ORIGINAL ARTICLE

Pre- and post-impact muscle activation in the tennis volley: effects of ball speed, ball size and side of the body

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Aim: To examine the pre- and post-impact activation of five upper extremity muscles in the tennis volley across conditions of ball speed, ball type and side of the body.

Methods: A repeated measures design in a biomechanics laboratory setting was used. A total of 24 recreational tennis players (mean (SD) age 24 (5) years, height 176 (10) cm, mass 76 (13) kg) were recruited from a university. Participants performed tennis volleys under 18 ball conditions: three ball speeds (slow, medium and fast), with three ball types (two oversize and one regular size) each from two sides (forehand and backhand). Average normalised electromyographic levels of the flexor carpi radialis, extensor carpi radialis, triceps brachii, anterior/middle deltoid and posterior/middle deltoid of the hitting arm during pre- and post-impact phases (200 ms before and after ball–racquet impact, respectively) were assessed.

Results: For the pre-impact phase, a significant muscle and side interaction ($p<0.001$) and significant main effects for speed ($p=0.002$) and muscle ($p<0.001$) were observed. For the post-impact phase, significant interactions were observed for ball type and side ($p=0.002$), ball speed and side ($p=0.011$) and muscle and side ($p=0.001$), as well significant main effects for muscle ($p<0.001$), speed ($p=0.035$) and side ($p<0.001$).

Conclusion: Oversize tennis balls do not significantly increase upper extremity muscle activation compared to regular size balls during a tennis volley. The highest post-impact activation was observed in the ECR indicating a vigorous wrist stabilisation role that could irritate players with lateral epicondylalgia.

There has been considerable revision of the rules of tennis by International Tennis Federation (ITF) in the past few decades. One of the most recent changes involving equipment was the introduction of a larger tennis ball. The use of a 6% wider ball with the same mass as a regular ball was approved as a possible remedy for the increasing speed of the game.[1 2]

Studies of match play statistics[3] and aerodynamics[4 5] have reported data supporting the logic of increasing ball diameter to slow ball speeds in tennis. However, manufacturers selling the larger (type 3) tennis balls found most tennis players were not interested in using them. Some recreational tennis players have been concerned about the long-term effect of the larger ball on arm injuries.[6 7]

Research on the immediate effects of play with the larger ball on risk of overuse injuries has focused on impulsive loading and muscle activation. Several studies have shown that post-impact racquet accelerations are similar between the regular and the oversize ball in a variety of strokes.[8–10] Muscle activation is also not significantly different across subjects between the two types of ball in the forehand and serves.[9 10]

When compared to more complex tennis strokes such as the forehand and serve, the volley requires significantly less movement from the player. Furthermore, while the mechanics of the forehand and serve have changed dramatically over the past few decades due to alterations in typical grips, swing paths and lower extremity loading preferences, the biomechanics of the volley have remained relatively unchanged despite advances in racquet technology. There is evidence, however, that the temporal demands of intercepting volleys can be affected by the larger tennis ball.[8]

Muscle activity immediately before impact (pre-activation) during drop landing and downward stepping, for example, serves to stiffen the lower extremity joints in preparation for the impact.[11–14] In drop landings, a higher lower limb muscle pre-activation was observed with increasing drop height indicating that preparatory muscle activity varies with the anticipated demands of impact.[11] Muscle activity, specifically coactivity, immediately after the initial contact also helps to stabilise the joints involved.[11 13] Although muscle activation during different phases of the tennis volley has been reported,[14 16 17] no attempts have been made to examine pre- and post-impact muscle activity of upper extremity muscles during a tennis volley. For example, Chow and colleagues examined the activity of different muscles of the stroking arm and shoulder and lower extremities during the tennis volley and reported average electromyographic (EMG) levels for different phases between 200 ms before ball release from a ball machine and the instant of ball impact.[16] However, they did not analyse the post-impact muscle activity.

