ORIGINAL ARTICLE

Biomechanical analysis of the "waiter's serve" on upper limb loads in young elite tennis players

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Abstract

Waiter's serve (WS) is a specific tennis serve posture frequently observed in young players, and commonly considered as a technical error by tennis coaches. However, biomechanical impact of WS is unknown. The aims of this study were to identify the potential consequences of WS in young elite players relating to performance and injury risk, and to explain the kinematic causes of WS. Serve of 18 male junior elite players (Top 10 national French ranking, aged 12-15 years) was captured with a 20 camera, 200 Hz VICON MX motion analysis system. Depending on their serve technique, the players were divided into two groups (WS versus Normal Serve [NS]) by experienced coaches. Injury data were collected for each player during a 12-months period following the motion capture. Normalized peak kinetic values of the dominant arm were calculated using inverse dynamics. In order to explain WS posture, upper limb kinematics were calculated during the cocking and the acceleration phases of the serve. Shoulder internal rotation (IR) torque, wrist proximal and anterior forces ($P < 0.05$) and elbow varus torque ($P < 0.01$) were significantly higher in WS group, with no difference from NS group concerning serve velocity. Moreover, significant lower shoulder abduction and higher wrist extension ($P < 0.05$) were observed for WS players during the cocking phase. Even if no significant difference was found between groups concerning injuries, higher upper limb joint loads suggested WS could be considered as pathomechanical in young elite players and could lead to upper limb joint injuries.

Keywords: *Tennis, waiter's serve, young elite, joint loads, biomechanics.*

Introduction

The serve is described as the most important stroke in elite tennis players (Johnson, McHugh, Wood, & Kibler, 2006; O'Donoghue & Brown, 2008). The ability for these players to produce high-ball velocity, keeping accuracy and consistency, is a key element of successful play (Brody, 2003; O'Donoghue & Brown, 2008). However, serve is a violent stroke, involving large ranges of motion, high segmental velocities and excessive joint loads in upper limbs to powerfully hit the ball (Abrams, Harris, Andriacchi, & Safran, 2014; Elliott, Fleisig, Nicholls, & Escamilla, 2003; Fleisig, Nicholls, Elliott, & Escamilla, 2003; Wagner et al., 2014).

In tennis, epidemiological studies often associated overuse injuries with upper limb joints, and the etiology of these overuse injuries is assumed to be multifactorial (Abrams, Renstrom, & Safran, 2012; Pluim & Staal, 2010). Since high joint loads in shoulder and elbow have been measured during serve motion (Abrams et al., 2014; Elliott et al., 2003; Martin, Bideau, Ropars, Delamarche, & Kulpa, 2014) with peak values considered as dangerous for player's physical integrity (Dillman, Schultheis, Hintermeister, & Hawkins, 1995), excessive joint loads are commonly cited as causes of these injuries (Abrams et al., 2014; Elliott et al., 2003; Martin et al., 2014; Reid, Elliott, & Alderson, 2007).

Studies about upper limb joint loads in tennis serve focused on adult players (Abrams

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et al., 2014; Elliott et al., 2003; Martin et al., 2014; Reid et al., 2007). However, it seems that a particular attention must be paid to young elite tennis serve. First, young elite players are a specific population, systematically involved in a high-intensity training and tournament program. While no consensus seems to be established concerning exposure to tennis and injury, some epidemiological investigations suggested that an increased volume of play is likely to be a risk factor for tennis injury (Abrams et al., 2012; Pluim & Staal, 2010). Therefore, young elite players may be naturally considered as a high-risk population for injury. Serve is also the most difficult stroke in tennis, involving complex coordination of limbs and joint movements in order to transfer forces along the kinetic chain (Kovacs & Ellenbecker, 2011; Wagner et al., 2014). Thus, skill acquisition of serve for young players induces repetitive training, leading potentially to overuse injury (Ellenbecker, Roetert, & Riewald, 2006). Finally, mechanisms generating overuse injuries in adult athletes may be initiated during the athlete's early playing years, as Andrews and Fleisig (1998) affirmed it for baseball pitching. Interestingly, previous scientific studies in tennis showed that improper serve patterns could increase joint loads without increasing ball velocity (Elliott et al., 2003; Martin, Kulpa, Ropars, Delamarche, & Bideau, 2013). Consequently, these patterns are defined as "pathomechanical factors" (Fortenbaugh, Fleisig, & Andrews, 2009; Martin et al., 2013). Thus, teaching efficient technique to young elite without increasing joint loads appears to be crucial (Elliot, 2006).

