Energy Flow Analysis During the Tennis Serve

Comparison Between Injured and Noninjured Tennis Players

Caroline Martin,^{*†} Benoit Bideau,[†] Nicolas Bideau,[†] Guillaume Nicolas,[†] Paul Delamarche,[†] and Richard Kulpa[†] [AQ: 1][AQ: 2] Investigation performed at University of Rennes 2–ENS Cachan, Bruz, France [AQ: 3]

Background: Energy flow has been hypothesized to be one of the most critical biomechanical concepts related to tennis performance and overuse injuries. However, the relationships among energy flow during the tennis serve, ball velocity, and overuse injuries have not been assessed.

Purpose: To investigate the relationships among the quality and magnitude of energy flow, the ball velocity, and the peaks of upper limb joint kinetics and to compare the energy flow during the serve between injured and noninjured tennis players.

Study Design: Case-control study; Level of evidence, 3.

Methods: The serves of expert tennis players were recorded with an optoelectronic motion capture system. The forces and torques of the upper limb joints were calculated from the motion captures by use of inverse dynamics. The amount of mechanical energy generated, absorbed, and transferred was determined by use of a joint power analysis. Then the players were followed during 2 seasons to identify upper limb overuse injuries with a questionnaire. Finally, players were classified into 2 groups according to the questionnaire results: injured or noninjured.

Results: Ball velocity increased and upper limb joint kinetics decreased with the quality of energy flow from the trunk to the hand + racket segment. Injured players showed a lower quality of energy flow through the upper limb kinetic chain, a lower ball velocity, and higher rates of energy absorbed by the shoulder and elbow compared with noninjured players.

Conclusion: The findings of this study imply that improper energy flow during the tennis serve can decrease ball velocity, increase upper limb joint kinetics, and thus increase overuse injuries of the upper limb joints.

Keywords: tennis serve; energy flow; injuries; biomechanics

The tennis serve has been reported to be one of the most important strokes for winning a match.¹⁸ This stroke is a sequence of motions referred to as a "kinetic chain" that begins with lower limb actions and is followed by rotations of the trunk and the upper limb.¹² This kinetic chain allows the generation, summation, and transfer of mechanical energy to generate high ball velocity.^{10,19} Energy transfer refers to the transmission of mechanical energy from one segment to another. Energy flow refers to the movement of energy into the human body: It includes

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energy generation and absorption at the joints and energy transfer between segments. Although many investigations of the tennis serve refer to the term *energy transfer*, 2,10,14,15,23,32 the energy flow through the kinetic chain during the tennis serve has not, to our knowledge, been documented. Yet understanding the ways that mechanical energy can be generated and transferred between segments during the serve has considerable interests for tennis players, coaches, and medical practitioners.

From the perspective of orthopaedic sport biomechanics,⁶ energy transfer between segments is considered one of the most critical concepts related to sports injury.^{4,35,38} Two parameters, magnitude and quality of energy transfer, are usually considered to be risk factors for injury in sports.^{3,22,26} Concerning the magnitude of energy transfer, it is believed that injuries occur when mechanical energy is transferred or absorbed by the joints in amounts or at rates that exceed the threshold of human tissue damage.^{7,26,27} The quality of energy transfer refers to the proximodistal sequence pattern of energy transfer during the serve.^{19,22,29} It is hypothesized that upper limb joint injuries could be caused by alterations in the energy flow

^{*}Address correspondence to Caroline Martin, M2S Laboratory, UFR APS, University of Rennes 2–ENS Cachan, Campus de Ker Lann, Avenue Robert Schuman, 35170 Bruz, France (e-mail: caromartin@numeric able.fr).

[†]M2S Laboratory, UFR APS, University of Rennes 2–ENS Cachan, Campus de Ker Lann, Bruz, France.

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across segments during the tennis serve.^{11,19,22} Indeed, if the action of one joint in the kinetic chain is altered, then the contribution of the other joints increases to accommodate the loss of energy, which may lead to increased joint loadings and, consequently, overuse joint injuries.^{10,19,20} However, the relationships among energy flow, upper limb joint kinetics, and overuse joint injuries have never been assessed.

