



# The contribution of the supraspinatus muscle at sub-maximal contractions

David Phillips<sup>a,\*</sup>, Peter Kosek<sup>b</sup>, Andrew Karduna<sup>c</sup>

<sup>a</sup> Department of Exercise Science and Physical Education, Montclair State University, 1 Normal Avenue, Montclair, NJ 07043, United States

<sup>b</sup> Oregon Neurosurgery, 3355 Riverbend Drive, Suite 400, Springfield, OR 97477, United States

<sup>c</sup> Department of Human Physiology, University of Oregon, 1240, Eugene, OR 97403, United States

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## ABSTRACT

During maximum effort, the supraspinatus muscle contributes approximately 50% of the torque need to elevate the arm, but this has not been examined at sub-maximal levels. The purpose of this study was to determine the contribution of the supraspinatus muscle to shoulder elevation at sub-maximal levels. Seven healthy subjects (four males, three females) performed isometric ramp contractions at the shoulder. Middle deltoid electromyography (EMG) and force applied at the wrist were collected before and after a suprascapular nerve block. For the same level of deltoid EMG, less external force will be measured after the nerve block as the supraspinatus muscle no longer contributes. The difference between the EMG/force curve was the contribution of the supraspinatus muscle. The supraspinatus contributed 40%, 95% CI [32%–48%], to shoulder elevation. The effect of angle ( $p = .67$ ) and % maximal voluntary contraction ( $p = .13$ ) on supraspinatus contribution were not significant. The maximum is slightly less than reported in a previous suprascapular nerve block study using maximal contractions. The results from this study can be used to assess supraspinatus contribution in rotator cuff tears, after rehabilitation interventions, and as a restraint in computation modelling.

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## 1. Introduction

Shoulder complaints have a prevalence between 7% and 49% (Brox, 2003) and pain often persists beyond a year after the initial insult (Chard et al., 1991). The supraspinatus muscle unit is a common site of injury for these shoulder complaints (Fehring et al., 2008; Milgrom et al., 1995). In order to prevent and treat supraspinatus injuries effectively, the mechanical behavior of this muscle needs to be understood. However, this is difficult due to the large number of muscles crossing the glenohumeral joint and changing muscle moment arms throughout the range of motion (Ackland et al., 2008). This makes inverse dynamics calculations statistically indeterminate and the computation of individual muscle forces challenging.

Functionally, the supraspinatus helps elevate the arm and counteracts the superiorly directed forces generated by the deltoid and keeps the joint reaction force directed into the glenoid cavity (de Witte et al., 2014; Yanagawa et al., 2008). Paralyzing the supraspinatus with a suprascapular nerve block results in an

approximate drop in maximal torque of 50% (Howell et al., 1986). A suprascapular nerve block also results in superior migration of the humeral head (Juan et al., 2013) and a compensatory increase in deltoid electromyographic (EMG) amplitude (McCully et al., 2007). As there is a direct relationship between EMG amplitude and force generated by a muscle (Kuriki et al., 2012), the magnitude of the force that the deltoid applies on the humerus increases under these conditions. These studies provide evidence that the supraspinatus assists with both humeral elevation and glenohumeral stabilization. A final note on supraspinatus function is that it is reported in anatomy texts as an initiator of shoulder abduction (Marieb and Hoehn, 2016; Moore et al., 2014). However, this is not supported by the evidence, as the supraspinatus is activated before movement begins, but not before than the deltoid (Reed et al., 2013).

While the torque contribution of the supraspinatus at maximum contraction is estimated at 50% (Howell et al., 1986), some models indicate that the deltoid provides the majority of the elevation torque (Wuelker et al., 1994; Yanagawa et al., 2008). Based on the shoulder mechanics and muscle anatomy, it would be expected that the deltoid contributes more than the supraspinatus to shoulder elevation, particularly at higher elevation angles. This is because the cross-sectional area of the deltoid is much greater than

\* Corresponding author.

E-mail addresses: [phillipsdav@montclair.edu](mailto:phillipsdav@montclair.edu) (D. Phillips), [PKosek@peacehealth.org](mailto:PKosek@peacehealth.org) (P. Kosek), [karduna@uoregon.edu](mailto:karduna@uoregon.edu) (A. Karduna).

the supraspinatus (Aluisio et al., 2003; Bouaicha et al., 2016) and the deltoid moment arm increases with humeral elevation, while the supraspinatus moment arm decreases (Ackland et al., 2008).

