Journal of Electromyography and Kinesiology 20 (2010) 212–222

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Quantifying 'normal' shoulder muscle activity during abduction

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ARTICLE INFO

Article history:
Received 4 February 2009
Received in revised form 20 April 2009
Accepted 1 June 2009

Keywords:
Electromyography
Shoulder
Abduction
Muscle
Normal

ABSTRACT

The purpose of this experiment was to obtain electromyographic (EMG) activity from a sample of healthy shoulders to allow a reference database to be developed and used for comparison with pathological shoulders. Temporal and intensity shoulder muscle activation characteristics during a coronal plane abduction/adduction movement were evaluated in the dominant healthy shoulder of 24 subjects. Surface and intramuscular fine wire electrodes recorded EMG activity from 15 shoulder muscles (deltoid $\times$ 3, trapezius $\times$ 3, subscapularis $\times$ 2, latissimus dorsi, pectoralis major, pectoralis minor, supraspinatus, infraspinatus, serratus anterior and rhomboids) at 2000 Hz for 10 s whilst each subject performed 10 dynamic coronal plane abduction/adduction movements from 0° to 166° to 0° with a light dumbbell. Results revealed that supraspinatus (−.102 s before movement onset) initiated the movement with middle trapezius (−.019 s) and middle deltoid (−.014 s) also activated before the movement onset. Similar patterns were also found in the time of peak amplitude and %MVC with a pattern emerging where the prime movers (supraspinatus and middle deltoid) were among the first to reach peak amplitude or display the highest %MVC values. In conclusion, the most reproducible patterns of activation arose from the more prime mover muscle sites in all EMG variables analysed and although variability was present, there emerged 'invariant characteristics' that were considered 'normal' for this group of non pathological shoulders. The authors believe that the methodology and certain parts of the analysis in this study can be duplicated and used by future researchers who require a reference database of muscle activity for use as a control group in comparisons to their respective pathological shoulder group.

1. Introduction

The glenohumeral joint is an incongruent ball and socket type synovial joint. Due to its lack of bony congruence, it is very much reliant on a balance between the capsuloligamentous structures and musculature surrounding the joint. The muscular stability of the glenohumeral joint is provided through the recruitment of primarily the rotator cuff, deltoid and long head of biceps (Kronberg et al., 1990) whilst muscles such as latissimus dorsi, teres major and pectoralis major have been stated as being primarily responsible for movement (Hess, 2000). While ligaments and passive mechanisms such as negative intra-articular pressure do provide considerable support, it is only the more neurally driven muscle activity (dynamic stabilisation) that has the capacity to respond to different loading conditions and limb configurations (Barden et al., 2005). Consequently, it is of interest to determine whether shoulder joint muscles, both stabilisers and movers, respond in predictable activation patterns when performing certain movements.

Electromyography (EMG) has been used as a tool to determine muscle activity since the classical studies of Inman in 1944. In regard to the shoulder, EMG has been used for a variety of uses including; the assessment of muscle activity during commonly prescribed therapeutic exercises (Decker et al., 1999; McCann et al., 1993; Moseley et al., 1992; Reinold et al., 2007) kinesiological investigations (Bradley and Tibone, 1991; Pearl et al., 1992; Scheving and Pauly, 1959; Shevlin et al., 1969), sports specific movements (Jobe et al., 1984, 1989; Ryu et al., 1988) and for the development of a reference database for dynamic movements to use in comparisons with pathological shoulders (Kronberg et al., 1990). This latter use of EMG, to define a regular pattern of EMG in standardised dynamic planar movements for healthy shoulders, is of particular interest for this investigation.

Kronberg et al., 1990 recorded muscle activity from eight shoulder muscles in five subjects (10 shoulders) whilst performing the dynamic movements of flexion, extension, abduction, and internal and external rotation performed at 0°, 45° and 90° of abduction. Although a range of different movements were

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doi:10.1016/j.jelekin.2009.06.004

employed, methodological limitations of this study included the use of only 10 shoulders from five subjects, only eight muscles investigated, the use of a constant 20 N weight for each subject and no eccentric muscle activity included in analysis. Furthermore, no analysis of temporal variables such as muscle onset was investigated.

Based on limitations and a lack of previous literature there is a need to fully quantify muscle activity around the shoulder joint in order to establish a reference database of shoulder muscle activity in dynamic movements that can be used by future researchers for comparisons with pathological shoulders. Therefore, the purpose of the present study was to use EMG as a tool to establish the temporal and intensity patterns of muscle activity in fifteen muscles during a dynamic abduction/adduction movement for a group of 24 participants with normal shoulders.

2. Method

2.1. Procedures

Twenty-four subjects (13 male, 11 female) aged between 18 and 37 years ($X = 23.6 \pm 5.3$) with no known history of shoulder pathologies volunteered to participate in this experiment. Informed consent was obtained and ethics approval was granted by the Latrobe University Human Ethics Committee (03-129). After adequate practice, subjects were asked to stand in the anatomical position whist holding a light dumbbell and perform a coronal plane abduction/adduction movement (0°–180°–0°) within a 10 s recording period whilst the experimenter monitored speed and movement plane. To ensure a standardised movement plane, each participant was required to pass the hand between two chains hanging from the ceiling 20 centimetres apart (see Fig. 1).

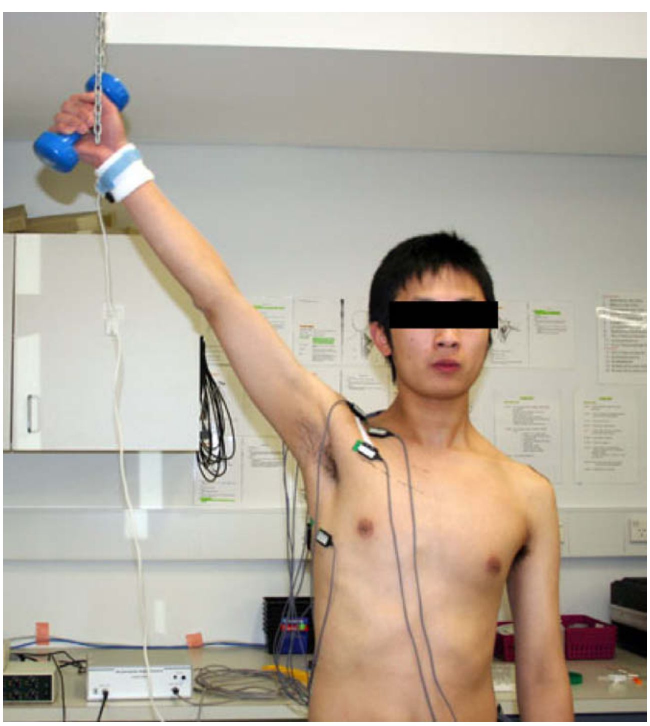

Fig. 1. Photograph depicting a subject performing the dynamic abduction trials. Note the chains hung from the ceiling, one in front of the hand and one behind spaced 200 mm apart, in the left corner of photo. Subjects had to pass their arm between these chains without touching to record an acceptable trial. Subjects started with arms at their sides and performed shoulder abduction to 165° and then back down to their side again in 8.5 s on average. Also note the accelerometer angle processor attached to the subjects wrist that measured shoulder joint angle with full elbow extension.