From the perspective of sport performance, it has been suggested that an effective energy flow during the serve would allow the player to produce a high ball velocity,¹⁰ which is a key element of successful play.¹⁸ However, it is still unknown whether ball velocity is related to the quality and magnitude of the energy flow through the upper limb kinetic chain during the tennis serve. As a consequence, an analysis of the mechanical energy flow during the tennis serve is necessary because the mechanisms that increase ball velocity and reduce upper limb joint injury risks could be improved.

The purposes of this study were (1) to investigate the relationships among the quality and magnitude of energy flow, the ball velocity, and the peaks of upper limb joint kinetics and (2) to compare energy flow during the serve between injured and noninjured tennis players.

MATERIALS AND METHODS

Participants

[AQ: 4] A total of 19 high-level male tennis players (ranking, international tennis number¹⁷ 4 to 1; mean age, 25.1 ± 5.9 years; height, 1.84 ± 0.07 m; weight, 75.1 ± 9.0 kg) participated voluntarily in this study. At the time of testing, all players were considered healthy, with no significant joint injury or history of pain or surgery on the dominant arm. Kinematic data from the tennis serve of these subjects were previously published.²⁵

Experiment Protocol

Before experimentation, participants were fully informed of the experimental procedures. Written consent was obtained from each player. The local ethics committee approved the study. After a warm-up of 10 minutes, each player performed 5 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.

In Situ Motion Capture

The experiment took place in an indoor tennis court during an Association of Tennis Professionals (ATP) tournament. Players were equipped with 38 retroreflective markers placed on anatomic landmarks. Five additional landmarks were positioned on the racket (Figure 1). A Vicon MX-40 motion capture system (Oxford Metrics Inc) was used to record the trajectories of the 3-dimensional (3D) landmarks. The system was composed of 12 high-resolution cameras (4 megapixels) operating at a nominal frame



Figure 1. The marker positions.

rate of 300 Hz and positioned as shown in Figure 2. Players wore only tight shorts to limit movement of the markers from their anatomic landmarks. After the capture, the 3D coordinates of the landmarks were reconstructed with ViconIQ software (IQ; Vicon) with a residual error of less than 1 mm. The 3D motions of each player were expressed in a right-handed inertial reference frame, where the origin was at the center of the baseline. X represented the parallel direction to the baseline, Y pointed forward, and Z was vertical and pointed upward (Figure 2). The 3D coordinate data of the markers were smoothed using a Butterworth low-pass filter with a cut-off frequency of 15 Hz.

Postimpact Ball Velocity

Postimpact ball velocity was measured for each trial by use of a radar (Stalker Professional Sports Radar; precision, ± 1.6 km/h; frequency, 34.7 GHz; target acquisition time, 0.01 seconds) fixed on a 2.5-m height tripod placed 2 m behind the players in the direction of the serve.

Phases of the Serve

To simplify energy flow interpretation, the serve motion was divided into 4 phases between meaningful events that showed the importance of these temporal phases in relation to serve kinetics and ball velocity, in accordance



Figure 2. The filming setup.

with previous studies^{2,24} (Figure 3). The early cocking phase began when the server tossed the ball (BT); it ended with the maximal elbow flexion (MEF). Next was the middle cocking phase, from the MEF to the lowest point of the racket (RLP). Then the late cocking phase began with RLP until the maximal external rotation of the shoulder (MER). The arm acceleration phase followed, ending with ball impact (IMP). We determined BT and IMP by direct observation of the recorded data, and the other time events were calculated from the kinematic data.

Determination of the Joint Forces and Torques of the Racket Arm

The stroking arm was modeled as a 3-link kinetic chain composed of the hand + racket segment, the forearm, and the upper arm. The hand and racket were assumed to move as a single rigid segment during the serve. Segmental masses and moments of inertia used in the inverse dynamics calculations were obtained from previously published data.⁹ The inverse dynamics approach was used to calculate the joint forces and torques based on the stroking arm model. All these data were resolved in the inertial reference frame and were included in energy flow calculations.

