Electromyographic Analysis of the Shoulder Girdle Musculature during External Rotation Exercises

Abstract

Background: Implementation of overhead activity, a key component of many professional sports, requires an effective and balanced activation of shoulder girdle muscles particularly during forceful external rotation motions.

Purpose: The study aimed to identify activation strategies of 16 shoulder girdle muscles/muscle segments during common shoulder external rotational exercises.

Study Design: Cross-Sectional Study

Method: EMG was recorded in 30 healthy subjects from 16 shoulder girdle muscles/muscle segments (<u>surface electrode</u>: anterior, middle and posterior deltoid, upper, middle and lower trapezius, serratus anterior, teres major, upper and lower latissimus dorsi, upper and lower pectoralis major; <u>fine wire electrodes</u>: supraspinatus, infraspinatus, subscapularis and rhomboid major) using a telemetric EMG system. Five external rotation (ER) exercises (standing ER at 0^{o} and 90^{o} of abduction, and with under-arm towel roll, prone ER at 90^{o} of abduction, side-lying ER with under-arm towel) were studied. Exercise EMG amplitudes were normalised to EMG_{max} (EMG at maximal ER force in a standard position). Univariate analysis of variance (ANOVA) and post-hoc analysis applied on EMG activity of each muscle to assess the main effect of exercise condition.

Results: Muscular activity differed significantly among the ER exercises ($P<0.05$ – $P<0.001$). The highest activation for anterior and middle deltoid, supraspinatus, upper trapezius, and serratus anterior occurred during standing ER at 90^{o} of abduction; for posterior deltoid, middle trapezius, and rhomboid during side-lying ER at 0° of abduction; for lower trapezius, upper and lower latissimus dorsi, subscapularis, and teres major during prone ER at 90^{o} of abduction, and for clavicular and sternal part of pectoralis major during standing ER with Under-Arm Towel.

Conclusion: Key glenohumeral and scapular muscles can be optimally activated during the specific ER exercises particularly in positions that stimulate athletic overhead motions.

Clinical Relevance: These results enable sport medicine professionals to target specific muscles during shoulder rehabilitation protocols while minimising the effect of others, providing a foundation for optimal evidence-based exercise prescription. They also provide information for tailored muscle training and injury prevention in overhead sports.

Key Terms: Overhead Sports; Electromyography; Shoulder Exercises; External Rotation; Rehabilitation

What is already there? Several EMG studies have investigated shoulder girdle musculature in order to rationalise the use of common shoulder rotational exercises for developing evidence-based rehabilitation and training programmes. These studies have varied considerably in the methodology and measurement protocols in terms of EMG electrode (type and placement), EMG normalisation method, experimental procedure, selection of muscles and exercises, and sample size. Results across the studies have therefore been inconclusive and inconsistent. While studies have provided limited evidence for some of the exercises, there is a clear need for further evidence from more comprehensive EMG studies.

What is new in here? Although effective shoulder function during sport-specific overhead movements requires a broad contribution by several shoulder girdle muscles, most existing EMG studies have examined only a small number of muscles during external rotation exercises. To address this, the present study investigated 16 key muscles/muscle segments, giving a much more comprehensive analysis of muscle activation strategies. An enhanced understanding of the activation pattern of these functionally inter-linked muscles would underpin more optimal rationalisation of exercise selection in both healthy and affected shoulder. While previous studies mainly included the muscles based on their primary function (e.g. infraspinatus in external rotation exercises, as an external rotator), the present study conducted an exploratory examination of many key glenohumeral and scapular muscles/muscle segments regardless of their primary function. The study also aimed to address the existing knowledge gap in the activation of muscles such as rhomboid, teres major, and sub-regions of latissimus dorsi and pectoralis major in external rotation exercises. As well as providing support for some of the exercises recommended by other researchers, the results suggest some novel strategies for the selective activation of key shoulder girdle muscles and their implementation in training and rehabilitation programmes.