Movement speed was standardised by having the investigator count the timing of the movement aloud, counting four seconds for the upper limb to reach full elevation and then four seconds for the upper limb to return back to anatomical position. Subjects performed the required 10 abduction trials with a dumbbell equalling 25% of the force output (Lafayette Manual Muscle Tester; positioned on the subjects' wrist) for an abduction maximum voluntary isometric contraction (MVC) performed at 90° abduction. Typically, for most subjects this equated to a 2½ kg dumbbell as the average weight of dumbbell used with a SD of ±.65 kg. Each participant was given 30 s rests between each of the 10 trials to eliminate possible muscle fatigue. In addition to the abduction trials, seven different isometric MVCs were completed to allow the EMG data to be normalised. These consisted of the following:

1. Abduction at 90° of shoulder joint elevation in the coronal plane.
2. Flexion at 90° of shoulder joint elevation in the sagittal plane.
3. Internal rotation at 90° of shoulder joint elevation with neutral rotation.
4. External rotation at 90° of shoulder joint elevation with neutral rotation.
5. Horizontal flexion at 90° of shoulder joint elevation in coronal plane.
6. Retraction done seated with arms at sides with subject told to squeeze shoulder blades together as hard as possible.
7. Extension at 0° of shoulder joint elevation in the sagittal plane.

Each subject was asked to perform a maximal isometric contraction for five seconds. The middle two seconds of each MVC was recorded (the recording commenced after the subject had been contracting for approximately two seconds) with a total of three MVCs performed for each movement. Participants rested for three minutes between MVCs to prevent fatigue limiting maximal output.

2.2. Instrumentation

Bipolar fine wire intramuscular electrodes, as first described by Basmajian and Stecko (1962), were used to record the EMG signal from the deep muscles of upper subscapularis, lower subscapularis, rhomboids, pectoralis minor, and supraspinatus. The intramuscular electrodes were fabricated from 75 μm Teflon® coated stainless steel single strand wire (A-M Systems, Washington, USA). One millimetre of the Teflon coated insulation was stripped from one end of the two wires to form the recording surface and 10 mm was stripped on the other end of the two wires in order to fit between the springs of the electrode housing. The electrode wires were inserted into a 23 gauge single use hypodermic needle with the exposed electrode tips bent at 3 mm and 5 mm to prevent the contact areas from touching whilst in the muscle. The wire and needle assemblies were then autoclaved for sterilisation purposes. A Siemens Elegra 256 Advance ultrasound machine was used to guide the needle of the intramuscular electrodes into each of the five deep muscles according to the ultrasound image. The surface electrodes used were DE-3.1 electrodes (Delsys Inc., Boston, USA) which featured a double differential three-bar type configuration with a 99.9% silver contact material and an inter-electrode distance of 10 mm. A large 2-inch self-adhering Dermatrode electrode (American Imex, CA, USA) was used as the reference, with it being placed on the acromion of the shoulder not being tested.

An accelerometer angle processor, which converted voltages into degree values by use of a conversion factor, was attached to the participant's wrist and used to give a measurement of the shoulder angle (degrees) during the dynamic movement (see Fig. 1). The starting position for the abduction trials, with the subject holding a dumbbell in the anatomical position, was considered zero degrees and approximated the arm being perpendicular to the horizontal.

A Delsys® Bagnoli-16 EMG system (Delsys Inc., Boston, USA 02215) was used to record both the raw EMG signals and accelerometer signals at a sampling rate of 2 kHz for a 10 s period before A–D conversion and storage on an IBM compatible computer. A band pass filter (built into the amplifier: Delsys Inc., Boston, USA) of 20–2000 Hz was applied to the intramuscular electrodes and 20–450 Hz for the surface electrodes. The gain was set for all channels at 1000.

2.3. Electrode placement

Needle position within the supraspinatus, rhomboids, and pectoralis minor were located using the guidelines of Delagi and Perotto (1980). The investigators modified the conventional technique of inserting an intramuscular electrode into subscapularis (Nemeth et al., 1990) to allow two electrodes to be inserted into this muscle. With the subject lying halfway between supine and side-lying and with the arm abducted and the hand placed behind the head, the lateral border of the scapula was palpated with markings for needle insertion placed 20 mm anterior to the lateral border at distances of 45–60 mm and 95–110 mm above the inferior angle. Needle insertions varied within these two length ranges due to differences in scapula length and the lack of a reliable superior landmark in the axilla for normalisation. Surface electrodes were placed, according to the guidelines of Delagi and Perotto (1980), on the more superficial muscles of anterior, middle and posterior deltoid; upper, middle and lower trapezius; and infraspinatus. The three remaining surface electrode positions of latissimus dorsi, serratus anterior and the clavicular head of pectoralis major were determined using the guidelines of Geiringer (1999).

Table 1
Ranked average muscle onset times for the 24 subjects during dynamic abduction.

Rank	Muscles	Onset time (s)
1st	Supraspinatus (16)	−0.102 ± 0.117
2nd	Middle trapezius (22)	−0.019 ± 0.082
3rd	Middle deltoid (22)	−0.014 ± 0.056
4th	Serratus anterior (22)	0.019 ± 0.169
5th	Upper trapezius (24)	0.067 ± 0.146
6th	Rhomboids (16)	0.072 ± 0.354
7th	Anterior deltoid (22)	0.087 ± 0.111
8th	Posterior deltoid (6)	0.097 ± 0.099
9th	Lower trapezius (23)	0.231 ± 0.460
10th	Lower subscapularis (13)	0.290 ± 0.164
11th	Infraspinatus (12)	0.423 ± 0.361
12th	Latissimus dorsi (9)	0.471 ± 0.358
13th	Upper subscapularis (8)	0.558 ± 0.329
14th	Pectoralis minor (5)	0.559 ± 0.334
15th	Pectoralis major (12)	0.909 ± 0.485

Note: Values represent mean ± standard deviation. Negative values indicate that the muscle was active before the start of the movement. Bracketed numbers represent the number of subjects analysed for that particular muscle with lower numbers typically indicating the muscle not being active (<10%MVC) in some subjects or wires being dislodged for intramuscular electrodes.