During the serve development of tennis players, coaches frequently notice technical errors. One of them is the WS, which refers to a very open racket face (racket face parallel to the ground) in the backswing of the serve (Smith, 2004). No scientific study focused on the biomechanical influence of this serve technique on ball velocity and upper limb joint loads. Consequently, the purposes of this study were to determine if the WS is a pathomechanical factor in young elite tennis players, to identify the kinematic causes of WS posture and to discuss its potential relationship with given overuse injuries. We hypothesized to find lower serve velocities and/or higher upper limb joint loads for WS group compared to NS group. We also expected to find higher wrist extension during the backswing of the serve as an explanation of WS posture.

Materials and Methods

Subjects

18 junior elite male tennis players (Top 10 national French ranking for their respective birth years, under 14 [n = 9], under 16 [n = 9]; mean ± SD: age 13.9 ± 0.7 years, height 1.72 ± 0.08 m, weight 59.1 ± 7.5 kg) participated in this study. All the players were involved in a National training program coordinated by the French Tennis Federation (FFT). At the time of testing, all the players were considered healthy, with no history of surgery on the dominant arm.

Experiment protocol

Before experimentation, participants were fully informed of the procedures. The study was approved by the Research Ethical Committee of the M2S Laboratory from the University of Rennes 2 and conducted in accordance with the 1975 Declaration of Helsinki. After a warm-up of at least 15 minutes, including general warm-up and serve repetitions (as many repetitions as needed to familiarize with the testing equipment), each player performed five successful flat serves from the right service court to a 1.50 x 1.0 m target area bordering the T of the deuce service box.

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 (Leardini et al., 1999; Reed, Manary, & Schneider, 1999; Zatsiorsky, Seluyanov, & Chugunova, 1990). Five additional landmarks were positioned on the racket: mid-height of both racket-face sides, bottom of the handle, top and bottom of the racket-face (Martin et al., 2014, Martin et al., 2013). A Vicon motion capture system (Oxford Metrics Inc., Oxford, UK) was used to record the trajectories of the 3-dimensional (3D) anatomical landmarks. The system was composed of 20 high-resolution cameras (4 megapixels) operating at a nominal frame of 200 Hz. Players were shirtless and wore only tight short to limit movement of the markers. After the capture, the 3D coordinates of the landmarks were reconstructed with Blade software (Blade; Vicon, Oxford, UK) with a residual error of less than 1 mm. The 3D 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.

Post-impact Ball Velocity

Post-impact ball velocity was measured for each trial by using a radar (Stalker Professional Sports Radar, Applied Concepts, Plano, Texas, USA; accuracy: ± 1.6 $km \cdot h^{-1}$, frequency: 34.7 GHz, target acquisition time: 0.01 s) fixed on tripod and placed 2 m behind the players in the direction of the serve. Radar's height on the tripod was adjusted with impact height for each player.

Kinetic values

An inverse dynamics approach was used to calculate the peak of joint loads (forces and torques). The serving arm was modeled as a three-link kinetic chain composed of the racket/hand segment, forearm, and upper arm. Shoulder proximal, anterior and inferior forces, shoulder abduction and IR torques (Figure 1a), elbow proximal, anterior and medial forces, elbow varus torque (Figure 1b), wrist proximal, anterior and medial forces (Figure 1c) were analysed. These kinetics have been chosen because they are thought to be indicative of injury potential during overhand sport movements (Elliott et al., 2003; Fleisig, Andrews, Dillman, & Escamilla, 1995; Martin et al., 2014). 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. To facilitate the comparison between groups, kinetic peaks were normalized: forces were divided by body weight, and torques were divided by the product of body weight by height, and then multiplied by 100 (Davis et al., 2009; Martin et al., 2014). The moment of inertia of the racket about its mediolateral axis was computed using the parallel axis theorem and published racket "swing weight" data (United States Racquet Stringers Association [USRSA], 2016). Racket moment of inertia about the longitudinal axis was calculated as reported in the literature (Brody, 1985):

$$\text{moment of inertia } (kg \cdot m^2) = \text{mass (kg) x } [\text{head width (m)}]^2 / 17.75$$

Racket moment of inertia about its anteroposterior axis was defined as the sum of the racket's other two principal moments of inertia (Brody, 1985). Segmental masses and moments of inertia used in the inverse dynamics computations were obtained from previously published data (De Leva, 1996). All the kinetic values were calculated by Matlab software 7.9 (Mathworks, Natick, MA).