BACKGROUND

Effective overhead activity, a key element of many professional sports such as baseball, cricket, swimming, tennis, and volleyball, requires effective activation of shoulder girdle muscles during forceful rotational movements to produce a healthy balance between mobility and functional stability of the shoulder.[3,8,11,16,45,47] Several shoulder pathologies such as RC tears, subacromial impingement syndrome, internal impingement, joint laxity, and labral lesions, and scapular dyskinesis are common in overhead athletes, arguing the need to develop effective training, injury prevention, and rehabilitation strategies.[8,9,16,18,27,50,59]

The glenohumeral joint (GHJ) presents a greater range of motion than any other human body articulation. The osseous structure provides limited intrinsic stability to the shoulder joint[61] so that functional stability is mainly achieved through integrated contribution of the joint capsule, ligaments, and synchronised activity of surrounding glenohumeral musculature.[8,33] The rotator cuff muscles, chiefly supraspinatus, infraspinatus, and subscapularis, contribute substantially to normal shoulder function by compressing the humeral head into the concaved glenoid and hence maintaining joint stability during arm elevation and overhead activities.[45,59,61] In overhead sports, adequate activation of the rotator cuff muscles is critical for both satisfactory force development and stabilisation of GHJ during cocking and acceleration phases.[14] Three parts of the deltoid interact with the rotator cuff in a coordinated manner to establish the muscle force couple necessary for arm elevation.[58] Pectoralis major, latissimus dorsi, and teres major generate synchronized adduction moments during arm elevation and abduction around the glenohumeral and scapulothoracic joints and together with subscapularis inferiorly stabilise the shoulder.[1,31]

A balanced scapular muscle function is also integral to achieving optimal shoulder position, motion, and stability. In addition to its anatomical function within the glenohumeral and acromioclavicular joints and as a linkage between the upper extremity and the trunk, the scapula provides a stable base for the attachment of key muscles contributing to dynamic glenohumeral stability and upper extremity motion.[9,11,51] Therefore, scapular stability is crucial for the effective production of force from muscles originating from the scapula. As described by Kibler and McMullen,[27] scapular stabilizers: 1) maintain a constant centre of glenohumeral rotation once the arm, scapula, trunk, and body are in motion; 2) provide scapular motion along the thoracic wall; 3) elevate the acromion to provide clearance of rotator cuff during glenohumeral rotation, thereby avoiding impingement; and 4) link the upper extremity to the trunk in a kinetic chain and facilitate transmission of forces from the feet on the ground to the hand.

Overhead athletic motion requires a delicate balance between mobility and functional stability to allow safe transmission of powerful rotational forces. However, repetitive stress on the shoulder joint during such movements can exceed physiologic limits of glenohumeral capsule, glenoid labrum and the RC musculature, and thus result in injury. EMG studies have described the activity of both glenohumeral and scapular muscles during common exercises to guide evidence-based and sport-specific rehabilitation programmes.[7,9,14,37,39] EMG studies of glenohumeral musculature in overhead sports have mainly focused on the detrimental effect of superior humeral head migration in relation to high deltoid activity.[46,47,56,63] Furthermore, EMG studies of the both glenohumeral and scapular stabilizers in overhead sports have predominantly analysed activity of the muscles in association with movement phases such as cocking and follow-through phases of the pitch/serve which require considerable external and internal rotation.[19,25,26] Collectively, EMG studies have underpinned the need for coordinated motion of the scapula and humerus for efficient arm movement and optimal joint stability. This notion has been further supported by several EMG studies showing alterations in glenohumeral and scapular kinematics following fatigue of the external rotators and scapular stabilizers, respectively.[9,53,57]

While previous studies in sports medicine and orthopaedics have reported the activity of muscles during selected activities and exercises, there is a lack of comprehensive data regarding shoulder musculature activation strategies during common external rotation exercises. This knowledge would guide the planning of effective training programmes, and establish sound evidence for developing optimal rehabilitation and training programmes for overhead athletes with and without shoulder pathology. This study aimed to provide such a knowledge base by comprehensive measurement of the EMG activity of 16 shoulder girdle muscles/muscle segments during commonly prescribed shoulder external rotation exercises.

