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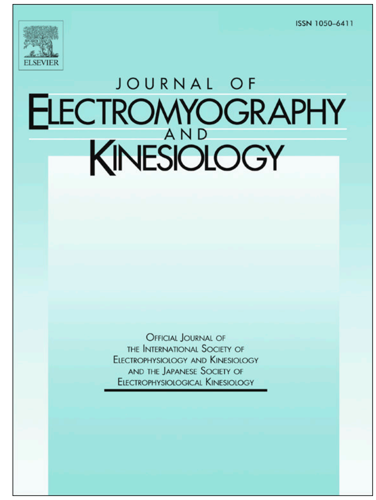

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Talia Alenabi, Rachel Whittaker, Soo Y. Kim, Clark R. Dickerson

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Talia Alenabi, MD, PhD[1], Rachel Whittaker, MSc[1], Soo Y. Kim, PT, PhD[2], Clark R. Dickerson, PhD[1]

[1] University of Waterloo, Faculty of Applied Health Sciences, Department of Kinesiology, Digital Industrial Ergonomics and Shoulder Evaluation Laboratory (DIESEL), Waterloo, Ontario, Canada

[2] School of Physical Therapy, College of Medicine, University of Saskatchewan, Saskatoon, Canada

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Corresponding Author:

Clark R. Dickerson clark.dickerson@uwaterloo.ca

Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo

200 University Ave W, Waterloo, Ontario, Canada, N2L 3G1

Phone: 519-888-4567 x37844

Fax: 519-746-6776

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Abstract

This study aimed to identify optimal sets of maximal voluntary isometric contractions (MVICs) for normalizing EMG data from anterior and posterior regions of the supraspinatus, and superior, middle and inferior regions of the infraspinatus.

31 right-handed young healthy individuals (15 males, 16 females) participated. EMG activity was obtained from two regions of supraspinatus and three regions of infraspinatus muscles via fine wire electrodes. Participants performed 15 MVIC tests against manual resistance. The EMG data were normalized to the maximum values. Optimal sets of MVIC combinations, defined as those which elicited >90% MVIC activation in the muscles of interest in >80% and >90% of the population, were obtained.

EMG data from the inferior region of infraspinatus were removed from analysis due to technical problem. No single test achieved maximal activation of both regions of either the supraspinatus or infraspinatus. Instead, a combination of 6-8 MVICs were required to reach >90% MVIC activation in both parts of those muscles. In all regions of the rotator cuff muscles, the optimal combination was obtained with 8-10 MVICs. The proposed combinations can reduce inter-participant variability in generating maximal activation from different regions of the supraspinatus and infraspinatus muscles.

INTRODUCTION

Conventional methods for evaluating EMG activity of supraspinatus and infraspinatus muscles consist of inserting a single paired intramuscular electrode into each muscle, assuming each muscle acts as a single unit. However, anatomical studies have defined two architecturally distinct regions in the supraspinatus (anterior and posterior)(Kim et al., 2007; Roh et al., 2000) and three regions in the infraspinatus muscles (superior, middle, and inferior) (Fabrizio and Clemente, 2014); each region is innervated by a distinct nerve branch of the suprascapular nerve (Hermenegildo et al., 2013). According to these defined regions, most EMG data in the literature has been obtained from the anterior region of the supraspinatus and middle region of the infraspinatus. Establishing the codependence or independence of activation and control of these muscle partitions requires deliberate comparison of EMG from the various supraspinatus and infraspinatus regions. These comparisons will help identify the exact functions of these two complex muscles and the relative contribution of each region to rotator cuff pathologies.

Normalization of EMG data by the maximum voluntary isometric contractions (MVIC) is a common method for describing muscle activation (Burden and Bartlett, 1999) and allows comparison of muscle activity levels between muscles, tasks and individuals (Wattanaprakornkul et al., 2011). Different exertions are commonly used to elicit MVIC in supraspinatus and infraspinatus muscles (Escamilla et al., 2009); however, it is not known which set of test exertions can generate maximal activations in all regions of these two muscles. It is crucial to standardize the normalization tests for different regions of the supraspinatus and infraspinatus muscles to provide a basis for future comparisons.

Previous studies (Boettcher et al., 2008; Castelein et al., 2015; Dal Maso et al., 2016; Ekstrom et al., 2005; Schwartz et al., 2017) have investigated different exertions leading to maximal activations of some shoulder muscles. These studies concluded that no single test could produce maximal activation of a specific muscle for all subjects. Therefore, a combination of MVIC tests was suggested for effective normalization. Although they suggested a combination of 4-12 MVICs for maximum or near maximum activation of certain shoulder muscles, none considered the activation of different partitions of the supraspinatus and infraspinatus muscles.

The primary purpose of this study was to quantify the activation of the anatomically distinct regions within the supraspinatus (anterior, posterior) and infraspinatus (superior, middle and inferior) muscles during different MVIC test exertions in order to identify optimal combinations of tests for normalizing EMG data from various regions of these two rotator cuff muscles. It was hypothesized that different MVIC tests would be required to generate maximal activation in each region of the supraspinatus or infraspinatus muscles across study population and no single test could induce MVIC in all partitions of the supraspinatus or infraspinatus.