WS posture

To simplify interpretation, the serve motion was divided into cocking phase, acceleration phase and deceleration phase, as described in Martin et al. (2014). WS posture is observed during the cocking phase, when the player drives the racket down and behind the trunk. We chose more precisely the instant when the racket longitudinal axis (***Y2***) was parallel to the floor to calculate kinematic data (moment of interest [MOI]). For WS posture, the racket transverse axis (***X2***) tends to be parallel to the ground at MOI (Figure 1f).

Two experimented coaches formed two groups among the 18 participants: WS group (n = 10) in which players served with the WS posture, and NS group (n = 8) in which players did not. To validate groups' composition, the relative angle between racket transverse axis and horizontal axis was computed at MOI (θ angle, Figure 1f). All serves were time normalized to the ball contact point, which was identified visually and verified with racket head coordinate data, as Wagner et al. (2014) did. The measurements were conducted from 0.5 s before to 0.1 s after ball contact, and timing variables were measured relative to ball contact (a negative value corresponded to an event before the ball contact). Angles of shoulder external rotation (ER), shoulder abduction, shoulder horizontal abduction, elbow flexion and wrist extension were computed during the measurement interval. Values at MOI and maximal values of these angles (minimal value for shoulder abduction) with their relative timing to ball contact were noted. Technically, the type of grip depends on which bevel the index knuckle and heel pad rest (Figure 1e). For the purpose of the study, player's grip was estimated as the relative angle between hand and racket at MOI. In the hand coordinate system, the transverse axis (***X1***) was determined by the vector joining the ulnar styloid process with the radial styloid process, and the longitudinal axis (***Y1***) was determined by a vector joining the mid-point between the two styloid processes and the third metacarpal styloid process. Then, we calculated the sagittal axis (***Z1***), determined as the cross product of ***X1*** and ***Y1***. Concerning the racket coordinate system, we used the racket transverse axis (***X2***), and the racket longitudinal axis (***Y2***) to calculate ***Z2***, cross product of these two vectors. Finally, the grip estimation was given by the relative angle between ***Z1*** and ***Z2*** (Figure 1d, 1e and 1f).

Injury data

Injury was defined following the consensus statement of Pluim et al. (2009). Injury data were prospectively collected by the medical staff of the National Tennis Center during a 12-months period following the motion capture. For each player, medical staff reported the number, the name, the location, the type of injuries (traumatic or overuse) and the injury severity (time loss before return to tennis training).

Statistical Analyses

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, serve velocity, kinematic data, and resultant joint forces between the two groups. When the normality test failed, Mann-Whitney tests were used. The level of significance was established at $P < 0.05$ (SigmaStat 3.1; Jandel Corporation, San Rafael, CA). 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). A Fisher's exact test was used to determine the effect of WS on the incidence and the magnitude of upper limb injuries.

Results

Anthropometric and ball velocity data

No significant difference was found between the two groups concerning anthropometric data and serve velocity (Table I).

Kinetic data

The results show a significantly higher peak of wrist anterior force between WS and NS (respectively 3.0 ± 0.2 N·kg^{-1} and 2.7 ± 0.4 N·kg^{-1}; $P < 0.05$; $r = 1.076$) and a significantly higher peak of wrist proximal force (respectively 3.5 ± 0.5 N·kg^{-1} and 3.0 ± 0.2 N·kg^{-1}; $P < 0.05$; $r = 1.128$). Shoulder IR torque (57.2 ± 4.9 N·m·kg^{-1}·m^{-1} for WS and 51.4 ± 4.2 N·m·kg^{-1}·m^{-1} for NS; $P < 0.05$; $r = 1.127$) and elbow varus torque (58.9 ± 4.9 N·m·kg^{-1}·m^{-1} and 52.0 ± 5.0 N·m·kg^{-1}·m^{-1}; $P < 0.01$; $r = 1.398$) were significantly higher in WS. All these significant results were noted to have large effect sizes (Table I).

Overuse injuries

Among all participants, 17 players experienced injuries during the year following the motion capture, representing 81 injuries in total. 12 players experienced overuse injuries in the dominant upper limb during this period, including nine players with shoulder tendinopathy (15 injuries), seven players with elbow tendinopathy (10 injuries), and two players with wrist tendinopathy (two injuries). No significant difference was found between groups concerning incidence or magnitude for upper limb injuries. However, there was a trend for players in WS to sustain more elbow injury than players in NS ($P = 0.07$; $r = 0.397$). Number of players who sustained an upper limb overuse injury, total number of upper limb overuse injuries and mean time loss by injury are detailed for each group in Table II.