MATERIALS AND METHODS

Participants

A total of 30 physically active healthy volunteers (15 male; 15 female) with normal shoulder examination, no previous shoulder injury, and no pain with activities of daily living were recruited from University Hospital staff and students. All participants were involved in moderate levels of exercise/physical activity. The mean (±SD) age, height and weight for the whole group was 33.1±9.9 y, 1.71±0.08 m, and 70.5±12.7 kg. The study received approval from the local research ethics committee and all patients gave written informed consent prior to their participation.

Exercises

Exercise conditions are described in Table1. Participants were tested for five external rotation (ER) shoulder exercises in a random order: standing ER at 0° of abduction (ER at 0°ABD), standing ER with under-arm towel roll (ER with Under-Arm Towel), standing ER at 90° of abduction (ER at 90°ABD), prone ER at 90° of abduction (Prone ER at 90°ABD), and side-lying ER at 0° abduction (Side-Lying ER with Under-Arm Towel). The execution of each exercise using correct upper body positioning (scapula in particular) and posture was precisely demonstrated by one of the investigators prior to measurements and participants were given time to familiarise themselves with the exercise. Participants performed 12 cycles of each exercise with a weight (1kg) in hand according to a metronome set at 60 beats per minute (each concentric and eccentric phase was performed during 1 beat). Synchronized video recording (25 frames/s; 50 fields/s) enabled accurate ER phase definition. One of the investigators closely monitored the accurate body positioning and execution of exercises Participants were given time to rest between the exercises.

EMG measurements

A TeleMyo 2400 G2 Telemetry System (Noraxon Inc., Arizona; USA) and associated software (MyoResearch XP) were used for signal acquisition, processing and analysis. Signals were differentially amplified (CMRR>100 dB; input impedance>100 Mohm; gain 500 dB), digitised at a sampling rate of 3000 Hz and band-pass filtered at 10-500 Hz and 10-1500 Hz for surface and fine wire electrodes, respectively.[24,52] ECG signal contamination was eliminated using an adaptive cancellation algorithm.

Disposable, self-adhesive pre-gelled Ag/AgCl bipolar surface electrodes with 10 mm diameter conducting area and 20mm inter-electrode distance (Noraxon Inc., Arizona, USA) were used to record the EMG from anterior, middle, and posterior deltoid (AD, MD, PD), upper, middle and lower trapezius (UT, MT, LT), upper and lower latissimus dorsi (ULD, LLD), upper and lower pectoralis major pectoralis major (UPM, LPM), serratus anterior (SA), and teres major (TM), consistent with established guidelines.[10,41] Skin was prepared by shaving and abrasive paste (Nuprep, Weaver and Company, Aurora, USA). Crosstalk was minimised by the careful placement of suitably-sized electrodes parallel to the muscle fibres based on standard anatomical criteria. Fine wire electrodes were used to record signals from the supraspinatus (SSP), infraspinatus (ISP), subscapularis (SUBS), and rhomboid major (RHOM).[5,41] Bipolar disposable hook wire electrodes (Nicolet Biomedical, Division of

VIASYS, Madison, USA) were inserted using a hygienic technique according to Basmajian and DeLuca.[5]

Raw EMG signals from 10 ER exercise cycles (the first and last ER exercise cycles were omitted) were full-wave rectified and smoothed (100 ms RMS). For normalisation purpose, $\mathrm{EMG}_{\mathrm{max}}$ was recorded during a standardised production of maximal ER force (MVC) using a shoulder Nottingham Mecmesin Myometer with an accuracy of ±0.1 % of full-scale and 1,000 N capacity (Mecmesin Ltd., Slinfold, UK) while seated, shoulder in a neutral position, elbow in 90° flexion tucked to the side of the body, and forearm in neutral position. EMG data were collected for 5 seconds during 3 trials and the average was taken as $\mathrm{EMG}_{\mathrm{max}}$ which was used as a reference value for the normalisation of EMG amplitudes during ER exercises.