For the purpose of the study, kinetics values from the motion capture were calculated before the epidemiological follow-up of the tennis players. The peaks of shoulder anterior and inferior forces, shoulder horizontal abduction and internal rotation torques, elbow medial force, elbow varus and flexion torques, wrist flexion and radial deviation torques were analyzed. [AQ: 5] These joint kinetics were first computed in the inertial reference frame and were later transformed to a series of noninertial, anatomically relevant, right-handed orthogonal reference frames at each joint. Kinetic peaks were normalized. Forces were normalized by body mass and torques were divided by the product of body mass by height.⁸ The moment of inertia of the racket about its mediolateral axis (I_M) was computed using the parallel axis theorem and published racket "swing

weight" data.³⁶ The racket moment of inertia about the long-axis was calculated as used by Brody⁵:

$$I_L(kg.m^{-2}) = \frac{mass(kg) \times head \, width^2m}{17.75}$$

Racket moment of inertia about its anterior-posterior axis (I_A) was the sum of the racket's other 2 principal moments of inertia.⁵

Energy Flow Calculations

Muscular joint forces and torques produce energy that flows through the joints of the kinetic chain. In this study, variables concerning energy flow were quantified from the resultant joint forces and torques using a joint power analysis detailed by Robertson and Winter³⁴ and Zatsiorsky.³⁹ The variables of energy flow were the joint force powers (*JFP*), the segment torque powers (*STP*), the joint torque powers (*JTP*), and the segment powers (*SP*). All the power flow variables were normalized by the body mass of each participant.

Joint Force Power: Rate of Energy Transfer by the Joint Forces. The joint force power, *JFP*, is computed as the scalar product of the vectors of joint force (F_j) and linear univelocity (v_j) of the joint center *j*:

$$JFP = F_j \cdot v_j$$
.

The role of the joint force has been described as a simple mechanism of energy transfer between adjacent segments since the rate at which mechanical energy is lost by one segment is equivalent to the rate at which energy is gained by its neighbor.³⁴ The larger the joint force and linear velocity of the joint center, the greater is the rate of energy transfer—that is, the amount of energy transmitted per unit of time from one body segment to another.³⁹ As a consequence, the joint powers due to the joint forces (*JFP*) are hereafter referred to as the rates of energy transfer by the joint forces (Table 1).

Segment Torque Power: Rate of Energy Transfer by the Joint Torques. The segment torque power, STP, for the body segment is computed as the scalar product of the vectors of joint torque (T_j) and angular velocity $\dot{\theta}_s$ of the body segment s:

$$STP = T_j \cdot \dot{\theta}_s$$

Joint Torque Power: Rate of Energy Absorption or Generation by the Joint Torques. The joint torque power, JTP, is computed as the scalar product of the vectors of joint torque (T_j) and angular velocity $(\dot{\alpha})$ of the joint j:

$$JTP = T_i \cdot (\dot{\theta}_d - \dot{\theta}_p) = T_i \cdot \dot{\alpha},$$

where $\dot{\theta}$ is the vector of the angular velocity of the body segment and subscripts *d* and *p* refer to the distal and proximal segments adjacent to the joint.



Figure 3. The main phases and events of the serve. BT, ball toss; IMP, ball impact; RLP, racket lowest point; MEF, maximal elbow flexion; MER, maximal external rotation of the shoulder.

 TABLE 1

 Summary of the Relationships Between Joint Power Analysis and Rates of Energy Flow

Relationship	Equation
Joint force powers (<i>JFP</i>) = rates of energy transfer by the joint forces	$JFP{=}F_j \cdot v_j$
Joint torque powers (JTP) = rates of energy generation or absorption by the joint torques	$JTP = T_j \cdot (\dot{ heta}_d - \dot{ heta}_p) = T_j \cdot \dot{lpha}$
Segment torque powers (STP) = rates of energy transfer by the joint torques for specific situations ³⁴	$STP{=}T_j\cdot\dot{ heta}_s$
Segment powers (SP) = rates of energy output from or input into the segments	$SP {=} JFP_d {+} JFP_p {+} STP_d {+} STP_p$

^{*a*}*d*, distal joint of the segment; F_j , joint force vector; *j*, joint; *p*, proximal joint of the segment; T_j , joint torque vector; v_j , univelocity vector; $\dot{\alpha}$, vector of angular velocity of the joint; $\dot{\theta}$, vector of the angular velocity of the body segment.