Andrew *et al*[8] reported a significant interaction of ball size and shot speed on stroke technique in volleys, so that the larger ball significantly increased the movement time (17–29 ms) to intercept higher speed shots. It is unknown if variation in the time to intercept shots or flight properties of the larger ball affects the activation of muscles required to execute volleys Information on pre- and post-impact muscle activation would provide insights into demands placed on muscles of the hitting arm and likely muscular loads. Therefore, it was the purpose of this investigation to compare selected upper extremity muscle activation immediately before and after ball–racquet impact in the tennis volley across ball types, ball speed and sides of the body. Based on the association between preparatory muscle activation and drop height reported by Arampatzis *et al*[11] and the fact that larger balls travel slower in the air,[8] we

Abbreviations: AMD, anterior/middle deltoid; ECR, extensor carpi radialis; EMG, electromyograph; FCR, flexor carpi radialis; LE, lateral epicondylalgia; NTRP, National Tennis Rating Program; PMD, posterior/middle deltoid; TBR, triceps brachii hypothesised that pre- and post-impact activation would increase with increasing ball speed and decrease with increasing ball size for forehand and backhand volleys.

METHODS

Eighteen male and six female recreational tennis players (mean (SD) age 24 (5) years, height 176 (10) cm, mass 76 (13) kg) signed informed consent documents that were approved by the Institutional Review Board of the University of Florida (Gainesville, Florida, USA) before their participation. Subjects rated themselves from 3.0–4.5 (mean (SD) 3.6 (0.6)) in accordance with the United States Tennis Association's National Tennis Rating Program (NTRP).

The experimental set-up and protocol have been reported in detail previously.[8] Tennis balls were projected by a ball machine (Prince Portable Model #1, Master Sports, Fort Wayne, Indiana, USA) located behind the baseline on a tennis court marked in an indoor gymnasium. The ball machine was shielded from the subject's view so that variations in direction were hidden to simulate volleys in competition. The subjects hit two volleys in 18 ball conditions in a random order. The ball conditions studied created a fully crossed design of three ball speeds (27.0, 22.7 and 20.0 m/s), three ball types (Wilson Rally, Penn Oversize and Wilson US Open extra-duty felt) and two sides (forehand and backhand). Ball speeds were the ball's speed as it initially exited the ball machine, not the speed when it reached the subject.

The subjects used one of two identical Wilson Hyper Hammer 4.3 oversize racquets (Wilson Sporting Goods Co., Chicago, Illinois, USA) strung with nylon at 267 N of tension. They were asked to choose the grip size that felt most comfortable to them; L3 (4 3/8″) or L4 (4 1/2″). A miniature uniaxial accelerometer (Model 3115A, Dytran Instruments, Inc., Chatsworth, California, USA) was attached to the throat of the preferred racquet of the subject using a low-mass aluminium brace (0.4 N weight) to measure acceleration at right angles to the racquet face. The accelerometer was connected to an amplifier on the back of the subject and the amplifier was connected to the data collection computer via a long cable.

Five pairs of 3.4 cm diameter Ag/AgCl surface electrodes (Blue Sensors type M-00-S, Medicotest Inc. Rolling Meadows, Illinois, USA) were placed on the racquet side of the body on the anterior/middle deltoid (AMD), posterior/middle deltoid (PMD), triceps brachii (TBR), flexor carpi radialis (FCR) and extensor carpi radialis (ECR). Electrode locations had been described elsewhere.[16] The skin surface where electrodes were located was cleaned with alcohol and shaved when necessary. Electrodes were placed over the bellies of each muscle parallel to the muscle's line of action with a centre-to-centre distance of 2.5 cm. Using a MESPEC 4000 telemetry system (Mega Electronics Ltd, Kuopio, Finland), an FM transmitter was tied to the lower back of the subject using a belt. The EMG signals were preamplified with a gain of 500 and band pass filtered at 8–1500 Hz (common mode rejection ratio (CMRR) >130 dB) close to the electrodes and telemetrically transmitted to a central receiver (gain = 1, Butterworth filter, 8–500 Hz band pass). The amplified EMG and accelerometer data were sampled at 1000 Hz (12-bit A/D conversion) using a Peak Motus® 2000 system (Peak Performance Technologies, Inc., Englewood, Colorado, USA).

