ORIGINAL ARTICLE

Muscle activation in coupled scapulohumeral motions in the high performance tennis serve

William B Kibler, T Jeff Chandler, Robert Shapiro, Michael Conuel

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See end of article for authors' affiliations

Correspondence to: William Benjamin Kibler, Lexington Clinic Sports Medicine Center, Lexington, KY, USA; wkibler@aol.com

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Objective: To evaluate muscle activation patterns in selected scapulohumeral muscles in the tennis serve. These patterns of muscle activation have not been evaluated in other studies of the tennis serve. Fine wire and surface EMG was used to calculate onset and offset timing of muscle activation.
Design: Controlled laboratory study.
Setting: Biomechanical laboratory.
Subjects: 16 tennis players (age 18–40) with rated skills (National Tennis Rating Program (NTRP) rating 4.5–6.5; club tournament level or higher) were subjects.
Main outcomes measure: Dependent variables of muscle activation onset and offset as well as sequencing of the stabilising muscles of the scapula (upper trapezius, lower trapezius, serratus anterior; the muscles that position the arm) anterior deltoid and posterior deltoid; and the muscles of the rotator cuff muscles (supraspinatus, infraspinatus, teres minor) during the tennis serve motion.
Results: Patterns of muscle activation were observed during the tennis serve motion. The serratus anterior (−287 ms before ball impact) and upper trapezius (−234 ms) were active in the early cocking phase, while the lower trapezius (−120 ms) was activated in the late cocking phase just before the acceleration phase. The anterior deltoid (−250 ms) was activated in early cocking, while the posterior deltoid (−157 ms) was activated later. The teres minor (−214 ms) was activated early in the cocking phase. The supraspinatus (−103 ms) was activated in late cocking. The infraspinatus (+47 ms after ball impact) was activated in follow-through. All muscles except infraspinatus were activated in duration of more than 50% of the service motion.
Conclusions: This study demonstrates that there are patterns of activation of muscles around the scapulohumeral articulation in the normal accomplished tennis serve. Rehabilitation and conditioning programs for tennis players should be structured to restore and optimise the activation sequences (scapular stabilisers before rotator cuff), task specific functions (serratus anterior as a retractor of the scapula, lower trapezius as a scapular stabiliser in the elevated rotating arm) and duration of activation of these muscles.

The tennis serve motion places high demands on the shoulder. It requires large ranges of motion of the glenohumeral and scapulothoracic joint and produces large rotational velocities and forces on the joint.[1–3] Motions and forces around the shoulder are produced and controlled by sequenced activation of muscles in force couple patterns.[4–8] Because of the importance of muscle activations, knowledge of the intensity and patterning of muscle activations can be key in understanding performance, injury and rehabilitation.

Previous muscle activation studies in tennis have concentrated on the intensity of activation in each of the phases of throwing or serving.[9] This study showed that this type of analysis gives information about how intensely a muscle is activated, but does not give information to determine how the muscles are coordinated in patterns of activation to produce the motions and forces. There have been no studies on activation sequencing patterns in tennis.

A study in baseball players did evaluate activation sequencing and did document a pattern of peak individual muscle activation that started in the trunk, continued into the scapular stabilisers, and then continued into the deltoid and arm muscles.[7] Initial peak activation was noted in the contralateral gluteus maximus and external oblique muscles, followed by bilateral rectus abdominis. The activation progressed into the ipsilateral upper and lower trapezius and latissimus dorsi around the scapula. Deltoid and rotator cuff muscles achieved peak activation at the end of the sequencing. These patterns were considered to be the basic patterns for the throwing motion.

The present study investigated muscle activation patterns in tennis in order to evaluate the sport-specific muscle activation patterns in this particular sport. It evaluated the activation sequencing of selected muscles that have roles to maximise anatomic congruence and mechanical efficiency, and have been identified to act to coordinate joint motions in the high-performance tennis serve.

The study's research goals were to evaluate muscle activation using "on/off" electromyographic (EMG) analysis, to elucidate the patterns of activation, to relate the patterns to the observed scapulohumeral motions, and to use the information to set up appropriate clinical applications for sport-specific conditioning programs and sport-specific rehabilitation programs for optimal tennis performance. The research hypothesis was that the activation patterns would be similar to patterns in other sports and activities, and that they could be related to specific scapulohumeral motions.