Joint torques can generate and absorb mechanical energy whereas segment torques can transfer energy. The sign and relative magnitudes of these power terms indicate whether the joint torques generate or absorb energy and whether the energy is transferred across segments.³¹ When segments on either side of the joint rotate in opposite directions, joint torques either generate or absorb power but energy is not transferred between adjacent segments. If the adjacent segments rotate in the same direction, energy transfer due to segment torque powers occurs.³¹ For these specific situations (adjacent segments rotating in the same direction), the segment torque powers are consequently hereafter referred to as the rates of energy transfer by the joint torques (Table 1). The joint torque powers (JTP) are hereafter referred to as the rates of energy absorption or generation by the joint torques (Table 1).

Segment Power: Rate of Energy Output From or Input Into the Segments. The segment power (SP) is the summation of the segment torque powers and the joint force powers at each end of the body segment:

$$SP = JFP_d + JFP_p + STP_d + STP_p$$

where subscripts d and p refer to the distal and proximal joints of the segment. The segment powers (SP) are hereafter referred to as the rates of energy output from or input into the segments (Table 1).

Indicator of Energy Flow Quality. Late cocking (RLP to MER) and acceleration (MER to IMP) are crucial periods for energy flow from the trunk to the hand during overhead movements.²² Martin et al²³ highlighted that the trunk contribution to ball velocity is overwhelming during the late cocking phase (RLP to MER) whereas the hand + racket segment plays an important role during the acceleration phase (MER to IMP) of the tennis serve. In the same way, it has been shown that skilled ball throwers adopt

a hierarchical control in which the proximal muscle torques create a dynamic foundation for the entire limb motion that is beneficial for arm velocity.¹⁶

Moreover, the kinetic chain theory proposes that energy flows in the upper body by following a proximodistal pattern from the trunk to the hand + racket. Consequently, to estimate the quality of energy flow, it appears interesting to determine and compare the energy flow patterns between the trunk during late cocking (RLP to MER) and the hand + racket during acceleration (MER to IMP). In this study, the ratio between the mean rate of energy that left the trunk during the cocking phase (RLP to MER) and the mean rate of energy that went in the hand + racket during the acceleration phase (MER to IMP) was calculated. This ratio was proposed to be an indicator of the quality of energy flow from the trunk to the hand + racket during the last crucial phases of the serve.

Injury Data and Questionnaire

A questionnaire was used to prospectively determine all injuries related to tennis for a given player during a 2season period after the motion capture and the calculation of joint kinetics. In this questionnaire, players were asked, "Did you have any injuries that prevented you from playing at 100% of capacity?" The players were asked to report the number of injuries, the name of injuries, the type of injuries (traumatic or overuse), the location of injuries, the injury severity, and the tennis strokes affected by injuries. The players received written information about the definition of injury and the injury reporting procedure. To reduce limitations of the questionnaire approach³ and verify injury data reported by players, we contacted the coaches and physical therapists of the ATP tour. Moreover, we consulted TennisInsight, a website that gathers data on injury location and withdrawal of each player during international tournaments (www.tennisinsight.com). Among all the injuries reported by the players, only the overuse injuries that were directly related to the dominant upper limb joints (shoulder, elbow, and wrist) and that were painful during the serve 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.¹

Injury Definition

In the present study, an injury was defined as any physical complaint or manifestation sustained by a player that results from a tennis match or tennis training, irrespective of the need for medical attention or time loss from tennis activities.³⁰ Definitions of injury location, type of injury, and severity classification were based on the previous consensus statement of Pluim et al.³⁰ Injury severity was measured according to the period of missed tennis practice: slight (0 days), minimal (1-3 days), mild (4-7 days), moderate (8-28 days), severe (>28 days–6 months), and long-term (>6 months).³⁰

Statistical Analyses

Means and standard deviations (5 trials for each player) were calculated for all variables. Student t tests were used to compare rates of energy flow between injured and noninjured players. When the normality test failed, Mann-Whitney tests were used. The relationships among the quality and magnitude of the energy flow, peaks of upper limb joint kinetics, and ball velocity were analyzed with Spearman or Pearson correlation coefficients. The level of significance was established at P < .05 (SigmaStat 3.1; Jandel Corp).