Kinematic data

Kinematic data are summarized in Table I and means of shoulder ER, shoulder horizontal abduction, shoulder abduction and wrist extension during the serve are represented in Figure 2. The relative angle between horizontal axis and racket transverse axis (θ angle) was significantly lower at MOI in WS (19.0 ± 11.6° vs 48.5 ± 8.7°; $P < 0.001$; $r = 1.020$), validating the two groups we formed. For WS players, wrist was significantly more extended at MOI (35.7 ± 13.6° vs 23.0 ± 10.3°; $P < 0.05$; $r = 1.051$), and a non-significant difference for maximal wrist extension was also observed between groups (57.7 ± 10.4° vs 49.6 ± 7.4°; $P = 0.08$). Moreover, shoulder abduction was significantly lower at MOI (50.4 ± 11.0° in WS vs 64.5 ± 10.4° in NS; $P < 0.05$; $r = 0.980$). The results were quite similar concerning minimal shoulder abduction, which occurred close to MOI (48.0 ± 13.2° vs 62.5 ± 10.1°; $P < 0.05$; $r = 1.234$). We found no significant difference for grip, for elbow flexion, for shoulder ER, for shoulder horizontal abduction angles (both at MOI and for maximal angles) and for all timing variables. Even if no significant difference was found for shoulder ER before MOI, this rotation seemed to be lower for WS players (15–20° from 0.5 s to 0.3 s before impact, Figure 2).

Discussion

Despite WS is often considered by tennis coaches as a technical error (Smith, 2004), no biomechanical study clarified the consequences of this pattern relating to performance and injury risk. The purposes of this study were to determine if WS is a pathomechanical factor in young elite tennis players, to identify the kinematic causes of WS posture and to discuss its potential relationship with given overuse injuries.

It has been reported that tennis may induce repetitive stresses on the wrist, leading potentially to tenosynovitis, triangular fibrocartilage complex injury, extensor or flexor carpi ulnaris tendinopathies (Parmelee-Peters & Eathorne, 2005). The current study suggests that WS could be at risk for wrist because higher peaks of wrist anterior and proximal forces were obtained (Table I). However, our results do not show any difference between groups about the onset of wrist injury (Table II), and more generally, wrist injuries were not common in our population (2.5% of overall injuries).

Since a higher peak of elbow varus torque has been found in WS players (Table I), the results also indicate that these players were more likely to sustain elbow injuries than others. Elbow varus torque is produced during serve motion, following maximal ER to counter valgus opening (Dillman et al., 1995; Fleisig et al., 1995; Hurd & Kaufman, 2012). Previous works have defined "the valgus extension overload syndrome" as the combination of varus torque and violent extension of the elbow joint before impact. This syndrome may be responsible for tensile forces along the ulnar collateral ligament, compression on the lateral portion of the elbow, and shear forces in the posterior compartment (Eygendaal, Rahussen, & Diercks, 2007). The total number of elbow injuries seemed to be higher in WS (7 injuries in WS against 3 in NS, $P = 0.07$), as well as the mean time loss for elbow injury (6.7 days by injury before return to play in WS against 2.7 days in NS, P = 0.22 [Table II]). Although these results seem to support our findings concerning elbow varus torque, we miss significant difference to clearly conclude that WS and elbow injury are linked.

Shoulder appears to be the upper limb joint the most affected in young elite players (Abrams et al., 2012; Pluim et Staal, 2010), and this statement is confirmed in our population (18.5% of overall injuries). During serve motion, shoulder IR velocity may reach more than $2500°\cdot s^{-1}$ just before impact (Abrams et al., 2014; Fleisig et al., 2003, Wagner et al. 2014). Shoulder IR torque occurs just before maximal ER and is produced by eccentric contraction of the anterior shoulder muscles to decelerate ER before violent IR of the upper arm (Elliott, 2006; Fleisig et al., 1995). This torque represents stress to the anterior aspect of the glenohumeral joint, which may contribute to functional anterior shoulder instability (Hurd & Kaufman, 2012). Our results suggest WS players required more IR torque to reverse the ER of upper arm (Table I), and finally had a greater potential for shoulder injury. Once again, this hypothesis is not confirmed by injury data as no significant difference was found concerning the incidence or severity of shoulder injuries between groups (Table II).

Interestingly, serve velocity was identical in our two groups (Table I). In order to compare them, it should be recalled that serve velocity is correlated with age and height (Ulbricht, Fernandez-Fernandez, Mendez-Villanueva, & Ferrauti, 2015; Vaverka & Cernosek, 2013). However, our two groups were very similar concerning age and anthropometric characteristics (Table I). Since higher upper limb joint kinetics were found for WS players, with no difference in serve velocity compared to NS players, our results support that WS can be considered as a pathomechanical pattern in young elite tennis players (Fortenbaugh et al., 2009).