2.4. Data analysis

All EMG data from the dynamic abduction trials and MVCs were full wave rectified and low pass filtered at a cut-off frequency of 6 Hz through a 4th order Butterworth filter with phase lag. The angle accelerometer processor data was just low pass filtered and not rectified to prevent distortion of movement onset. For the MVC value of each muscle the highest RMS value derived from a 600 ms window was used. The window was always taken from the middle of the recorded 2 s MVC traces. All 7 MVC positions were analysed for each muscle in order to obtain the highest MVC reference value. This value (100%) was compared to the RMS values obtained from the 10 abduction trials with this RMS window placed between the particular muscles' onset and termination.

Delsys® EMGworks signal analysis software was used to determine the dependent variables of muscle/segment onset, termination, time of peak intensity and %MVC. Muscle onset was visually determined as the first detectable rise from the fluctuating baseline and to avoid bias the researcher was blinded to the goniometer trace. Dependent variables were calculated as follows;

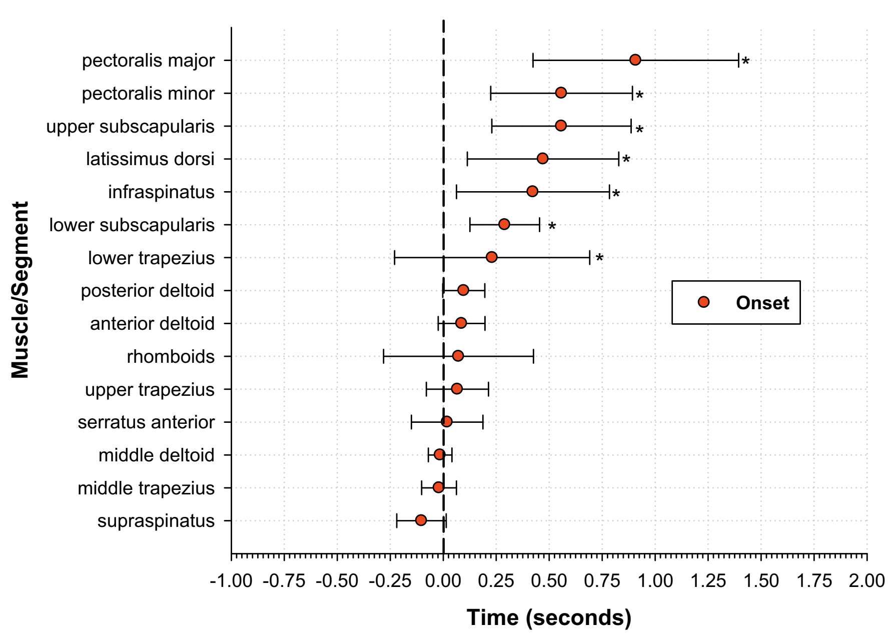

Fig. 2. Average muscle/segment onset time(s) for 24 subjects during dynamic shoulder joint abduction. The vertical dashed line at zero seconds represents the start of the abduction movement with muscle/segment onset times to the left (negative) of this line being activated before the beginning of the movement. The ⁎ symbol represents significant differences ($p < .05$) to supraspinatus according to One Way Repeated Measures ANOVA Post hoc comparison procedure (Holm–Sidak method). Note the large variability in the later activated muscles. Standard deviation bars are shown.

- **Muscle/Segment Onset** – the muscle onset minus the movement onset to provide a value in seconds before (−) or after (+) the beginning of the movement onset.
- **Muscle/Segment Termination** – determined by taking the value (degrees) of when the amplitude first dropped below the same amplitude threshold level on the *Y* axis at which the onset was found.
- **% MVC** – calculated as stated above with a window used between a muscles' onset and termination.
- **Time of Peak Intensity –** the degrees in the range of motion at which the highest amplitude was recorded.

Further analyses were aimed at obtaining average intensity profiles for each muscle. For this purpose Matlab 6.1 software (Mathworks Inc., Massachusetts, USA) was used to produce an ensemble average from ten trials for each muscle and participant. The ensembles were temporally aligned to the start of the movement onset with the duration being the average movement duration calculated from all movement traces. All EMG data for the intensity profiles were also initially full wave rectified and low pass filtered at 6 Hz with amplitude normalised to the same muscle's MVC using the root mean square amplitude measure. Ensemble averages for each muscle and each subject were derived from the 10 abduction trials. To then create a grand ensemble average for each muscle (average intensity profile) our programmed Matlab script summed and averaged each corresponding data point (equal to the sampling rate; 20,000 data points for 10 s at a sampling rate of 2000 Hz) for each subject. The script was also written to display the standard deviation on either side of the intensity profile.

