3 ± 6.6*	0.023	0.231

*Significantly different from the noninjured group.
Hor, horizontal; BM, body mass; H, height.

TABLE 5. Mean ± SD values of temporal parameters and comparisons between the injured and the noninjured groups.

Temporal Parameters (% Serve)	Whole Group (N = 20)	Noninjured Group (n = 9)	Injured Group (n = 11)	P	Effect Size r
Timings of maximal angular velocities					
Pelvis longitudinal rotation	88.6 ± 4.9	85.7 ± 3.9	91.5 ± 4.1*	<0.001	0.610
Upper torso longitudinal rotation	89.3 ± 2.7	87.4 ± 3.4	91.1 ± 2.7*	<0.001	0.536
Trunk transverse rotation	87.4 ± 3.4	85.6 ± 3.5	89.2 ± 2.3*	<0.001	0.454
Trunk sagittal rotation	93.8 ± 2.5	92.6 ± 2.7	94.9 ± 1.9*	<0.001	0.445
Timing between the shoulder horizontal adduction and the external rotation	2.2 ± 7.9	−0.4 ± 5.7	4.4 ± 8.8*	0.002	0.264

*Significantly different from the noninjured group. The parameters are expressed in percentage of serve (where 0% corresponds to ball toss and 100% corresponds to ball impact). A positive value indicates that the instant of shoulder horizontal adduction came after the instant when the shoulder exceeds 90° of external rotation. A negative value indicates that the instant of shoulder horizontal adduction came before the instant when the shoulder exceeds 90° of external rotation.

overuse joint injuries. However, further research on this transfer of energy is required to substantiate this hypothesis.

The remaining pathomechanical factor identified in the current study concerns the relative instants of shoulder horizontal adduction and external rotation. During the cocking and acceleration phases of the tennis serve, the arm moves from horizontal abduction to adduction and to extreme angles of external rotation. Our correlation analyses show that the more the instant of shoulder external rotation precedes the instant of shoulder horizontal adduction, the more the shoulder anterior force and horizontal abduction torque increase and the more the ball velocity decreases. Furthermore, our findings demonstrate that the injured players “left” their arm in horizontal abduction for too long during the shoulder external rotation phase, increased their shoulder kinetics, and decreased ball velocity. These results are in accordance with clinical findings. Excessive shoulder horizontal abduction that occurs during the late cocking phase of the throwing motion has been reported to be critical for internal impingement (28) caused by a translation of the humeral head relative to the glenoid (4), which may lead to rotator cuff tears, shoulder tendinopathies, and labral lesions. It has been suggested that this phenomenon, called *hyperangulation*, leads to excessive kinetics on the shoulder anterior capsule (18) and increases anterior shoulder instability and anterior labral lesions. Our results confirm this statement (Table 3). Moreover, our findings show that noninjured players, who were able to achieve shoulder horizontal adduction just before extreme positions of external rotation, demonstrated lower shoulder joint kinetics. Consequently, our findings address the importance of anticipating shoulder horizontal adduction before significant extreme external rotation occurs during the cocking phase of the tennis serve. This anticipation can avoid a pathomechanical hyperangulation of the shoulder and limit risks of overuse joint injuries. However, the relationship between relative timings of shoulder horizontal abduction and external rotation and ball velocity remains unclear and requires further specific investigations.

Interestingly, there is an apparent disparity in the skill level of the players in the two separate groups (injured and noninjured players). Indeed, of the nine noninjured participants, only one player has a national or regional competitive level, and the others were professional players. This result confirms previous findings showing that regional tennis players are more susceptible to high risk of upper limb joint injuries than professionals (27) because they use an improper serve technique with temporal pathomechanical factors.