The second purpose of this work was to investigate kinematic, attempting to explain the reasons of WS, and providing information to coaches in order to correct it. Our results reveal that WS demonstrated a more extended wrist than NS during the cocking phase (Table I and Figure 2). A previous cadaveric study showed that the flexor carpi ulnaris was the first dynamic stabilizer against varus torque. Inversely, when the extensor-supinator mass was loaded, increases in valgus movements and in medial ulnar collateral ligament strain were recorded (Lin, 2007). Valgus stress generated during tennis serve requires dynamic stabilization of the wrist and forearm musculature, particularly from the flexor-pronator mass, to prevent injury to the medial ulnar collateral ligament (Dillman et al., 1995). One may hypothesize that WS posture could be induced by higher wrist extension during the cocking phase. This pattern could contribute to a restriction of dynamic stabilization of the elbow, increasing joint loads and injury risks.

Abduction, horizontal abduction and shoulder rotation were known to be related to each other during arm movements (Eckenrode & Kelley, 2009; Inui, Hashimoto, & Nobuhara, 2009). The limited shoulder abduction measured for WS players in the current study might induce a restriction in shoulder ER during the cocking phase, more precisely when the arm was horizontally abducted (Figure 2). As a remind, the ability for players to drive efficiently the racket during the cocking phase depends on the coordination of several joint movements, among which shoulder ER (Kovacs & Ellenbecker, 2011). In order to correctly drop the racket behind torso and create appropriate racket velocity, WS players seemed to counteract the early restriction in shoulder ER by increasing wrist extension, which finally could induce WS posture. Then, whereas all the variables became relatively similar after MOI, a no statistically significant difference in wrist extension seemed to persist between groups until acceleration phase (maximal wrist extension in Table I, and Figure 2). The racket inertia during the downward acceleration could avoid players to stop this action, leading to an increased wrist extension in both groups until the upward acceleration (close to maximal shoulder ER). Finally, several throwing motion studies established relationship between shoulder kinematic parameters and joint loads (Aguinaldo & Chambers, 2009; Davis et al., 2009). A limited shoulder abduction angle (<70°), associated with high magnitude of shoulder ER during the late cocking phase, might contribute to shoulder anterior stress, then increasing shoulder IR torque and injury risks. Further researches should investigate more accurately the link between shoulder abduction and upper limb joint loads during the tennis serve.

Racket orientation during serve obviously depends on player's grip (Smith, 2004). The player's grip was estimated as the relative angle between hand plane and racket plane. Although no significant difference was found between groups, a particular attention must be paid to this element. The lower angle between hand and racket identified in WS suggests that these players had a more pronounced "eastern forehand" grip (i.e index knuckle and heel pad on the third bevel of the racket), whereas players in NS used a more "continental" grip (i.e index knuckle and heel pad on the second bevel of the racket [Figure 1e]). The more eastern forehand grip changes the orientation of the racket and may contribute to WS posture.

Limitations

We chose to couple a motion analysis with a prospective registration of injuries to assess the relation between WS pattern and injury risk (Krosshaug, Andersen, Olsen, Myklebust, & Bahr, 2005). We found higher upper limb loads in WS than in NS, and it is well admitted in the literature that an increase in joint kinetics of the serving arm represents a risk factor for upper limb overuse injury in tennis (Abrams et al., 2014; Elliott et al., 2003; Martin et al., 2014; Reid et al., 2007). Nonetheless, results about injuries in this study should be considered with caution. First, in our total population of 18 players, nine participants reported shoulder injuries, six participants reported elbow injuries, and two participants reported wrist injuries (Table II), so we may lack power for statistical analysis on injuries. Secondly, injuries reported in this study could not only be caused by excessive joint kinetics. Indeed, the etiology of overuse injuries is presumed to be multifactorial, and overuse injuries may be considered as the interaction between high joint kinetics and several factors such as volume of play, muscular imbalance or sport equipment (Abrams et al., 2012; Pluim & Staal, 2010). Finally, we restricted the observation of injury to a limited period of one year. Since mechanisms generating overuse injuries may be initiated much before the onset of injury (Andrews & Fleisig, 1998), we strongly believe that it was necessary to extend this follow-up period to capture the overuse effect of WS.