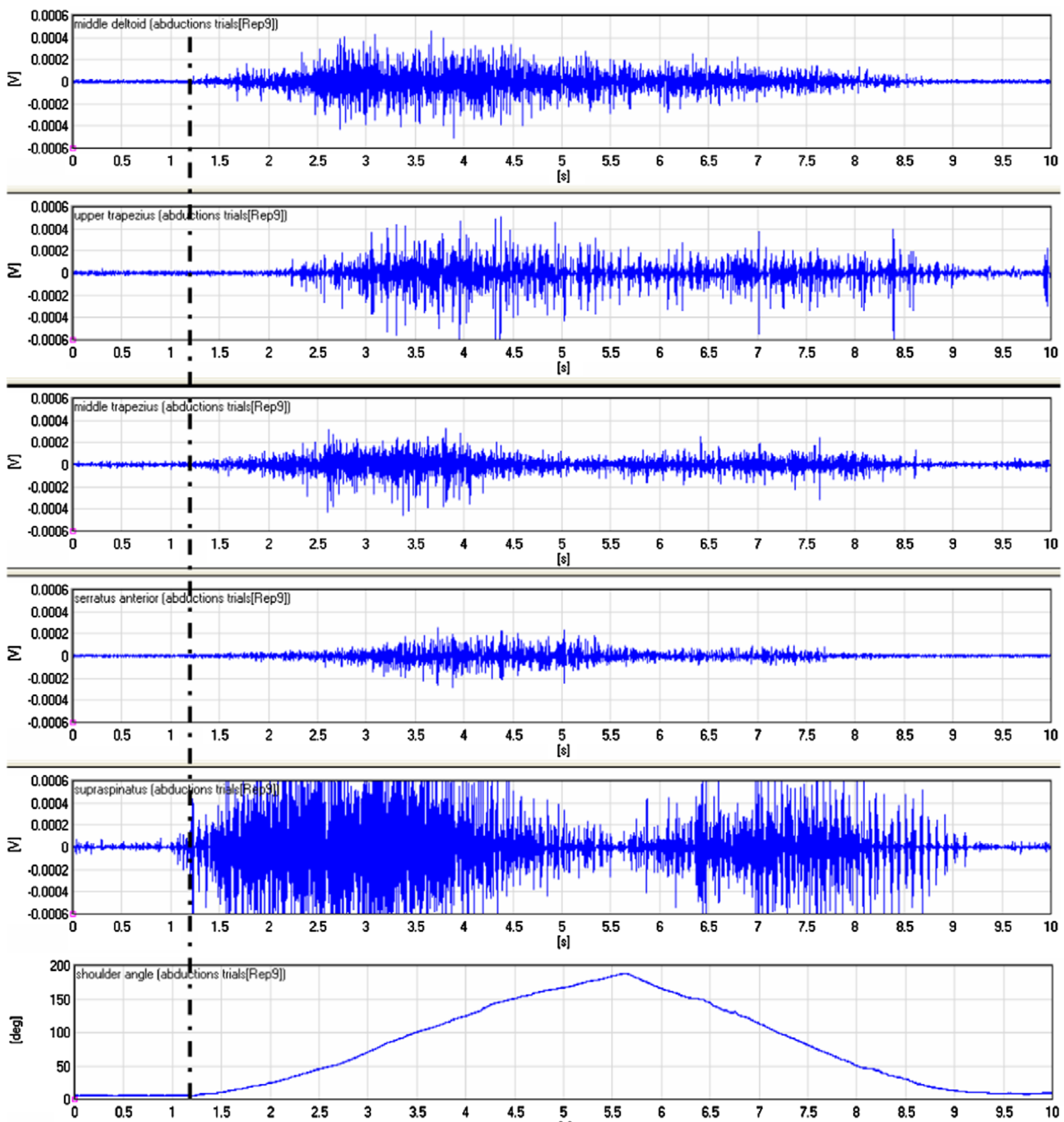

Fig. 3. A representative raw EMG trial taken from Delsys analysis software of one subject displaying the movement trace (bottom diagram) and the first five muscles (from the top diagram down; middle deltoid, upper trapezius, middle trapezius, serratus anterior and supraspinatus) which had the earliest onsets on average. The *Y* axis displays the voltage and the *X* axis displays the 10 s recording period. For the movement trace the *Y* axis displays the degrees of abduction. Note the early preactivation of supraspinatus with regard to the onset of the movement trace (dotted line).

2.5. Statistical evaluations

Statistical analysis software (Sigma Plot 10) was utilised to compute a one-way analysis of variance (ANOVA) for the dependent variables of onset, % MVC and time of peak intensity. Statistical evaluations were designed to determine if differences existed in the timing and intensity between the 15 muscles investigated. A pair-wise multiple comparison procedure (Holm–Sidak method) was utilised to determine which muscles were significantly different from each other. For clarity and ease of illustration, significant differences were typically compared against the prime mover segment (earliest activation and peak intensity). The level of significance was set at ($p < .05$).

The reliability of the testing procedure and data analysis were separately evaluated. Data analysis reliability was examined when 125 randomly selected trials were re-analysed four months after data analysis was completed. An Intraclass Correlation Coefficient (ICC ^{2,1}) was used to statistically compare the two sets of data. The reliability of the actual testing procedure was assessed when three participants were re-tested five months after their first test had been completed. Average onset data of test one was compared to the average onset of test two using the Spearman rank-order correlation coefficient.

3. Results

3.1. Temporal variables

The grand average onset times and standard deviations for each muscle were calculated from the mean muscle onset times of each subject. These results are presented in Table 1 and Fig. 2.

Note that three muscles (supraspinatus, middle trapezius and middle deltoid) were activated before the movement onset with pectoralis major being the last activated at nearly a second after movement onset which equated to 26.2° of abduction. Table 1 also shows a relationship whereby the earlier activated muscles displayed the least variability as represented by their smaller standard deviations. A representative raw EMG trial showing the first 5 muscles that on average (Table 1) had the earliest onset times is displayed in Fig. 3.

The average shoulder angle where peak EMG occurred can be viewed in Fig. 4. Muscles are displayed in order of peak activity throughout dynamic abduction. Supraspinatus muscle activity was the first to reach peak muscle activity which corresponded to an abduction angle of 89 degrees. As the overall average maximum shoulder angle for 24 participants was 165.7, values in excess of this are defined as occurring when the arm adducted back to the starting position. The late peak observed in pectoralis minor is representative of its occurrence approximately 4.87 degrees after the arm started to descend back to its starting position i.e. the shoulder was in 160.9 degrees of abduction.

An overall average summary of temporal variables for the 24 participants including onset, time of peak intensity and termination is depicted in Fig. 5 for the abduction/adduction movement.

3.2. Intensity variables

The overall contraction intensity (RMS) of each muscle, calculated by a window set between the muscle onset and termination, can be viewed in Fig. 6. This data was normalised by expressing it as a% MVC to enable comparison between muscles and their relative contraction intensities. The muscle that contracted at the relative highest intensity was rhomboids at approximately 46%MVC.

For a more graphic representation of muscle intensity during the entire abduction/adduction movement grand ensemble averages were assembled for each muscle (Fig. 7). These figures display intensity profiles (grand ensemble averages) and their standard deviations. Of interest are the muscles that show relatively little variation between subjects such as the supraspinatus and middle deltoid in contrast to muscles that show high variability between subjects like rhomboids and lower trapezius.