METHODS

Participants

Thirty-one right-handed healthy volunteers including 15 males (age = 23.2 ± 3.4 years, height= 176 ± 8.9 cm, and weight = 77.4 ± 12.9 kg) and 16 females (age = 21.8 ± 1.6 years, height = 160.5 ± 8.6 cm and weight = 58.2 ± 7.7 kg) participated in this cross-sectional study. All participants were healthy without history of injury or surgery in their right upper limb. The study was approved by the university office of research ethics and all participants provided written informed consent.

Instrumentation

Five fine wire electrodes were used to measure the activation of the anterior and posterior regions of supraspinatus and superior, middle and inferior regions of infraspinatus muscles. Needle insertion into the anterior partition of supraspinatus and the middle partitions of infraspinatus followed the recommendations by Perotto & Delagi, (2005). Either 30 mm (27 gauge) or 50 mm (25 gauge) manufactured needles (Chalgren Enterprises, Inc, CA, USA) were used. Reaching the posterior region of supraspinatus required insertion of a 75 mm (23 gauge) custom made needle (Quinke Point, Kimberly Clark Spinal QP Needle) under ultrasound guidance (SonoSite M-Turbo, L38e linear array transducer probe, 5-10 MHz) as described by Kim et al., (2017), (Figure 1).

For the superior partition of infraspinatus, the needle was inserted vertically, 0.5 cm below the spine of scapula in the lateral half of the middle third of the spine of scapula, (Figure 1). This corresponds to the area beneath the spine curvature. For the inferior region of infraspinatus, the needle was inserted at the intersection of the line demarcating the division of the lateral and middle third of the scapular spine with the mid-point of lateral border of scapula. The needle was angled 30 degrees toward the inferior angle of scapula (Figure 1). This insertion method was previously validated by cadaver piloting.

Figure 1

A reference surface electrode was placed over the right clavicle. All EMG data were collected using a Noraxon telemyo 2400 G2 system (Noraxon, Arizona, USA). Raw EMG signals were band-pass filtered (10-1000 Hz), differentially amplified (common-mode rejection ratio >100 dB at 60 Hz, input impedance 100 MΩ), sampled at 3000 Hz, and converted to a digital signal (16-bit A/D card, maximum +/-10V range).

Test Protocol

Participants performed 15 MVIC tests in a randomly assigned order against manual resistance applied by a researcher (Table 1, Figure 2). Two strategies were used for choosing the test positions: 1) common MVIC tests for normalizing the data from supraspinatus, infraspinatus and some other shoulder muscles, published in the literature as identified in Table 1, 2) some new tests based on the previous studies that reported highest involvement of supraspinatus in arm elevations and infraspinatus in external rotations (Ackland et al., 2008; Kuechle et al., 1997; Langenderfer et al., 2006). We added elevations and external rotations in different body postures (side lying, seated, prone) and arm postures (different planes and angles). Before each MVIC trial, participants were provided with verbal instructions and a demonstration of exertion. They were then asked to perform a practice trial, exerting submaximal force, to ensure they understood the instructions. Each MVIC test was performed once for 5 seconds (s) and 1 minute of rest was provided between tests to minimize muscle fatigue. Participants were instructed to ramp up their force (1s), sustain maximum force for 3s, and then decrease the exerted force gradually (1s). MVIC trials were repeated if performed incorrectly.

Table 1, Figure 2

Data Analysis

EMG Signal Processing

Analysis focused on the middle 3s of the MVIC tests. The raw EMG data were digitally bandpass filtered (10-1000Hz) using a 2nd order Butterworth filter, then, all signals were full wave rectified and linear enveloped using a low pass filter (fc = 2Hz). For each muscle, the maximum value across the MVIC trials was extracted to represent the global muscle-specific maximum voluntary excitation (gMVE). The peak activation of each muscle during each MVIC trial was subsequently normalized to the gMVE to obtain a normalized value (%MVIC). This method of processing is commonly used for normalizing EMG data (Brookham et al., 2010; Calvin et al., 2016; Delfa et al., 2014). Using a smoothing technique such as linear enveloping mitigates the likelihood of transient spikes affecting the analysis substantially. Lastly, for each muscle, the MVICs during which an activation of >90%MVIC was obtained were identified.

Determination of Optimal MVIC Combination

A custom algorithm was written in Matlab (Mathworks, Inc., USA) to identify a series of optimal MVIC combinations in which 90% activation was attained in 80% and 90% of the participants for various muscle combinations. Two combinations that differed in the percentage of the sample population were introduced to provide alternative choices for researchers who need to minimize the number of MVICs in certain situations, such as those investigating injured or clinical population. The muscle combinations investigated are 1) each muscle region individually, 2) both regions of infraspinatus, 3) both regions of supraspinatus, and 4) all regions of infraspinatus and supraspinatus. The basis of this procedure is outlined by Del Maso et al., (2016) and consisted of testing every possible combination (x) of a given subset (k) of all 15 MVICs (n) (Figure 3). All of the combinations of MVICs obtained in this analysis can be found in the supplementary table. The optimal combinations presented in this article are those, which contained MVICs that overlapped across the muscle combinations studied.

