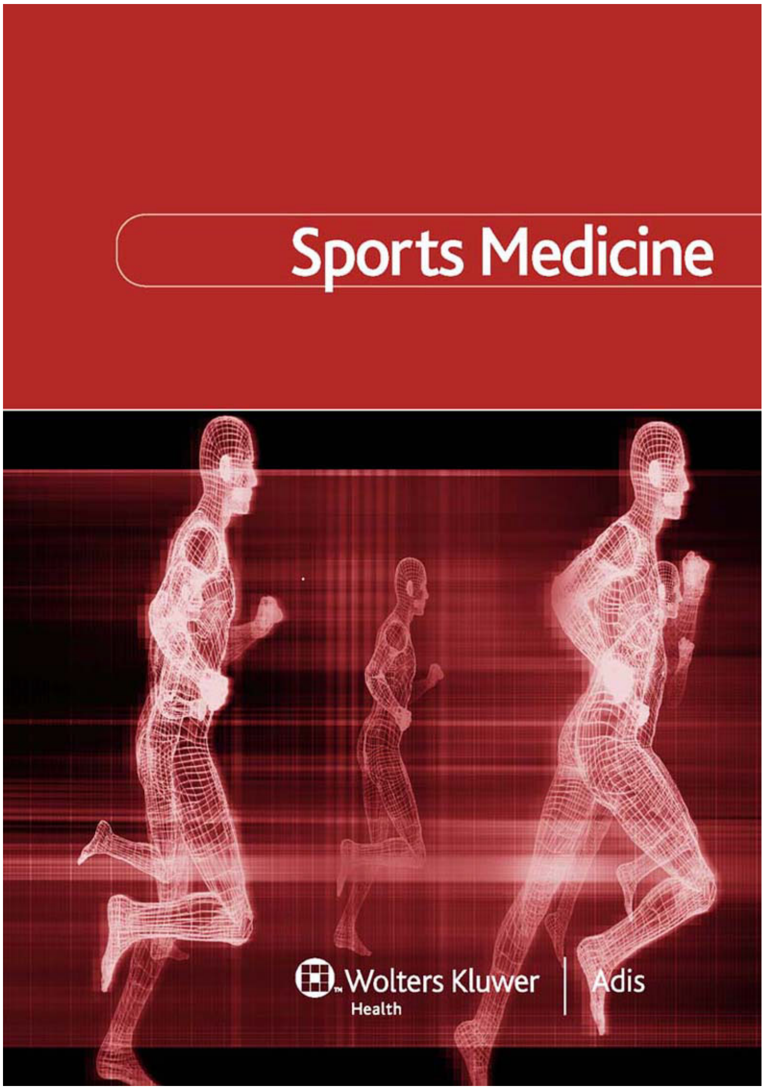
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Shoulder Muscle Activity and Function in Common Shoulder Rehabilitation Exercises

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Abstract

The rotator cuff performs multiple functions during shoulder exercises, including glenohumeral abduction, external rotation (ER) and internal rotation (IR). The rotator cuff also stabilizes the glenohumeral joint and controls humeral head translations. The infraspinatus and subscapularis have significant roles in scapular plane abduction (scaption), generating forces that are two to three times greater than supraspinatus force. However, the supraspinatus still remains a more effective shoulder abductor because of its more effective moment arm.

Both the deltoids and rotator cuff provide significant abduction torque, with an estimated contribution up to 35–65% by the middle deltoid, 30% by the subscapularis, 25% by the supraspinatus, 10% by the infraspinatus and 2% by the anterior deltoid. During abduction, middle deltoid force has been estimated to be 434 N, followed by 323 N from the anterior deltoid, 283 N from the subscapularis, 205 N from the infraspinatus, and 117 N from the supraspinatus. These forces are generated not only to abduct the shoulder but also to stabilize the joint and neutralize the antagonistic effects of undesirable actions. Relatively high force from the rotator cuff not only helps abduct the shoulder but also neutralizes the superior directed force generated by the deltoids at lower abduction angles. Even though anterior deltoid force is relatively high, its ability to abduct the shoulder is low due to a very small moment arm, especially at low abduction angles. The deltoids are more effective abductors at higher abduction angles while the rotator cuff muscles are more effective abductors at lower abduction angles.

During maximum humeral elevation the scapula normally upwardly rotates 45–55°, posterior tilts 20–40° and externally rotates 15–35°. The scapular muscles are important during humeral elevation because they cause these motions, especially the serratus anterior, which contributes to scapular upward rotation, posterior tilt and ER. The serratus anterior also helps stabilize the medial border and inferior angle of the scapular, preventing scapular IR (winging) and anterior tilt. If normal scapular movements are disrupted by abnormal scapular muscle firing patterns, weakness, fatigue, or injury, the shoulder complex functions less efficiency and injury risk increases.

Scapula position and humeral rotation can affect injury risk during humeral elevation. Compared with scapular protraction, scapular retraction has been shown to both increase subacromial space width and enhance supraspinatus force production during humeral elevation. Moreover, scapular IR and scapular anterior tilt, both of which decrease subacromial space width and increase impingement risk, are greater when performing scaption with IR ('empty can') compared with scaption with ER ('full can').

There are several exercises in the literature that exhibit high to very high activity from the rotator cuff, deltoids and scapular muscles, such as prone horizontal abduction at 100° abduction with ER, flexion and abduction with ER, 'full can' and 'empty can', D1 and D2 diagonal pattern flexion and extension, ER and IR at 0° and 90° abduction, standing extension from 90–0°, a variety of weight-bearing upper extremity exercises, such as the push-up, standing scapular dynamic hug, forward scapular punch, and rowing type exercises. Supraspinatus activity is similar between 'empty can' and 'full can' exercises, although the 'full can' results in less risk of subacromial impingement. Infraspinatus and subscapularis activity have generally been reported to be higher in the 'full can' compared with the 'empty can', while posterior deltoid activity has been reported to be higher in the 'empty can' than the 'full can'.

This review focuses on the scientific rationale behind choosing and progressing exercises during shoulder rehabilitation and training. Specifically, shoulder biomechanics and muscle function are presented for common open and closed chain shoulder rehabilitation exercises. Although weight-bearing closed chain positions do occur in sport, such as a wrestler in a quadriceps position with hands fixed to the ground, it is more common in sport for the hand to move freely in space against varying external loads, such as in throwing a football, discus or shot put, passing a basketball, pitching a baseball, swinging a tennis racket, baseball bat or golf club, or lifting a weight overhead. The movements performed in these latter activities are similar to the movements that occur in open chain exercises. Nevertheless, weight-bearing exercises are still used in shoulder rehabilitation, such as facilitation of proprioceptive feedback mechanisms, muscle co-contraction, and dynamic joint stability.[1]

A summary of glenohumeral and scapular muscle activity (normalized by a maximum voluntary isometric contraction [MVIC]) during numerous open and closed chain shoulder exercises commonly used in rehabilitation, with varying intensities and resistive devices, are shown in tables I–IX. Several exercises presented

Table I. Mean (± SD) tubing force and glenohumeral electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), during shoulder exercises using elastic tubing and bodyweight resistance, with intensity for each exercise normalized by a ten-repetition maximum. Data for muscles with EMG amplitude >45% of a MVIC are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Decker et al.,[10] with permission)

Exercise	Tubing force (N)*	Upper subscapularis EMG (%MVIC)†	Lower subscapularis EMG (%MVIC)†	Supraspinatus EMG (%MVIC)†	Infraspinatus EMG (%MVIC)†	Pectoralis major EMG (%MVIC)†	Teres major EMG (%MVIC)†	Latissimus dorsi EMG (%MVIC)†
Standing forward scapular punch	260 ± 50	33 ± 28[a]	<20[a,b,c,d]	***46 ± 24***[a]	28 ± 12[a]	25 ± 12[a,b,c,d]	<20[a]	<20[a,d]
Standing IR at 90° abduction	270 ± 30	***58 ± 38***[a]	<20[a,b,c,d]	40 ± 23[a]	<20[a]	<20[a,b,c,d]	<20[a]	<20[a,d]
Standing IR at 45° abduction	260 ± 40	***53 ± 40***[a]	26 ± 19	33 ± 25[a,b]	<20[a]	39 ± 22[a,d]	<20[a]	<20[a,d]
Standing IR at 0° abduction	270 ± 40	***50 ± 23***[a]	40 ± 27	<20[a,b,d,e]	<20[a]	***51 ± 24***[a,d]	<20[a]	<20[a,d]
Standing scapular dynamic hug	260 ± 50	***58 ± 32***[a]	38 ± 20	***62 ± 31***[a]	<20[a]	***46 ± 24***[a,d]	<20[a]	<20[a,d]
D2 diagonal pattern extension, horizontal adduction, IR (throwing acceleration)	270 ± 30	***60 ± 34***[a]	39 ± 26	***54 ± 35***[a]	<20[a]	***76 ± 32***	<20[a]	21 ± 12[a]
Push-up plus	300 ± 90	***122 ± 22***	***46 ± 29***	***99 ± 36***	***104 ± 54***	***94 ± 27***	***47 ± 26***	***49 ± 25***

a Significantly less EMG amplitude compared with push-up plus ($p < 0.002$).

b Significantly less EMG amplitude compared with standing scapular dynamic hug ($p < 0.002$).

c Significantly less EMG amplitude compared with standing internal rotation at 0° abduction ($p < 0.002$).

d Significantly less EMG amplitude compared with D2 diagonal pattern extension, horizontal abduction, internal rotation ($p < 0.002$).

e Significantly less EMG amplitude compared with standing forward scapular punch ($p < 0.002$).

