Technique effects on upper limb loading in the tennis serve

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The purpose of this study was to compare the shoulder and elbow joint loads during the tennis serve. Two synchronised 200 Hz video cameras were used to record the service action of 20 male and female players at the Sydney 2000 Olympics. The displacement histories of 20 selected landmarks, were calculated using the direct linear transformation approach. Ball speed was recorded from the stadium radar gun. The Peak Motus system was used to smooth displacements, while a customised inverse-dynamics program was used to calculate 3D shoulder and elbow joint kinematics and kinetics. Male players, who recorded significantly higher service speeds (male=183 km hr^{-1}: female=149 km hr^{-1}) recorded significantly higher normalised and absolute internal rotation shoulder torque at the position when the arm was maximally externally rotated (MER) (male=4.6% and 64.9 Nm: female=3.5% and 37.5 Nm). A higher absolute elbow varus torque (67.6 Nm) was also recorded at MER, when compared with the female players (41.3 Nm). Peak normalised horizontal adduction torque (male=7.6%: female=6.5%), normalised shoulder compressive force (male=79.6%: female=59.1%) and absolute compressive force (male=608.3 N: female=363.7 N), were higher for the male players. Players who flexed at the front knee by 7.6˚, in the backswing phase of the serve, recorded a similar speed (162 km hr^{-1}), and an increased normalised internal rotation torque at MER (5.0%), when compared with those who flexed by 14.7˚. They also recorded a larger normalised varus torque at MER (5.3% v 3.9%) and peak value (6.3% v 5.2%). Players who recorded a larger knee flexion also recorded less normalised and absolute (4.3%, 55.6 Nm) peak internal rotation torque compared with those with less flexion (5.6%, 63.9 Nm). Those players who used an abbreviated backswing were able to serve with a similar speed and recorded similar kinetic values. Loading on the shoulder and elbow joints is higher for the male than female players, which is a reason for the significantly higher service speed by the males. The higher kinetic measures for the group with the lower knee flexion means that all players should be encouraged to flex their knees during the backswing phase of the service action. The type of backswing was shown to have minimal influence on service velocity or loading of the shoulder and elbow joints.

Introduction

Three-dimensional (3D) kinematic analyses of the service technique of high performance tennis players have provided the athlete and coach with practical information on the key mechanical characteristics of this action[1,2]. However, sport physicians, therapists, and trainers need to know the forces associated with these movements, as the aetiology of musculoskeletal injuries generally has a kinetic mechanical cause[3]. A better understanding of the physical demands placed upon the body during this activity will enable health professionals to design more optimal injury prevention, treatment and rehabilitation programs.

While epidemiological studies have reported a range of injuries in tennis, elite players commonly suffer from shoulder and medial elbow injuries [4, 5]. Hill [6] reported 56% of competitive players suffered rotator cuff and impingement injuries to the shoulder. It has been hypothesised that the combination of abduction and external rotation of the upper arm overloads the static and dynamic stabilisers of the shoulder joint [7, 8]. A high elbow varus force is also present during the above actions, which has been identified as the tennis stroke that causes most medial elbow pain [9]. In addition to these preparatory movements, the upper arm is involved in explosive inward rotation prior to ball impact, which may place additional stress on the shoulder region [2].

While it has been well documented that the action of throwing in baseball is associated with high loads at the shoulder and elbow joints [10], there is a paucity of information describing the loading of the shoulder and elbow joints during the tennis serve. Bahamonde [11] and Noffal [12] in data presented as conference abstracts, reported peak shoulder internal rotation torques of approximately 50 Nm and 100 Nm respectively as the trunk rotates forward and the shoulder joint externally rotates. This occurs at the extreme limits of the shoulder joint range of motion, during the late stage of the service backswing and early forwardswing. They also reported a peak varus torque at the elbow of approximately 43 Nm and 106 Nm respectively at this phase of the service action. The upper arm in abducting, horizontally flexing and vigorously inwardly rotating to ball impact produced large shoulder horizontal flexion (164 Nm) and elbow varus (74 Nm) torques [11]. Dillman et al. [13] stated that any torque greater than 50 Nm in the upper extremity was a significant factor in loading that area of the body. It is therefore apparent that the upper limb is subject to high loads during the service action, and this movement if repeated many times may have the potential to cause injury.