To obtain maximum EMG levels of the selected muscles, a maximum effort isometric contraction was performed for each muscle/muscle group before the experimental trials.[16] Each isometric contraction lasted for about 5 s. The raw EMG signals were filtered using a recursive digital filter (Matlab Elliptic filter, 10–500 Hz band pass) and full-wave rectified. The maximum isometric trial data were smoothed using a moving average of 2 s and the largest rectified EMG value recorded for each muscle/muscle group was considered the maximum EMG level. The pre-impact phase was defined as the 200 ms prior to the instant of ball–racquet contact.[13] Because racquet vibrations are completely damped by 200 ms after the instant of ball–racquet contact (fig 1), this time duration is considered the post-impact phase. For each subject, average normalised EMG (NEMG) levels for the pre- and post-impact phases were determined for each muscle in each experimental trial. The average over two trials for each ball condition was used in statistical analyses.

For each ball condition, means and SD were computed for the NEMG of each muscle. Mean NEMG levels for the pre- and post-impact phases were analysed using two separate $5\times3\times3\times2$ factorial (muscle × speed × ball type × side) ANOVAs. Significant interactions were interpreted using interaction plots and estimated marginal means for the interaction. Significant main effects without interactions were compared using Tukey post hoc tests. Statistical significance for ANOVA and post hoc tests was accepted at the $p<0.05$ level, generating an experiment-wise error rate of $p<0.098$.

RESULTS

All five muscles monitored were moderately active (25–65% maximum) in pre- and post-impact phases for different ball conditions (tables 1 and 2). Varying degrees of FCR/ECR and AMD/PMD coactivity were present in both phases. Relatively large SD values were observed signifying individual differences in muscle activation patterns exhibited in these players.

Pre-impact phase

A significant muscle and side interaction ($F(4, 2156) = 51.3$; $p<0.001$; $\eta^2 = 0.090$) was observed for the pre-impact phase mean muscle activation. Consistent with anatomical muscle actions, the FCR and AMD had greater activation in the forehand than the backhand volley, while the ECR, TRB and PMD had greater activation in the backhand volley (fig 2).

Significant main effects were noted for muscle ($F(4, 2156) = 36.1$; $p<0.001$; $\eta^2 = 0.065$) and speed ($F(2, 2158) = 6.5$; $p = 0.002$; $\eta^2 = 0.006$) for the mean muscle activation before impact. Tukey post hoc tests revealed that mean muscle activation for: (A) AMD was significantly greater than the FCR ($p<0.001$), ECR ($p<0.001$), TBR ($p<0.001$) and PMD ($p<0.001$); (B) ECR was significantly greater than the FCR ($p = 0.026$) and PMD ($p<0.001$); and (C) TBR was significantly greater than the PMD ($p<0.001$) (table 1). Post hoc tests also revealed that mean muscle activity for the fast ball speed was significantly greater than the slow ball speed ($p = 0.001$) (table 1). No significant main effect for ball type ($p = 0.772$) or side ($p = 0.870$) was detected and all other interactions were not statistically significant ($p\geqslant0.329$).

Post-impact phase

Muscle activation after ball impact showed different effects than the pre-impact activation, indicating different muscle function across stroke phase. Significant interactions were observed for ball type and side ($F(2, 2158) = 6.4$; $p = 0.002$; $\eta^2 = 0.006$), ball speed and side ($F(2, 2158) = 4.5$; $p = 0.011$; $\eta^2 = 0.004$) and muscle and side ($F(4, 2156) = 4.9$; $p = 0.001$; $\eta^2 = 0.009$) for the post-impact phase mean muscle activation. Greater differences in overall activation were observed between forehand and backhand volleys in regular balls than in oversize balls (fig 3). A greater overall muscle activity was observed in forehand volleys for slow and medium speed conditions, but not for the fast speed shots (fig 4). All muscles exhibited greater