MATERIALS AND METHODS

This study evaluated muscle activation using electromyographic (EMG) electrodes during the entire tennis motion and determined onset and offset of the activations. It then related the activation sequencing to the standard phases of the service motion: cocking, acceleration and ball impact (T_0), deceleration and follow-through. Activations prior to T_0 are negative numbers, while those after T_0 are positive numbers.

Abbreviations: EMG, electromyography; NTRP, National Tennis Rating Program

Population

This study was conducted on 16 accomplished tennis players (National Tennis Rating Program (NTRP) rating 4.5–6.5;club tournament level or higher). Subjects with a history or finding of shoulder problems, occult or overt instability, rotator cuff tendinitis, or other current shoulder pathology were excluded. The subjects were all males and ranged in age from 18–40 years. They were recruited from the local tennis community; all filled out personal data and injury forms, and were evaluated by the senior author before participation. The University of Kentucky Institutional Review Board approved the study, and all subjects signed appropriate consent forms.

Study protocol

Muscle activation in selected muscles of the dominant arm was examined using a combination of surface and fine wire insertional electrodes. The muscles evaluated were the upper trapezius, lower trapezius and serratus anterior, all prime scapular stabilisers, the supraspinatus, infraspinatus and teres minor, components of the rotator cuff, and the anterior and posterior deltoids; the primary positioners of the arm. Surface electrodes were placed over the anterior and posterior heads of the deltoid, serratus anterior, and superior and inferior portions of the trapezius, and fine wires were inserted into the supraspinatus, infraspinatus and teres minor muscle bellies. All electrode placements were consistent with previously published protocols.[10] After each electrode was placed, manual muscle testing was then performed to show proper placement and appropriate EMG signal. The surface electrodes were silver/silver-chloride with built-in pre-amplifier. The fine wire electrodes were introduced through a 23-gauge hypodermic needle. Therapeutics Unlimited (Iowa City, Iowa, USA) manufactured the electrodes and amplifier. EMG signals were recorded at 2000 Hz on an AT-type personal computer. Quiet files were collected for each muscle, to establish the baseline from which muscle activity was determined. Analog to digital conversion was performed with a Data Translation A to D board and subsequent analysis of EMG data was accomplished on a Sun SPARC 330 workstation. The signal was rectified and the mean established for the quiet file. Each muscle was considered ''on'' when its amplitude was 3 SD points above baseline signal for a 25 ms window. The duration of activation was measured, and the muscle was considered to be ''off'' when the amplitude dropped below 3 SD above baseline signal. The subjects reported no differences in their motion from the surface or the indwelling electrodes and the mechanics of the service motions were noted to be unchanged after the electrodes were placed, when compared with the preplacement service motions.

The normal service motion was accomplished by having each subject take as many trials as were needed to feel comfortable with the electrodes and wires. Once the subjects felt comfortable and warmed up, the study trials were performed, using a Tennis Target Trainer (Tennis Target, Burbank, California, USA) as the target to aim for. The target trainer was placed the same distance away from the subject, as the net is located from the baseline on the tennis court. A successful trial occurred when the ball went through the target. Each subject had to complete three successful service trials. Four NAC 60/200 Hz black and white high-speed cameras at 200 frames/s recorded each service motion, and the video data was used to track arm motion and to delineate the phases of the service motion as they related to the arm motion: cocking, acceleration, ball impact, deceleration, and follow-through. Ball impact was considered as time zero. Arm motion was measured as glenohumeral rotation and as humeral motion in horizontal plane abduction and adduction.

RESULTS

Muscle activations

One-way ANOVA revealed no statistically significant differences in timing or duration of activation between the individual subjects, so the group results were pooled and expressed as means. The means and SD of the onset and offset times of muscle activation relative to ball impact ($T = 0$) are listed in table 1 and displayed graphically in fig 1. Negative numbers represent activations before ball impact (T_0) while positive numbers represent activations after T_0. Table 1 also lists the duration of activation and percentage of the serve motion the muscle was activated.

Timing of phases of service motion

The subject was considered ''involved'' in the serve motion from the initiation of downward arm movement until forward arm movement across the body ceased. According to those criteria, the serve motion lasted an average of 651 ms from –326 ms before to +325 ms after ball impact. The phases previously established for the service motion were used for the analysis and could be quantified from kinematic data.[9] The cocking phase started at the initiation of arm movement, and ended at maximum shoulder external rotation, which in this study occurred at −87 ms. The acceleration phase started at maximal shoulder external rotation and ended at maximum shoulder internal rotation velocity, which occurred at −8 ms. The deceleration phase of follow-through started at maximum internal rotation velocity and ended at maximum elbow extension occurring at +59 ms. Follow-through continued until the end of the arm movement and muscle activity at +325 ms.