Kibler [14, 15] indicated that any disruption to the kinetic chain could result in increased loading of other joints in the sequence of movements. While a coordinated action may reduce upper limb loading in the serve, it is plausible that modifications to this flow may increase forces on the shoulder and elbow joints. In baseball, changes to technique have been advocated in an attempt to reduce forces and torques at the shoulder and elbow joints [16]. Saal [5] stressed the need for a “deep knee bend” in the preparatory tennis service movements to avoid thoracolumbar hyperextension. Both a full backswing and an effective “leg-drive” have been advocated as features of an efficient service technique [17]. No research has been published that shows how modification to these actions affects shoulder and elbow joint loading.

The purpose of this study was to compare two variations in service technique for elite players under championship match conditions. Shoulder and elbow joint torques and forces at key phases of the service action were compared for players with a full and an abbreviated backswing, and for those with a larger front knee joint flexion compared to those with minimal knee flexion. The above kinetic variables were also compared for male and female players.

Methods and Procedure

All data were collected during singles matches on centre court during the XXVII Olympic Games in Sydney, Australia. Since professional tennis players are allowed in Olympic competition, most of the competitors were of professional status. Thirty-six tennis matches were videotaped over a seven-day period with two electronically synchronised high-speed video cameras. Human rights clearance was obtained from universities involved in the project and from the International Olympic Committee and the International Tennis Federation.

Video data were collected at a rate of 200 Hz. For each camera, the shutter rate was set at 0.001 s and the aperture was adjusted according to weather conditions. Each camera was positioned approximately 20-40 m from the service area, with both side and front views. These views were adjusted to capture the entire serving motion, while optimising the field of view (Figure 1). Ball velocity was recorded as the ball left the tennis racket from a radar gun positioned in-line with the centre-mark and perpendicular to the baseline at the opposite end of the stadium.

A 2x1.9x1.6m calibration frame (Peak Performance Technologies, Inc., Englewood, CO), surveyed with a measurement tolerance of 0.005m, was videotaped at one end of the court prior to and after each match. The position of the frame encompassed the space used by players during the serve (from initial ball toss to impact) on the ad-side (left-side) of one end of the court. Since kinematic parameters were measured only from ball toss to just prior to ball impact, and not during the follow-through phase, the volume was large enough to contain the portion of the tennis serve that was digitised.

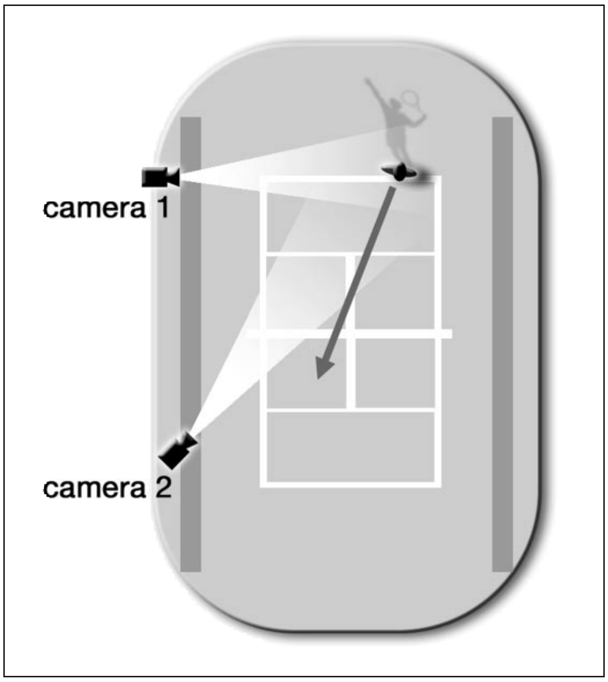

Figure 1: Camera locations on the centre court.