Conclusions

In summary, this study identified the WS posture as a pathomechanical pattern in young elite tennis serve, involving higher upper limb joint kinetics with no effect on ball velocity. While no significant difference existed between groups concerning injury to the shoulder, the elbow or the wrist, the higher loadings recorded in the dominant upper limb in WS might indicate these players should be more susceptible to sustain upper limb overuse injuries. With classic video analyses, WS is a quite easily observable motion for coaches. To correct it and thus to minimize joint loads, coaches should focus on wrist extension and shoulder abduction angles during the cocking phase of the serve. They also must be careful on player's grip, which can play a role on the incidence of WS.

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Table I. Comparison of anthropometric data, ball velocity, normalized peak values of upper limb joint loads and kinematic data between groups.

Anthropometric and ball velocity data	WS (n = 10)	NS (n = 8)	P Value	Effect size
Age (yr)	13.9 (0.6)	14.0 (0.9)	0.88	0.131
Height (cm)	171.2 (7.1)	174.0 (10.0)	0.50	0.323
Weight (kg)	57.6 (6.9)	60.9 (8.3)	0.37	0.432
Serve velocity (km·h^{-1})	159.4 (8.6)	160.7 (11.8)	0.80	0.126
Normalized peak values				
Shoulder proximal force (N·kg^{-1})	5.3 (0.7)	5.1 (0.6)	0.634	0.233
Shoulder anterior force (N·kg^{-1})	2.8 (0.4)	2.9 (0.6)	0.490	0.328
Shoulder inferior force (N·kg^{-1})	2.7 (0.5)	2.7 (0.3)	0.656	0.221
Shoulder internal rotation torque * (N·m·kg^{-1}·m^{-1})	57.2 (4.9)	51.4 (4.2)	0.030	1.127
Shoulder abduction torque (N·m·kg^{-1}·m^{-1})	47.3 (5.8)	51.2 (6.3)	0.189	0.647
Elbow proximal force (N·kg^{-1})	5.5 (0.7)	4.9 (0.5)	0.068	0.949
Elbow anterior force (N·kg^{-1})	1.5 (0.2)	1.6 (0.2)	0.211	0.612
Elbow medial force (N·kg^{-1})	2.3 (0.2)	2.4 (0.3)	0.360	0.529
Elbow varus torque ** (N·m·kg^{-1}·m^{-1})	58.9 (4.9)	52.0 (5.0)	0.009	1.398
Wrist proximal force * (N·kg^{-1})	3.5 (0.5)	3.0 (0.2)	0.035	1.128
Wrist anterior force * (N·kg^{-1})	3.0 (0.2)	2.7 (0.4)	0.033	1.076
Wrist medial force (N·kg^{-1})	0.9 (0.1)	0.9 (0.1)	0.658	0.217
Kinematic data at MOI				
Timing of MOI (s)	-0.209 (0.019)	-0.214 (0.028)	0.652	0.209
θ Angle (°) ***	19.0 (11.6)	48.5 (8.7)	< 0.001	1.020
Grip (°)	39.5 (7.6)	47.5 (11.4)	0.282	0.201
Wrist extension (°) *	35.7 (13.6)	23.0 (10.3)	0.045	1.051
Elbow flexion (°)	61.1 (14.1)	59.3 (8.6)	0.744	0.031
Shoulder external rotation (°)	147.9 (12.9)	145.2 (19.8)	0.725	0.019
Shoulder horizontal abduction (°)	-16.9 (7.8)	-14.9 (9.3)	0.628	0.125
Shoulder abduction (°) *	50.4 (11.0)	64.5 (10.4)	0.014	0.980
Maximal / Minimal angle values and timing				
Wrist extension (°)	57.7 (10.4)	49.6 (7.4)	0.084	0.897
Timing of maximal wrist extension (s)	-0.110 (0.023)	-0.097 (0.024)	0.250	0.553
Elbow flexion (°)	55.6 (13.8)	56.1 (9.3)	0.928	0.042
Timing of maximal elbow flexion (s)	-0.186 (0.046)	-0.198 (0.025)	0.522	0.324
Shoulder external rotation (°)	175.0 (3.1)	175.6 (3.4)	0.711	0.184
Timing of maximal shoulder external rotation (s)	-0.076 (0.019)	-0.084 (0.012)	0.333	0.503
Shoulder horizontal abduction (°)	12.8 (11.8)	9.3 (11.0)	0.520	0.418
Timing of maximal shoulder horizontal abduction (s)	-0.404 (0.067)	-0.446 (0.045)	0.130	0.736
Shoulder abduction (°) *	48.0(13.2)	62.5(10.1)	0.021	1.234
Timing of minimal shoulder abduction (s)	-0.229 (0.034)	-0.212 (0.041)	0.354	0.451

Mean (SD). *** P < 0.001; ** *P < 0.01; * P < 0.05.* N: newtons. MOI: moment when racket longitudinal axis was parallel to horizontal axis during the cocking phase. θ Angle: angle between racket transverse axis and horizontal axis.