Activation sequencing

The sequencing of the mean onset of activation revealed activation of serratus anterior (−286.98 ms), anterior deltoid (−250.3 ms), and upper trapezius (−234.45 ms) in early cocking. Activation in mid and late cocking included teres minor (−214.75 ms), posterior deltoid (−157.8 ms), lower trapezius (−119.7 ms), and supraspinatus (−103.83 ms). Infraspinatus was activated in deceleration (+47.05 ms).

Mean offset sequencing revealed early deactivation of anterior deltoid (+170.1 ms) and serratus anterior (+199.97 ms). Upper trapezius (+225.29) and infraspinatus (+230.95) were deactivated midway through follow-through. Late deactivation included supraspinatus (+262.17), posterior deltoid (+281.54), lower trapezius (+296.25), and teres minor (+319.5).

Most of the muscles were activated for a long proportion of the time that the shoulder was involved in the serving cycle. All muscles but the infraspinatus were activated on average for more than 50% of the cycle, and serratus anterior, upper trapezius, and teres minor were activated on average for more than 70% of the cycle.

DISCUSSION

By using an ''onset/duration/offset'' method of evaluation, this study showed that the tested muscles exhibited a pattern of activation during the time the shoulder was involved in the tennis service motion (table 1, fig 1). These patterns involve coupling of activation to accomplish initial motion and stabilisation of the scapula by the trapezius and serratus anterior, followed by positioning of the arm by the deltoid, and finally stabilisation of the humeral head by the rotator cuff. This pattern of proximal to distal activation, involving the scapular stabilisers before the arm positioners and rotator cuff, is qualitatively similar to that found in baseball.[7] The implications of these patterns can be analysed in relation to the recognised phases of the tennis service motion.

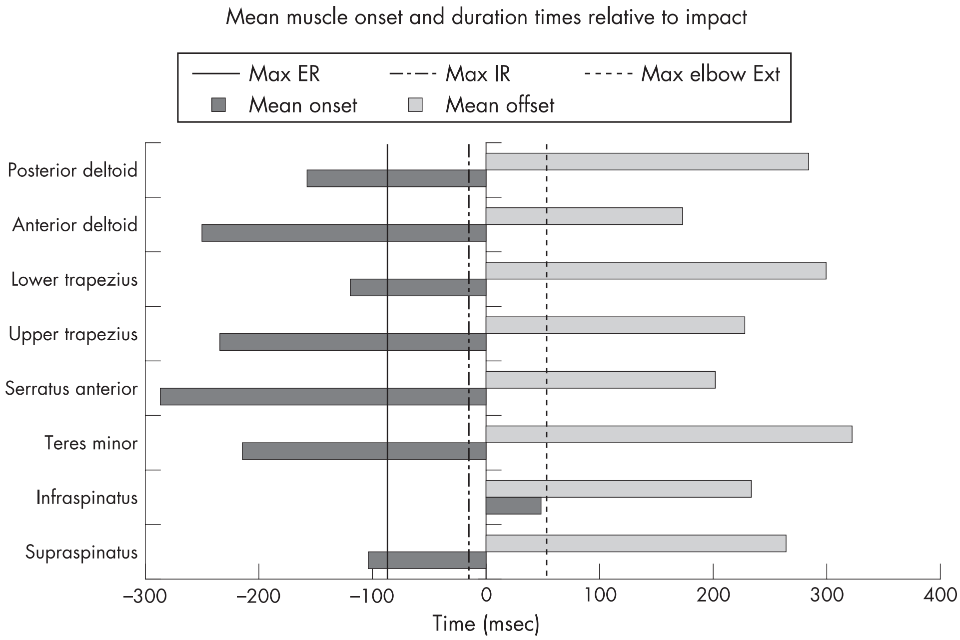

Figure 1 Muscle activation onset and offset in relation to the phases of the serve motion. T_0, ball impact; cocking, initiation of motion to maximal exerternal rotation (Max ER); acceleration, Max ER to maximum internal rotation velocity (Max IR); deceleration, Max IR to maximum elbow extension (Max Elbow Ext); follow-through, Max elbow ext to end of arm motion.