All videotapes were qualitatively analysed, and it was determined that data from 20 players were of the quality required for quantitative analysis. For each of these subjects, the three successful serves with the greatest ball velocity were manually digitised with the Peak Motus system (Peak Performance Technologies, Inc., Englewood, CO). A 20-point spatial model was created, comprising the centres of the left and right mid-toes, ankles, knees, hips, shoulders, elbows, wrists, and the subject's head, hand racket grip, and four points around the racket head (medial, lateral, proximal, and distal). Each of these 20 points was digitised in every video field (200 Hz), starting at five frames prior to when the ball left the hand and ending one frame prior to the racket impacting the ball. The Peak Motus system then calculated the 3D coordinate data from the 2D digitised images utilising the direct linear transformation method. An average root mean square calibration error of 0.014 m was produced.

A computer program was specifically written to calculate kinematic and kinetic parameters. In this program, 3D coordinate data were filtered with a 12 Hz low-pass Butterworth filter. Shoulder external rotation was calculated as the angle between the forearm and the anterior direction of the hitting-shoulder, in a plane perpendicular to the long-axis of the upper arm (a horizontal forearm positioned anterior to the shoulder represents 0˚, while 90˚ of rotation has the forearm vertically aligned when the upper arm is abducted 90˚ to the trunk). Because external rotation is calculated using the forearm instead of the upper arm, the accuracy of the calculation may diminish as the forearm and upper arm segments become parallel. No measures were taken at impact, when this alignment is most likely to occur. Flexion of the lead knee was determined as the relative angle between the thigh and the shank (full knee extension equals 0˚ of flexion).

Resultant force and torque levels at the elbow and shoulder joints were calculated using inverse dynamics. Because of the dynamic effect of impact on the racket, kinetic analysis was limited to data just before ball impact. Drag effect of each segment through the air was neglected. Shoulder force was reported as the proximal/distal and anterior/posterior components of the force applied by the trunk onto the upper arm (Figure 2A).

Following a procedure first described by Feltner and Dapena [18], the sum of all torques applied to each segment was set equal to the vector product of the segment's moment of inertia and angular acceleration. Moment of inertia of the racket about its medial-lateral axis was computed using the parallel axis theorem and published racket "swingweight" data [19]. Racket moment of inertia about the long-axis was calculated as: Moment of inertia (kg•m^2) = Mass (kg)* [head width (m)]^2/17.75 [20]. Racket moment of inertia about its anterior-posterior axis was the sum of the racket's other two principal moments of inertia (20). Moment of inertia of the hand was assumed to be negligible. The positions of centre of mass of the forearm and upper arm were determined using cadaveric data [21]. The mass of each upper extremity segment was assumed to be a percentage of the subject's total mass [21]. Moments of inertia of the forearm and upper arm were initially determined from Dempster's [22] cadaveric study, and then individualised using each subject's height and mass[23]. Shoulder internal rotation torque and horizontal adduction torque were the components of the torque applied by the trunk onto the upper arm

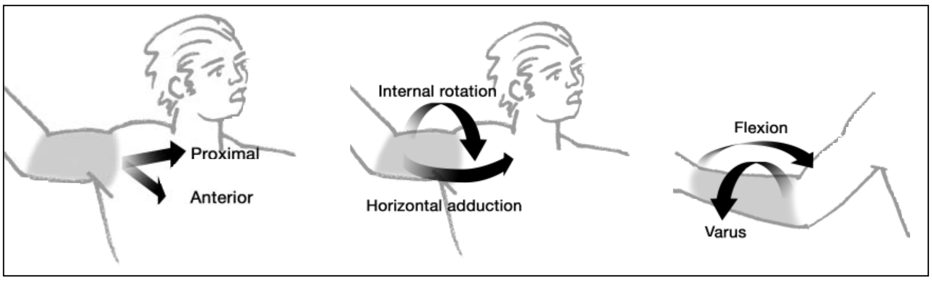

Figure 2: Convention for kinetic measurements: (A) shoulder force, (B) shoulder torque, (C) elbow torque

Figure 3: Front knee joint flexion (θ) in the service backswing (straight limb = 0° flexion).

Figure 4: Full (A) and abbreviated (B) backswings in the serve.

(Figure 2B). Elbow varus torque was reported as the torque applied by the upper arm onto the forearm about the anterior direction of the forearm (Figure 2C). Elbow flexion torque was the torque applied by the upper arm onto the forearm, about the medial direction of the elbow.