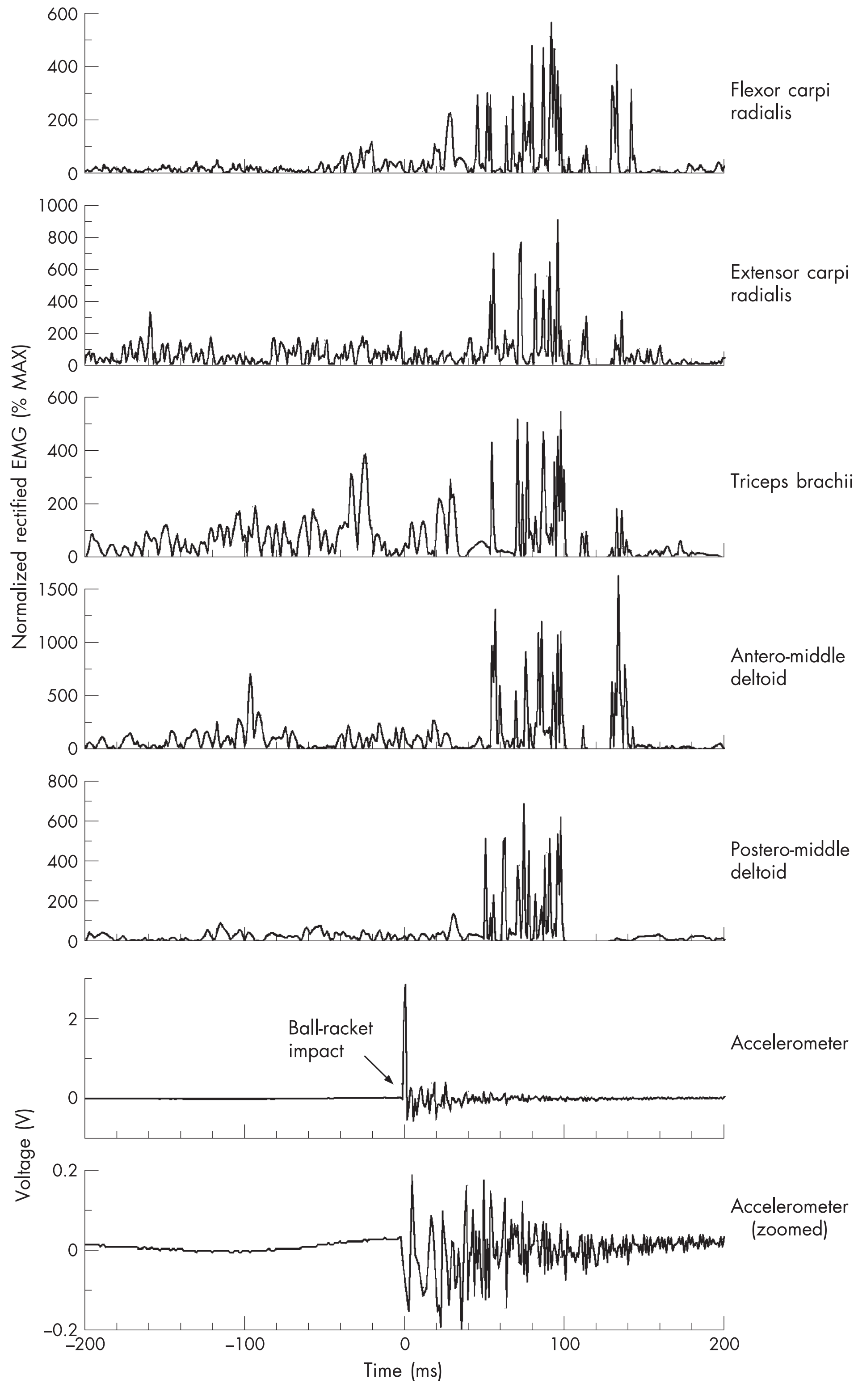

Figure 1 Normalised rectified EMG levels of different muscles and accelerometer recordings of a fast speed-regular ball-forehand volley trial.

activity in forehand volleys than in backhand volleys except FCR (fig 5).

Significant main effects were found for muscle (*F*(4, 2156) = 79.1; $p<0.001$; $\eta^2 = 0.133$), speed (*F*(2, 2158) = 3.4; $p = 0.035$; $\eta^2 = 0.003$) and side (*F*(1, 2159) = 14.6; $p<0.001$; $\eta^2 = 0.007$) for the post-impact phase mean muscle activation. Tukey post hoc tests revealed that mean muscle activation for the: (a) ECR was significantly greater than the AMD ($p<0.001$), FCR ($p<0.001$), TBR ($p<0.001$) and PMD ($p<0.001$); (b) AMD was significantly greater than the FCR ($p = 0.006$), TBR ($p = 0.003$) and PMD ($p<0.001$); (c) FCR was significantly greater than the PMD ($p = 0.016$); and (d) TBR was significantly greater than the PMD ($p = 0.028$) (table 2). Post hoc tests also revealed that mean muscle activity for the fast ball speed was significantly greater than the slow ball speed ($p = 0.028$) and the overall muscle activity during forehand volleys was significantly greater than during backhand volleys ($p<0.001$) (table 2). No significant main effect for ball type was