Cocking phase (−326 ms to −87 ms)

The first muscle in this group to be activated is the serratus anterior. The upper trapezius is activated within 50 ms, establishing the force couple for initial scapular stabilisation and acromial elevation.[8 11] The functional consequences of this force couple activation are initiation of acromial elevation and positioning the scapula in external rotation and posterior tilt in relation to the moving humerus.[4 7 8 11–14]

Lower trapezius activation occurs later to complete scapular stabilisation and acromial elevation. Concentric lower trapezius activation is necessary to provide a stable platform for rotator cuff activation.[5 8 9 15] When the scapula has rotated about 45 to 60°, in late cocking, the lower trapezius is mechanically efficient to continue acromial elevation and control internal rotation as the arm abducts, decreasing rotator cuff impingement.[12 16 17]

The anterior deltoid is activated early in cocking to provide eccentric control of the arm as it is horizontally abducting and externally rotating, which storing elastic energy and facilitating plyometric force generation in the acceleration phase.[3 18]

The supraspinatus is activated to work as a force couple with the deltoid to depress the humeral head and control external rotation after the scapula is stabilised.[14 19] In this cohort, the teres minor was activated in cocking rather than the infraspinatus. This short duration of infraspinatus activation is consistent with other tennis studies[9] that show relatively low intensity of infraspinatus activation. In tennis, it appears that the infraspinatus is a relatively unimportant muscle.

Acceleration phase (−87 ms to −8 ms)

Activation of all of the muscles continues above the onset threshold.

Deceleration phase (−8 ms to +59 ms)

All muscles continue their activation, and the infraspinatus is activated. It is now in a good anatomic position as an assistive muscle to help control humeral deceleration and shoulder joint distraction.[3]

Follow-through phase (+59 ms to +325 ms)

This phase is concerned with dissipating the distraction and acceleration forces, and reacquiring normal trunk and shoulder posture.[4 20] As these functions are accomplished, the muscles are sequentially deactivated. The anterior deltoid is offset first, as it is no longer needed for active horizontal adduction or internal rotation. Most of this function is developed by the interactive moment created by trunk rotation.[21] All of the other muscles are deactivated relatively late in follow-through, emphasising their importance in eccentric control of the arm. The serratus anterior and upper trapezius muscles are offset as acromial elevation is diminished, and the infraspinatus is offset as humeral rotation slows. Final elements of force control and posture reacquisition are conferred to the scapula by the lower trapezius, humeral head by the supraspinatus and teres minor, and the upper arm by the posterior deltoid.

Table 1 Muscle Onset, Duration, and Offset

	Mean (SD) onset (ms)	Mean (SD) offset (ms)	Mean (SD) duration (ms)	Serve motion (%)	Range (%)
Supraspinatus	−103.83 (50.98)	262.17 (153.8)	366.0 (112.7)	58	38–69
Infraspinatus	47.05 (101.9)	230.95 (113.6)	183.9 (101.5)	28	18–31
Teres minor	−214.75 (64.7)	319.5 (66.2)	534.25 (66.1)	81	77–91
Serratus anterior	−286.98 (297.4)	199.87 (128.7)	486.85 (226.4)	74	39–89
Upper trapezius	−234.45 (211.9)	225.29 (186.5)	459.74 (193.7)	70	39–92
Lower trapezius	−119.7 (100.5)	296.25 (195.5)	425.95 (148)	62	46–71
Anterior deltoid	−250.3 (194.8)	170.1 (147.1)	420.4 (164.5)	63	40–72
Posterior deltoid	−157.8 (45.9)	281.54 (97.4)	439.34 (67.7)	67	54–77

Values expressed in relation to ball impact (T_0). Activations prior to T_0 = negative numbers. Activations after T_0 = positive numbers.