3.3. Reliability

To examine the reliability of onset determination, 125 trials (five trials of five randomly selected muscles for five randomly

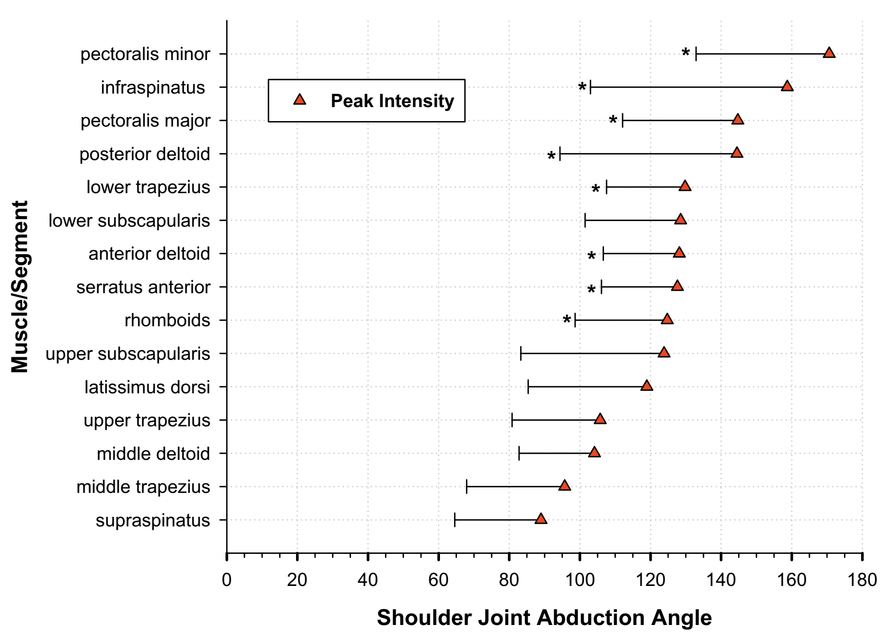

Figure 4. Shoulder joint angle at which the average muscle/segment peak intensity occurred for 24 subjects during dynamic shoulder joint abduction. Muscle/segments have been aligned according to earliest to latest in the time of peak muscle intensity. The * symbol represents significant differences ($p < .05$) to supraspinatus according to One Way Repeated Measures ANOVA Post hoc comparison procedure (Holm–Sidak method). Note the large variability in some muscles. Standard deviation bars are shown.

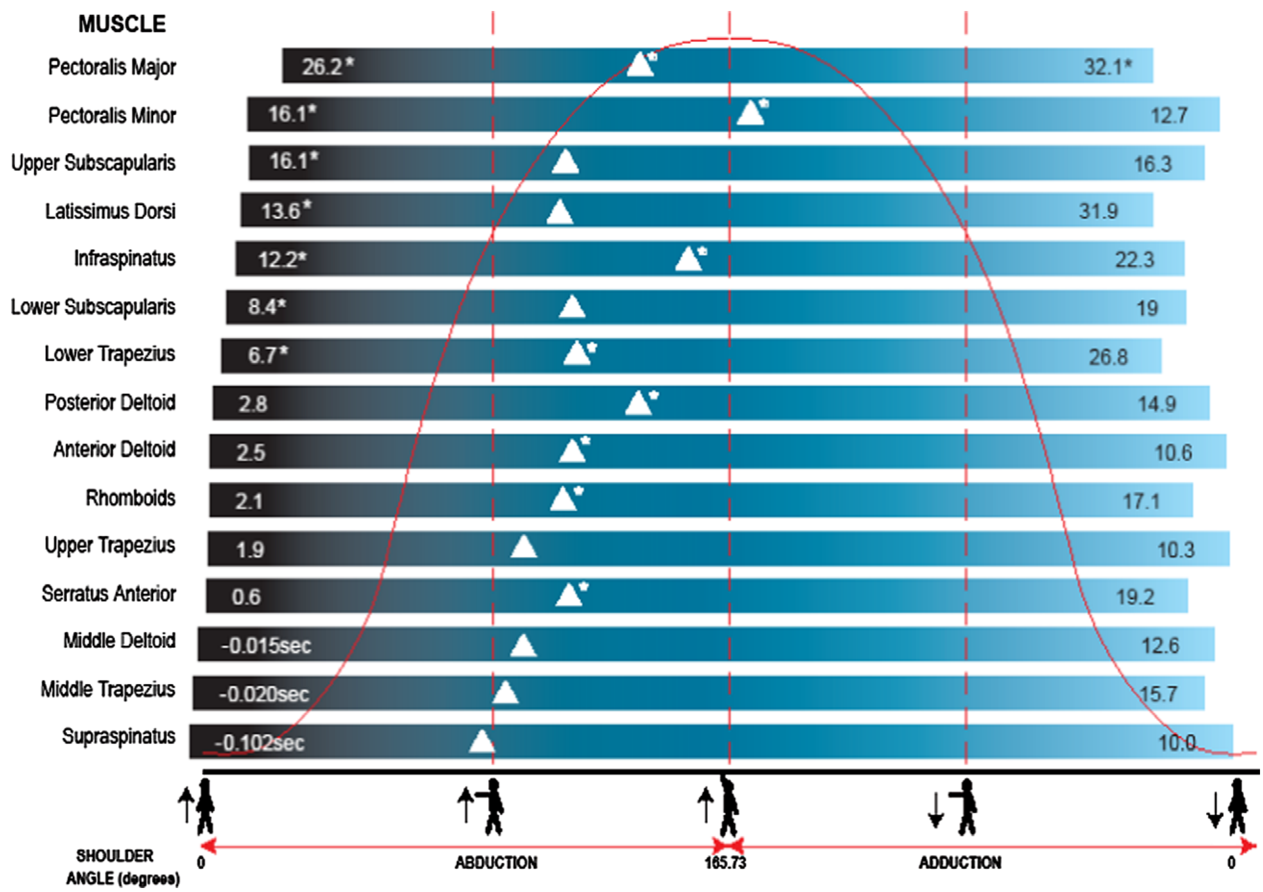

Fig. 5. Graphical representation of average muscle activity encompassing onset, peak and termination of the 24 participants during the dynamic shoulder joint abduction/adduction movement. Duration of muscle/segment activation is represented by the length of the bar with muscles ordered from earliest to latest activated. Onset has been expressed in seconds before the movement began or degrees after the start of the movement with termination expressed in degrees before the arm finished back in the starting position. Note the early activation and peak intensity of supraspinatus. Triangles represent the time of peak intensity. The * symbol represents significant differences ($p < .05$) in the time of onset, peak intensity or offset in relation to supraspinatus according to One Way Repeated Measures ANOVA Post hoc comparison procedure (Holm–Sidak method).