RESULTS

Overuse Injuries

Among all the participants, 11 players had overuse injuries involving an upper limb joint, including 6 players with shoulder tendinopathy, 5 players with elbow tendinopathy, and 1 with wrist tendinopathy (Table 2). Symptoms of shoulder injuries reported by the players were clinically accorded to rotator cuff tendinopathies, labral tears, or type 2 superior labral anterior-posterior (SLAP) lesions. Symptoms of elbow injuries reported by players were accorded to medial or lateral "tennis elbow." Demographic data revealed no statistically significant difference between the injured and the noninjured groups (respective mean age, 25 ± 7 vs 25 ± 5 years [P = .967]; height, $1.87 \pm$ 0.09 vs 1.83 ± 0.06 m [P = .282]; weight, 75.4 ± 10.4 vs $78.7 \pm$ 7.1 kg [P = .429]).

Rates of Energy Transfer

by the Joint Forces and the Joint Torques

Figure 4 presents the mean rates of energy transfer by the joint forces and the joint torques during the phases of serve. During the BT-to-MEF phase, the mean rates of energy transfer by the shoulder, elbow, and wrist forces were higher for noninjured than for injured players. During the MEF-to-RLP phase, the mean rate of energy transfer by the wrist forces was significantly larger for noninjured players than for injured ones. Conversely, the mean rate of energy transfer by the wrist torques was significantly larger during the same phase for injured players than for noninjured players. During the RLP-to-MER phase, injured players significantly transferred more energy by the shoulder, elbow, and wrist forces than did noninjured players. Between MER and IMP, the mean rate of energy transfer by the shoulder forces was significantly higher for injured players than for noninjured players.

Rates of Energy Generation: Absorption by the Joint Torques

The mean rates of energy generation and absorption by the joint torques during the phases of the serve are presented

injury Data						
Player	Ranking	Injury	Location	Severity		
1	ITN 4	Type 2 SLAP lesions	Shoulder	Severe		
2	ITN 4	RC tendinopathy	Shoulder	Severe		
3	ITN 1	RC tendinopathy	Shoulder	Severe		
4	ITN 1	Labral tears	Shoulder	Severe		
5	ITN 3	RC tendinopathy	Shoulder	Moderate		
6	ITN 1	RC tendinopathy	Shoulder	Moderate		
		Tendinopathy	Elbow	Severe		
7	ITN 4	Medial tennis elbow	Elbow	Moderate		
8	ITN 4	Medial tennis elbow	Elbow	Moderate		
9	ITN 1	Lateral tennis elbow	Elbow	Moderate		
10	ITN 4	Medial tennis elbow	Elbow	Moderate		
11	ITN 1	Tendinopathy	Wrist	Severe		

TABLE 2 Injury Data^a

^aITN, international tennis number, RC, rotator cuff; SLAP, superior labral anterior-posterior.



Figure 4. Mean \pm SD rates of energy transfer by the joint forces (W/kg) and segment torque powers (W/kg) during the phases of the serve. BT, ball toss; IMP, ball impact; RLP, racket lowest point; MEF, maximal elbow flexion; MER, maximal external rotation of the shoulder. ****P* < .001; ***P* < .01; **P* < .05.

in Table 3. The shoulder and the elbow torques of noninjured players generated significantly higher rates of energy than did the shoulder and the elbow torques of injured players, which absorbed energy, respectively, during the RLP-to-MER and MER-to-IMP phases of the serve (P < .05). Concerning the wrist joint, noninjured players generated energy at the wrist joint, whereas injured players absorbed energy during the same phase. At the wrist, the joint torques of injured players absorbed higher rates of energy between MEF and MER (P < .001). Rates of Energy Output From or Input Into the Upper Limb Segments During the Serve Phases

Significantly higher rates of energy output from the trunk, the upper arm, the forearm, and the hand + racket were noticed for noninjured players compared with injured players for the BT-to-MEF phase (Table 4). Significant differences existed between injured and noninjured players for the rate of energy output from the trunk between RLP and MER and between MER and IMP.