Figure 3

RESULTS

EMG data from the inferior partition of infraspinatus were not available for several MVIC tests in the majority of the sample population, due to displacement of the electrodes. Thus, data from this partition were removed from analysis.

No single MVIC test induced maximal activation for a muscle across all participants. Table 2 shows the number of participants who could generate maximal activation of a muscle partition across all MVICs. In general, MVIC tests could generate maximal activation in each muscle partition in 3-23% (1-7/31) of study participants.

Table 2

Variability in Muscle Activations

The variability in muscle activation, across participants, for each MVIC can be seen in Figures 4. The activity of the studied rotator cuff muscle regions exhibited large variability across participants in several MVIC postures as seen by the large boxes and whiskers (Figure 4). Further, the box or whisker portions of the data for several MVICs cross 90%MVIC activation (indicated by a red line). This is consistent with the number of different MVICs during which participants attained a maximum activation (Table 2).

Figure 4

Optimal MVIC Combinations

To obtain >90% activation in 80% and 90% of participants for any single region of the infraspinatus or supraspinatus muscles, a combination of 5-8 MVICs were needed respectively, (Table 3). A series of 6 and 8 MVICs were required to reach >90%MVIC activation in both parts of supraspinatus and infraspinatus, respectively. In all studied regions of the rotator cuff muscles, >90%MVIC activation was obtained with 8 and 10 MVICs.

Table 3 A&B

DISCUSSION

The aim of this study was to quantify the activation of the anatomically distinct regions of the supraspinatus (anterior, posterior) and infraspinatus (superior, middle and inferior) muscles during different MVIC tests, in order to identify minimum combinations of MVICs that could elicit >90% activation in >80% and >90% of the study population. Inferior infraspinatus was removed from this analysis due to technical problem. This difficulty can be attributed to the novelty of electromyographic investigation of the superior and inferior partitions of the infraspinatus muscle, as this study was one of the first to attempt to insert a fine wire electrode into these areas of the muscle. Large variability existed for maximal activation of the rotator cuff muscles across participants during various MVICs. This may indicate that the stabilizing muscles have more individualized activation strategies than the mover muscles. No single test could maximally activate a single region of the supraspinatus or infraspinatus muscles across all individuals. Thus, a combination of different MVICs was required to obtain >90% of maximal activation of the infraspinatus or supraspinatus muscles in >80% and >90% of study population. The most important contribution of this research is that it establishes a basis for continued electromyographic research of the distinct regions of supraspinatus and infraspinatus muscles by outlining reliable MVIC test combinations to normalize the fine wire EMG data.

Number of MVICs

The results are consistent with previous studies, indicating that a combination of MVICs is required to normalize EMG data from either a single muscle or a group of shoulder muscles across a population (Boettcher et al., 2008; Dal Maso et al., 2016; Ekstrom et al., 2005; Schwartz et al., 2017). Different combinations of MVICs were suggested by those studies using different criterion. Ekstrom et al., (2005) described 2-3 tests for each of the four muscles studied, selecting the MVIC tests during which the highest percentage of participants (ranging from 36-70%) attained maximal activation of a given muscle. Boettcher et al., (2008) suggested a combination of four MVICs for 13 shoulder muscles that could produce 90%MVIC activation, but in 5-69% of the sample population. Dal Maso et al., (2016) criticized the use of only 4 MVICs to normalize the EMG data, and showed that 2-6 MVICs were required to attain >90%MVIC activation of a single shoulder muscle in >90% of population. Thus, they proposed a combination of 12 MVICs for 12 shoulder muscles. Schwartz et al.,(2017), using the same criterion as Dal Maso et al., (2016) (i.e. >90% of MVIC in >90% of population) reported that 1-4 tests were needed for each of 8 muscles of their study and a combination of 9 MVICs for the normalization of all 8 muscles. Although these studies investigated one to three of the rotator cuff muscles (Boettcher et al., 2008; Dal Maso et al., 2016; Schwartz et al., 2017), none evaluated the activation of different regions within supraspinatus and infraspinatus muscles. The current results not only reiterate the importance of selecting MVICs based on the muscle/s of interest but also clearly show the specific region of the muscle of interest must be considered. The number of MVIC tests identified in this study align with Dal Maso et al., (2016) and Schwartz et al., (2017) and show that high inter-subject variability in maximal muscle activation requires a larger number of MVICs to elicit near maximal activation across a sample population. 4-8 tests are necessary for robust normalization of EMG data from a single region of the supraspinatus or infraspinatus muscles. If all four regions of these muscles are of interest, 8-10 MVICs are required. Not adhering to these guidelines may cause the overestimation of muscle activity during a given task, if true MVIC values are not obtained from several participants.