Limitations

There are several limitations to this study. Exact measurement of muscle onset, duration, and offset to examine patterns can be technically difficult due to muscle "cross-talk," impure EMG signal, or difficulty in precisely determining onset and offset times. This difficulty is reflected in the relatively large SD values in the activation timing some of the muscles. This is very characteristic of muscle activation studies.[7 22] Because of the large potential variation, there were no statistically significant differences seen within the individual subjects in this study. The SD values also reflect the fact that muscles are activated in different subjects in slightly different sequences depending on arm position and speed. Despite their skilful ranking, none of the subjects had exactly the same serving pattern. Inter-subject variation is usually small, but intra-subject variation can be large.[7 22] To minimise the EMG component of the SD, this study followed DeLuca's recommendations to measure activation time in concentric and eccentric activation, place the recording electrodes in positions to minimise cross-talk, and utilise short sampling windows of 25 ms duration.[23] This allowed the construction of quiet files of minimal baseline activation with precise ability to detect activation from the baseline in any phase of the service motion. The onset-offset level was established at a firing intensity greater than 3 SD from baseline. This generated a 95% confidence level that the activation signal differed from baseline noise, and that the muscle was being significantly activated. This method of analysis was not as mathematically complex as other studies[7 22] but did result in a level of resolution regarding muscle activation patterns that was consistent with the other studies.

In addition, all of the subjects were males. There can be different patterns of activation in females, as has been shown in studies of leg muscle activation in runners.[24] This should be further investigated.

Finally, this study describes patterns that are valid for the conditions of this study. The data do not support any statements about injury risk or optimal performance nor do they suggest strict adherence to the exact timing of the activations. However, the patterns do correlate with the results in other activities and sports, and can be considered favourable as guidelines for conditioning and rehabilitation programs.

Clinical implications for conditioning and rehabilitation

One of the goals of a conditioning program is to optimise muscle activation and one of the goals of rehabilitation is to restore optimal muscle activation. This study suggests some guidelines towards those goals. As different parts of the same muscle (upper and lower trapezius, anterior and posterior deltoid) are activated at different times, and for different durations, during the service motion, they can act as separate muscles. Conditioning or rehabilitation exercises must be directed at activation of each part of the muscle in their proper position and function.

Second, as the muscle activations start at the scapular stabilisers and proceed towards the rotator cuff, conditioning and rehabilitation exercises should adhere to the same progression. They should emphasise scapular stability and control as a basis for rotator cuff activation, and should integrate the training of the muscles along kinetic chain principle.[25] Eccentric activation of the scapular stabilisers, the anterior deltoid and the posterior deltoid should be implemented, and plyometric or stretch/shortening activities with medicine balls or tubing should be emphasised. A stable scapular base is required for maximal rotator cuff activation, so rotator cuff emphasis should be delayed until adequate scapular control is achieved.[26]

Third, most of the muscles are activated for a high percentage of the duration of the tennis serve motion. This implies that part of the training of these muscles should involve endurance exercises. The early activation of the serratus anterior in the cocking phase shows that this muscle should be rehabilitated as a scapular external rotator. The patient can progress to rotator cuff exercises after scapular control is regained.[25]

What is already known on this topic

- Previous studies have utilised EMG to investigate muscles in the tennis serve.
- Intensity of muscle activation, as a percentage of maximal voluntary isometric contraction, in the various phases of the serve has been reported.
- Muscles have been found to be active during all phases of the serve at varying levels of intensity.

What this study adds

- Patterns and sequencing of muscle activation are investigated.
- Specific patterns of activation are established.
- A clearer picture of how coupled activations accomplish the motions and positions of the arm in the tennis serve is given
- Guidelines for goals and content of rehabilitation and conditioning programs are suggested.

CONCLUSIONS

EMG analysis used an onset/offset method to demonstrate that scapular and shoulder muscles are activated in patterns during the service motion. In wind-up, cocking and acceleration, the onset sequences show that the scapular stabilisers and anterior eccentric shoulder stabilisers are activated first, followed by the rotator cuff. In deceleration and follow-through, the offset sequences show that most muscles work into follow-through to control tensile loads. These patterns of activation are consistent with other studies in activities and sports. The muscle activation might differentially involve separate parts of the same muscle. The duration of activation of most of the tested muscles can be quite long. Conditioning and rehabilitation programs should be designed with these activation sequences (scapular stabilisers before rotator cuff), differential activations (upper and lower trapezius, anterior and posterior deltoid), and duration (endurance work for serratus anterior, trapezius and deltoid) in mind.

Authors' affiliations

William B Kibler, Lexington Clinic Sports Medicine Center, Lexington, Kentucky, USA
T Jeff Chandler, Jacksonville State University, Jacksonville, Alabama, USA
Robert Shapiro, Michael Conuel, University of Kentucky, Lexington, Kentucky, USA

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REFERENCES

1 **Pink MM**, Perry J. Biomechanics of the shoulder, In: Jobe FW, ed. *Operative techniques in upper extremity sports injuries*. St Louis: Mosby, 1996:109–24.
2 **Kibler WB**. Biomechanical analysis of the shoulder during tennis activities. *Clin Sports Med* 1995;**14**:79–85.