Phase	Noninjured Players $(n = 8)^b$	Injured Players $(n = 11)^b$	Function	P Value	
Shoulder					
BT to MEF	0.14 ± 0.15	0.10 ± 0.12	Generation	.151	
MEF to RLP	1.00 ± 1.11	0.66 ± 0.67	Generation	.593	
RLP to MER	1.10 ± 2.32^{c}	-0.35 ± 2.71	Generation/absorption	.013	
MER to IMP	6.60 ± 2.85	5.78 ± 3.79	Generation	.168	
Elbow					
BT to MEF	0.11 ± 0.09	0.08 ± 0.05	Generation	.313	
MEF to RLP	0.17 ± 0.30	0.13 ± 0.11	Generation	.419	
RLP to MER	1.26 ± 1.23	0.79 ± 0.68	Generation	.348	
MER to IMP	1.28 ± 1.40	-1.63 ± 1.88^d	Generation/absorption	<.001	
Wrist			-		
BT to MEF	0.02 ± 0.03	0.02 ± 0.04	Generation	.170	
MEF to RLP	0.01 ± 0.09	-0.10 ± 0.12^{e}	Generation/absorption	<.001	
RLP to MER	-0.21 ± 0.26	-0.35 ± 0.35^{d}	Absorption	.033	
MER to IMP	1.35 ± 0.69	1.37 ± 0.86	Generation	.917	

TABLE 3Rates of Energy Generation or Absorption by the Joint TorquesDuring the Phases of the Serve in Noninjured and Injured Players^a

^{*a*}BT, ball toss; IMP, ball impact; RLP, racket lowest point; MEF, maximal elbow flexion; MER, maximal external rotation of the shoulder. ^{*b*}Rates of energy generation/absorption are expressed as W/kg, mean \pm SD.

 $^{d}P < .05.$

 $^{e}P < .001 \ [AQ: 6]$

Indicator of Energy Flow Quality. The indicator of energy flow quality was significantly higher for noninjured players (88.1% \pm 16.9%) than for injured players (71.1% \pm 15.0%) (P < .001). The indicator of energy flow quality was significantly correlated to the ball velocity and to several peaks of upper limb joint kinetics (Table 5).

Ball Velocity

Ball velocity was significantly higher for noninjured players (170.9 \pm 19.5 km/h) than for injured players (159.5 \pm 23.9 km/h) (P = .023).

DISCUSSION

The aims of this study were (1) to investigate the relationships among the quality and magnitude of energy flow, ball velocity, and the peaks of upper limb joint kinetics and (2) to compare the energy flow during the serve between injured and noninjured players.

Relationships Among Energy Flow, Ball Velocity, and Upper Limb Joint Kinetics

The correlation analyses show that the quality of energy flow is positively related to joint kinetics and negatively to ball velocity (Table 5). Consequently, the players with high quality of energy flow from the trunk to the hand + racket are those with the highest ball velocities and the lowest upper limb joint kinetics. Based on these findings, it appears that minimizing the risk of injury (ie, decreased kinetics) and maximizing performance quality (ie, increased ball velocity) are compatible with one another. Conversely, these results confirm that a poor energy flow from the trunk to the hand + racket during the serve limits ball velocity and consequently decreases the performance of tennis players, as suggested by previous researchers.^{21,22} These findings confirm also that poor energy flow can cause a "catch-up" situation,^{19,22} during which players with a poor energy flow must create more loads at the most distal joints to offset energy dissipation along the kinetic chain.

Comparison of Energy Flow Between Injured and Noninjured Players

The results demonstrate that significantly higher rates of energy left the trunk and entered the upper arm and the forearm for noninjured players compared with injured players for the BT-to-MEF phase. This result could explain why higher rates of energy came into the hand + racket segment for noninjured players than for injured players during the BT-to-MEF and MEF-to-RLP phases.

Energy transfer seemed to be more efficient for noninjured players than for players who would be injured during the prospective follow-up. Consequently, the results suggest that an impairment of proximodistal energy transfer predisposed players to increased injury risk. It seemed that injured players did not take advantage of the higher output of energy from the trunk during the last crucial phases of the serve. Although the mean rate of energy that left the trunk was significantly higher for injured players during late cocking (RLP to MER), similar mean rates of energy came into the hand + racket for both groups of players during the acceleration (MER to IMP). The indicator of energy flow quality revealed that 71% of