This study presents limitations. We restricted the observation of injury to a limited period, and we did not specifically analyze the relationship between shoulder injury and hyperangulation phenomenon. Only six participants reported shoulder injuries, so we most likely lacked enough power for any meaningful statistical analysis. Researchers generally believe that increased joint kinetics of the serving arm constitute a risk factor for upper limb overuse joint injury in tennis (9,20,24,33). Our results comply with those reported for the baseball pitching (2) and support this long-held theory by emphasizing the fact that the players with overuse upper limb joint injury showed higher joint kinetics during the serve compared with noninjured players. As recommended in the literature (22), the methodology of this study consisted in coupling a motion analysis with a prospective registration of injuries to assess the relation between a specific movement pattern and an injury risk. However, authors were aware that the injuries reported in the study were probably caused not only by excessive joint kinetics but also by the interaction between joint kinetics and several factors such as anatomy, sport equipment, and overuse (training and competitive planning) (15). As a consequence, further studies taking into account all these potential risk factors are necessary to extend the present results, to understand and prevent tennis injuries, and to propose possible treatments.

CONCLUSIONS

In conclusion, this study identified temporal pathomechanical factors during the tennis serve. The later timing of peak trunk angular velocities and the improper timing between the shoulder horizontal adduction and the external rotation were indeed associated to higher upper limb joint kinetics and lower ball velocity. According to the results, noninjured players were more effective because they are able to maximize ball velocity and limit upper limb joint loadings by using proper temporal parameters during the serve.

Conversely, injured players demonstrated improper timings of trunk and shoulder rotations, reached significantly lower ball velocities, and demonstrated higher joint kinetics. These findings imply that using proper temporal mechanics during the tennis serve can increase ball velocity, decrease upper limb joint kinetic levels, and thus possibly decrease injury rates.

No source of funding was received to complete this project.

The authors thank Marc Christie for his critical review of this manuscript.