IR = internal rotation. * There were no significant differences ($p = 0.122$) in tubing force among exercises; † there were significant differences ($p < 0.001$) in EMG amplitude among exercises.

in tables I–IX that demonstrated effective glenohumeral and scapular muscle recruitment and muscle activity are illustrated in figures 1–10. To help generalize comparisons in muscle activity from tables I–IX, 0–20% MVIC was considered low muscle activity, 21–40% MVIC was considered moderate muscle activity, 41–60% MVIC was considered high muscle activity, and >60% MVIC was considered very high muscle activity.[2]

Because many papers that analyse muscle activity during shoulder exercises involve the use of electromyography (EMG), such as exercises shown in tables I–IX, it is important that clinicians understand what information EMG can and cannot provide. Although EMG-driven mathematical knee models have been successfully developed to estimate both knee muscle and joint force and stress,[3,4] clinically applicable mathematical shoulder models have not yet been developed to estimate individual shoulder muscle and joint forces and stress during exercise. Therefore, the clinician should be careful not to equate EMG with muscle or joint force. However, a somewhat linear relationship between muscle EMG and force has been demonstrated during near isometric and constant velocity contractions.[5-7] However, this relationship may be highly nonlinear during rapid or fatiguing muscle contractions.[8] During muscle fatigue, EMG may increase, decrease or stay the same while muscle force decreases.[9] In addition, EMG amplitude has been shown to be similar or less in maximum eccentric contractions compared with maximum concentric contractions, even though peak force is greater with maximum eccentric contractions. Therefore, caution should be taken in interpreting the EMG signal during exercise. Nevertheless, shoulder EMG during exercise can still provide valuable information to the clinician that can be applied to shoulder rehabilitation and training. EMG provides information on when, how much and how often a muscle is active throughout an exercise range of motion (ROM). For example, early after rotator cuff surgery the recovering patient may want to avoid exercises that generate high rotator cuff activity so as not to stress the healing tissue, but exercises that

Table II. Mean (± SD) rotator cuff and deltoid electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), during shoulder external rotation exercises using dumbbell resistance with intensity for each exercise normalized by a ten-repetition maximum. Data for muscles with EMG amplitude >45% of an MVIC are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Reinold et al.,[12] with permission)

Exercise	Infraspinatus EMG (%MVIC)*	Teres minor EMG (%MVIC)*	Supraspinatus EMG (%MVIC)*	Middle deltoid EMG (%MVIC)*	Posterior deltoid EMG (%MVIC)*
Side-lying external rotation at 0° abduction	***62±13***	***67±34***	***51±47***[e]	36±23[e]	***52±42***[e]
Standing ER in scapular plane at 45° abduction and 30° horizontal adduction	***53±25***	***55±30***	32±24[c,e]	38±19[e]	43±30[e]
Prone ER at 90° abduction	***50±23***	***48±27***	***68±33***	***49±15***[e]	***79±31***
Standing ER at 90° abduction	***50±25***	39±13[a]	***57±32***	***55±23***[e]	***59±33***[e]
Standing ER at approximately 15° abduction with towel roll	***50±14***	***46±41***	41±37[c,e]	11±6[c,d,e]	31±27[a,c,d,e]
Standing ER at 0° abduction without towel roll	40±14[a]	34±13[a]	41±38[c,e]	11±7[c,d,e]	27±27[a,c,d,e]
Prone horizontal abduction at 100° abduction with ER (thumb up)	39±17[a]	44±25	***82±37***	***82±32***	***88±33***

a Significantly less EMG amplitude compared with side-lying external rotation at 0° abduction ($p<0.05$).

b Significantly less EMG amplitude compared with standing external rotation in scapular plane at 45° abduction and 30° horizontal adduction ($p<0.05$).

c Significantly less EMG amplitude compared with prone external rotation at 90° abduction ($p<0.05$).

d Significantly less EMG amplitude compared with standing external rotation at 90° abduction ($p<0.05$).

e Significantly less EMG amplitude compared with prone horizontal abduction at 100° abduction with external rotation (thumb up; $p<0.05$).

ER = external rotation. * There were significant differences ($p<0.01$) in EMG amplitude among exercises.

activate scapular muscles with minimal cuff activity may be appropriate during this phase of rehabilitation. During more advanced phases of rotator cuff rehabilitation, employing exercises that produce moderate to higher levels of rotator cuff activity may be appropriate.

In the scientific literature there is a wide array of methods used during EMG studies involving shoulder exercises, so the clinician should interpret EMG data cautiously. A practical application of EMG is to compare the EMG signal of one muscle across different exercises of relative intensity, and express the EMG signal relative to some common reference, such as percentage of a MVIC (tables I–IX). For example, in table I supraspinatus activity was significantly greater in the standing scapular dynamic hug (62±31% MVIC) compared with the standing internal rotation (IR) at 45° abduction (33±25% MVIC), with intensity for both of these exercises expressed by a ten-repetition maximum (10 RM).

It is more difficult to compare muscle activity between studies when exercise intensity is different between exercises. For example, in one study exercise intensity may be 30% 1 RM, while another study examining the same exercises and muscles may involve an exercise intensity of 80% 1 RM. It is obvious that the normalized EMG would be much higher in the study that used the 80% 1 RM intensity. Comparing muscle activity between studies is also difficult for other reasons, such as differences in MVIC determination, the use of different normalization techniques, EMG differences in isometric versus dynamic contractions, fatigued versus nonfatigued muscle, surface versus indwelling electrodes, electrode size and placement, and varying signal processing techniques.

Another difficulty in interpreting EMG data is that some studies perform statistical analyses (tables I–IV)[1,10-12] while other studies do not (tables V–IX).[13-16] Without statistics, it may be more difficult to compare and interpret muscle activity among exercises. For example, for one exercise a muscle may have a normalized mean activity of 50% and a standard deviation of 50%, and for another exercise this same muscle may only have a normalized mean activity of 20%

and standard deviation of 40%. From the mean activity it may appear that the exercise with 50% activity is more effective than the exercise with 20% activity. However, the high standard deviations implies there was high variability in muscle activity among subjects, and statistically there may be no significant difference in muscle activity between these two exercises.

1. Rotator Cuff Biomechanics and Function in Rehabilitation Exercises

Rotator cuff muscles have been shown to be a stabilizer of the glenohumeral joint in multiple shoulder positions.[17] Appropriate rehabilitation progression and strengthening of the rotator cuff is important in order to provide appropriate force to help elevate and move the arm, compress and centre the humeral head within the glenoid fossa during shoulder movements, and resist humeral head superior translation due to deltoid activity.[18-22] This latter function is important in early humeral elevation when the resultant force vector from the deltoids is directed in a more superior direction. This section presents rotator cuff biomechanics and function during a large array of shoulder exercises.

1.1 Supraspinatus

The supraspinatus compresses, abducts and provides a small external rotation (ER) torque to

Table III. Mean (± SD) trapezius and serratus anterior muscle activity (electromyograph [EMG] normalized by a maximum voluntary isometric contraction [MVIC]) during shoulder exercises using dumbbell or similar resistance with intensity for each exercise normalized by a five-repetition maximum. Data for muscles with EMG amplitude >50% of a MVIC are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Ekstrom et al.,[11] with permission)

Exercise	Upper trapezius EMG (%MVIC)*	Middle trapezius EMG (%MVIC)*	Lower trapezius EMG (%MVIC)*	Serratus anterior EMG (%MVIC)*
Shoulder shrug	***119 ± 23***	***53 ± 25***[b,c,d]	21 ± 10[b,c,d,f,g,h]	27 ± 17[c,e,f,g,h,i,j]
Prone rowing	***63 ± 17***[a]	***79 ± 23***	45 ± 17[c,d,h]	14 ± 6[c,e,f,g,h,i,j]
Prone horizontal abduction at 135° abduction with ER (thumb up)	***79 ± 18***[a]	***101 ± 32***	***97 ± 16***	43 ± 17[e,f]
Prone horizontal abduction at 90° abduction with ER (thumb up)	***66 ± 18***[a]	***87 ± 20***	***74 ± 21***[c]	9 ± 3[c,e,f,g,h,i,j]
Prone external rotation at 90° abduction	20 ± 18[a,b,c,d,e,f,g]	45 ± 36[b,c,d]	***79 ± 21***	***57 ± 22***[e,f]
D1 diagonal pattern flexion, horizontal adduction and ER	***66 ± 10***[a]	21 ± 9[a,b,c,d,f,g,h]	39 ± 15[b,c,d,f,g,h]	***100 ± 24***
Scaption above 120° with ER (thumb up) 'full can'	***79 ± 19***[a]	49 ± 16[b,c,d]	***61 ± 19***[c]	***96 ± 24***
Scaption below 80° with ER (thumb up) 'full can'	***72 ± 19***[a]	47 ± 16[b,c,d]	***50 ± 21***[c,h]	***62 ± 18***[e,f]
Supine scapular protraction with shoulders horizontally flexed 45° and elbows flexed 45°	7 ± 5[a,b,c,d,e,f,g,h]	7 ± 3[a,b,c,d,f,g,h]	5 ± 2[b,c,d,f,g,h]	***53 ± 28***[e,f]
Supine upward scapular punch	7 ± 3[a,b,c,d,e,f,g,h]	12 ± 10[b,c,d]	11 ± 5[b,c,d,f,g,h]	***62 ± 19***[e,f]

a Significantly less EMG amplitude compared with shoulder shrug ($p < 0.05$).

b Significantly less EMG amplitude compared with prone rowing ($p < 0.05$).

c Significantly less EMG amplitude compared with prone horizontal abduction at 135° abduction with external rotation ($p < 0.05$).

d Significantly less EMG amplitude compared with prone horizontal abduction at 90° abduction with external rotation ($p < 0.05$).

e Significantly less EMG amplitude compared with D1 diagonal pattern flexion, horizontal adduction and external rotation ($p < 0.05$).

f Significantly less EMG amplitude compared with scaption above 120° with ER (thumb up) [$p < 0.05$].

g Significantly less EMG amplitude compared with scaption below 80° with ER (thumb up) [$p < 0.05$].

h Significantly less EMG amplitude compared with prone external rotation at 90° abduction ($p < 0.05$).

i Significantly less EMG amplitude compared with supine scapular protraction with shoulders horizontally flexed 45° and elbows flexed 45° ($p < 0.05$).

j Significantly less EMG amplitude compared with supine upward scapular punch ($p < 0.05$).