Data analyses

Descriptive statistics are reported and displayed for each individual muscle as mean ± standard deviation (SD) or standard error of the mean (SEM) as appropriate. The mean average muscle action amplitude (the mean of the average EMG activity during the entire ER range of motion for each exercise) were normalized to the ER MVC (%$\mathrm{EMG}_{\mathrm{max}}$), averaged, and used for analysis. A univariate analysis of variance (ANOVA) was performed in order to determine if ER exercise conditions had a statistically significant effect on mean EMG activity of each muscle tested (within- exercise differences) ($\alpha = 0.05$). A post hoc analysis for multiple pair-wise comparisons (Bonferroni) was then applied to make specific comparisons among the five ER exercises and determine individual effect differences. The level of statistical significance was set at $P<0.05$ unless otherwise noted. Statistical Package for Social Sciences (SPSS) release 20.0 for Windows (Armonk, NY: IBM Corp.) was used for data analysis.

RESULTS

Table 2 and Figure 1summarise and compare the mean activation of muscles during ER exercises.

Deltoids: Exercise condition had a significant main effect on the activity of AD ($F_{4,\ 136}$ = 22.89, P<0.001), MD ($F_{4,\ 142}$ = 19.95, P<0.001), and PD ($F_{4,\ 142}$ = 14.12, P<0.001). AD and MD activations were significantly higher during ER at 90^{o}ABD compared to other ER exercises (P <0.001). PD activity during Prone ER at 90°ABD, Side-Lying ER, and ER at 90^{o}ABD was significantly higher than ER at 0°ABD and ER with Under-Arm Towel (P<0.001).

Rotator Cuff: A statistically significant main effect of exercise condition was found for the activity of SSP ($F_{4,\ 125}$ = 4.13, P= 0.004), SUBS ($F_{4,\ 118}$ = 6, P= 0.0002), but not for ISP ($F_{4,\ 50}$ = 0.6, P= 0.7). SSP activity was significantly higher in ER at 90°ABD compared to all other ER exercises except Side-Lying ER (P=0.01–0.02). SUBS activation was significantly higher during Prone ER at 90°ABD compared to ER at 0°ABD and ER with Under-Arm Towel (P=0.001–0.007). ISP showed a higher tendency towards higher activation albeit not significant during Prone ER at 90°ABD.

Pectoralis Major: Exercise condition had a significant main effect on the activity of both UPM ($F_{4,\ 131}$ = 14.84, P<0.001), LPM ($F_{4,\ 130}$ = 6.26, P= 0.0001). Both UPM and LPM had significantly higher activation during ER with Under-Arm Towel compared to other ER exercises (P=0.007 - 0.0003). The activity of UPM was also higher during ER at 0°ABD compared to ER at 90°ABD and Prone ER (P<0.05).

Latissimus Dorsi: A statistically significant main effect of muscle condition on muscle activity was detected for ULD ($F_{4,\ 137}$ = 10.4, P<0.001) and LLD ($F_{4,\ 131}$ = 8.23, P<0.001). Activation of both ULD and LLD was significantly higher in Prone ER at 90°ABD and Side-

Lying ER with Under-Arm Towel compared to ER at 0°ABD and ER with Under-Arm Towel (P=0.01 - <0.001). Activation of ULD was also higher during ER at 90°ABD compered to standing ER at 0°ABD and ER with Under-Arm Towel (P=0.002 - 0.006).

__Teres Major__: Exercise condition had a significant main effect on the activity of TM ($F_{4, 138}$ = 22.2, P<0.001). The highest TM activation occurred in Prone ER at 90°ABD compared to all other exercises (P=0.03 - <0.001). The next highest activation was observed in Side-Lying ER with Under-Arm Towel which was markedly higher than ER at 90°ABD and ER with Under-Arm Towel (P=0.03 - <0.001).

__Serratus Anterior:__ Exercise condition had a significant main effect on the activity of SA ($F_{4, 134}$ = 12.7, P<0.001). The activation of SA in ER at 90^{o}ABD and Prone ER at 90^{o}ABD was significantly higher than other ER exercises (P=0.003 - <0.001).