Identified Tests

Some MVIC tests chosen in this study are commonly used to obtain maximal activation of the supraspinatus and infraspinatus muscles. However, no existing literature appears to have evaluated the effectiveness of MVIC tests in generating maximal activity of the posterior region of supraspinatus and superior region of infraspinatus. Thus, different elevation and external rotation postures were examined, as biomechanical studies suggest that the infraspinatus and supraspinatus have the largest potential moment capacities in these postures (Ackland et al., 2008; Kuechle et al., 1997; Langenderfer et al., 2006).

Supraspinatus

Anatomical distinction of posterior and anterior regions of supraspinatus was first suggested by Vahlensieck et al. (1994). Further studies confirmed that the pennation angles (Kim et al., 2007; Roh et al., 2000), the muscle fiber type (Kim et al., 2013) and the innervation pattern (Hermenegildo et al., 2014) are all distinct in these two regions. However, the activity of posterior region of supraspinatus was only recently studied by Kim et al., (2017) who normalized the EMG data with MVIC tests at three elevation angles in scaption and external rotations. Empty can or full can positions have been suggested for maximal activation of anterior supraspinatus (Kelly et al., 1996; Rowlands et al., 1995). The current data indicated that both anterior and posterior regions of supraspinatus were highly activated during full can and empty can positions; however, more participants maximally recruited the anterior supraspinatus compared to the posterior region during these tests (Table 2). Some researchers prefer the position of side-lying shoulder abduction in 5-10° to obtain maximal activation of supraspinatus muscle (Alenabi et al., 2013; Brookham et al., 2010) as it was suggested that supraspinatus might be more active in low abduction angles (Liu et al., 1997; Otis et al., 1994). Based on the current findings, maximal activation of the anterior and posterior regions of supraspinatus during this single MVIC test occurred in only 3% and 10% of population, respectively. Similar to Kim et al., (2017), the activation of the posterior region of supraspinatus was greater in external rotation exertion when the humerus was elevated to 90° (65.52 ± 18.64 %MVIC) compared to the arm at the side in 0° of abduction (46.95 ± 20.21 %MVIC). The large variability in the activation of posterior supraspinatus across participants may indicate a potential stabilizing role of this region in adjusting rotator cuff tension (Kim et al., 2017) while the anterior partition may contribute as a mover in certain elevation postures. This is deducted from the observation that lower number of test position were required to maximally activate the anterior supraspinatus compared to the posterior partition. To achieve near-maximal activation of the anterior supraspinatus, Dal Maso et al., (2016) suggested four MVICs including three different test positions that involved 90º abduction of the shoulder and empty can position in 90º. To maximally activate both partitions of supraspinatus, the current data suggest that at least 6 MVICs should be applied including

Fullcan (90º), Fullcan (60º), Abduction (90º), Flexion (90º), Side Abduction (45º) and Prone ER (90º).

Infraspinatus

Although previous studies have reported neuroanatomical distinctions within the infraspinatus muscle (Fabrizio and Clemente, 2014; Hermenegildo et al., 2013; Kato et al., 2012; Keating et al., 1993), no EMG-based study has evaluated the individual regions of infraspinatus muscle. EMG values for both regions of infraspinatus were considerably higher during MVICs tests involving external rotation. Otis et al.,(1994) suggested that superior, middle and inferior heads of infraspinatus muscle generate their largest ER torque at 0º abduction. Kelly et al., (1996) also suggested that ER at 0º abduction was the optimal position to isolate the infraspinatus muscle. Large variability in the activation of superior and middle regions of the infraspinatus existed across participants. Only a quarter of participants generated maximal activation in either of the two partitions of infraspinatus during external rotations at 0º of arm abduction (in sitting and side lying positions). In the current study, higher number of participants activate the superior region of infraspinatus while the tests were performed in prone position (e.g. prone ER 90º and prone Ext 90º). In addition, middle infraspinatus was more active in flexion 90º as well as elevation in empty can and full can positions. This coincides with Wattanaprakornkul et al., (2011) who observed higher supraspinatus (anterior) and infraspinatus (middle) activation during shoulder flexion and attributed it to attempted reduction of humeral head anterior glide. In three out of four MVIC test positions suggested by Dal Maso et al., (2016) for middle infraspinatus, elevation in the sagittal plane was included. Schwartz et al., (2017) has also suggested the combination of flexion 90º, flexion 120º, Sit ER (0º), Sit ER (90º) and prone extension for middle infraspinatus. The current suggested combination of MVICs for near maximal activation of both partitions of the infraspinatus muscle includes Flexion 90º, Prone Ext 90º, Fullcan 90º, Sit ER 0º, Sit ER 110º, Prone ER 90º and Side ER 0º.