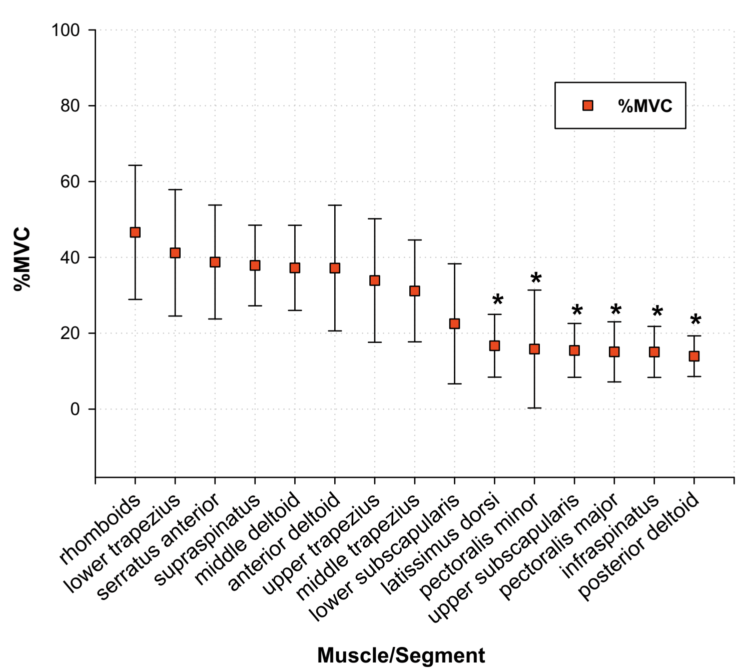

Fig. 6. Average muscle intensity (%MVC) of the 24 participants during dynamic shoulder abduction. Muscle/segment %MVC has been calculated from an RMS window between onset and termination. Muscle/segments have been aligned from highest to lowest overall muscle intensity. The * symbol represents significant differences ($p < .05$) to supraspinatus according to One Way Repeated Measures ANOVA Post hoc comparison procedure (Holm–Sidak method). Standard deviation bars are shown.

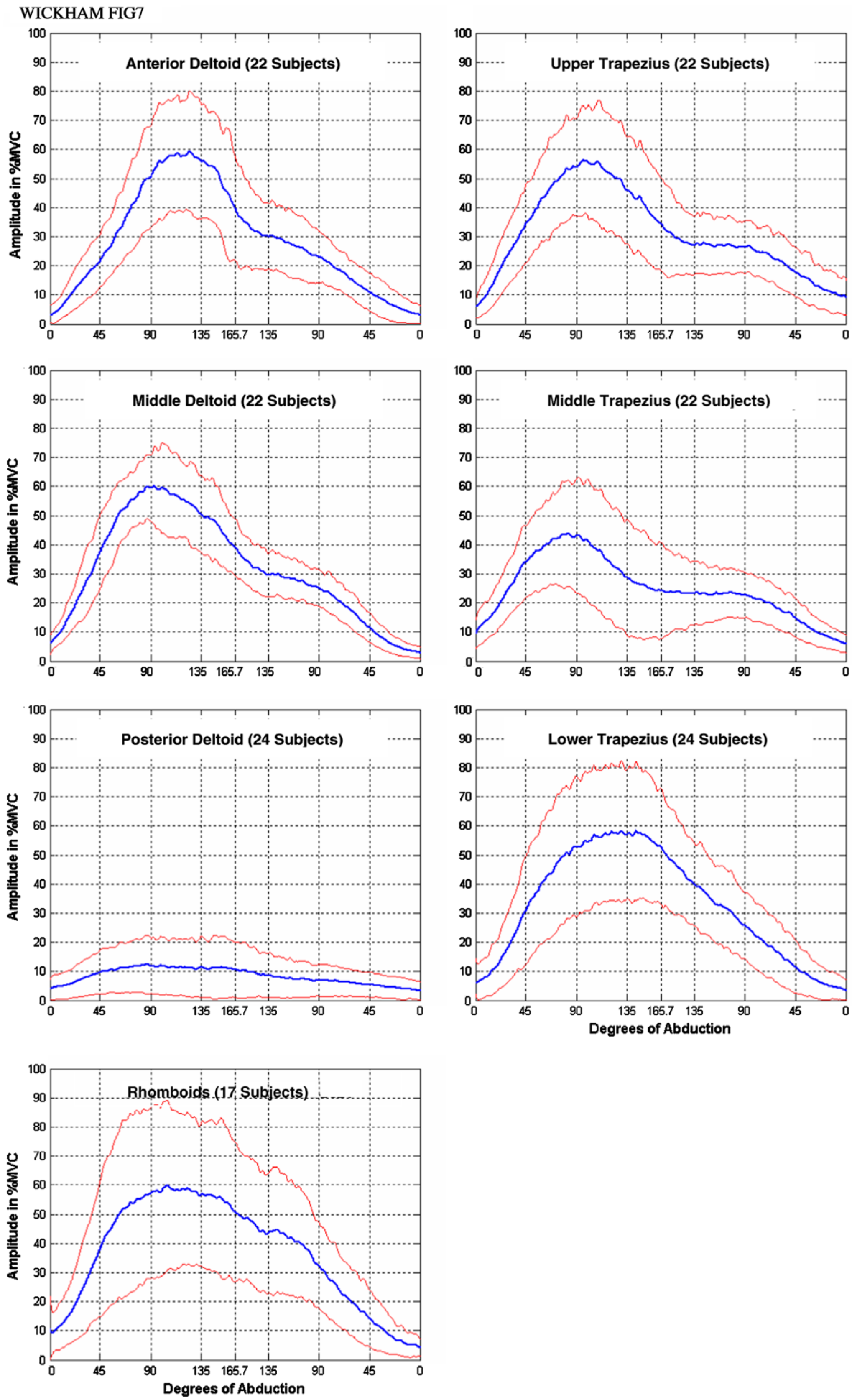

Fig. 7. Grand ensemble averages (intensity profiles) for each of the 15 muscles during the abduction/adduction movement. The middle line represents the average intensity (%MVC) at a particular range of motion during the movement and the upper and lower lines represent the standard deviation. The *X* axis in degrees shows the abduction movement from 0° to 165.7° (average movement peak for subjects) and then back down in adduction to 0°. Note that due to electrode problems sometimes less than 24 subjects were used in the grand ensemble average.