__Trapezius__: A statistically significant main effect of exercise condition was found for the activity of UT ($F_{4, 140}$ = 8.49, P<0.001), MT ($F_{4, 138}$ = 5.1, P=.001), LT, and ($F_{4, 142}$ = 18.43, P<0.001). UT was significantly higher during ER at 90^{o}ABD was significantly higher that all other exercises (P=0.03 – 0.0003). MT had higher activity during Side-Lying ER with Under-Arm Towel compared to ER at 0^{o}ABD and ER with Under-Arm Towel (P=0.005-0.007). LT had markedly higher activation during Prone ER at 90^{o}ABD compared to other exercises except Side-Lying ER (P=0.002 - <0.001). LT also had higher activation level during Side-Lying ER compared to ER at 90^{o}ABD and ER with Under-Arm Towel.

__Rhomboid Major__: Exercise condition had a significant main effect on the activity of RHOM ($F_{4, 249}$ = 6.58, P<0.001). Its highest activation detected during Side-Lying ER with Under-Arm Towel was markedly higher than ER at 0^{o}ABD and ER with Under-Arm Towel (P=0.001 - 0.0001).

DISCUSSION

Current trends in the rehabilitation of overhead athletes emphasise the importance of tailored and individualised programmes for re-establishing muscle balance and strength by selectively targeting dysfunctional and weakened glenohumeral and scapular muscles. Furthermore, there is increasing emphasis on functional rehabilitation of overhead athletes through main sport-specific exercises and in positions which mirror the capsular strain and muscular length-tension relationships during sport competition (e.g. ER and IR at 90°ABD).[44,59,61,62]

In view of the important role of balanced external-internal rotation strength for effective shoulder function during overhead sporting activities, several EMG studies have reported the activation strategies of glenohumeral and scapular musculature during shoulder rotational exercises, yet with inconsistent results and recommendations regarding optimal exercises.[4,6,12,13,37-39,46,51,56] ER exercises have received most research attention as inadequate ER strength appears to be an important underlying factor in the development of shoulder pathologies in overhead sports.[15,49,60]

In the present study the activity of RC muscles SSP was highly activated during ER at 90°ABD. This is in line with finding of a functional RC EMG study which reported a larger averaged SSP activity during dynamic ER at 90°ABD, to stabilise the shoulder joint and maintain arm position with a weight.[55] This higher activity can be attributed to the simultaneous contribution of SSP to both abduction and ER in this position.[12] Previous EMG studies have also reported substantial SSP activation during concentric ER exercises.[30,31,38,47]

Sufficient activation of ISP is fundamental during overhead throwing for the development of force at the shoulder to prevent joint distraction. In the current study a tendency to higher ISP activation was observed in Prone ER at 90°ABD followed by Side-Lying ER. In a comparative study of three ER exercises, Ballantyne et al[4] reported both Prone ER at

90°ABD and Side-Lying ER to be equally effective in eliciting ISP activity. Comparing the same exercises, Blackburn et al[6] found greater ISP activity during Prone ER at 90°ABD. In another study, Reinolds et al[51] reported higher ISP activation in Side-Lying ER with Under-Arm Towel, yet it was not different from that of Prone ER at 90°ABD. These findings, combined with that of Townsend et al[56] who found the greatest ISP activity during horizontal abduction in ER, suggests that better ISP activation may be achieved during Prone ER exercises in abducted shoulder positions (90°-100°).

SUBS had its highest activation during Prone ER at 90°ABD. Despite observations of its multi-functionality during different phases of overhead sports,[13,16,34,44,56] EMG investigations have mainly focused on SUBS activation in relation to IR exercises due to its primary function as internal rotator of the humerus. Accordingly, knowledge on its contribution to shoulder ER exercises is limited and contradictory.[13,31,56] In an EMG study of shoulder rotational exercises at various intensities with the arm by the side, Dark et al[12] reported minimal SUBS activation during ER exercises. A relatively high activation of SUBS found in the present study during ER exercises performed in an abducted position (90°ABD) may be attributed to the abductor moment arm of the SUBS[48] and its other functions such as glenohumeral stabilisation during sport-specific overhead activities. [13,40,56]

In the present study, the activation of both AD and MD was significantly higher in standing ER at 90°ABD compared to other ER exercises, consistent with their role as effective abductors at higher abduction angles. Higher activation of PD during Prone ER at 90°ABD is in agreement with that of Reinolds et al[47] who reported significantly higher activity of PD during Prone ER at 90°ABD and ER at 90°ABD compared to ER with Under-Arm Towel. They did not study AD activity.