Table II. Number of players who sustained upper limb overuse injury (% of players in the group), total number of upper limb overuse injuries (% of injuries in the group) and mean time loss by injury for both groups.

Injuries	**WS (n = 10)**	**NS (n = 8)**	**P Value**	**Effect size**
Shoulder				
Number of players affected (n)	5 (50)	4 (50)	0.95	0
Total number of shoulder injuries (n)	9 (20.9)	6 (15.8)	0.72	0.134
Mean time loss (days / injury)	9.4	10.7	0.76	0.098
Elbow				
Number of players affected (n)	4 (40)	3 (37.5)	0.83	0.150
Total number of elbow injuries (n)	7 (16.3)	3 (7.9)	0.07	0.397
Mean time loss (days / injury)	6.7	2.7	0.22	0.738
Wrist				
Number of players affected (n)	1 (10)	1 (12.5)	0.74	0.075
Total number of wrist injuries (n)	1 (2.3)	1 (2.6)	0.74	0.060
Mean time loss (days / injury)	8	5	/	/

Figure captions

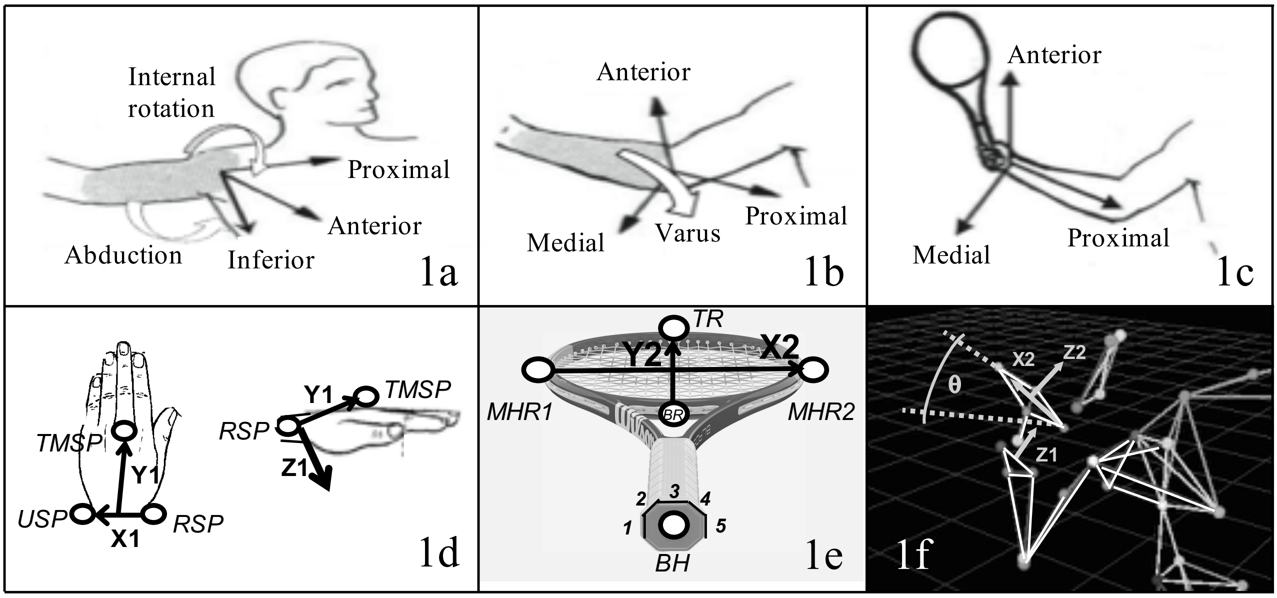

Figure 1. Schematic representation of joint forces (black arrows) and torques (white arrows) for shoulder, elbow and wrist (Figure 1a, 1b and 1c). Calculation of the hand coordinate system (Figure 1d) and calculation of the racket coordinate system with representation of bevel 1 to bevel 5 (Figure 1e). The grip estimation was the angle defined between **Z1** and **Z2**. WS angle (θ) was calculated when **Y2** was parallel to the floor (at MOI), and was represented by the angle between **X2** and horizontal axis (Figure 1f). When the racket face is parallel to the floor, the WS angle value is 0°.
USP: Ulnar styloid process; RSP: Radial styloid process; TMSP: Third metacarpal styloid process; BH: Bottom of the handle; BR: Bottom of the racket-face; TR: Top of the racket face; MHR1 & MHR2: Mid-height of both racket-face sides.