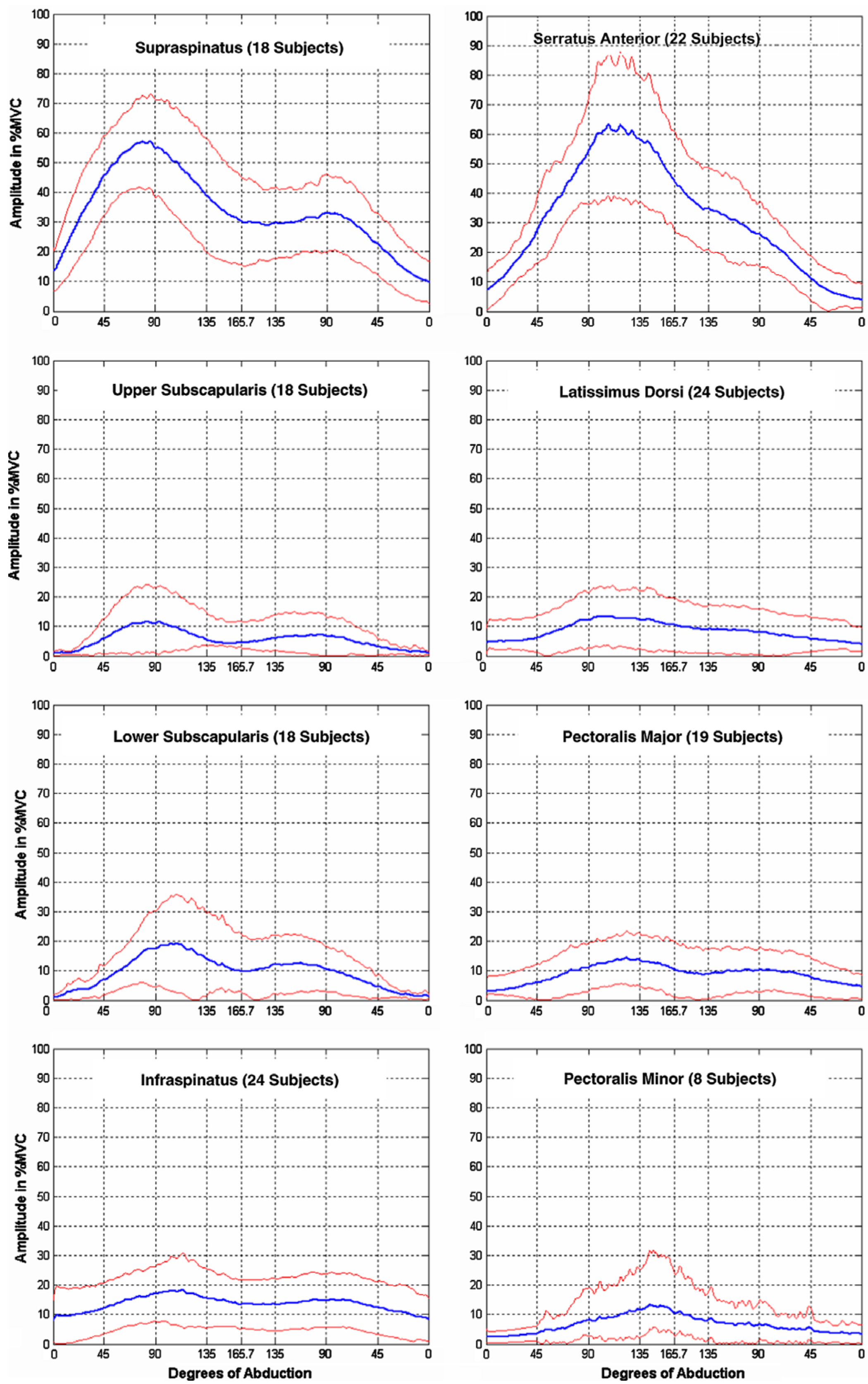

Fig. 7 *(continued)*

selected participants) were re-analysed four months after the original analysis was completed. The data was statistically analysed using an Intraclass Correlation Coefficient ($ICC^{2,1}$). This onset analysis technique was found to have excellent reliability (ICC = .98).

To investigate the reliability of the testing procedure three subjects were tested twice with approximately five months in-between testing sessions. The average onset of test one was compared to the average onset of test two using the Spearman rank-order correlation coefficient (as the data was not normally distributed). Using the onset as an indicator, the test procedure was found to be reliable ($r_s = 0.885$).

4. Discussion

The aim of this investigation was to establish temporal and intensity shoulder muscle activation parameters in order to establish a reference database for future use in comparisons with pathological shoulders. This was achieved by sampling muscle activity from a large number of muscle segments (15), from a relatively large sample of healthy shoulders (24 subjects) whilst performing a well defined repeatable movement (abduction). Glenohumeral abduction was selected for investigation as it involves a large range of motion, requires precise muscular activity to control the movement, and it is often affected by dysfunction of the shoulder musculature. The analysis procedure incorporated a variety of dependent variables both temporal (onset, time of peak amplitude, termination) and intensity (%MVC and intensity profiles), in order to fully quantify 'normal' shoulder muscle activity for this movement.

For the measured variable of muscle onset the results showed that supraspinatus, middle trapezius and middle deltoid were on average activated before the movement began. The early activation of supraspinatus is in accordance with previous research (Barden et al., 2005; Illyes and Kiss, 2005) as being an initiator of the abduction movement. The earlier activation when compared to middle deltoid, although not significant ($p < .05$), is also consistent with its larger moment arm during the early phases of abduction when compared to middle deltoid (Poppen and Walker, 1978). The middle trapezius activated early, potentially to stabilise the scapula and provide an initial stable base to allow the scapulo-humeral muscles to generate force. The onsets of serratus anterior and upper trapezius at 0.019s ± 0.169 and 0.067s ± 0.146, respectively just after movement onset reflect their dual roles as upward rotators and stabilisers for preventing any scapulothoracic downward rotation action by middle deltoid (Levangie and Norkin, 2005).

The data also revealed that the early pre-activated muscles displayed the least amount of variability as represented by their lower standard deviation values in comparison to later activated muscles. The data indicated that a relatively consistent muscle recruitment pattern was necessary to get the limb moving but once the limb was moving any number of muscle recruitment strategies (based on the larger variation in onset times in later activated muscles) kept the limb elevating in the desired plane.

Also interesting in the onset results was the late activation of the lower and upper subscapularis (0.290s ± 0.164 and 0.558s ± 0.329, respectively) and infraspinatus (0.423s ± 0.361). These rotator cuff muscles are thought to counteract the unwanted superior translatory pull of deltoid on the humerus, particularly in the early phases of elevation, by the fact that their lines of action promote joint compression and hence humeral head stabilisation (Levangie and Norkin, 2005). Our results suggest that the stabilisation action of these muscles is not necessary until the limb has moved approximately 10°. Perhaps the secondary function of supraspinatus as a humeral head depressor is enough to offset any unwanted superior translatory forces by middle deltoid during these early stages of abduction.