ER = external rotation. * There were significant differences ($p < 0.05$) in EMG amplitude among exercises.

Table IV. Mean (± SD) ground reaction force on hand (normalized by bodyweight [BW]) and glenohumeral electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), during low-to-high demand weight-bearing shoulder exercises. Data for muscles with EMG amplitude >40% of a MVIC are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Uhl et al.,[1] with permission)

Exercise	Ground reaction force on hand (%BW)*	Supraspinatus EMG (%MVIC)†	Infraspinatus EMG (%MVIC)†	Anterior deltoid EMG (%MVIC)†	Posterior deltoid EMG (%MVIC)†	Pectoralis major EMG (%MVIC)†
Prayer	6 ± 3[a,b,c,d,e,f]	2 ± 2[a,b,c,d]	4 ± 3[a,b,c,d,e]	2 ± 4[a,b,c]	4 ± 3[a,d,e]	7 ± 4[a,b,c]
Quadruped	19 ± 2[a,b,c,d,e]	6 ± 10[a,b]	11 ± 8[a,b,c,d,e]	6 ± 6[a,b,c]	6 ± 4[a,d,e]	10 ± 4[a,b,c]
Tripod	32 ± 3[a]	10 ± 11[a]	37 ± 26[a]	12 ± 10[a,b]	27 ± 16[a]	16 ± 8[a,b]
Bipod (alternating arm and leg)	34 ± 4[a]	12 ± 13[a]	***42 ± 33***[a]	18 ± 10[a]	28 ± 16[a]	22 ± 10[a]
Push-up	34 ± 3[a]	14 ± 14[a]	***44 ± 31***[a]	31 ± 16	18 ± 12[a]	33 ± 20
Push-up feet elevated	39 ± 5[a]	18 ± 16[a]	***52 ± 32***[a]	37 ± 15	23 ± 14[a]	***42 ± 28***
One-arm push-up	60 ± 6	29 ± 20	***86 ± 56***	***46 ± 20***	***74 ± 43***	***44 ± 45***

a Significantly less compared with the one-arm push-up ($p < 0.002$).

b Significantly less compared with the push-up feet elevated ($p < 0.002$).

c Significantly less compared with the push-up ($p < 0.002$).

d Significantly less compared with the pointer ($p < 0.002$).

e Significantly less compared with the tripod ($p < 0.002$).

f Significantly less compared with the quadruped ($p < 0.002$).

* There were significant differences ($p < 0.001$) in ground reaction force among exercises; † there were significant differences ($p < 0.001$) in EMG amplitude among exercises.

the glenohumeral joint. From three-dimensional (3-D) biomechanical shoulder models, predicted supraspinatus force during maximum effort isometric scapular plane abduction (scaption) at the 90° position was 117 N.[18] In addition, supraspinatus activity increases as resistance increases during scaption movements, peaking at 30–60° for any given resistance (table IX). At lower scaption angles, supraspinatus activity increases to provide additional humeral head compression within the glenoid fossa to counter the humeral head superior translation from the deltoids (table IX).[13] Due to a decreasing moment arm with abduction, the supraspinatus is more effective during scaption at smaller abduction angles, but it still generates abductor torque (a function of both moment arm and muscle force) at larger abduction angles.[18-20] The abduction moment arm for the supraspinatus peaks at approximately 3 cm near 30° abduction, but maintains an abduction moment arm of greater than 2 cm throughout shoulder abduction ROM.[19,20] Its ability to generate abduction torque during scaption appears to be greatest with the shoulder in neutral rotation or in slight IR or ER.[19,20] This is consistent with both EMG and magnetic resonance imaging (MRI) data while performing scaption with IR ('empty can')[23,24] and scaption with IR ('full can'),[25] with both exercises producing similar amounts of supraspinatus activity.[16,25,26]

Even though supraspinatus activity is similar between 'empty can' and 'full can' exercises, there are several reasons why the 'full can' may be preferred over the 'empty can' during rehabilitation and supraspinatus testing. Firstly, the internally rotated humerus in the 'empty can' does not allow the greater tuberosity to clear from under the acromion during humeral elevation, which may increase subacromial impingement risk because of decreased subacromial space width.[27,28] Secondly, abducting in extreme IR progressively decreases the abduction moment arm of the supraspinatus from 0 to 90° abduction.[19] A diminished mechanical advantage may cause the supraspinatus to have to work harder, thus increasing its tensile stress (which may be problematic in a healing tendon). Thirdly, scapular kinematics are different between 'empty can' and 'full can' exercises. Scapular IR (transverse

Table V. Peak (± SD) glenohumeral electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), over 30° arc of movement during shoulder exercises using dumbbells. Data for muscles with EMG amplitude >50% of a MVIC over at least three consecutive 30° arcs of motion are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Townsend et al.,[16] with permission)

Exercise	Anterior deltoid EMG (%MVIC)	Middle deltoid EMG (%MVIC)	Posterior deltoid EMG (%MVIC)	Supraspinatus EMG (%MVIC)	Subscapularis EMG (%MVIC)	Infraspinatus EMG (%MVIC)	Teres minor EMG (%MVIC)	Pectoralis major EMG (%MVIC)	Latissimus dorsi EMG (%MVIC)
Flexion above 120° with ER (thumb up)	***69±24***	***73±16***	≤50	***67±14***	***52±42***	***66±15***	≤50	≤50	≤50
Abduction above 120° with ER (thumb up)	***62±28***	***64±13***	≤50	≤50	***50±44***	***74±23***	≤50	≤50	≤50
Scaption above 120° with IR (thumb down) 'empty can'	***72±23***	***83±13***	≤50	***74±33***	***62±33***	≤50	≤50	≤50	≤50
Scaption above 120° with ER (thumb up) 'full can'	***71±39***	***72±13***	≤50	***64±28***	≤50	***60±21***	≤50	≤50	≤50
Military press	***62±26***	***72±24***	≤50	***80±48***	***56±48***	≤50	≤50	≤50	≤50
Prone horizontal abduction at 90° abduction with IR (thumb down)	≤50	***80±23***	***93±45***	≤50	≤50	***74±32***	***68±36***	≤50	≤50
Prone horizontal abduction at 90° abduction with ER (thumb up)	≤50	***79±20***	***92±49***	≤50	≤50	***88±25***	***74±28***	≤50	≤50
Press-up	≤50	≤50	≤50	≤50	≤50	≤50	≤50	***84±42***	***55±27***
Prone rowing	≤50	***92±20***	***88±40***	≤50	≤50	≤50	≤50	≤50	≤50
Side-lying ER at 0° abduction	≤50	≤50	***64±62***	≤50	≤50	***85±26***	***80±14***	≤50	≤50
Side-lying eccentric control of 0–135° horizontal adduction (throwing deceleration)	≤50	***58±20***	***63±28***	≤50	≤50	***57±17***	≤50	≤50	≤50

ER = external rotation; **IR** = internal rotation.

Table VI. Peak (± SD) scapular electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), over 30° arc of movement during shoulder exercises using dumbbells with intensity normalized for each exercise by a ten-repetition maximum. Data for muscles with EMG amplitude >50% of a MVIC over at least three consecutive 30° arcs of motion are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Moseley et al.,[15] with permission)

Exercise	Upper trapezius EMG (%MVIC)	Middle trapezius EMG (%MVIC)	Lower trapezius EMG (%MVIC)	Levator scapulae EMG (%MVIC)	Rhomboids EMG (%MVIC)	Middle serratus anterior EMG (%MVIC)	Lower serratus anterior EMG (%MVIC)	Pectoralis minor EMG (%MVIC)
Flexion above 120° with ER (thumb up)	≤50	≤50	***60±18***	≤50	≤50	***96±45***	***72±46***	≤50
Abduction above 120° with ER (thumb up)	***52±30***	≤50	***68±53***	≤50	***64±53***	***96±53***	***74±65***	≤50
Scaption above 120° with ER (thumb up) 'full can'	***54±16***	≤50	***60±22***	***69±46***	***65±79***	***91±52***	***84±20***	≤50
Military press	***64±26***	≤50	≤50	≤50	≤50	***82±36***	***60±42***	≤50
Prone horizontal abduction at 90° abduction with IR (thumb down)	***62±53***	***108±63***	***56±24***	***96±57***	***66±38***	≤50	≤50	≤50
Prone horizontal abduction at 90° abduction with ER (thumb up)	***75±27***	***96±73***	***63±41***	***87±66***	≤50	≤50	≤50	≤50
Press-up	≤50	≤50	≤50	≤50	≤50	≤50	≤50	***89±62***
Prone rowing	***112±84***	***59±51***	***67±50***	***114±69***	***56±46***	≤50	≤50	≤50
Prone extension at 90° flexion	≤50	***77±49***	≤50	***81±76***	≤50	≤50	≤50	≤50
Push-up plus	≤50	≤50	≤50	≤50	≤50	***80±38***	***73±3***	***58±45***
Push-up with hands separated	≤50	≤50	≤50	≤50	≤50	***57±36***	***69±31***	***55±34***