 $^{^{}c}P < .01.$

Phase	Noninjured Players $(n = 8)^b$	Injured Players $(n = 11)^b$	Energy Flow	P Value	
Trunk					
BT to MEF	-0.5 ± 0.6^c	-0.0 ± 0.2	Output	<.001	
MEF to RLP	-11.8 ± 5.2	-10.8 ± 4.7	Output	.346	
RLP to MER	-20.4 ± 4.6	-24.7 ± 4.1^c	Output	<.001	
MER to IMP	-7.1 ± 2.1	-8.8 ± 3.2^c	Output	<.001	
Upper arm			-		
BT to MEF	0.3 ± 0.3^c	0.0 ± 0.1	Input	<.001	
MEF to RLP	5.4 ± 2.7	5.2 ± 2.0	Input	.570	
RLP to MER	3.3 ± 1.7	3.7 ± 2.1	Input	.345	
MER to IMP	-5.3 ± 1.8	-4.8 ± 1.9	Output	.158	
Forearm			-		
BT to MEF	0.3 ± 0.2^d	0.1 ± 0.1	Input	.002	
MEF to RLP	4.9 ± 2.4	$4.7~\pm~2.0$	Input	.617	
RLP to MER	8.3 ± 1.6	8.8 ± 2.2	Input	.243	
MER to IMP	-2.0 ± 0.8	-2.4 ± 0.5	Output	.087	
Hand + racket			-		
BT to MEF	0.2 ± 0.1^d	0.1 ± 0.1	Input	.002	
MEF to RLP	2.4 ± 1.4^e	1.8 ± 0.9	Input	.048	
RLP to MER	11.8 ± 3.3	12.2 ± 3.0	Input	.488	
MER to IMP	$17.7~\pm~4.2$	17.5 ± 4.0	Input	.978	

 TABLE 4

 Rates of Energy Output From or Input Into the Upper Limb Segments

 During the Phases of the Serve in Injured and Noninjured Players^a

^aBT, ball toss; IMP, ball impact; RLP, racket lowest point; MEF, maximal elbow flexion; MER, maximal external rotation of the shoulder. ^bRates of energy output and input are expressed as W/kg, mean \pm SD.

 $e^{P} < .05.$

 TABLE 5

 Spearman and Pearson Correlation Coefficients for Energy Flow Quality, Ball Velocity, and Peaks of Upper Limb Joint Kinetics^a

		Shoulder			Elbow					
	Ball velocity	Proximal Force	Anterior Force	Inferior Force	Horizontal Adduction Torque	Internal Rotation Torque	Anterior Force	Medial Force	Varus Torque	Flexion Torque
Indicator of energy flow quality	0.55^{b}	-0.28^c	-0.48^{b}	-0.63^{b}	-0.25^d	NS	-0.27^c	-0.25^{d}	NS	-0.25^{d}

^aNS, nonsignificant.

 $^{d}P < .05.$

the mean rate of energy that left the trunk during the late cocking phase (RLP to MER) entered the hand + racket segment during the acceleration phase (MER to IMP) in injured players, while this percentage reached about 88% in noninjured players (Table 5). Consequently, this result suggests a poor quality of energy flow from the trunk to the hand + racket for injured players during the crucial last phases (RLP to MER, MER to IMP) of the tennis serve. This poor quality of energy flow was probably responsible for the lower ball velocity noticed for injured players and could be one of the causes of the upper limb joint injuries registered for injured players. An optimal use of the sequential involvement of each link in the kinetic chain should allow the generation, summation, transfer, and regulation of mechanical energy from the legs to the hand +racket.^{10,19,22,37} But for injured players, the results suggested that the energy was partly dissipated through the upper limb kinetic chain, decreasing ball velocity and probably increasing the risk of upper limb joint injury. It has been suggested that alterations in the energy flow across segments during the tennis serve could lead to overuse injuries of the upper limb joints.^{11,19,22} Indeed, it has been hypothesized that if the action of one joint of the kinetic chain is altered, the contribution of the other joints