Several EMG studies have attempted to identify the exercises that produce the highest RC activity with the lowest deltoid involvement, to avoid detrimental effect of superior humeral head migration caused by strong AD and MD activity.[45,47,54,63] While the resultant force vector of the deltoids and RC muscles during ER at 90°ABD has been shown to provide an assistive compressive force rather than superior humeral head migration in healthy athletes,[42] this exercise may be disadvantageous to athletes with shoulder pathology particularly if the RC is affected (e.g. impingement syndrome). Hence, our results suggest avoiding ER at 90°ABD in athletes with RC pathology due to markedly higher activation of both AD and MD. In view of the moderate activity of RC muscles with lower deltoid involvement (MD in particular) we observed for Side-Lying ER with Under-Arm Towel and standing ER with Under-Arm Towel, these rehabilitation exercises may be more beneficial for athletes with RC pathology. It has been suggested that using an under-arm towel roll when performing standing or side-lying ER exercises reduces the compensatory shoulder abduction forces (adduction strategy) leading to a greater isolation of the external RC, ISP in particular, from the larger shoulder muscles such as MD.[18,29,45]

PM, LD, and TM muscles have mainly been examined during IR exercises and little is known about their activity during ER exercises. We recorded segmental EMG from upper and lower fibres of PM (UPM and LPM) and LD (ULD and LLD) as these have been shown to contribute differently to shoulder movements. UPM acts as a humeral adductor in the early phases of abduction but becomes an effective abductor from 40° abduction. LPM has one of the largest adductor moment arms. Collectively, PM is an effective humeral internal rotator and adductor at lower abduction angles.[1,32] In the present study, both UPM and LPM elicited higher activity during ER with Under-Arm Towel compared to other ER exercises. UPM also had higher activity in ER at 0°ABD compared to ER at 90°ABD and Prone ER at 90°ABD. This higher activation of PM segments during lower abduction may be attributed to their balancing co-contraction opposed to a loaded ER. On the contrary, Dark et al[12] reported that averaged PM activity during ER at 0°ABD did not exceed 6% of the MVC.

LD sub-regions have several actions including adduction, extension, and internal rotation of the humerus as well as depression and adduction of the scapula.[1,22,32] The activation of both ULD and LLD was highest during Prone ER at 90°ABD with ULD also having high activity during standing ER at 90°ABD. Myers et al[40] studied LD activation during several resistance exercises and found moderate activity of LD during ER at 90°ABD but not during ER at 0°ABD. Dark et al[12] found the averaged LD activity to be less than 6% of the MVC during ER at 0°ABD. These findings suggest that higher activation of LD may be achieved in ER exercises in abducted positions. Peak moment arms of the LD sub-regions have been shown to be close to the midrange of abduction likely because of superior movement of the lines-of-action of the LD with respect to the scapula during abduction.[1]

Similar to that of LD, the highest TM activation occurred in Prone ER at 90°ABD. EMG studies of TM during ER shoulder exercises are very limited, possibly because of its obvious primary functions as humeral adductor, extensor, and internal rotator.[1,22,32] In addition to its normal contribution to overhead sports,[16] TM activation may have clinical relevance: increased TM activity during arm elevation and reaching tasks in patients with RC deficiency has been hypothesized to limit humeral head translation by exerting an inferiorly directed force to balance superiorly directed deltoid force.[23]