Limitations

This study had some limitations. First, although attempts were made to collect EMG data from the inferior partition of infraspinatus, in almost half the cases, the fine wires were displaced out of the muscle during forceful contractions. A more vertical approach to this tiny muscle partition might have resulted in placing the electrodes into deeper tissues and reducing the risk of displacement. Future studies may find an alternative insertion approach into this small partition of infraspinatus muscle. Second, it would have been of upmost interest to evaluate the activation of the two sub-regions of subscapularis muscle in this study, however, doing so would require an additional two deep electrode insertions. The ensuing discomfort might have deteriorated the capacity of performing maximal exertions. Third, all the MVIC tests were performed once to avoid muscle fatigue. Different activations in a few MVICs could possibly be attained if tests were repeated. However, Ekstrom et al., (2005) reported good intra-session reliability for their recommended MVIC tests and Schwartz et al., (2017) reported good inter-session reproducibility for their combination of nine normalization tests. Thus, performing of 8 to 10 MVICs once should sufficiently recruit maximal activation in all four regions of supra and infraspinatus muscles. Fourth, evaluating all different MVIC exertions that could potentially activate different regions of supra and infraspinatus muscles is intractable. Other test combinations might conceivably elicit higher activations; however, the tests selected were identified on the basis of biomechanical plausibility and precedence.

CONCLUSION

Robust normalization of EMG data from the anterior and posterior regions of supraspinatus requires 6-8 MVIC exertions to generate >90% activation in the all muscle regions across 80% and 90% of population respectively. Considering the same criterion, for both superior and middle regions of infraspinatus, it requires 6-7 MVICs and for all four regions of the supraspinatus and infraspinatus muscles, 8-10 MVICs are needed. The proposed MVIC combinations can reduce inter-participants variability in generating maximal activation from different regions of the supraspinatus and infraspinatus and harmonize normalization.

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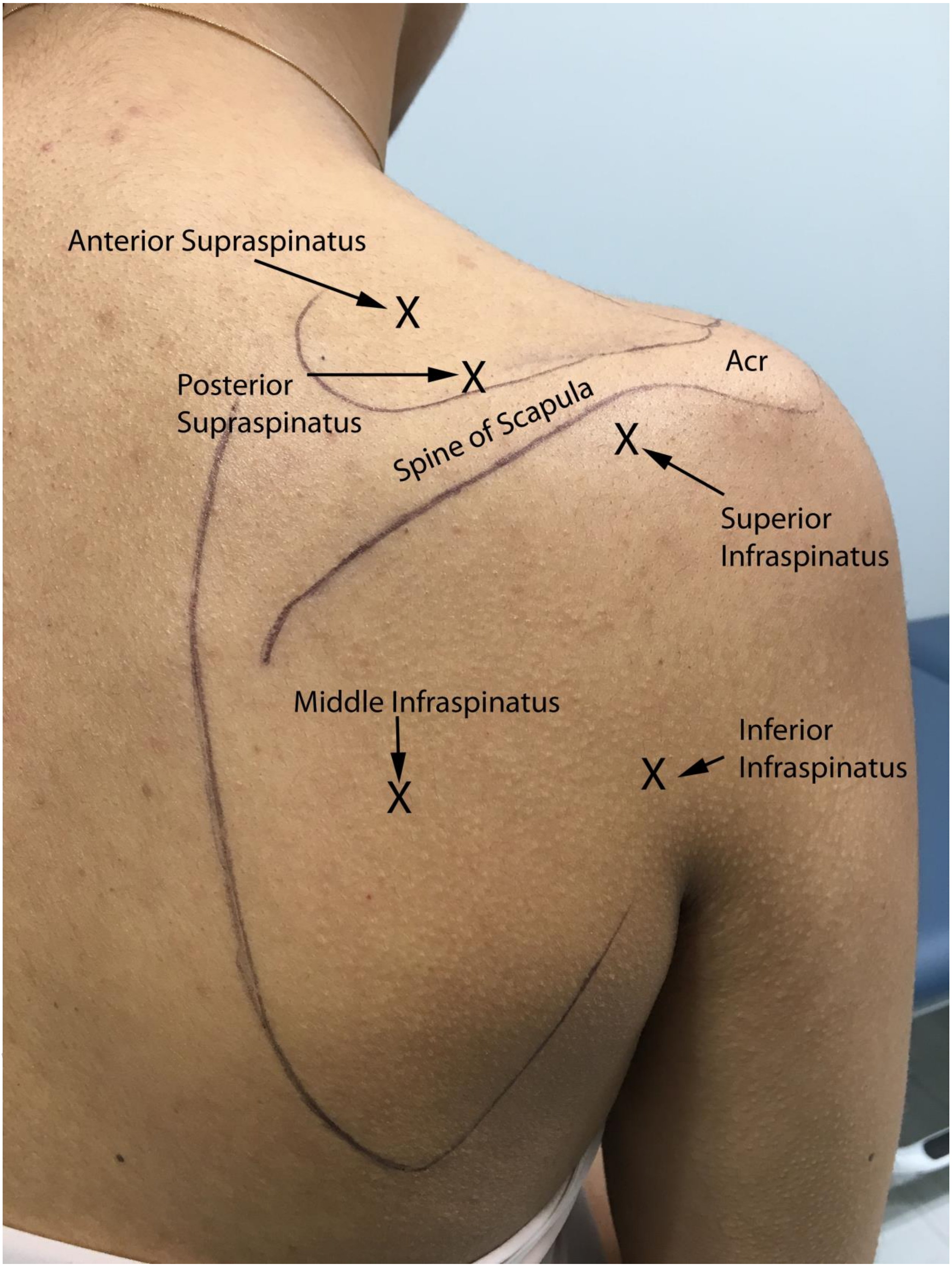
Figures:

Figure 1: The insertion sites (black X) for different regions of supraspinatus and infraspinatus. The borders of the scapula and the spine of scapula are also outlined and used to guide the placement of the insertion sites.