Repeatability of data was assessed by redigitising 30 consecutive frames, after one week, for the period from MER to immediately before impact. Shoulder internal rotation and elbow extension angles were compared using Student's t-tests. Mean data re-digitised over the 30 consecutive frames were shown to be reliable in that shoulder internal rotation and elbow extension were not significantly different and varied by 0.8% and 0.4% respectively.

Players were classified as exhibiting an effective (>10° of knee flexion; Figure 3) or less-effective leg drive (<10° of knee flexion); at MER in the service action. Players were also categorised by their type of backswing. Players who used a full rotation of the shoulder joint during the service action (Figure 4A) were classified as full backswing, whereas players who lifted the racket vertically during the early backswing (Figure 4B) were considered to have an abbreviated backswing. Players were also classified by their gender.

Hypotheses were that males would record higher kinetic values than females, and those players with an effective leg drive would record lower values than those with minimal knee flexion during the backswing. It was also hypothesised that players with a full backswing would record lower kinetic values than those with an abbreviated backswing. All comparisons were tested through a three way ANOVA (Data desk 6.1: Data Description Inc., USA). T-tests for uneven cell sizes were used to further compare data where trends were identified from the above statistics [(24)]. A 0.01 level of acceptance was established with respect to the above hypotheses.

In addition to absolute values, normalised values of all force and torque data were calculated to improve comparison of groups containing varying numbers of male and female players. Force data were divided by bodyweight and then multiplied by 100%, as has occurred in the baseball literature [(16)]. Torque data were divided by weight by height, then multiplied by 100% [(16)].

Results and Discussion

Gender, age, body mass, height, and service velocity for the mean of the best three trials are shown in Table 1. Serving speeds for the male players (182.8 km hr^{-1}) was significantly higher ($F=24.7$, $p=0.01$) than for the female competitors (149.3 km hr^{-1}). The speed recorded by both groups testifies to the elite quality of this sample, as values for high performance data in the literature are reported as approximately 155 and 125 km hr^{-1} for male and female players respectively [(1)].

Male and female players

Although the mean angle at MER was similar between groups (≈170°), significantly larger normalised ($F=5.4$, $p<0.01$) and absolute ($F=12.2$, $p<0.01$) internal rotation torques were recorded at this instant for male (4.6%: 64.9 Nm) compared with female competitors (3.5%: 37.5 Nm) (Table 1). Similar mean angle (165°) and absolute internal rotation torque (67 Nm) were recorded at MER for highly skilled male pitchers [(16)]. While normalised mean elbow varus torque at MER was similar for both groups, the absolute value was significantly higher for male players (67.6 Nm) than for their female counterparts (41.3 Nm)

Anthropometric and ball velocity data	Males (n=8)		Females (n=12)	
Height* (m)	185.0	(5.5)	174.0	(8.6)
Mass* (kg)	81.0	(9.0)	62.2	(7.7)
Velocity* (km hr^{-1})	182.8	(13.9)	149.3	(14.0)
Data at MER				
Shoulder internal rotation torque* (% weightxheight)	4.6	(0.9)	3.5	(1.2)
Shoulder internal rotation torque* (Nm)	64.9	(15.8)	37.5	(15.0)
Shoulder external rotation angle (˚)	169.2	(9.0)	170.9	(8.1)
Shoulder horizontal adduction torque (% weightxheight)	4.2	(1.7)	3.5	(1.4)
Shoulder horizontal adduction torque (Nm)	61.7	(31.0)	36.8	(16.3)
Elbow varus torque (% weightxheight)	4.8	(0.9)	3.9	(1.2)
Elbow varus torque* (Nm)	67.6	(15.2)	41.3	(14.1)
Peak values				
Shoulder internal rotation torque (% weightxheight)	5.1	(0.9)	4.5	(1.3)
Shoulder internal rotation torque (Nm)	71.2	(15.1)	47.8	(16.3)
Time prior to impact (s)	0.06	(0.02)	0.06	(0.02)
Shoulder horizontal adduction torque* (% weightxheight)	7.6	(0.8)	6.5	(0.9)
Shoulder horizontal adduction (Nm)	107.8	(24.9)	68.8	(14.3)
Shoulder anterior force (% weight)	38.5	(14.0)	30.5	(10.2)
Shoulder anterior force (N)	291.7	(119.8)	185.1	(60.9)
Shoulder proximal force* (%weight)	79.6	(5.3)	59.1	(8.4)
Shoulder proximal force* (N)	608.3	(109.5)	363.7	(87.8)
Elbow flexion torque (% weightxheight)	2.6	(1.6)	1.7	(1.3)
Elbow flexion torque (Nm)	36.7	(22.9)	18.1	(14.5)
Elbow varus torque (% weightxheight)	5.6	(0.9)	5.3	(1.1)
Elbow varus torque** (Nm)	78.3	(12.2)	58.2	(13.1)