ER = external rotation; **IR** = internal rotation.

plane movement with medial border moving posterior, resulting in 'winging') and anterior tilt (sagittal plane movement with the inferior angle moving posterior), both of which decrease subacromial space width, are greater in the 'empty can' compared with the 'full can'.[29] This occurs in part because humeral IR in the 'empty can' tensions both the posteroinferior capsule and rotator cuff (infraspinatus primarily), which originate from the posterior glenoid and infraspinous fossa. Tension in these structures contributes to an anterior tilted and internally rotated scapula, which protracts the scapula. This is clinically important, as Smith et al.[30] reported that relative to a neutral scapular position, scapular protraction significantly reduced glenohumeral IR and ER strength by 13–24% and 20%, respectively. Moreover, scapular protraction has been shown to decrease subacromial space width, increasing impingement risk.[31] In contrast, scapular retraction has been shown to both increase subacromial space width[31] and enhance supraspinatus force production during humeral elevation compared with a protracted position.[32] This emphasizes the importance of strengthening the scapular retractors and maintaining good posture. Fourthly, although both the 'empty can' and 'full can' test positions have been shown to be equally accurate in detecting a torn supraspinatus tendon, the use of the 'full can' test position may be desirable in the clinical setting because there is less pain provocation,[33] and it has been shown to be a more optimal position for supraspinatus isolation.[25]

The supraspinatus is active in numerous shoulder exercises other than the 'empty can' and 'full can'. High to very high supraspinatus activity has been quantified in several common rotator cuff exercises, such as prone horizontal abduction at 100° abduction with ER, prone ER at 90° abduction, standing ER at 90° abduction, flexion above 120° with ER, military press (trunk vertical), side lying abduction, proprioceptive neuromuscular facilitation (PNF) scapular clock, and PNF D2 diagonal pattern flexion and extension (tables I, II, V and VII).[10,12,14,16,34-39] When these shoulder exercises are compared with each other, mixed results have been reported. Some

Table VII. Mean (± SD) tubing force and rotator cuff and deltoid electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), during shoulder exercises using elastic tubing. Data for muscles with EMG amplitude >45% of an MVIC are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Meyers et al.,[14] with permission)

Exercise	Tubing force (N)	Anterior deltoid EMG (%MVIC)	Middle deltoid EMG (%MVIC)	Subscapularis EMG (%MVIC)	Supraspinatus EMG (%MVIC)	Teres minor EMG (%MVIC)	Infraspinatus EMG (%MVIC)
D2 diagonal pattern extension, horizontal adduction, IR (throwing acceleration)	30±11	27±20	22±12	***94±51***	36±32	***89±57***	33±22
Eccentric arm control portion of D2 diagonal pattern flexion, abduction, ER (throwing deceleration)	13±8	30±17	44±16	***69±48***	***64±33***	***90±50***	***45±21***
Standing ER at 0° abduction	13±7	6±6	8±7	***72±55***	20±13	***84±39***	***46±20***
Standing ER at 90° abduction	12±8	22±12	***50±22***	***57±50***	***50±21***	***89±47***	***51±30***
Standing IR at 0° abduction	16±8	6±6	4±3	***74±47***	10±6	***93±41***	32±51
Standing IR at 90° abduction	16±11	28±18	41±21	***71±43***	41±30	***63±38***	24±21
Standing extension from 90–0°	21±11	19±15	27±16	***97±55***	30±21	***96±50***	***50±57***
Flexion above 120° with ER (thumb up)	26±12	***61±41***	32±14	***99±38***	42±22	***112±62***	***47±34***
Standing high scapular rows at 135° flexion	15±11	31±25	34±17	***74±53***	42±28	***101±47***	31±15
Standing mid scapular rows at 90° flexion	15±11	18±10	26±16	***81±65***	40±26	***98±74***	27±17
Standing low scapular rows at 45° flexion	12±8	19±13	34±23	***69±50***	***46±38***	***109±58***	29±16
Standing forward scapular punch	19±11	***45±36***	36±24	***69±47***	***46±31***	***69±40***	35±17

ER = external rotation; **IR** = internal rotation.

EMG data support prone horizontal abduction at 100° abduction with ER over the 'empty can' in supraspinatus activity,[35,38] while other EMG data show no difference in supraspinatus activity between these two exercises.[37] In contrast, MRI data support both 'empty can' and 'full can' over prone horizontal abduction at 100° abduction with ER in activating the supraspinatus.[26] Interestingly, high to very high supraspinatus activity has also been reported in several exercises that are not commonly thought of as rotator cuff exercises, such as standing forward scapular punch, rowing exercises, push-up exercises, and two-hand overhead medicine ball throws (tables I, IV and VII).[1,10,40,41]

The supraspinatus also provides weak rotational torques due to small rotational moment arms.[20] From 3-D biomechanical shoulder models, predicted supraspinatus force during maximum effort ER in 90° abduction was 175 N.[18] The anterior portion, which is considered the strongest,[42] has been shown to be a weak internal rotator at 0° abduction (0.2 cm moment arm), no rotational ability at 30° abduction, and a weak external rotator at 60° abduction (approximately 0.2 cm moment arm).[20] In contrast, the posterior portion of the supraspinatus has been shown to provide an ER torque throughout shoulder abduction, with an ER moment arm that progressively decreases as abduction increases (approximately 0.7 cm at 0° abduction and 0.4 cm at 60° abduction).[20] When anterior and posterior portions of the supraspinatus are viewed as a whole, this muscle provides weak ER regardless of abduction angle, although it appears to be a more effective external rotator at smaller abduction angles.[20]

1.2 Infraspinatus and Teres Minor

The infraspinatus and teres minor comprise the posterior cuff, which provides glenohumeral compression, ER and abduction, and resists superior and anterior humeral head translation by exerting an posteroinferior force to the humeral head.[22] The ER provided from the posterior cuff helps clear the greater tuberosity from under the coracoacromial arch during overhead movements, minimizing subacromial impingement.

Table VIII. Mean (± SD) tubing force and glenohumeral and scapular electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), during shoulder exercises using elastic tubing. Data for muscles with EMG amplitude >45% of an MVIC are set in bold italic type, and these exercises are considered to be an effective challenge for that muscle (adapted from Meyers et al.,[14] with permission)

Exercise	Tubing force (N)	Pectoralis major EMG (%MVIC)	Latissimus dorsi EMG (%MVIC)	Biceps brachii EMG (%MVIC)	Triceps brachii EMG (%MVIC)	Lower trapezius EMG (%MVIC)	Rhomboids EMG (%MVIC)	Serratus anterior EMG (%MVIC)
D2 diagonal pattern extension, horizontal adduction, IR (throwing acceleration)	30 ± 11	36 ± 30	26 ± 37	6 ± 4	32 ± 15	***54 ± 46***	***82 ± 82***	***56 ± 36***
Eccentric arm control portion of D2 diagonal pattern flexion, abduction, ER (throwing deceleration)	13 ± 8	22 ± 28	35 ± 48	11 ± 7	22 ± 16	***63 ± 42***	***86 ± 49***	***48 ± 32***
Standing ER at 0° abduction	13 ± 7	10 ± 9	33 ± 39	7 ± 4	22 ± 17	***48 ± 25***	***66 ± 49***	18 ± 19
Standing ER at 90° abduction	12 ± 8	34 ± 65	19 ± 16	10 ± 8	15 ± 11	***88 ± 51***	***77 ± 53***	***66 ± 39***
Standing IR at 0° abduction	16 ± 8	36 ± 31	34 ± 34	11 ± 7	21 ± 19	44 ± 31	41 ± 34	21 ± 14
Standing IR at 90° abduction	16 ± 11	18 ± 23	22 ± 48	9 ± 6	13 ± 12	***54 ± 39***	***65 ± 59***	***54 ± 32***
Standing extension from 90–0°	21 ± 11	22 ± 37	***64 ± 53***	10 ± 27	***67 ± 45***	***53 ± 40***	***66 ± 48***	30 ± 21
Flexion above 120° with ER (thumb up)	26 ± 12	19 ± 13	33 ± 34	22 ± 15	22 ± 12	***49 ± 35***	***52 ± 54***	***67 ± 37***
Standing high scapular rows at 135° flexion	15 ± 11	29 ± 56	36 ± 36	7 ± 4	19 ± 8	***51 ± 34***	***59 ± 40***	38 ± 26
Standing mid scapular rows at 90° flexion	15 ± 11	18 ± 34	40 ± 42	17 ± 32	21 ± 22	39 ± 27	***59 ± 44***	24 ± 20
Standing low scapular rows at 45° flexion	12 ± 8	17 ± 32	35 ± 26	21 ± 50	21 ± 13	44 ± 32	***57 ± 38***	22 ± 14
Standing forward scapular punch	19 ± 11	19 ± 33	32 ± 35	12 ± 9	27 ± 28	39 ± 32	***52 ± 43***	***67 ± 45***

ER = external rotation; **IR** = internal rotation.