3 **Kibler WB**. Analysis of sport as a diagnostic aid. *The shoulder, a balance of mobility and stability*. Rosemont, Illinois: AAOS, 1993.
4 **Happee R**, Van Der Helm FCT: The control of shoulder muscles during goal directed movements. *J Biomech* 1995;**28**:1179–91.
5 **Happee R**. Goal directed movements II: a kinematic model and its relation to EMG. *J Electromyogr Kinesiology* 1993;**3**:13–23.
6 **Nieminen H**, Niemi J, Takala EP, *et al.* Load sharing patterns in the shoulder during isometric flexion tasks. *J Biomech* 1995;**28**:555–66.
7 **Hirashima M**, Kadota H, Sakurai S, *et al.* Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *J Sports Sci* 2002;**20**:301–10.
8 **Bagg SD**, Forrest WJ. Electromyographic study of the scapular rotators during arm abduction in the scapular plane. *Am J Physical Med* 1986;**65**:111–24.
9 **Ryu RKN**, McCormick J, Jobe FW, *et al.* An electromyographic analysis of shoulder function in tennis players. *Am J Sports Med* 1988;**16**:481–5.
10 **Nieminen H**, Takala EP, Vikari-Juntura E. Normalization of electromyogram in the neck-shoulder region. *Eur J Appl Physiol* 1993;**67**:199–207.
11 **McClure PW**, Michener LA, Sennet BJ, *et al.* Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *J Shoulder Elb Surg* 2001;**10**:269–78.
12 **Bagg SD**, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. *Am J Physical Med* 1988;**67**:238–45.
13 **Kibler WB**. The role of the scapula in athletic shoulder function. *Am J Sports Med* 1998;**26**:325–37.
14 **Speer KP**, Garrett WE. Muscular control of motion and stability about the pectoral girdle. In: Matsen FA, Fu F, Hawkins RJ, eds. *The shoulder: a balance of mobility and stability*. Rosemont, Illinois: AAOS, 1994:159–73.
15 Kebatse M, McClure P, Pratt N: Thoracic position effect on shoulder range of motion, strength, and 3-dimensional scapular kinetics. *Arch Phys Med Rehab* 1999;**80**:945–50.
16 **McQuade KJ**, Dawson J, Smidt GL. Scapulothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. *J Orthop Sports Phys Ther* 1998;**28**:74–80.
17 **Ludewig PM**, Cook TM. Alterations in shoulder kinematics and associated activity in people with symptoms of shoulder impingement. *Phys Ther* 2000;**80**:276–92.
18 **Wilk KE**, Voight ML, Keirns MA. Stretch-shortening exercises for the upper extremity: theory and clinical application. *J Orthop Sports Phy Ther* 1993;**17**:225–39.
19 **Inman VT**, Saunders JB, Abbott LC. Observations on the function of the shoulder joint. *J Bone Joint Surg* 1944;**26**:1–30.
20 **Kraemer WJ**, Triplett NT, Fry AC. An in-depth sports medicine profile of women college players. *J Sports Rehab* 1995;**4**:79–88.
21 **Putnam CA**. Sequential motions of body segments in stroking and throwing skills. *J Biomech* 1993;**26**:125–35.
22 **Latash ML**, Scholz JP, Schoner G. Motor control strategies revealed in the structure of motor variability. *Exerc Sports Sci Rev* 2002;**30**:26–32.
23 **DeLuca C**. The use of surface electromyography in biomechanics. *J Appl Biomech* 1997;**13**:135–63.
24 **DeMont RG**, Lephart SM. Effect of sex on preactivation of the gastrocnemius and hamstring muscles. *Br J Sport Med* 2004;**38**:120–4.
25 **Kibler WB**, McMullen J, Uhl TL. Shoulder rehabilitation strategies, guidelines, and practices. *Orthop Clin N Am* 2001;**32**:527–38.
26 **Kibler WB**, Sciascia AD, Dome DC. Evaluation of apparent and absolute supraspinatus strength in patients with shoulder injury using the scapular retraction test. *Am J Sports Med* 2006;**34**:1643–7.