* Significant difference at the 0.01 level.
**Significant difference at the 0.05 level as calculated using a t-test.

Table 1: Mean (Standard Deviation) service data for male and female players.

(F=13.2, p<0.01). Again data from the male players were almost identical to the 64 Nm reported by Fleisig et al. [16] for male baseball pitchers.

The peak normalised horizontal adductor torque was significantly higher for the male players (7.6%)(F=7.47, p<0.01) when compared with the females (6.5%), while other shoulder torque values were similar in the swing to impact (Table 1). The mean horizontal adduction torque (107.8 Nm) for the male players was less than reported by Bahamonde [11] for college-level male tennis players (164 Nm), who presumably served at a lesser speed than this sample of professional players. Mean peak internal rotation torque values were relatively high during this phase of the service action for both groups (males = 71.2 Nm and females = 47.8 Nm), which supports the importance of internal rotation as one of the most important contributors to racket speed at impact[2]. The level of internal rotation torque for the male players was larger than the 33 Nm reported just prior to impact by Bahamonde [11]. However, it should be stressed that the values reported in this study were peak values, and not those immediately prior to impact.

Normalised (F=6.7, (proximal) p<0.01) and absolute (F=7.3, p<0.01) mean peak shoulder compressive proximal forces were significantly larger for the male players (79.6%: 608.3 N) compared with the female competitors (59.1%: 363.7 N). This is again similar to baseball [16]. To prevent distraction at the shoulder during this part of the action, the trunk applies a resultant force to the upper arm to stabilise the joint. Anterior forces about the shoulder joint were similar for all players irrespective of sex. The magnitudes of shoulder kinetics during the present tennis study for the male players were smaller than the shoulder kinetics previously reported for baseball pitching [16, 10].

There was a trend for peak absolute elbow varus torque to be higher for males (78.3 Nm) when compared with the female players (58.2 Nm). The torque magnitude for the male players was greater than the 64 Nm reported for highly skilled and professional male baseball pitchers by Fleisig et al. [16, 10], but less than the 100 Nm recorded by Feltner and Dapena [18] for baseball pitching.

The fact that the male players served at a significantly higher mean velocity was presumably the result of the higher kinetic values in the upper limb. The relationship between service velocity and upper limb kinetics, particularly with respect to injury, is the subject of further investigation.

Level of knee flexion

At MER there was a significantly lower normalised internal rotation torque (3.5%) recorded by the group with a mean knee flexion of 15.9˚, when compared with the group with a mean knee flexion 5.8˚ (5.0%: F= 8.08, p= 0.01). The group with the larger flexion recorded a similar level (43.7 Nm), and the less effective group a greater level (57.8 Nm) than the 43 Nm reported by Bahamonde [11], for college level tennis players. However, both groups recorded lower values than the 94 Nm reported by Noffal [12]. This torque was associated with the eccentric contraction of the muscles responsible for internal shoulder rotation (eg latissimus dorsi, pectoralis major and subscapularis, teres major, and anterior deltoid) following MER. The players with the potential for a better leg-drive may therefore use the inertial transfer from the trunk to upper limb to move the upper arm into a position of MER. This then requires less internal rotator torque to stop the external rotation. The group with less effective drive must therefore primarily use the external rotators to achieve MER , which then requires a greater internal rotator torque to reverse the rotation of the upper arm.