Table 1 Mean (SD) normalised EMG levels during the pre-impact phase of the volley

	Ball speed			Ball type			Side*		
Muscle*	**Slow**	**Medium**	**Fast**	**Penn Oversize**	**Wilson Rally**	**Regular**	**Forehand**	**Backhand**	**Muscle overall**
Flexor carpi radialis	42.8 (27.5)	42.7 (26.1)	45.4 (29.4)	43.4 (28.4)	42.3 (26.3)	45.2 (28.4)	50.2 (29.1)	37.0 (24.6)	43.6†,‡ (3.7)
Extensor carpi radialis	46.5 (21.3)	49.6 (21.1)	52.0 (23.2)	49.6 (22.0)	50.5 (23.3)	48.0 (20.6)	42.4 (20.2)	56.3 (21.4)	49.4†§¶ (4.1)
Triceps brachii	46.2 (21.1)	47.6 (22.5)	51.9 (25.6)	48.0 (23.9)	49.3 (23.9)	48.5 (21.9)	45.2 (24.4)	52.0 (21.4)	48.6**,†† (2.4)
Antero-middle deltoid	58.2 (44.1)	61.7 (42.7)	65.0 (42.0)	63.9 (44.7)	62.4 (44.2)	58.7 (39.8)	75.5 (47.6)	47.8 (32.4)	61.7†,§,**,‡‡ (7.8)
Postero-middle deltoid	36.4 (24.6)	40.5 (27.1)	42.9 (27.8)	40.5 (29.2)	39.5 (26.4)	39.8 (25.5)	30.4 (21.8)	49.5 (28.4)	39.9§,¶,††,‡‡ (5.4)
Average (SD)	46.0§§ (7.9)	48.4 (8.3)	51.4§§ (8.6)	49.1 (9.0)	48.8 (8.9)	48.0 (6.9)	48.7 (16.6)	48.5 (7.2)	

*Significant interaction between muscle and side ($p<0.05$).
†,‡,§,¶,**,††,‡‡,§§, Significant difference between levels of the same symbol ($p<0.05$).

Table 2 Mean (SD) normalised EMG levels during the post-impact phase of the volley

	Ball speed†			Ball type‡			Side*†‡		
Muscle*	**Slow**	**Medium**	**Fast**	**Penn Oversize**	**Wilson Rally**	**Regular**	**Forehand**	**Backhand**	**Muscle overall**
Flexor carpi radialis	30.8 (21.6)	31.7 (20.1)	32.0 (18.5)	31.3 (20.1)	30.3 (20.0)	32.8 (20.1)	29.9 (20.6)	33.1 (19.4)	31.5§,¶,** (1.1)
Extensor carpi radialis	50.4 (24.0)	52.7 (27.0)	58.6 (31.4)	52.4 (24.8)	53.6 (27.5)	55.8 (30.9)	59.8 (27.1)	48.0 (27.3)	53.9§,††,‡‡,§§ (4.0)
Triceps brachii	27.5 (20.6)	32.5 (25.7)	33.6 (24.3)	32.4 (26.0)	30.0 (22.9)	31.2 (22.4)	32.8 (26.9)	29.57 (20.1)	31.2††,¶¶,# (2.0)
Antero-middle deltoid	37.4 (29.6)	38.9 (29.6)	35.6 (25.2)	37.5 (28.0)	35.2 (23.9)	39.3 (32.0)	40.1 (30.0)	34.6 (26.0)	37.3¶,‡‡,¶¶,$ (2.0)
Postero-middle deltoid	24.6 (25.2)	26.0 (25.3)	27.9 (25.8)	25.0 (22.5)	25.9 (23.3)	27.7 (29.9)	27.8 (28.9)	24.5 (21.2)	26.2**,§§,#,$ (1.4)
Average (SD)	34.1ˆ (10.3)	36.4 (10.2)	37.5ˆ (12.1)	35.7 (10.3)	35.0 (10.9)	37.4 (11.1)	38.1& (13.0)	34.0& (8.8)	

*†‡Significant interaction between factors of the same symbol ($p<0.05$).
§,¶,**,††,‡‡,§§,¶¶,#,$,ˆ,&, Significant difference between levels of the same symbol ($p<0.05$).

detected (p = 0.187) and all other interactions were not statistically significant (p⩾0.088).