Scapular Muscles

Efficient scapular muscle activity is critical for optimal performance in throwing and other overhead sporting activities such as volleyball serve and spike, tennis serve and volley, and baseball pitching.[16,25] Among scapular muscles that primarily control coordinated scapular motion during arm movements (scapulohumeral rhythm), we examined three parts of trapezius (UT, MT, and LT), SA, and RHOM major. While no significant difference was found in the activation of trapezius segments across ER exercises, UT, MT, and LT showed higher activation in standing ER at 90^o ABD, Side-Lying ER with Under-Arm Towel, and Prone ER at 90^o ABD, respectively. It is clinically advantageous to improve the LT/UT and MT/UT activity ratios as several shoulder pathologies such as impingement syndrome have been associated with poor posture and muscle imbalance caused by more dominant UT.[9] The results of the present study suggest Side-Lying ER with Under-Arm Towel and Prone ER at 90^{o}ABD as the more beneficial exercises to enhance the LT/UT and MT/UT activity ratios. These recommendations, particularly Prone ER at 90^{o}ABD, are in agreement with those of Cools et al[9] and Ekstrom et al[14] but differ from that of McCabe et al[37] who found the greatest LT/UT activity ratio during ER at 0°ABD when compared with some trapezius exercises. LT activity has been shown to have a tendency to lower activity at angles below 90°ABD and then increasing from 90° to 180°.[14,39,53]

SA also plays a substantial role in maintaining normal scapulohumeral rhythm by contributing to all components of scapular 3D motion (upward rotation, posterior tilt, and external rotation) during arm elevation.[14,35] Furthermore; SA plays an important role during the acceleration phase of overhead sports by accelerating the scapula. Poor SA activation, if overpowered by the UT activity, can lead to abnormal scapular motion and shoulder pathology due to excessive scapular elevation and anterior tilt.[9,11,14,28,35] According to Cools et al,[9] in the presence of scapular muscle imbalance, exercises that selectively activate the underactive muscles with the minimal activation of the hyperactive muscles are key components of balance restoration. Hence, consideration must be given to scapular muscle balance by means of UT/SA activation/strength ratio. The present study found markedly higher activation of SA in standing ER at 90^{o}ABD and Prone ER at 90^{o}ABD compared to other ER exercises. These findings, considered along with UT activation, suggest Prone ER at

90°ABD as the optimal ER exercise for the optimal activation of SA because of minimal UT involvement (likely due to elimination of postural activation of the UT), followed by standing ER at 90°ABD. Other studies also reported relatively high SA activity during ER at 90°ABD, which also activated rotator cuff muscles.[14,40] However, the choice of Prone ER at 90°ABD to promote strength, balance, and coordination between UT and SA and the rotator cuff is supported by other findings of this study including higher ISP activation and a greater LT/UT ratio.

RHOM functions as scapular retractor, downward rotator, and elevator. It shows relatively high activation during the arm cocking and arm deceleration phases of throwing sports.[16] RHOM activation during ER exercises has been poorly examined possibly because of technical difficulties in locating the muscle for indwelling EMG recording. The present study found a higher RHOM activity during Side-Lying ER with Under-Arm Towel followed by Prone ER at 90°ABD. Myers et al[40] reported relatively high RHOM activity during standing ER at 0°ABD and 90°ABD, but did not examine Side-Lying ER with Under-Arm Towel. Moseley et al, reported only minimal RHOM activity during ER at 0°ABD.[39]

Any EMG study has inherent limitations. Applying established EMG guidelines together with our long-term experience of shoulder studies informed optimal electrode positioning. Considering uncertainties surrounding the reliability of MMTs and related MVC for EMG amplitude normalisation,[21] we normalised each muscle’s EMG activity (mean RMS) during each ER exercise as a percentage of a reference value, i.e. EMGmax during in a standard ER position, allowing appropriate assessment and comparison of each muscles’ contribution across the exercise. This method was appropriate for comparing activity of each individual muscle across the ER exercises (between-exercise) as the reference value is task dependent. Several studies have employed alternative normalisation methods, as the use of MVC method to study muscle activation remains questionable particularly in relation to dynamic movements.[2,17,21,48] A similar method has been applied by previous studies (e.g. maximum sprinting for normalizing the EMG during walking, maximum sprint cycling for normalizing the EMG during cycling). This normalization method avoided intrinsic limitations in reliability and validity associated with the more common reference to MVC.[10,20,36] This normalization method may have advantages for the examination of relative muscle function around the shoulder