There is no conflict of interest for any of the authors. None of the authors have any links with companies or manufacturers who would benefit from the present work.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various level. *J Appl Biomech*. 2007;23(1):42–51.
2. Anz AW, Bushnell BD, Griffin LP, Noonan TJ, Torry MR, Hawkins RJ. Correlation of torque and elbow injury in professional baseball pitchers. *Am J Sports Med*. 2010;38(7):1368–74.
3. Brody H. The moment of inertia of a tennis racket. *Phys Teach*. 1985;23(4):213–6.
4. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: spectrum of pathology. Part I: pathoanatomy and biomechanics. *Arthroscopy*. 2003;19(4):404–20.
5. Carroll R. Tennis elbow: incidence in local league players. *Br J Sports Med*. 1981;15(4):250–6.
6. Cohen J. *Statistical Power Analysis for Behavioral Sciences*. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988. p. 567.
7. Davis JT, Limpisvasti O, Fluhme D, et al. The effect of pitching biomechanics on the upper extremity in youth and adolescent baseball pitchers. *Am J Sports Med*. 2009;37(8):1484–91.
8. De Leva P. Joint center longitudinal positions computed from a selected subset of Chandler's data. *J Biomech*. 1996;29(9):1231–3.
9. Elliott B, Fleisig G, Nicholls R, Escamilia R. Technique effects on upper limb loading in the tennis serve. *J Sci Med Sport*. 2003;6(1):76–87.
10. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med*. 1995;23(2):233–9.
11. Fleisig GS, Barrentine SW, Escamilla RF, Andrews JR. Biomechanics of overhand throwing with implications for injuries. *Sports Med*. 1996;21(6):421–37.
12. Fleisig GS, Nicholls R, Elliott B, Escamilla R. Kinematics used by world-class tennis players to produce high-velocity serves. *Sports Biomech*. 2003;2(1):51–64.
13. Fortenbaugh D, Fleisig GS, Andrews JR. Baseball pitching biomechanics in relation to injury risk and performance. *Sports Health*. 2009;1(4):314–20.
14. Girard O, Micallef JP, Millet GP. Influence of restricted knee motion during the flat first serve in tennis. *J Strength Cond Res*. 2007;21(3):950–7.
15. Hjelm N, Werner S, Renstrom P. Injury risk factors in junior tennis players: a prospective 2-year study. *Scand J Med Sci Sports*. 2012;22(1):40–8.
16. International Tennis Federation. ITN on court assessment [cited 2009 Aug 10]. Available from: http://www.itftennis.com/shared/medialibrary/pdf/original/IO_43630_original.PDF.
17. Jayanthi N, Sallay PI, Hunker P, Przybylski M. Skill-level related injuries in recreational competition tennis players. *J Med Sci Tennis*. 2005;10:12–5.
18. Jobe FW, Pink MM. *Operative Techniques in Upper Extremity Sports Injuries*. St. Louis: Mosby; 1996. p. 730.
19. Kannus P. Etiology and pathophysiology of chronic tendon disorders in sports. *Scand J Med Sci Sports*. 1997;7:78–85.
20. Kibler WB. Biomechanical analysis of the shoulder during tennis activities. *Clin Sports Med*. 1995;14(1):79–85.
21. Kibler WB, Thomas SJ. Pathomechanics of the throwing shoulder. *Sports Med Arthrosc*. 2012;20(1):22–9.
22. Krosshaug T, Andersen TE, Olsen OE, Myklebust G, Bahr R. Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities. *Br J Sports Med*. 2005;39(6):330–9.
23. Leardini A, Cappozzo A, Catani F, et al. Validation of a functional method for the estimation of hip joint centre location. *J Biomech*. 1999;32:99–103.
24. Lintner D, Noonan TJ, Kibler WB. Injury patterns and biomechanics of the athlete's shoulder. *Clin Sports Med*. 2008;27(4):527–51.
25. Martin C, Bideau B, Nicolas G, Delamarche P, Kulpa R. How does the tennis serve technique influence the serve-and-volley? *J Sports Sci*. 2012;30(11):1149–56.
26. Martin C, Kulpa R, Delamarche P, Bideau B. Professional tennis players' serve: correlation between segmental angular momentums and ball velocity. *Sports Biomech*. 2012. AQ3
27. Martin C, Bideau B, Ropars M, Delamarche P, Kulpa R. Upper limb joint kinetic analysis during tennis serve: assessment of competitive level on efficiency and injury risks. *Scand J Med Sci Sports*. (in press). AQ4
28. Mihata T, McGarry MH, Kinoshita M, Lee TQ. Excessive glenohumeral horizontal abduction as occurs during the late cocking phase of the throwing motion can be critical for internal impingement. *Am J Sports Med*. 2010;38(2):369–74.
29. Pluim BM, Fuller CW, Batt ME, et al. Consensus statement on epidemiological studies of medical conditions in tennis. *Br J Sport Med*. 2009;43(12):893–7.
30. Pluim BM, Staal JB, Windler GE, Jayanthi N. Tennis injuries: occurrence, aetiology, and prevention. *Br J Sports Med*. 2006;40(5):415–23.
31. Priest JD, Nagel DA. Tennis shoulder. *Am J Sports Med*. 1976;4(1):28–42.
32. Reed MP, Manary MA, Schneider LW. Methods for measuring and representing automobile occupant posture. Technical Paper 990959. *SAE Trans J Passenger Cars*. 1999;108. AQ5
33. Reid M, Elliott B, Alderson J. Shoulder joint loading in the high performance flat and kick tennis serves. *Br J Sports Med*. 2007;41(12):884–9.
34. Stodden DF, Fleisig GS, McLean SP, Andrews JR. Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation. *J Appl Biomech*. 2005;21(1):44–56.
35. Taimela S, Kujala UM, Osterman K. Intrinsic risk factors and athletic injuries. *Sports Med*. 1990;9(4):205–15.
36. USRSA. *Racquet Sports Industry Magazine*. 2010,38(4):29–32. AQ6
37. Van der Hoeven H, Kibler WB. Shoulder injuries in tennis players. *Br J Sports Med*. 2006;40(5):453–40.
38. Whiteley R. Baseball throwing mechanics as they relate to pathology and performance. A review. *J Sports Sci Med*. 2007;6(1):1–20.
39. Wight J, Richards J, Hall S. Influence of pelvis rotation styles on baseball pitching mechanics. *Sports Biomech*. 2004;3(1):67–83.
40. Winter DA. *Biomechanics and Motor Control of Human Movement*. 2nd ed. New York (NY): John Wiley & Sons; 1990. p. 384.

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = Please define "ATP."

AQ2 = Please define "SLAP."

AQ3 = Please provide volume number and page range.

AQ4 = Please update the publication status of ref. 27.

AQ5 = Please provide page range.

AQ6 = Please provide the article title.

END OF AUTHOR QUERIES