DISCUSSION

The hypothesis that pre- and post-impact activation would decrease with increasing ball size for forehand and backhand volleys was not supported. The lack of a biologically meaningful difference in muscle activation across ball types is consistent with previous studies reporting that play with the larger ball does not significantly increase muscle activation nor impact accelerations compared to the regular tennis ball.[8–10] Our results provide further support to the postulation that concerns over possible arm injuries due to larger tennis ball are unjustified.

The hypothesis that pre- and post-impact activation would increase with increasing ball speed for forehand and backhand volleys was supported. For the pre-impact phase, mean activation increased by 12% when going from slow to fast speed condition. Similar to pre-activation of lower extremity muscles in drop landings, an increase in pre-impact mean activation with increasing ball speed indicates that muscle activation of the hitting arm varies with the anticipated demands of impact. On average, there was a 10% increase in post-impact muscle activity when the ball speed was increased from slow to fast. Increases in activation of different muscles (co-contractions) are important in the fast speed condition to stabilise different upper extremity joint of the hitting arm. Young junior players might need to limit the time on volley practice, especially volleys with fast shots, because they have less strength to stabilise the arm and dampen racquet vibrations than adult players.

Significant differences in mean muscle activity among different ball speed conditions were largely due to the differences in mean muscle activity in backhand volleys (fig 4). Regardless of the ball speed, muscles of the hitting arm are actively involved in shoulder external rotation, forearm supination and radial flexion (wrist cocking) in order to put the racquet in a proper position to hit a forehand volley. By contrast, some of the muscles might not be heavily involved in a backhand volley until the ball speed is fast.

Among the five muscles monitored, FCR activation seems to be fairly constant across different ball speed conditions during pre- and post-impact phases (tables 1 and 2). Chow *et al*[16] also did not find any significant differences in activation across different speed conditions in the FCR for the forward swing phase (from end of backswing to impact) of the tennis volley. It is possible that the tendency of players to use a firm grip in all volleys resulted in negligible differences in activation of this muscle across speed conditions. Van Gheluwe and Hebbelinck[17] reported high EMG levels (>75%MVC) in the flexor pollicis brevis during the impact phase (not defined in their paper) of the forehand volley, and their values are much greater than the FCR activity found in the present study. However, it can be difficult to compare EMG levels among different studies because of the differences in methodology (eg, differences in MVIC tests, electrode placement and definitions of phases). Through a theoretical

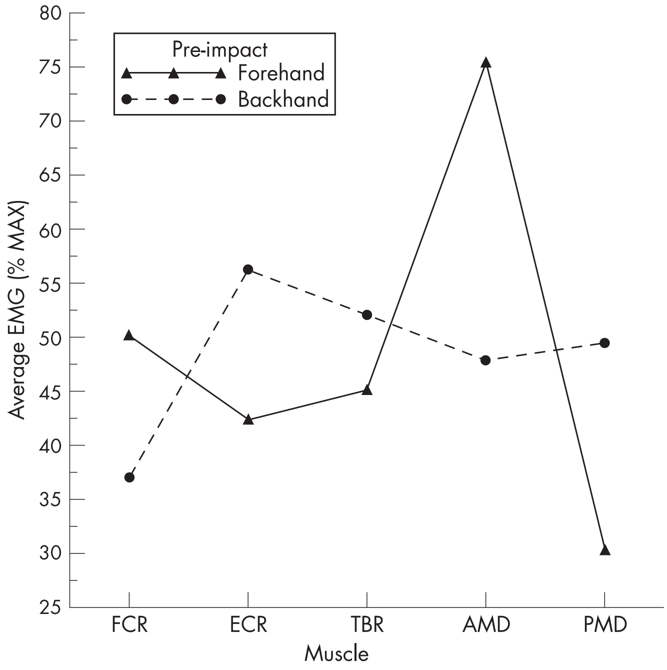

Figure 2 Interaction between muscle and side for the pre-impact phase.