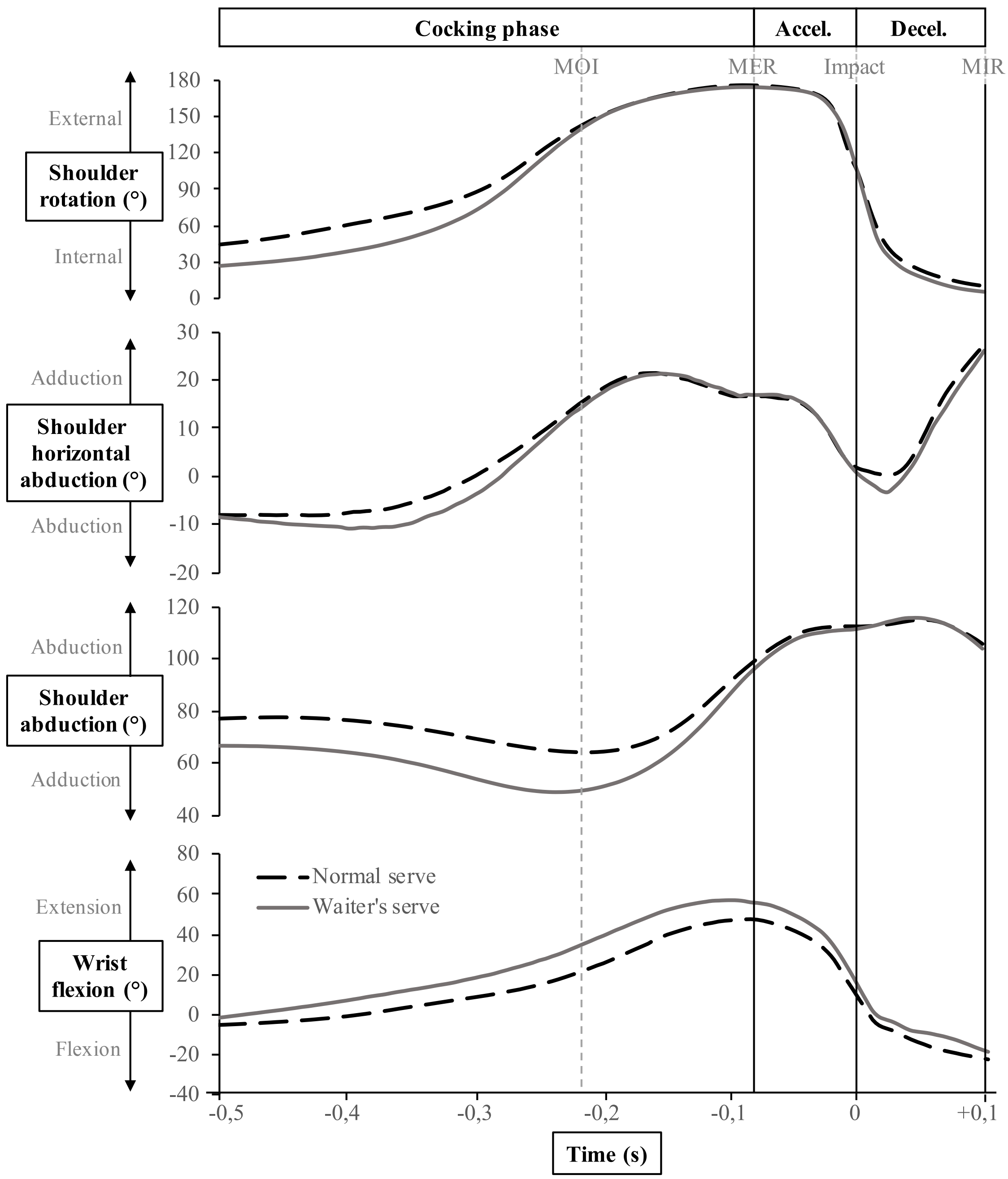

Figure 2. Mean shoulder rotation, shoulder horizontal abduction, shoulder abduction and wrist extension angle between NS group and WS group during the tennis serve.

Accel: acceleration phase; Decel: deceleration phase; MOI: moment of interest; MER: shoulder maximal external rotation; MIR: shoulder maximal internal rotation.