Figure 2: MVIC test positions

Figure 3: A schematic representation of the procedure used to identify optimal combinations of MVICs. For a given subset of the 15 MVICs examined (k = 8 in the above example) the total number of combinations were calculated as the binomial coefficient. Then, the combination of MVIC that yielded the largest number of muscles meeting the specified criteria were deemed the optimal combination of MVICs (green).

Figure 4: Box and whisker plots of the rotator cuff muscles studied. The distribution of participants activation during each of the 15 MVICs are displayed. The red line is shown to highlight 90% activation. The blue boxes indicate the MVICs included in the optimal combination of MVICs used to attain 90% activation in 90% of participants in the muscle of interest.


Anterior Supraspinatus
X
Posterior
Supraspinatus
X
Acr
Spine of Scapula
X
Superior
Infraspinatus
Middle Infraspinatus
X
Inferior
Infraspinatus
X

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Flexion (90°)	Abduction (90°)	Prone Ext (90°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Emptycan (90°)	Sit ER (0°)	Sit ER (45°)	Sit ER (90°)	Sit ER (110°)	Prone ER (90°)	Side ER (0°)	Side Abduction (10°)	Side Abduction (45°)

n = 15 MVICs total

k = 8 MVICs per subset

x = # of combinations

$$(x) = \frac{n!}{k!\,(n-k)!}$$

$$(6435) = \frac{15!}{8!\,(15-8)!}$$

Criteria

1) 90% activation
2) 90% of participants

Combination #	MVC1	MVC2	MVC3	MVC4	MVC5	MVC6	MVC7	MVC8	# of Muscles meet criteria
1	Side Abduction (10°)	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Sit ER (110°)	Abduction (90°)	Prone Ext (90°)	1
…	Side Abduction (10°)	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Sit ER (45°)	Abduction (90°)	Prone Ext (90°)	0
…	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Emptycan (90°)	Sit ER (110°)	Abduction (90°)	Prone Ext (90°)	3
…	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Sit ER (110°)	Side ER (0°)	Abduction (90°)	Prone Ext (90°)	4
…	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Sit ER (110°)	Abduction (90°)	Prone Ext (90°)	Prone ER (90°)	3
…	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Sit ER (45°)	Side ER (0°)	Abduction (90°)	Prone Ext (90°)	2
6435	Side Abduction (45°)	Fullcan (60°)	Fullcan (90°)	Emptycan (60°)	Sit ER (45°)	Abduction (90°)	Prone Ext (90°)	Prone ER (90°)	1