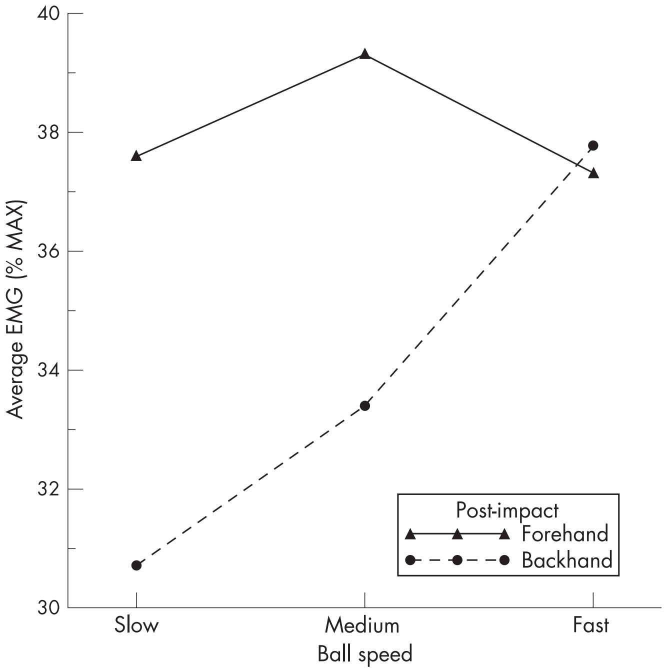

Figure 4 Interaction between ball speed and side for the post-impact phase.

review of the impact between a racquet and a ball, Hatze[18] reported that the vibration level at the hand at impact increased with increasing grip tightness. This implies that forearm muscles need to work harder in the fast ball speed condition to damp the hand vibration.

Interestingly, all significant interactions found in the current study involve the side of the body. The interaction plot for the muscle and side interaction of the pre-impact phase (fig 2) indicates a very high muscle pre-activation of AMD in forehand volleys (76% maximum). When the arm is in the neutral internal/external rotation position, the whole deltoid is active in abducting the arm. However, the AMD is the primary shoulder abductor when the arm is externally rotated as in the case of a forehand volley. Players with weak AMD or deltoid muscles in general might have difficulties in executing a forehand volley properly. To strengthen the AMD and prevent fatigue to this muscle, the lateral raise exercise should be performed with the arm externally rotated.

The results supporting the opposite effects of the side of the body on ball type were surprising (fig 3). For the same initial ball speed, a regular tennis ball will reach the subject sooner and with a greater speed than an oversize ball because of the lower air resistance. As expected, greater muscle activity was

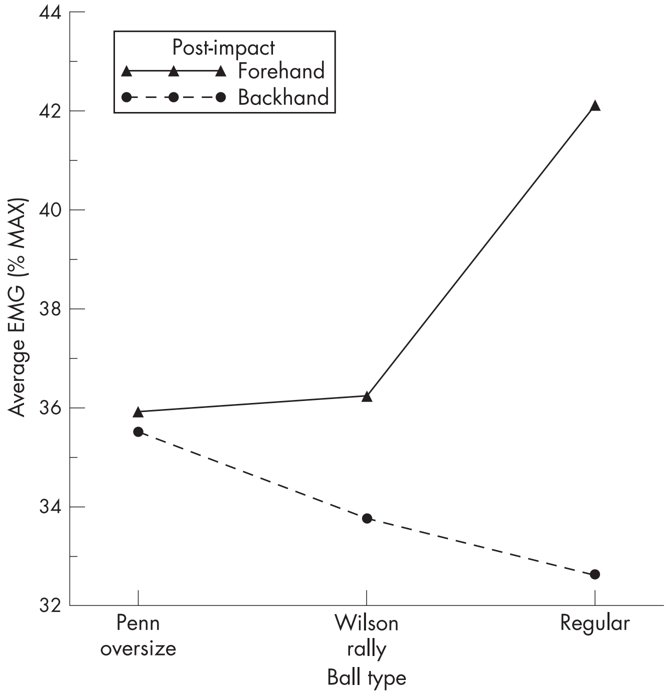

Figure 3 Interaction between ball type and side for the post-impact phase.