From 3-D biomechanical shoulder models, the maximum predicted isometric infraspinatus force was 723 N for ER at 90° abduction and 909 N for ER at 0° abduction.[18] The maximum predicted teres minor force was much less than the infraspinatus during maximum ER at both 90° abduction (111 N) and 0° abduction (159 N).[18] The effectiveness of the posterior cuff to laterally rotate depends on glenohumeral position. For the infraspinatus, its superior, middle and inferior heads all generate its largest ER torque at 0° abduction, primarily because its moment arm is greatest at 0° abduction (approximately 2.2 cm).[20] As the abduction angle increases, the moment arms of the inferior and middle heads decrease slightly but stay relatively constant, while the moment arm of the superior head progressively decreases until it is about 1.3 cm at 60° abduction.[20] These data imply that the infraspinatus is a more effective external rotator at lower abduction angles compared with higher abduction angles. Although infraspinatus activity during ER has been shown to be similar at 0°, 45° and 90° abduction (table II),[12,14,25] ER at 0° abduction has been shown to be the optimal position to isolate the infraspinatus muscle,[25] and there is a trend towards greater infraspinatus activity during ER at lower abduction angles compared with higher abduction angles.[12,43] The teres minor generates a relatively constant ER torque (relatively constant moment arm of approximately 2.1 cm) throughout arm abduction movement, which implies that the abduction angle does not affect the effectiveness of the teres minor to generate ER torque.[20] Teres minor activity during ER is similar at 0°, 45° and 90° abduction (table II).[12,14] In addition, both infraspinatus and teres minor activities are similar during external rotation movements regardless of abduction positions.[12,16,34]

What is not readily apparent is the significant role of the infraspinatus as a shoulder abductor in the scapular plane.[18-20] From 3-D biomechanical shoulder models, predicted infraspinatus force during maximum isometric effort scaption (90° position) is 205 N, nearly twice the predicted force from supraspinatus in this position.[18] Liu et al.[19] reported that in scaption with neutral rotation the infraspinatus had an abductor moment arm that was small at 0° abduction but increased to 1 cm at 15° abduction and remained fairly constant throughout increasing abduction angles. Moreover, infraspinatus activity increases as resistance increases, peaking at 30–60° for any given resistance (table IX).[13] As resistance increases, infraspinatus activity increases to help generate a higher torque in scaption, and at lower scaption angles infraspinatus activity increases to resist superior

Table IX. Mean (± SD) glenohumeral electromyograph (EMG), normalized by a maximum voluntary isometric contraction (MVIC), during scaption with neutral rotation and increasing load using dumbbells (adapted from Alpert et al.,[13] with permission)

	Anterior deltoid EMG (%MVIC)	Middle deltoid EMG (%MVIC)	Posterior deltoid EMG (%MVIC)	Supraspinatus EMG (%MVIC)	Infraspinatus EMG (%MVIC)	Teres minor EMG (%MVIC)	Subscapularis EMG (%MVIC)
0% NMW[a]							
0–30°	22 ± 10	30 ± 18	2 ± 2	36 ± 21	16 ± 7	9 ± 9	6 ± 7
30–60°	53 ± 22	60 ± 27	2 ± 3	49 ± 25	34 ± 14	11 ± 10	14 ± 13
60–90°	68 ± 24	69 ± 29	2 ± 3	47 ± 19	37 ± 15	15 ± 14	18 ± 15
90–120°	78 ± 27	74 ± 33	2 ± 3	42 ± 14	39 ± 20	19 ± 17	21 ± 19
120–150°	90 ± 31	77 ± 35	4 ± 4	40 ± 20	39 ± 29	25 ± 25	23 ± 18
25% NMW[a]							
0–30°	42 ± 14	55 ± 28	5 ± 11	64 ± 37	39 ± 16	17 ± 16	14 ± 10
30–60°	82 ± 20	81 ± 21	6 ± 8	79 ± 29	64 ± 23	24 ± 23	32 ± 15
60–90°	97 ± 33	87 ± 26	4 ± 4	65 ± 21	60 ± 24	23 ± 21	34 ± 18
90–120°	96 ± 30	85 ± 28	4 ± 4	53 ± 18	49 ± 24	21 ± 17	28 ± 18
120–150°	71 ± 39	70 ± 36	10 ± 6	41 ± 23	43 ± 30	32 ± 26	18 ± 19
50% NMW[a]							
0–30°	68 ± 21	79 ± 30	12 ± 18	89 ± 45	69 ± 27	36 ± 28	31 ± 14
30–60°	113 ± 33	96 ± 24	11 ± 14	98 ± 35	93 ± 27	45 ± 33	54 ± 24
60–90°	113 ± 41	91 ± 26	10 ± 11	82 ± 27	80 ± 30	40 ± 27	50 ± 31
90–120°	90 ± 34	79 ± 28	9 ± 10	53 ± 17	56 ± 28	27 ± 22	28 ± 22
120–150°	47 ± 38	44 ± 35	14 ± 15	29 ± 8	40 ± 28	30 ± 22	16 ± 18
75% NMW[a]							
0–30°	81 ± 18	88 ± 30	14 ± 19	99 ± 45	85 ± 30	48 ± 34	40 ± 20
30–60°	127 ± 44	104 ± 33	13 ± 14	109 ± 37	108 ± 33	61 ± 37	61 ± 32
60–90°	121 ± 45	97 ± 27	14 ± 13	91 ± 25	96 ± 35	54 ± 30	50 ± 31
90–120°	88 ± 35	79 ± 28	15 ± 16	56 ± 17	63 ± 28	39 ± 27	27 ± 22
120–150°	38 ± 33	35 ± 26	20 ± 22	28 ± 12	32 ± 18	36 ± 23	18 ± 15
90% NMW[a]							
0–30°	96 ± 33	108 ± 43	14 ± 14	120 ± 49	93 ± 16	41 ± 28	54 ± 19
30–60°	129 ± 47	115 ± 45	15 ± 9	122 ± 37	104 ± 24	56 ± 27	78 ± 41
60–90°	135 ± 53	102 ± 36	13 ± 11	104 ± 33	86 ± 20	54 ± 22	67 ± 40
90–120°	97 ± 41	78 ± 30	12 ± 6	67 ± 31	47 ± 12	32 ± 20	41 ± 29
120–150°	26 ± 14	19 ± 14	16 ± 9	22 ± 19	26 ± 15	23 ± 12	26 ± 17

a NMW = normalized maximum weight lifted in pounds, where 100% of NMW was calculated pounds by the peak torque value (in foot-pounds) that was generated from a 5-second maximum isometric contraction in 20° scaption divided by each subject's arm length (in feet). Mean (± SD) NMW was 21 ± 8 pounds (approximately 93 ± 36 N).

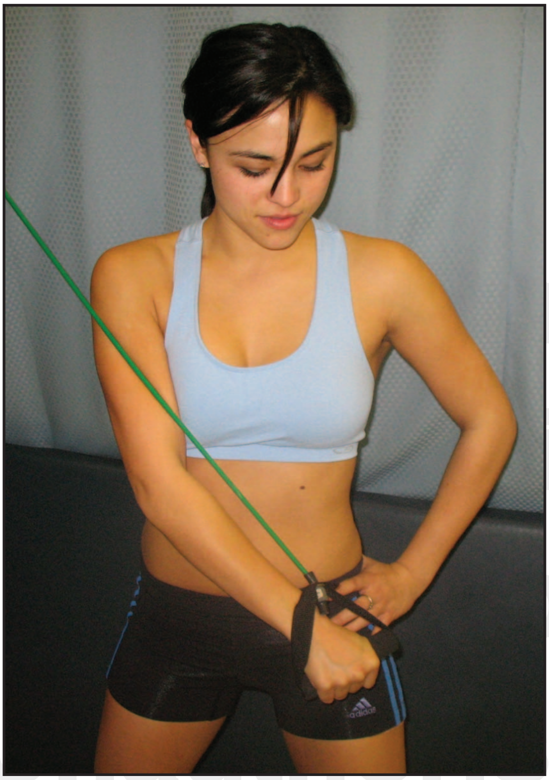

Fig. 1. D2 diagonal pattern extension, horizontal adduction and internal rotation (see tables I, VII and VIII for muscle activity during this exercise).

humeral head translation due to the increased activity from the deltoids.[22] Another finding is that the abductor moment arm of the infraspinatus generally increased as abduction with IR increased,[19] such as performing the 'empty can' exercise. In contrast, the abductor moment arm of the infraspinatus generally decreased as abduction with ER increased,[19] similar to performing the 'full can' exercise. Otis et al.[20] reported similar findings: the abductor moment arms for the three heads of the infraspinatus (greatest in superior head and least in inferior head) were approximately 0.3–1.0 cm at 45° of ER, 0.5–1.7 cm at neutral rotation and 0.8–2.4 cm at 45° of IR. These data imply that the infraspinatus may be more effective in generating abduction torque during the 'empty can' compared with the 'full can'. However, EMG data demonstrate greater infraspinatus activity during 'full can' compared with 'empty can' exercise.[16] Moreover, MRI data demonstrate similar infraspinatus activity during abduction with IR and abduction with ER.[26]

The infraspinatus is active in numerous shoulder exercises other than 'empty can', 'full can', abduction and ER exercises (tables V and VII). High to very high infraspinatus activity has been quantified in prone horizontal abduction at 100° abduction with ER and IR, flexion, side-lying abduction, standing extension from 90 to 0°, and D1 and D2 diagonal pattern flexion (tables V

Fig. 2. Press-up (see tables V and VI for muscle activity during this exercise).