 $^{{}^{}c}P < .001.$ ${}^{d}P < .01.$

 $^{{}^{}b}P < .001.$

 $^{{}^{}c}P < .01.$

will increase to accommodate the loss of energy, which may lead to tissue overloads.^{10,19,20} According to our results, the energy flow through the shoulder and the elbow joints seemed to be impaired in the group of players who would be injured during the prospective follow-up. Indeed, although the rate of energy that left the trunk to the upper arm was significantly higher in injured players than in noninjured players, it was mainly absorbed by the shoulder and elbow torques during the last cocking (RLP to MER) and acceleration (MER to IMP) phases for injured players rather than transferred to the upper arm. [AQ: 7]

We have previously published results on the tennis serve kinematics of our 2 groups that can enlighten the energy transfer differences observed between injured and noninjured players.²⁵ Our past results showed that players in our injured cohort demonstrated later timing of trunk rotation and shoulder hyperangulation because they left their arm in horizontal abduction for too long during the shoulder external rotation phase.²⁵ Moreover, in injured players, the maximal angular velocity of pelvis longitudinal rotation occurred after the maximal angular velocity of shoulder longitudinal rotation, while it was the opposite in noninjured players.²⁵ Consequently, the proximodistal sequence of rotations from the pelvis to the shoulders was not observed in injured players. To improve energy transfer, coaches should verify that their players longitudinally rotate their shoulders at maximal velocities after their pelvis, allowing the energy to pass from the trunk to the shoulder at precisely the right timing within the correct sequence of movements.

The shoulder, elbow, and wrist of injured players absorbed significantly higher rates of energy than those of noninjured players during the serve. During the late cocking phase, which is a crucial phase of the serve with regard to injury potential,^{12,24} the magnitude of energy transfer by the shoulder, elbow, and wrist forces was higher for injured than noninjured players (Figure 4). The Committee on Trauma Research⁷ included energy absorption as a causal mechanism in musculoskeletal injuries. Moreover, energy flow can result in overuse joint injury when the energy transferred exceeds the tolerance of the tissues involved.^{4,25,26} These statements about the relationships between the magnitude of energy transfer and injuries are confirmed by our results, since there were 6 players with shoulder injury, 4 players with elbow tendinopathy, and 1 with wrist tendinopathy among the injured players (Table 2). We were aware that impairment of proximodistal energy transfer precedes the reported injuries but may interact with several factors such as anatomy, physical fitness, or body composition to produce clinical symptoms.^{3,4}

Since joint power analysis assumes that the joint torques are produced by one-joint muscles,³³ the current study was limited to the analysis of energy transfer between adjacent segments due to muscular torques without taking account of multijoint muscles that can transfer energy between nonadjacent segments.³¹ Moreover, recent studies have focused on energy transfer mechanisms with a state-power analysis¹³ to decompose the mechanical energy of the segments to causal components resulting from the muscular and nonmuscular interactive torques in complex human movements.²⁸ Future research is needed to investigate more precisely the energy redistribution mechanisms among multiple segments involved in the tennis serve. Limitations of this study also include a small sample size. The sample size was somewhat small because we only included male professional and advanced tennis players and participation was voluntary. Moreover, we restricted observation for injury to a limited period and we did not specifically analyze the relationship between overuse injury at a given joint and energy flow variables. Indeed, only 6 participants reported shoulder injuries, 5 reported elbow injuries, and 1 reported wrist injury, so we most likely lacked enough power for any meaningful statistical analysis.

CONCLUSION

This study illustrates the concept of mechanical energy flow through the kinetic chain for the tennis serve. In the tennis serve, the ball velocity increased and the upper limb joint kinetics decreased with the quality of energy flow from the trunk to the hand + racket. Concerning the relationship between the quality and magnitude of energy flow during the serve and the appearance of upper limb injuries in tennis players, the results show that energy flow differences are present before the onset of clinical symptoms. Consequently, the alterations of energy flow from the trunk to the racket can play a predictive role in both serve performance and injury. For injured players, the results showed a poor quality of energy flow through the upper limb kinetic chain during the last phases of the serve, decreasing ball velocity and probably increasing risks of overuse joint injuries, anywhere in the dominant arm, not only in the shoulder. Moreover, the shoulder, the elbow, and the wrist of injured players absorbed significantly higher rates of energy than did the joints of noninjured players during the serve. This phenomenon could be responsible for the appearance of overuse joint injuries in the upper limb reported in this study. Our results indicate that the development of an efficient energy flow appears to be crucial to reach optimal performance and minimize injury risk.

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