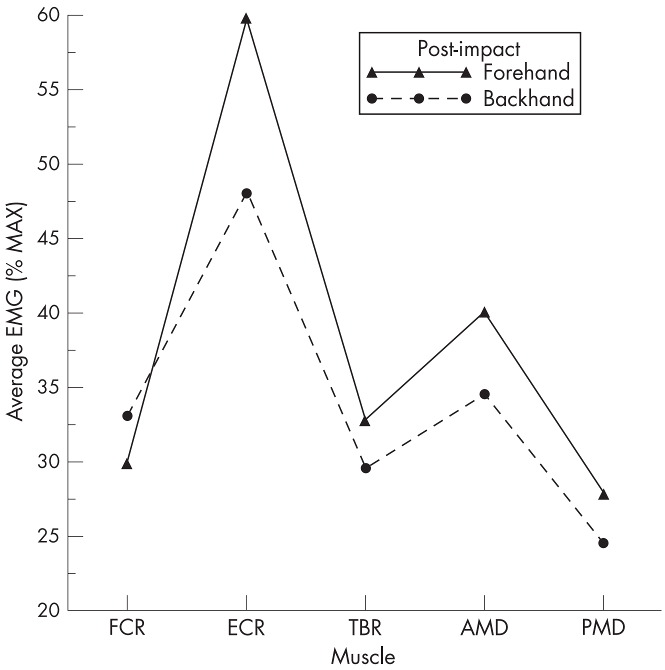

Figure 5 Interaction between muscle and side for the post-impact phase.

observed in forehand volleys using regular balls. However, it is not clear why lower muscle activity was observed in backhand volleys using regular balls. One possible explanation is that the subjects might ''block'' the ball more often than ''punch'' the ball in backhand side when they have shorter time to react to regular balls on their weaker side.

In general, forehand volleys demand greater muscle activation of the hitting arm than backhand volleys (fig 5). In other words, forehand volleys are associated with greater loads to the upper extremity joint because of the greater co-contractions. The muscle with the greatest post-impact activation in both strokes was the ECR (fig 5). This is consistent with the co-activation of forearm muscles used in powerful gripping and with the significantly larger post-impact forearm muscle activation during a backhand groundstroke found in lower skill level players.[19] It is possible that the high levels of activation of the ECR are important to stabilise the wrist and dampen post-impact shock and vibration transmitted to the hand. The marked activation in this muscle in forehand and backhand volleys has implications for recovery from lateral epicondylalgia (LE). The high ECR activation combined with the lack of racquet momentum in volleys means that players with LE should avoid volleys.

One of the limitations of the present study was that the ball speed at impact was not controlled across ball types. Therefore, the differences in ball speed at impact could have contributed to significant results pertinent to ball type. The significant main effects should also be interpreted with caution because the significant interactions show that combinations of side, speed and ball type affect muscle activation in the volley.

The present study was also limited to the upper extremity muscle activation of these recreational tennis players during the volley in several impact conditions. Several results were consistent with functional anatomy and previous EMG studies of the volley. This assists in extending our insights into demands placed on muscles of the hitting arm and joint loadings and supports the adequacy of the experimental design to detect differences in muscle activation across ball conditions in the tennis volley. In addition to forearm muscles, the deltoids likely experience high activation in the forward stroke of the volley.[16,17] More research on the activation of this complex muscle in the tennis volley is needed.[20] High levels of forearm muscle activation, especially the ECR, were observed in the present study of intermediate players, which was similar to previous studies of the volley and backhand.[16,19] The vigorous activation of the ECR before and after impact in tennis strokes places much stress on its tendons. This suggests that complete rest from the sport is necessary for the immediate recovery from LE.

What is already known on this topic

EMG levels of different muscles during early phases of the tennis volley (eg, ready, reaction, backswing and forwardswing phases)[16,17] and larger (type 3) tennis balls significantly affect the time and movement in the volley.[8]

What this study adds

- Pre-impact muscle activation differed from post-impact, and activation was affected by the interaction speed, side and ball type.
- The affect on activation has implications for muscle strengthening and treatment of lateral epicondylalgia.

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