The group average results for the time of peak muscle intensity showed that the same three muscles that displayed an onset before the movement began (supraspinatus, middle trapezius and middle deltoid) were also the first three muscles, in the same order, to reach their peak intensity the earliest in the abduction movement. This result is consistent with previous research (Brown et al., 2007) which also showed that prime mover segments displayed early onsets and early peak activation and that these muscles had optimal lines of action for the movement. In comparisons to the Kronberg et al. (1990) study, the peak intensities of muscles in this experiment occurred later in the abduction movement. Kronberg et al. reported peak intensity for supraspinatus at 60° and middle deltoid at 90° whereas our data indicated that supraspinatus and middle deltoid reached their respective peak intensities at 88° and 105° of abduction. It is not clear why this discrepancy exists between the two studies, however, the Kronberg study only displayed its peak intensity data graphically in 30° increments hence EMG data between points is not taken into consideration. Data from Inman and Dec, 1944 more closely approximates our own findings with peak activities of supraspinatus occurring at 100° of abduction and middle deltoid reaching peak activity at 110° of abduction. From a biomechanical perspective it is not surprising to record the largest amplitudes from supraspinatus around 90° as this corresponds to the angle where the largest shoulder joint compressive loads are recorded and the torque of gravity is greatest (Oatis, 2004).

The other temporal dependent variable analysed was the termination of muscle activity which was designated to be when the muscle activity dropped below the same threshold intensity level as that used for onset determination. The results showed that although supraspinatus was found to be the last muscle to cease activity (at 10° before the arm came back to reside in the starting position) only one muscle (pectoralis major) was significantly ($p < .05$) deactivated at an earlier stage (32.1°). The termination data, with an increased level of variability, thus did not provide any robust data for future comparisons to pathological shoulders. It did however confirm previous work (Wickham and Brown, 1998) where it was found that the prime mover muscles/segments with early activation also had late deactivation.

The intensity measures that were employed to analyse the amplitude of the signals included a %MVC value for a period of the entire muscle duration and intensity profiles which also used %MVC values in the form of grand ensembles. The overall %MVC results displayed relatively low values ranging from 46.6 (rhomboids) to 13.9%MVC (posterior deltoid). Interesting results included the significantly lower %MVC values for the stabilising rotator cuff muscles of infraspinatus 15.07 ± 6.7 and upper subscapularis 15.5 ± 7.1%MVC when compared to the prime mover rotator cuff muscle of supraspinatus at 37.9 ± 10.6%MVC. This indicates that these muscles were not required to exert large forces on the humerus in order to keep it centred in the glenoid fossa. The low values overall reflect that the %MVC intensity measure utilised in this study incorporated all phases of the abduction/adduction movement into one intensity measure and multiple peak EMG measurements were not specifically done at different angles of an abduction movement as has been done previously (Kronberg et al., 1990). Our results do provide one average measure for level of activation throughout the entire raising and lowering phases of the movement for 15 muscle segments which provides a protocol that can be easily duplicated to obtain an intensity measure in future studies of pathological shoulders.

In addition to this, the intensity level of each muscle segment throughout the abduction/adduction movement was constructed using the grand ensemble method which has been described (Winter, 1991) and utilised previously in numerous gait analysis studies (Jacobson et al., 1995; Murley et al., 2009; Yang and Winter, 1985). As would be expected, high contraction intensities throughout the abduction movement were seen for glenohumeral and scapulo-thoracic prime movers such as anterior and middle deltoid, supraspinatus, serratus anterior, rhomboids, and upper, middle and lower trapezius. Muscles demonstrating low standard deviations between subjects will provide a good intensity comparison for future studies of pathological shoulders. This is true of the supraspinatus, middle deltoid, middle trapezius, and upper trapezius muscles. The use of grand ensembles to depict activation levels for so many shoulder muscles is novel and should provide an important reference tool for future research.

A major strength of the present study was that the limitations of previous studies were considered when designing the investigation. Normalisation techniques, resistance and sample size were all carefully reviewed before data collection commenced. The EMG data was normalised using seven isometric maximum voluntary contractions (MVCs). These positions were determined from pilot testing of 17 positions and included those recommended by other authors (Kelly et al., 1996). The dumbbell resistance was standardised to the participant's strength using 25% of the average of three isometric abduction MVCs. This meant that each of 24 participants worked at 25% of their maximum intensity, promoting a greater likelihood of consistent muscle activation patterns. The study investigated 15 muscle sites using both surface and intramuscular electrodes. The intramuscular electrodes allowed deep muscles to be investigated, which are often impossible to record using surface electrodes due to the cross-talk from superficial muscle layers. In addition, the amplifier's bandwidth was wide enough for both intramuscular and surface electrode signals ensuring that the data from the intramuscular electrodes could be accurately compared to the surface electrodes once both had been normalised.

Another major strength of the present study was the high reliability of both the testing procedure and data analysis. Reliability has not been investigated previously in shoulder EMG studies and is an important potential confounder of results considering the variability in some of the EMG characteristics between subjects.

The limitations of the study are consistent with the difficulties associated with EMG research. The first is that occasionally electrodes become displaced during testing, resulting in incomplete data sets for some participants. On occasion, surface electrodes were pulled off when leads were caught up during testing. More commonly, the intramuscular electrodes were displaced when the wires were pulled out of the muscle of interest into the superficial muscle lying above. This was attributed to the fact that the dynamic abduction trial incorporated a large range of movement and the contraction of the superficial muscles could potentially pull on the fine wire and dislodge it. The data from any electrode that became displaced was excluded from the participant's results.

In some participant's their natural standing posture resulted in some muscles working hyper-tonically, creating a noisy baseline. This occasionally led to the muscle working above 10% (of the MVC) intensity at the initiation of recording and therefore the muscle was considered to have turned on prior to recording. As there could be no true onset established in this situation, the muscle was titled ''on" and the data not used. This also led to subjects having incomplete data and potentially affected how the muscles were ranked.

5. Conclusion

A comprehensive database of normal shoulder muscle activity was developed using the dominant shoulder of 24 participants, measuring 15 muscle segments and evaluating muscle onset, time of peak intensity, termination and intensity. The data collected will clarify and add to the findings of Kronberg et al. and can be used to further understand normal shoulder muscle activity and for comparisons against the muscle activity of pathological shoulders. The database can potentially be used to identify muscle deficits common to particular shoulder conditions and direct rehabilitation to restore normal muscle activity.

Acknowledgements

The authors would like to thank Professor Chris Handley for the financial support (large equipment grant, School of Human Biosciences, La Trobe University) he provided for EMG equipment purchases and also thanks to Warren James for his expertise in the writing of the complex Matlab ensemble script.

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