Fig. 3. Prone external rotation at 90° abduction (see tables II and III for muscle activity during this exercise).

and VII).[12,14,16,26,35-37,43,44] When these shoulder exercises are compared with each other, mixed results have been reported. Some EMG data support prone horizontal abduction at 100° abduction with ER over the 'empty can' and 'full can' in infraspinatus activity,[35] while other EMG data and MRI data show no difference in infraspinatus activity between these exercises.[26,37] High to very high infraspinatus activity has been reported in several closed chain weight-bearing exercises, such as a variety of push-up exercises and when assuming a bipod (alternating arm and leg) position (table IV).[1,10]

In contrast to the infraspinatus, the teres minor generates a weak shoulder adductor torque due to its lower attachments to the scapula and humerus.[18-20] A 3-D biomechanical model of the shoulder reveals that the teres minor does not generate scapular plane abduction torque when it contracts, but rather generates an adduction torque and 94 N of force during maximum effort scapular plane adduction.[18] In addition, Otis et al.[20] reported the adductor moment arm of the teres minor was approximately 0.2 cm at 45° IR and approximately 0.1 cm at 45° ER. These data imply that the teres minor is a weak adductor of the humerus regardless of the rotational position of the humerus. In addition, because of its posterior position at the shoulder, it also helps generate a weak horizontal abduction torque. Therefore, although its activity is similar to the infraspinatus during ER, it is hypothesized that the teres minor would not be as active as the infraspinatus during scaption, abduction and flexion movements, but would show activity similar to the infraspinatus during horizontal abduction type movements. This hypothesis is supported by EMG and MRI data, which show that teres minor activity during flexion, abduction and scaption is considerably less than infraspinatus activity (tables V and IX).[13,16,26,34,35,37] Even though the teres minor generates an adduction torque, it is active during humeral elevation movements as it contracts to enhance joint stability by resisting superior humeral head translation and providing humeral head compression within the glenoid fossa.[22] This is especially true at lower abduction angles and when abduction and scaption movements encounter greater resistance (table IX).[13] In contrast to arm abduction, scaption and flexion, teres minor activity is much higher during prone horizontal abduction at 100° abduction with ER, exhibiting activity similar to the infraspinatus (tables II and V).[12,16,26,35,37] Teres minor activity is also high to very high during standing high, mid and low scapular rows and standing forward scapular punch, and even

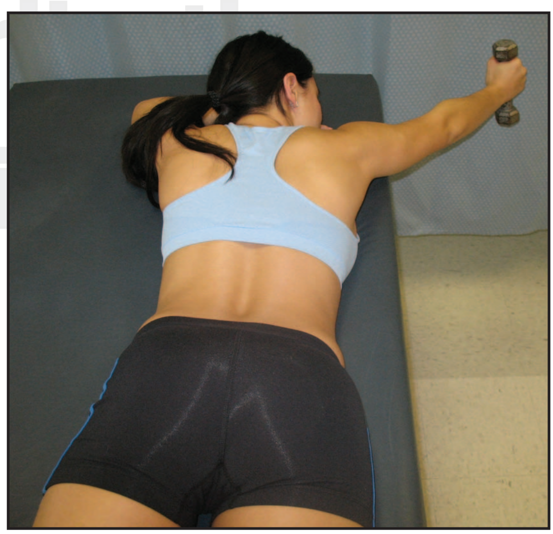

Fig. 4. Prone horizontal abduction at 90–135° abduction with external rotation (see tables II and III for muscle activity during this exercise).

Fig. 5. Rowing (see tables III, V and VI for muscle activity during this exercise).

during internal rotation exercises to help stabilize the glenohumeral joint.[14]

1.3 Subscapularis

The subscapularis provides glenohumeral compression, stability, IR and abduction. From 3-D biomechanical shoulder models, predicted subscapularis force during maximum effort IR was 1725 N at 90° abduction and 1297 N at 0° abduction.[18] Its superior, middle and inferior heads generate its largest IR torque at 0° abduction, with a peak moment arm of approximately 2.5 cm.[20] As the abduction angle increases, the moment arms of the inferior and middle heads stay relatively constant, while the moment arm of the superior head progressively decreases until it is about 1.3 cm at 60° abduction.[20] These data imply that the upper portion of the subscapularis muscle (innervated by the upper subscapularis nerve) is a more effective internal rotator at lower abduction angles compared with higher abduction angles. However, there is no significant difference in upper subscapularis activity among IR exercises at 0°, 45° or 90° abduction (table I).[10,45] Abduction angle does not appear to affect the ability of the lower subscapularis (innervated by the lower subscapularis nerve) to generate IR torque.[20] However, lower subscapularis muscle activity is affected by abduction angle. Decker et al.[10] reported significantly greater lower subscapularis activity with IR at 0° abduction compared with IR at 90° abduction (table I), while Kadaba et al.[45] reported greater lower subscapularis activity with IR at 90° abduction compared with IR at 0° abduction. Performing IR at 0° abduction produces similar amounts of upper and lower subscapularis activity.[10,45,46]

The movement most optimal for isolation and activation of the subscapularis muscle is the Gerber lift-off against resistance,[25,46,47] which is performed by 'lifting' the dorsum of the hand off the mid-lumbar spine (against resistance) by simultaneously extending and internally rotating the shoulder.[48] Although this was originally developed as a test (using no resistance) for subscapularis tendon ruptures,[48] it can be used as an exercise since: (a) it tends to isolate the subscapularis muscle by minimizing pectoralis major, teres major, latissimus dorsi, supraspinatus and infraspinatus activity when performed with no resistance;[25,46] (b) it generates as much or more subscapularis activity compared with resisted IR at 0° or 90° abduction;[25,46,47] and (c) it avoids the subacromial impingement position associated with IR at 90° abduction.[25] It is important to begin the Gerber lift-off test/exercise with the hand in the mid-lumbar spine, as lower

Fig. 6. Push-up plus (see tables I, IV and VI for muscle activity during this exercise).

Fig. 7. Scaption with external rotation (full can) [see tables III, V and VI for muscle activity during this exercise].

and upper subscapularis activity decreases approximately 30% when the exercise begins at the buttocks level.[46] Performing the Gerber lift-off test produces similar amounts of upper and lower subscapularis activity.[46]

The subscapularis generates significant abduction torque during humeral elevation.[19,20] From 3-D biomechanical shoulder models, predicted subscapularis force during maximum effort scaption (90° isometric position) was 283 N, approximately 2.5 times the predicted force from supraspinatus in this position.[18] Liu et al.[19] reported that in scapular plane abduction with neutral rotation the subscapularis generated a peak abductor moment arm of 1 cm at 0° abduction and then slowly decreased to 0 cm at 60° abduction. Moreover, the abductor moment arm of the subscapularis generally decreased as abduction with IR increased,[19] such as performing the 'empty can'. In contrast, the abductor moment arm of the subscapularis generally increased as abduction with ER increased, such as performing the 'full can'. This implies that the 'full can' may be more effective in generating subscapularis activity compared with the 'empty can'. While most studies that have examined the 'empty can' exercise have reported low subscapularis activity,[26,36,37] Townsend et al.[16] reported high to very high subscapularis activity during the 'empty can' and low subscapularis activity during the 'full can' (table V). In contrast, scaption with neutral rotation as well as flexion and abduction above 120° with ER generated high to very high subscapularis EMG amplitude (tables V, VII and IX).[13,14,16]

The subscapularis is active in numerous shoulder exercises other than flexion, abduction, scaption and IR exercises. High to very high subscapularis activity has been quantified in side-lying abduction, standing extension from

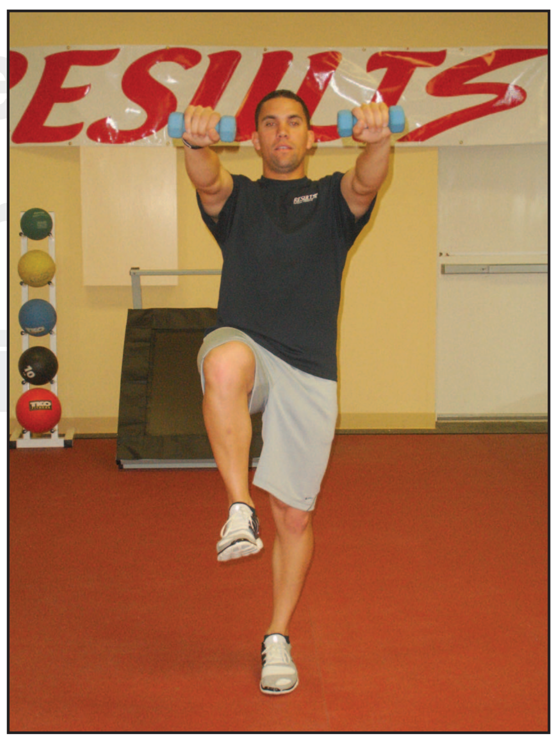

Fig. 8. Flexion (see tables V, VI, VII and VIII for muscle activity during this exercise).

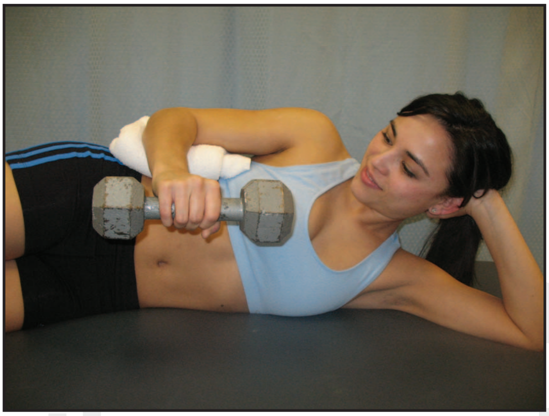

Fig. 9. Side-lying external rotation at 0° abduction (see tables II and V for muscle activity during this exercise).