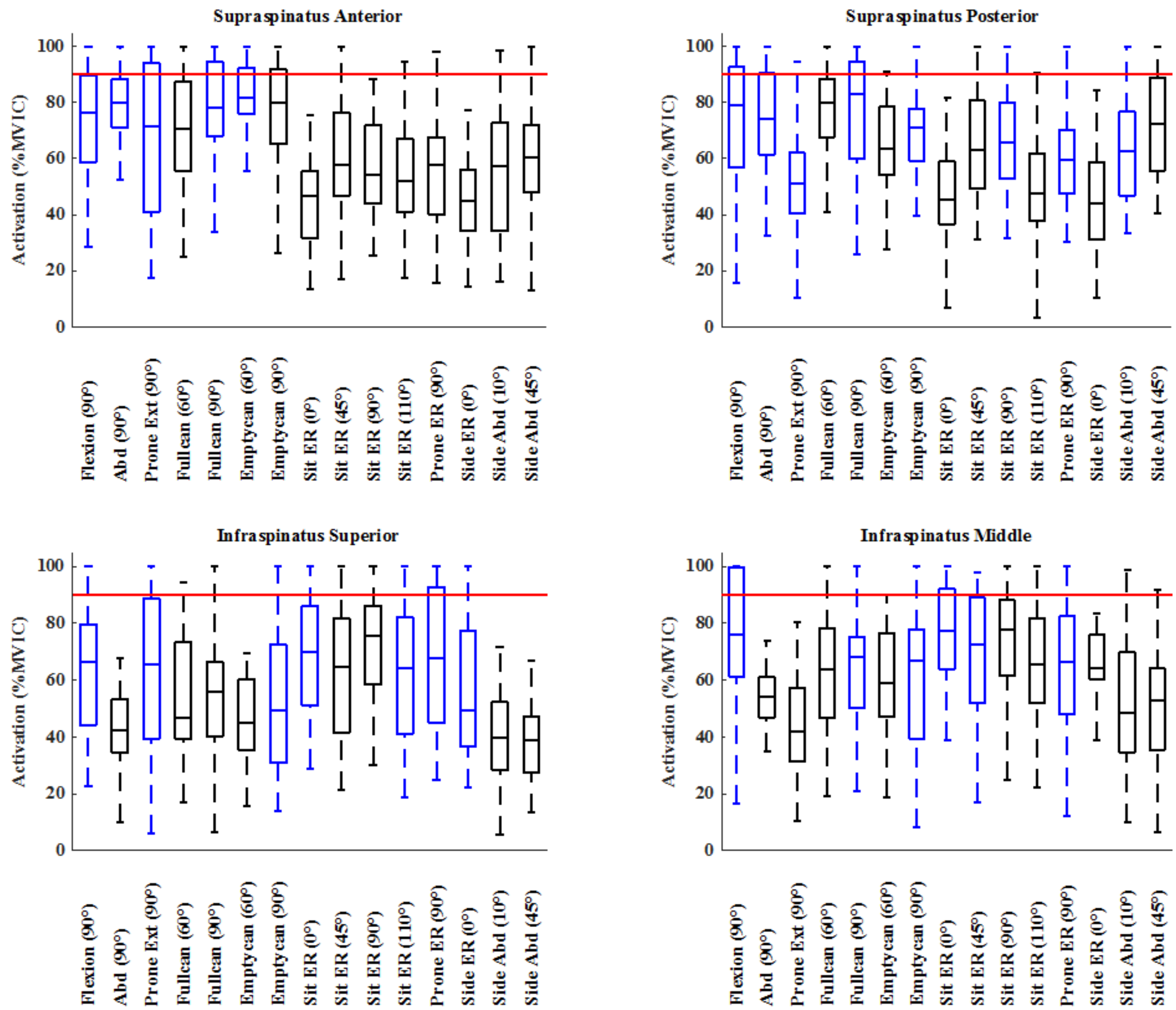

Supraspinatus Anterior
Supraspinatus Posterior
Infraspinatus Superior
Infraspinatus Middle
Activation (%MVIC)
0
20
40
60
80
100
Flexion (90°)
Abd (90°)
Prone Ext (90°)
Fullcan (60°)
Fullcan (90°)
Emptycan (60°)
Emptycan (90°)
Sit ER (0°)
Sit ER (45°)
Sit ER (90°)
Sit ER (110°)
Prone ER (90°)
Side ER (0°)
Side Abd (10°)
Side Abd (45°)

Table 1: MVIC test characteristics

MVIC #	Test Name	Description
1	Flexion (90°)*	Seated, flexion in 90° is resisted
2	Abduction (90°)*	Seated, abduction in 90°is resisted
3	Prone Ext (90°)*	Prone lying, arm abducted 90°, externally rotated, palm up, and arm elevation is resisted
4	Fullcan (60°)	Seated, arm elevated 60° in scapular plane, thumb is up; resistance is applied downward on the arm
5	Fullcan (90°)*	Seated, arm elevated 90° in scapular plane, thumb up; resistance is applied downward on the arm
6	Emptycan (60°)	Seated, arm elevated 60° in scapular plane, thumb down; resistance is applied downward on the arm
7	Emptycan (90°)*	Seated, arm elevated 90° in scapular plane, thumb down; resistance is applied downward on the arm
8	Sit ER (0°)*	Seated, arm beside the body, elbow flexed 90°, external rotation is resisted
9	Sit ER (45°)	Seated, arm in 45°abduction, elbow flexed 90°, external rotation is resisted
10	Sit ER (90°)	Seated, arm in 90°abduction, elbow flexed 90°, external rotation is resisted
11	Sit ER (110°)	Seated, arm in 90°abduction, elbow flexed 90°, external rotation is resisted
12	Prone ER (90°)	Prone lying, arm abducted 90°, palm facing the floor; external rotation is resisted
13	Side ER (0°)	Left side lying, arm close to the body, elbow flexed 90, external rotation is resisted
14	Side Abduction (10°)*	Left side lying, arm abducted 10°, resistance applied downward on the right arm
15	Side Abduction (45°)	Left side lying, arm abducted 45°, resistance applied downward on the right

ER = external rotation, Ext = extension

**= previously reported MVIC test positions: Boettcher et al. (2008), Brookham et al. (2010), Alenabi et al. (2013), Dal Maso et al.(2016)*

Table 2: The total number and percentage of total participants who could generate maximum activation of the interested muscle during the 15 different MVIC test positions. The total MVICs rows indicates the number of MVICs required for all participants to obtain a maximal activation of the muscle of interest. The bolded numbers are those representing the MVIC with the highest frequency of participants attaining a maximum activation of the muscle of interest.