A significantly reduced normalised (4.3 v 5.6%) and absolute peak internal rotation torque (55.6 Nm v 63.9 Nm), was recorded for the group with the larger knee joint flexion, when compared with the less effective leg-flexion group. This reduction placed a lesser load on the joint during the concentric contraction of the muscles involved in rotating the upper arm in the swing to impact. The group with the larger knee flexion recorded a lower mean maximum internal rotator torque and the group with the lesser flexion a similar torque to the 68 Nm reported for professional pitchers [10]. Lesser load is thus evident with the group with the larger front knee flexion in performing an action described by Elliott et al. [2] as being integral to an effective service action. No significant differences were recorded when the shoulder forces were compared between the two groups.

A significantly larger mean elbow varus torque was recorded at the position of MER for those players with a lesser knee flexion (5.3%: 60.2 Nm v 3.9%: 47.4 Nm). The group with the larger knee flexion recorded a similar varus torque (43

Anthropometric and ball velocity data	Effective (9F & 5M)		Minimal (3F & 3M)	
Height (m)	178.3	(10.1)	178.5	(9.9)
Mass (kg)	69.0	(12.2)	66.5	(11.0)
Service velocity (km hr^{-1})	162.9	(20.4)	162.2	(26.6)
Knee flexion* (°)	15.9	(4.9)	5.8	(1.8)
Data at MER				
Shoulder internal rotation torque* (% weightxheight)	3.5	(1.0)	5.0	(1.1)
Shoulder internal rotation torque (Nm)	43.7	(17.7)	57.8	(14.7)
Shoulder external rotation angle (°)	172.4	(7.7)	165.3	(8.1)
Shoulder horizontal adduction torque (% weightxheight)	3.9	(1.0)	3.5	(2.5)
Shoulder horizontal adduction torque (Nm)	49.6	(29.2)	41.4	(18.6)
Elbow varus torque* (% weightxheight)	3.9	(0.9)	5.3	(1.1)
Elbow varus torque (Nm)	47.4	(17.0)	60.2	(12.9)
Peak values				
Shoulder internal rotation torque* (% weightxheight)	4.3	(1.0)	5.6	(1.2)
Shoulder internal rotation torque* (Nm)	55.6	(18.0)	63.9	(12.4)
Time prior to impact (s)	0.01	(0.02)	0.01	(0.01)
Shoulder horizontal adduction torque (% weightxheight)	6.9	(1.0)	6.9	(1.7)
Shoulder horizontal adduction (Nm)	85.2	(26.4)	81.8	(26.4)
Shoulder anterior force (% weight)	34.1	(10.7)	32.7	(16.1)
Shoulder anterior force (N)	238.7	(108.8)	205.1	(88.9)
Shoulder proximal force (% weight)	66.2	(12.3)	69.9	(13.7)
Shoulder proximal force (N)	458.9	(162.3)	467.7	(150.5)
Elbow flexion torque* (% weightxheight)	1.7	(1.3)	3.1	(1.3)
Elbow flexion torque (Nm)	20.4	(19.6)	36.0	(15.8)
Elbow varus torque* (% weightxheight)	5.2	(0.8)	6.3	(0.6)
Elbow varus torque (Nm)	62.7	(14.3)	73.9	(15.2)

* Significant difference at the 0.01 level.

Table 2: Mean (Standard Deviation) data from players with an effective and minimal leg-flexion..

Nm) to that reported by Bahamonde [11] for lesser level payers. A significantly higher peak varus torque was also recorded by the group who flexed their front knee by 6° at MER (6.3%: 73.9 Nm)(F=6.0, p=0.01), when compared with the group with a mean of approximately 15° of front knee flexion (5.2%: 62.7 Nm). Interestingly the group with the more effective knee flexion recorded a lesser level than the peak 74 Nm reported by Bahamonde [11] for male college players. A significantly reduced normalised elbow flexion torque was also recorded for those players with more effective knee flexion (1.7%) when compared with the less effective group (3.1%).