90–0°, military press, D2 diagonal pattern flexion and extension, and PNF scapular clock, depression, elevation, protraction and retraction movements (tables I, V and VII).[10,14,16,36,39,43] Even ER exercises have generated high to very high subscapularis activity (table VII) to help stabilize the glenohumeral joint.[14] Although prone horizontal abduction at 100° abduction with ER was an effective exercise for the supraspinatus, infraspinatus and teres minor, it is not an effective exercise for the subscapularis (table V).[16,37] High to very high subscapularis activity has been reported in the push-up, standing scapular dynamic hug, standing forward scapular punch, standing high, mid and low scapular rows, and two-hand overhead medicine ball throw (tables I and VII).[10,14,40,41]

Otis et al.[20] reported that the superior, middle and inferior heads of the subscapularis all had abductor moment arms (greatest in the superior head and least in the inferior head) that vary as a function of humeral rotation. These moment arm lengths for the three muscle heads are approximately 0.4–2.2 cm at 45° of ER, 0.4–1.4 cm at neutral rotation and 0.4–0.5 cm at 45° of IR. This implies that the subscapularis is more effective with scaption with ER compared with scaption with IR. Moreover, the simultaneous activation of the subscapularis and infraspinatus during humeral elevation not only generate both abductor moments and inferior directed force to the humeral head to resist superior humeral head translation,[22] but these muscles also neutralize the IR and ER torques they generate, further enhancing joint stability.

2. Deltoid Biomechanics and Function in Rehabilitation Exercises

The abductor moment arms during scaption at 0° abduction with neutral rotation are approximately 0 cm for the anterior deltoid and 1.4 cm for

Fig. 10. Standing scapular dynamic hug-forward scapular punch (see tables I, VII and VIII for muscle activity during this exercise).

the middle deltoid, and progressively increase with increasing abduction.[19,20] By 60° abduction the moment arms increase to approximately 1.5–2 cm for the anterior deltoid and 2.7–3.2 cm for the middle deltoid. From 0 to 40° abduction the moment arms for the anterior and middle deltoids are less than the moment arms for the supraspinatus, subscapularis and infraspinatus.[19,20] This implies that the anterior and middle deltoids are not effective abductors at low abduction angles (especially the anterior deltoids), while the supraspinatus, infraspinatus and subscapularis are more effective abductors at low abduction angles. These biomechanical data are supported by EMG data, in which anterior and middle deltoid activity generally peaks between 60 and 90° of scaption, while supraspinatus, infraspinatus and subscapularis activity generally peaks between 30 and 60° of scaption (table IX).[13]

The abductor moment arm for the anterior deltoid changes considerably with humeral rotation, increasing with ER and decreasing with IR.[19] At 60° ER and 0° abduction, a position similar to the beginning of the 'full can', the anterior deltoid moment arm was 1.5 cm (compared with 0 cm in neutral rotation), which makes the anterior deltoid an effective abductor even at small abduction angles.[19] By 60° abduction with ER, its moment arm increased to approximately 2.5 cm (compared with approximately 1.5–2 cm in neutral rotation).[19] In contrast, at 60° IR at 0° abduction, a position similar to the beginning of the 'empty can' exercise, its moment arm was 0 cm, which implies that the anterior deltoid is not an effective abductor with humeral IR.[19] By 60° abduction and IR, its moment arm increased to only about 0.5 cm.[19] Although the abductor moment arms for the middle and posterior deltoids did change significantly with humeral rotation, the magnitude of these changes was too small to be clinically relevant. From EMG and MRI data, both the anterior and middle deltoids exhibit similar activity between the 'empty can' and 'full can' (table V).[16,26] Additional exercises that have exhibited high to very high anterior and middle deltoid activity are shown in tables IV, V and VII;[1,14,16,40,43,44,49-52] examples are D1 and D2 diagonal pattern flexion, flexion, push-up exercises, bench press, dumbbell fly, military press, two-hand overhead medicine ball throws, press-up, dynamic hug and standing forward scapular punch.

Comparing exercises, anterior and middle deltoid activity was significantly greater performing a free weight bench press compared with a machine bench press.[52] There was no difference in mean anterior deltoid activity among the dumbbell fly and the barbell and dumbbell bench press, but both the anterior deltoid and pectoralis major were activated for longer periods in the barbell and dumbbell bench press compared with the dumbbell fly.[50]

Bench press and military press technique variations also affect deltoid activity. Anterior deltoid increased as the trunk became more vertical, such as performing the incline press and military press,[51] but was less in the bench press and least in the decline press.[51]

Hand grip also affects shoulder biomechanics and deltoid activity during the bench press. Compared with a narrow hand grip, employing a wider hand grip resulted in slightly greater anterior deltoid activity during the incline press and military press.[51] In contrast, compared with a wide hand grip, employing a narrow hand grip resulted in greater anterior deltoid and clavicular pectoralis activity during the decline press and bench press.[51] This is consistent with biomechanical data during the bench press, in which a greater shoulder extension torque is generated by the load lifted with a narrower (95% biacromial breadth) hand grip (peak torque of approximately 290 N • m when bar was near chest) compared with a wider (270% biacromial breadth) hand grip (peak torque of approximately 210 N • m when bar was near chest), which must be countered by a shoulder flexor torque generated by the shoulder flexors (primarily the anterior deltoid and clavicular pectoralis major).[53] This greater shoulder flexor torque occurred because throughout the bench press movement the load is further away from the shoulder axis with a narrower hand grip (moment arm of approximately 7 cm at starting and ending positions and approximately 21 cm when bar was near chest) compared with a wider hand grip (moment arm of approximately 4 cm at starting and ending positions and approximately 15 cm when bar was near chest).[53]

Push-up technique variations also affect deltoid activity.[1,54] Anterior deltoid activity was least in a standard push-up, greater in a push-up with feet elevated and greatest in a one-arm push-up. Moreover, anterior deltoid activity was 60–70% of a MVIC during a plyometric push-up (clapping) and one-arm push-up, but only 40–50% of a MVIC during the standard push-up, push-up with hands staggered (left or right hand forward relative to other hand) and push-ups with one on both hands on a basketball.[54] These data illustrate how these exercises can be progressed in terms of increasing muscle activity. However, the plyometric and one-arm push-up resulted in approximately double lumbar spinal compressive loads compared with performing standard, ball or staggered hand push-ups, which may be problematic for individuals with lumbar spinal problems.[54] Moreover, these higher intensity push-up exercises result in greater loading of the glenohumeral joint resulting from greater muscle activity and greater ground reaction forces transmitted from the floor to the shoulder (plyometric push-up).

The posterior deltoid does not effectively contribute to scapular plane abductor from 0–90°, but more effectively functions as a scapular plane adductor due to an adductor moment arm.[19,20] Because its adductor moment arm decreases as abduction increases, this muscle becomes less effective as a scapular plane adductor at higher abduction angles, and may change to a scapular plane abductor beyond 110° abduction.[19,20] These biomechanical data are consistent with EMG and MRI data, in which posterior deltoid activity is low not only during scaption but also during flexion and abduction (tables V and IX).[13,16,26] However, high to very high posterior deltoid activity has been reported in the 'empty can' exercise when compared with the 'full can' exercise, which implies that IR during scaption increases posterior deltoid activity.[26,37] During rowing exercises and prone horizontal abduction at 100° abduction with ER and IR, both the posterior and middle deltoids produced high to very high activity (tables II and V), but low anterior deltoid activity.[12,16,37] Posterior and middle deltoid activity remain similar between IR and ER positions while performing prone horizontal abduction at 100° abduction (table V).[16] Other exercises that have exhibited high to very high posterior and middle deltoid activity include D1 diagonal pattern extension and D2 diagonal pattern flexion, push-up exercises, shoulder extension and side-lying ER at 0° abduction (tables IV and V).[1,14,16,43,44]

Peak isometric abduction torque has been reported to be 25 N • m at 0° abduction and neutral rotation.[19] Up to 35–65% of this torque is from the middle deltoid, up to 30% from the subscapularis, up to 25% from the supraspinatus, up to 10% from the infraspinatus, up to 2% from the anterior deltoid and 0% from the posterior deltoid.[19] This implies that both the deltoids and rotator cuff provide significant abduction torque. The ineffectiveness of the anterior and posterior deltoids to generate abduction torque may appear surprising,[19,20] but the low abduction torque for the anterior deltoid does not mean this muscle is only minimally active. In fact, because the anterior deltoid has an abductor moment arm near 0 cm at 0° abduction, the muscle could be very active and generating very high force but very little torque because of the small moment arm. At 0° abduction deltoid force attempts to translate the humeral head superiorly, which is resisted largely by the rotator cuff. Therefore, highly active deltoids may also result in a highly active rotator cuff, especially at low abduction angles during humeral elevation.

The aforementioned torque data are complemented and supported by muscle force data from Hughes and An,[18] who predicted forces from the deltoids and rotator cuff during maximum effort abduction with the arm 90° abducted and in neutral rotation. Posterior deltoid and teres minor forces were only 2 N and 0 N, respectively, which further demonstrates the ineffectiveness of these muscles as shoulder abductors. In contrast, middle deltoid force was the highest, at 434 N, which supports the high activity in this muscle during abduction exercises (tables II, V, VII and IX). The anterior deltoid generated the second highest force of 323 N, which may appear surprising given the low abductor torque for this muscle at 0° abduction. However, force and torque are not the same, and in this study by Hughes and An[18] the shoulder was positioned at 90° abduction (a position in which the deltoids are effective abductors), while in the study by Liu et al.[19] the shoulder was positioned at 0° abduction (a position in which the deltoids are not effective abductors). As previously mentioned, the moment arm of the anterior deltoid progressively increases as abduction increases. It is also important to remember that muscle force is generated not only to generate joint torque, but also to provide joint stabilization.

During maximum effort abduction, Hughes and An[18] also predicted 608 N of force from the subscapularis (283 N), infraspinatus (205 N) and supraspinatus (117 N). These large forces are generated not only to abduct the shoulder but also to stabilize the glenohumeral joint and neutralize the superior directed force generated by the deltoids, especially at lower abduction angles.