While measuring activation of biceps brachii would have provided valuable information in selecting ER exercises for patients with SLAP repairs/tears, it was not included in the study. We tested muscle activations during ER exercises only with a single load (1kg) in hand in order to gain further insight into functional roles of the muscles contributing to glenohumeral stability. According to current studies, increasing load does not alter shoulder muscle recruitment patterns and that functional role of muscles does not change with higher muscle activity levels associated with increased loads.[7,12,43] While our study would have benefited from comparing muscle activations in individuals with and without shoulder pathology, the results from asymptomatic individuals have implications for the development of future studies of both asymptomatic and symptomatic subjects.

Conclusion

The present study reported muscle activation patterns of 16 muscles/muscle segments during common ER exercises to assist clinicians, physical therapists and trainers with evidence-based selection of the exercises. A higher activation of RC muscles (SSP and SUBS) during ER exercises at 90°ABD (both prone and standing) supported the advantage of these exercises in healthy athletes as they biomechanically replicate the common sport-specific position in overhead sports. However, these exercises need to be avoided in athletes affected by RC pathologies such as tears and impingement syndrome due to detrimental effect of the AD and MD activity on superior humeral head migration. In the presence of these pathologies, Side-Lying ER with Under-Arm Towel and standing ER with Under-Arm Towel may be better as they produce moderate activation of RC muscles with a lower deltoid involvement. While integration of scapular muscles into training and rehabilitation programmes is undoubtedly important, priority should be given to shoulder exercises that produce a high LT/UT/, MT/UT, and SA/UT ratio to allow a more optimal activation of the SA and LT. This will reinforce the scapular balance and prevent the development of pathological conditions such as impingement syndrome. The findings of this study support the use of Prone ER at 90^{o}ABD and Side-Lying ER with Under-Arm Towel as the more beneficial ER exercises for scapular balance as they are associated with enhanced activation of SA, MT, and LT but a lower UT involvement.

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Table and Figure Legends

Table1. Description of shoulder ER exercises performed for EMG recording

ER: External Rotation; **ABD**: Ab*duction*

Table2. The normalised mean muscle activation (%EMG$_{max}$ $\pm$ SEM) during ER exercises

AD: Anterior Deltoid; **MD**: Middle Deltoid, **PD**: Posterior Deltoid; **UT**: Upper Trapezius, **MT**: Middle Trapezius; **LT**: Lower Trapezius: **SA**: Serratus Anterior; **TM**: Teres Major; **ULD**: Upper Latissimus Doris; **LLD**: Lower Latissimus Doris; **UPM**: Upper Pectoralis Major; **LPM**: Lower Pectoralis Major; **SSP**: Supraspinatus; **ISP**: Infraspinatus; **SUBS**: Subscapularis; **RHOM**: Rhomboid Major; **ER**: External Rotation; **ABD**: Abduction; **SEM**: Standard Error of Measurement

Figure1. Mean normalised EMG activation of all muscles expressed as a percentage of maximum voluntary isometric contraction (MVC) (Amplitude Mean %) across 5 shoulder ER exercises. All EMG amplitudes were normalised to the reference value determined from ER MVC in a standard position.

AD: Anterior Deltoid; **MD:** Middle Deltoid, **PD:** Posterior Deltoid; **UT:** Upper Trapezius, **MT:** Middle Trapezius; **LT:** Lower Trapezius: **SA:** Serratus Anterior; **TM:** Teres Major; **ULD:** Upper Latissimus Doris; **LLD:** Lower Latissimus Doris; **UPM:** Upper Pectoralis Major; **LPM:** Lower Pectoralis Major; **SSP:** Supraspinatus; **ISP:** Infraspinatus; **SUBS:** Subscapularis; **RHOM:** Rhomboid Major. **ER:** External Rotation; **ABD:** Abduction; **SEM:** Standard Error of Measurement; **SL:** Side-Lying