Full versus abbreviated backswing

Those players who served with a modified service action produced similar shoulder torques at MER and for the mean peak values, when compared with those who used a full swing. While normalised and absolute forces at the shoulder were similar between groups, there was a trend of a higher normalised anterior force at the shoulder joint for those players with an abbreviated swing (40.4%) compared with those players who used a full backswing (30.1%)(t= 2.34, p=0.05). Players with an abbreviated swing there-

Anthropometric and ball velocity data	Full (8F & 5M)		Abreviated (4F & 3M)	
Height (m)	179.4	(9.4)	176.2	(11.1)
Mass (kg)	69.4	(12.6)	66.5	(9.8)
Velocity (km hr^{-1})	163.8	(22.0)	160.6	(22.6)
Data at MER				
Shoulder internal rotation torque (% weightxheight)	4.2	(1.2)	3.5	(1.3)
Shoulder internal rotation torque (Nm)	52.2	(20.8)	41.3	(18.6)
Shoulder external rotation angle (°)	171.5	(8.7)	167.4	(10.1)
Shoulder horizontal adduction torque (% weightxheight)	3.9	(1.6)	3.6	(1.6)
Shoulder horizontal adduction torque (Nm)	48.9	(27.0)	42.6	(24.7)
Elbow varus torque (% weightxheight)	4.4	(0.9)	4.0	(1.5)
Elbow varus torque (Nm)	54.5	(18.4)	46.9	(21.5)
Peak values				
Shoulder internal rotation torque (% weightxheight)	4.7	(1.0)	4.8	(1.5)
Shoulder internal rotation torque (Nm)	57.1	(19.8)	57.2	(20.0)
Shoulder horizontal adduction torque (% weightxheight)	6.9	(1.1)	6.9	(1.1)
Shoulder horizontal adduction (Nm)	86.1	(30.0)	81.1	(22.2)
Shoulder anterior force** (% weight)	30.1	(13.0)	40.4	(6.8)
Shoulder anterior force (N)	207.1	(99.8)	267.5	(75.9)
Shoulder proximal force (% weight)	67.0	(13.3)	67.9	(11.8)
Shoulder proximal force (N)	465.0	(163.1)	455.1	(150.7)
Elbow flexion torque (% weightxheight)	1.7	(1.5)	2.7	(1.2)
Elbow flexion torque (Nm)	22.5	(22.3)	31.0	(14.9)
Elbow varus torque (% weightxheight)	5.4	(1.0)	5.8	(0.8)
Elbow varus torque (Nm)	65.8	(19.0)	66.9	(9.3)

** Significant difference at the 0.05 level as calculated using a t-test.

Table 3: Mean (Standard Deviation) data from players with a full and abbreviated backswing.

fore had more force applied by the trunk to the upper arm in a forward direction. These forces were generally smaller than reported by Noffal [12]. However, Noffal [12] included ball impact in his calculations, which Knudson and Bahamonde [25] suggested may alter the peak values.

Similar elbow varus and flexion torques were recorded for both “swing types” at MER and during the swing of the racket to impact. The sample size and homogeneity of the data from the male and female players reduced the probability of recording significant differences.

Conclusions

Dillman et al. [13] stated that any torque greater than 50 Nm in the upper extremity was a significant factor in loading that area of the body. This level was achieved for shoulder internal rotation torque, shoulder horizontal adduction torque, and elbow varus torque during different phases of the service action. Force and torque levels at the shoulder and elbow joints were often similar to those recorded for high performance baseball pitchers. It is therefore apparent that the shoulder and elbow joints are subject to high loads during the service action, and this movement if repeated many times, may have the potential to cause an overuse injury [26]. Training must be such that the muscles surrounding these joints are strengthened both in eccentric and concentric movement patterns to help protect the region from injury. However, it should be stressed that physical preparation must encompass all sections of the body that play a role in the kinetic chain [14, 15].

Male players commonly recorded higher torques and forces at the shoulder and elbow joints than their female counterparts. These higher kinetic measures are an important factor in producing the significantly higher service velocity for this group of players. Subjects with a smaller front knee flexion and thus lesser “leg-drive” also loaded the shoulder and elbow joints with larger torques, particularly at MER. Players should therefore develop an effective “leg-drive” during the service action to attain high velocities with as small a loading profile as possible. This requires that players flex the knee joint during the backswing phase of the service action, prior to rapidly extending during the drive to impact. While those with an abbreviated swing recorded a similar service velocity and upper limb torques to those who used a full swing, minor differences were recorded in the force profile at the shoulder. A trend of higher anterior shoulder force and the general trend of forces and torques for both groups would indicate that the full swing may be a preferred service technique from a loading perspective.

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