3. Scapular Muscle Function in Rehabilitation Exercises

Appropriate scapular muscle strength and balance is important because the scapula and humerus move together as a unit during humeral elevation, referred to as scapulohumeral rhythm. Near 30–40° of humeral elevation the scapula begins to upwardly rotate in the frontal plane, rotating approximately 1° for every 2° of humeral elevation until 120° humeral elevation, and thereafter rotating approximately 1° for every 1° humeral elevation until maximal humeral elevation, for a total of approximately 45–55° of upward rotation.[55,56] Interestingly, scapulohumeral rhythm is affected by humeral rotation. For example, it has been demonstrated that from 0–90° scapular plane abduction the scapula rotates upwardly 28–30° with neutral humeral rotation, 36–38° with humeral ER and 40–43° with IR.[57] Moreover, from 0–90° of scaption, scapular IR (winging) and anterior tilt are greater with humeral IR ('empty can') compared with humeral ER ('full can'); scapular IR and anterior tilt are associated with a smaller subacromial space width, increasing impingement risk.

During humeral elevation, in addition to scapular upward rotation, the scapula normally posterior tilts (inferior angle moving anterior in sagittal plane) approximately 20–40° and externally rotates (lateral border moves posterior in transverse plane) approximately 15–35°.[55,56] If these 3-D sequences of normal scapular movements are disrupted by abnormal scapular muscle firing patterns, weakness, fatigue or injury, the shoulder complex functions less efficiently and injury risk is increased. The primary muscles that cause and control scapular movements include the trapezius, serratus anterior, levator scapulae, rhomboids and pectoralis minor. The function of these muscles during shoulder exercises is discussed below.

3.1 Serratus Anterior

The serratus anterior works with the pectoralis minor to abduct (protract) the scapula and with the upper and lower trapezius to upwardly rotate the scapula. The serratus anterior is an important muscle because it contributes to all components of normal 3-D scapular movements during humeral elevation, which includes upward rotation, posterior tilt and external rotation.[55,56] The serratus anterior also helps stabilize the medial border and inferior angle of the scapula, preventing scapular IR (winging) and anterior tilt.

Tables III, VI and VIII show several exercises that elicit high to very high serratus anterior activity, such as D1 and D2 diagonal pattern flexion, D2 diagonal pattern extension, supine scapular protraction, supine upward scapular punch, military press, IR and ER at 90° abduction, flexion, abduction, scaption above 120° with ER, and push-up plus.[11,14,15,41,49] Serratus anterior activity tends to increase in a somewhat linear fashion with humeral elevation (tables III and VI).[11,15,56,58,59] However, increasing humeral elevation increases subacromial impingement risk,[27,28] and humeral elevation at lower abduction angles also generates high to very high serratus anterior activity (table III).[11]

It is interesting that performing IR and ER at 90° abduction generates high to very high serratus anterior activity (tables III and VIII), because these exercises are usually thought to primarily work rotator cuff muscles.[11,14] Not surprising is the high activity generated during the push-up. When performing the standard push-up, push-up on knees and wall push-up, serratus activity is greater when full scapular protraction occurs after the elbows fully extend (push-up plus).[60] Moreover, serratus anterior activity was lowest in the wall push-up plus, exhibited moderate activity during the push-up plus on knees, and high to very high activity during the standard push-up plus and push-up plus with the feet elevated (greatest activity with feet elevated)[49,60,61] – which illustrates how these exercises can be progressed.

Additional exercises that have been shown to be effective in activating the serratus anterior is the standing scapular dynamic hug,[49] PNF scapular depression and protraction movements,[39] 'empty can',[37] and the wall slide.[59] The wall slide begins by slightly leaning against the wall with the ulnar border of forearms in contact with wall, elbows flexed 90° and shoulders abducted 90° in the scapular plane. From this position the arms slide up the wall in the scapular plane while leaning into the wall. The wall slide produces similar serratus anterior activity compared with scaption above 120° with no resistance. One advantage of the wall slide compared with scaption is that, anecdotally, patients report that the wall slide is less painful to perform.[59] This may be because during the wall slide the upper extremities are supported against the wall in a closed chain position, making it easier to perform.

3.2 Trapezius

General functions of the trapezius include scapular upward rotation and elevation for the upper trapezius, retraction for the middle trapezius, and upward rotation and depression for the lower trapezius. In addition, the inferomedial-directed fibres of the lower trapezius may also contribute to posterior tilt and external rotation of the scapula during humeral elevation,[56] which decreases subacromial impingement risk.[61,62]

Tables III, VI and VIII show several exercises that elicit high to very high trapezius activity, such as shoulder shrug, prone rowing, prone horizontal abduction at 90° and 135° abduction with ER and IR, D1 diagonal pattern flexion, standing scapular dynamic hug, PNF scapular clock, military press, two-hand overhead medicine ball throw, and scaption and abduction below 80°, at 90° and above 120° with ER.[11,15,39,40,49] During scaption, upper trapezius activity progressively increases from 0 to 60°, remains relatively constant from 60 to 120° and continues to progressively increase from 120 to 180°.[58]

High to very high middle trapezius activity occurs in the shoulder shrug, prone rowing and prone horizontal abduction at 90° and 135° abduction with ER and IR.[11,15] Some studies have reported high to very high middle trapezius activity during scaption at 90° and above 120°,[11,49,58] while other EMG data show low middle trapezius activity during this exercise.[15]

High to very high lower trapezius activity occurs in the prone rowing, prone horizontal abduction at 90° and 135°, abduction with ER and IR, prone and standing ER at 90° abduction, D2 diagonal pattern flexion and extension, PNF scapular clock, standing high scapular rows, and scaption, flexion and abduction below 80° and above 120° with ER.[11,14,15,39] Lower trapezius activity tends to be low at <90° of scaption, abduction and flexion, and then increases exponentially from 90° to 180°.[11,15,39,58,59,63] Significantly greater lower trapezius activity has been reported in prone ER at 90° abduction compared with the 'empty can' exercise.[34]

3.3 Rhomboids and Levator Scapulae

Both the rhomboids and levator scapulae function as scapular adductors (retractors), downward rotators and elevators. High to very high rhomboid activity has been reported during D2 diagonal pattern flexion and extension, standing ER at 0° and 90° abduction, standing IR at 90° abduction, standing extension from 90 to 0°, prone horizontal abduction at 90° abduction with IR, scaption, abduction and flexion above 120° with ER, prone rowing, and standing high, mid and low scapular rows (tables VI and VIII).[14,15] High to very high levator scapulae activity has been reported in scaption above 120° with ER, prone horizontal abduction at 90° abduction with ER and IR, prone rowing, and prone extension at 90° flexion (table VI).[15]

4. Conclusions

During shoulder exercises the rotator cuff abducts, externally rotates and internally rotates, and stabilizes the glenohumeral joint. Although the infraspinatus and subscapularis generate muscle forces two to three times greater than the supraspinatus force, the supraspinatus still remains a more effective shoulder abductor because of its more effective moment arm.

Both the deltoids and rotator cuff provide significant abduction torque, with an estimated contribution up to 35–65% by the middle deltoid, 30% by the subscapularis, 25% by the supraspinatus, 10% by the infraspinatus and 2% by the anterior deltoid. During abduction, middle deltoid force has been estimated to be 434 N, followed by 323 N from the anterior deltoid, 283 N from the subscapularis, 205 N from the infraspinatus and 117 N from the supraspinatus. These forces are generated not only to abduct the shoulder but also to stabilize the joint and neutralize the antagonistic effects of undesirable actions. Relatively high force from the rotator cuff not only helps abduct the shoulder but also neutralizes the superior directed force generated by the deltoids at lower abduction angles. Even though anterior deltoid force is relatively high, its ability to abduct the shoulder is low due to a very small moment arm, especially at low abduction angles. The deltoids are more effective abductors at higher abduction angles, while the rotator cuff muscles are more effective abductors at lower abduction angles.

During maximum humeral elevation the scapula normally upwardly rotates 45–55°, posterior tilts 20–40° and externally rotates 15–35°. The scapular muscles are important during humeral elevation because they cause these motions, especially the serratus anterior, which contributes to scapular upward rotation, posterior tilt and ER. The serratus anterior also helps stabilize the medial border and inferior angle of the scapula, preventing scapular IR (winging) and anterior tilt. If normal scapular movements are disrupted by abnormal scapular muscle firing patterns, weakness, fatigue or injury, the shoulder complex functions less efficiently and injury risk increases.

Scapula position and humeral rotation can affect injury risk during humeral elevation. Compared with scapular protraction, scapular retraction has been shown to both increase subacromial space width and enhance supraspinatus force production during humeral elevation. Moreover, scapular IR (winging) and anterior tilt, both of which decrease subacromial space width and increase impingement risk, are greater when performing the ‘empty can’ compared with the ‘full can’.

There are several exercises in the literature that exhibit high to very high activity from the rotator cuff, deltoids and scapular muscles, such as prone horizontal abduction at 100° abduction with ER, flexion, abduction and scaption with ER, D1 and D2 diagonal pattern flexion and extension, ER and IR at 0° and 90° abduction, standing extension from 90 to 0°, a variety of weight-bearing upper extremity exercises (such as the push-up), standing scapular dynamic hug, forward scapular punch and rowing exercises. Supraspinatus activity in the ‘empty can’ and ‘full can’ is similar, although the ‘full can’ results in less risk of subacromial impingement. Infraspinatus and subscapularis activity have generally been reported to be higher in the ‘full can’ compared with the ‘empty can’, while posterior deltoid activity has been reported to be higher in the ‘empty can’ than the ‘full can’.

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