	Supraspinatus Anterior	Supraspinatus Posterior	Infraspinatus Middle	Infraspinatus Superior
Flexion (90°)	4 (13%)	**5 (16%)**	**7 (23%)**	2 (6%)
Abduction (90°)	3 (10%)	3 (10%)		1 (3%)
Prone Ext (90°)	5 (16%)	1 (3%)	1 (3%)	4 (13%)
Fullcan (60°)	3 (10%)	**5 (16%)**	1 (3%)	
Fullcan (90°)	3 (10%)	4 (13%)	2 (6%)	1 (3%)
Emptycan (60°)	**6 (19%)**			
Emptycan (90°)	5 (16%)	3 (10%)	3 (10%)	3 (10%)
Sit ER (0°)			6 (19%)	4 (13%)
Sit ER (45°)	1 (3%)	2 (6%)		1 (3%)
Sit ER (90°)			2 (6%)	2 (6%)
Sit ER (110°)		1 (3%)	3 (10%)	3 (10%)
Prone ER (90°)		2 (6%)	4 (13%)	**6 (19%)**
Side ER (0°)		1 (3%)	2 (6%)	3 (10%)
Side Abduction (10°)	1 (3%)	3 (10%)		
Side Abduction (45°)		1 (3%)		1 (3%)
Total MVICs	9	12	10	12

Table 3: Optimal combinations of MVICs that elicit 90% activation in the muscle combinations explored in 90% (A) or 80% (B) of participants. An x indicates the MVICs included in each combination presented and the total MVICs corresponds to the number of MVICs in the combination. Infra = Infraspinatus, Supra = Supraspinatus

A: **in >90% of study population**

	Infra & Supra	Infra (2 regions)	Supra (2 regions)	Infra Superior	Infra Middle	Supra Anterior	Supra Posterior
Flexion (90°)	×	×		×	×	×	×
Abduction (90°)	×		×			×	×
Prone Ext (90°)	×	×	×	×		×	×
Fullcan (60°)			×				
Fullcan (90°)	×		×		×	×	×
Emptycan (60°)	×		×			×	
Emptycan (90°)		×	×	×	×		×
Sit ER (0°)	×	×		×	×		
Sit ER (45°)					×		
Sit ER (90°)	×			×			
Sit ER (110°)		×	×				×
Prone ER (90°)	×	×		×	×		×
Side ER (0°)	×	×		×			
Side Abduction (10°)							
Side Abduction (45°)	×		×				×
Total MVICs	10	7	8	7	6	5	8

B: in >80% of study population

	Infra & Supra	Infra (2 regions)	Supra (2 regions)	Infra Superior	Infra Middle	Supra Anterior	Supra Posterior
Flexion (90°)	×	×	×		×	×	
Abduction (90°)			×	×			×
Prone Ext (90°)	×	×	×	×		×	
Fullcan (60°)	×		×				×
Fullcan (90°)	×		×		×		
Emptycan (60°)						×	
Emptycan (90°)	×	×		×	×		×
Sit ER (0°)	×	×		×	×		
Sit ER (45°)							
Sit ER (90°)							
Sit ER (110°)							×
Prone ER (90°)	×	×		×	×		
Side ER (0°)		×		×			
Side Abduction (10°)							
Side Abduction (45°)	×		×			×	×
Total MVICs	8	6	6	6	5	4	5

Talia Alenabi (MD, PhD) is a Post-Doctoral Fellow at the University of Waterloo, Canada. She has been a sports medicine clinician, working with elite athletes for many years. She received her MD from Tehran University of Medical Sciences, Master of science in Sports and Exercise Medicine from the Chinese University of Hong Kong and PhD in Kinesiology/biomechanics form the University of Montreal. Her research interests include rotator cuff pathologies, electromyography of shoulder musculature, prevention of shoulder injuries and disorders, work and sports related shoulder problems and rehabilitation of shoulder injuries. She has been a previous executive board member at the International Federation of Sports Medicine (2010-2014), current vice president of the Asian Federation of Sports Medicine, and a member of the Canadian Society of Biomechanics.

Rachel Whittaker received her MSc degree (2017) from the University of Waterloo, in the Digital Industrial Ergonomics and Shoulder Evaluation Lab and her HBSc Kin degree (2014) from McMaster University. Her research interests include shoulder biomechanics, ergonomics, electromyography, muscle fatigue and upper extremity kinematics.

Soo Kim (PhD) is an Associate Professor at the School of Rehabilitation Science, University of Saskatchewan (U of S), Canada. She received her B.Sc. degree in Physical Therapy from the University of Toronto. During her years as a clinician, she developed expertise in sports medicine and a special interest in shoulder rehabilitation. In 2008, she earned her PhD from the University of Toronto based on research investigating the detailed muscle and tendon architecture of the supraspinatus muscle and developed an ultrasound imaging protocol to quantify architectural changes in patients with rotator cuff pathology. She has an active research program investigating muscle architecture and function in response to pathology, surgery, radiation and rehabilitation. She is a member of the Bone and Joint Imaging Research Group (BIG).

Clark Dickerson (PhD) is a Professor of Kinesiology and Canada Research Chair of Shoulder Mechanics at the University of Waterloo, where he has been since 2005. His research focuses on human musculoskeletal biomechanics, particularly of the shoulder. He earned his BSME at Alfred University, his MS in bioengineering from Clemson University, and his PhD in biomedical engineering from the University of Michigan. His current research interests include the development and experimental evaluation of computational shoulder models, digital ergonomics, age and disease-related shoulder disorder prevention, assessment, and mitigation, in vitro tissue mechanical characterization, and comparative and developmental shoulder mechanics. He is the current past-president of the Canadian Society for Biomechanics and a member of the Board of the International Shoulder Group.