The maximal torque producing capacity of the arm is only reduced by 50% with either a suprascapular or axillary nerve block (Howell et al., 1986). Since these nerves innervate the supraspinatus and deltoid respectively, their relative contribution to shoulder elevation torque is approximately 50% during a maximal isokinetic contraction. A cadaveric study supports this finding, with a doubling of deltoid force needed to initiate shoulder abduction (Thompson et al., 1996). In contrast, a computation model indicates that the deltoid is the primary mover while the supraspinatus seemed to apply most of its force to stabilize the humeral head into the glenoid cavity (Yanagawa et al., 2008). This model also has supporting cadaveric evidence where researchers concluded that the supraspinatus functions more to compress the humeral head into the glenoid than generate an elevation torque (Wuelker et al., 1994).

EMG studies have demonstrated differing behavior of the supraspinatus. One observation indicates that when external load is increased, deltoid activation increases, while supraspinatus activation remains constant (de Witte et al., 2014). However, during scapular plane abduction at different maximal voluntary contraction levels, loads and speeds, all shoulder muscles increased their activity, including the supraspinatus (Alpert et al., 2000; Reed et al., 2016). Increased activation of a muscle indicates that it is contracting with more force, but the amount of force cannot be determined from EMG amplitude alone. Further examinations of the supraspinatus are necessary, as our current understanding of the supraspinatus function is not consistent in the literature. Quantifying the non-pathological contribution of the supraspinatus may be useful in early identification of shoulder dysfunction and improve treatment plans.

An approach to calculate supraspinatus contribution to glenohumeral abduction is to utilize the compensatory deltoid EMG, seen after a suprascapular nerve block, and externally measured force to indirectly calculate the torque contribution of the supraspinatus muscle at submaximal levels. The purpose of the study is to determine the contribution of the supraspinatus muscle to humeral elevation during sub-maximal isometric ramp contractions at three angles of humeral elevation. We hypothesize that the supraspinatus contribution will decrease with increasing humeral elevation and %MVC.

## 2. Methods

### 2.1. Subjects

Nine subjects initially enrolled in the experiment and data were utilized from seven subjects between 18 and 35 years of age (4 males, 3 females, age:  $24.9 \pm 3.6$  years, mass:  $76.5 \pm 11.0$  kg, height:  $178 \pm 12.2$  cm, all right hand dominant). Exclusion criteria included: (1) previous shoulder or neck injuries, (2) current shoulder or neck pain, (3) humeral elevation ROM less than  $135^\circ$ , (4) previous syncope due to needle insertion, (5) known allergic reaction to anesthetic, (6) BMI greater than 30 or (7) pregnancy. Subjects were briefed on the purpose and the experimental procedure prior to the start of the experiment and provided informed consent. The experiment received ethical clearance from the Internal Review Board at the University of Oregon.

### 2.2. Experimental set up

The force acting on the forearm immediately proximal to the radius styloid process was recorded using a uni-axial load cell

(Lebow Products, Troy, MI. Model 3397-50). Force data were sampled at 2000 Hz with custom LabVIEW software (LabVIEW v12.0, National Instruments, Austin, Tx). The load cell was offset at each angle to read 0 N. The forearm was flush with the surface of the load cell and secured with custom non-elastic lifting Velcro™ straps.

Surface EMG signals from the anterior deltoid, middle deltoid and posterior deltoid of both arms were recorded with oval, bipolar Ag/AgCl, conductive solid gel electrode pairs (Bio Protech Inc, Wonju, Korea). Only the middle deltoid EMG was used in this study. The skin surface was cleaned with rubbing alcohol. Electrodes were placed on the middle deltoid electrodes 2 cm below the acromion process. The electrodes were positioned along the muscle fiber direction with an inter-electrode distance of 2 cm. The ground electrode was fixed over the right lateral malleolus. The deltoid EMG was collected with a Myopac Jr unit (Run Technologies, Mission Viejo, CA) and sampled at 2000 Hz. This unit provided signal amplification (gain = 1000), band pass filtering (10–1000 Hz) and CMMR of 110 dB.

### 2.3. Maximal voluntary contractions

Prior to the ramp contraction protocol, a series of 5 s maximal voluntary contractions (MVCs) were taken. Subjects were verbally instructed on how to perform a MVC and a practice attempt was given prior to recording. To generate maximum deltoid muscle activity, a unique position was used for the middle deltoid MVC (Boettcher et al., 2008). The subject performed resisted abduction with the arm abducted  $90^\circ$  and elbow flexed to  $90^\circ$  with the forearm vertical.

Additional MVCs were taken for external rotation and abduction in the scapula plane ( $30^\circ$  anterior to the coronal plane) for three humeral elevation angles:  $30^\circ$ ,  $60^\circ$  and  $90^\circ$ . The subjects stood so that their arm was abducted in the scapula plane and that the styloid process of the ulna was placed on the far edge of the load cell surface in the 'thumbs up' position and the elbow fully extended. The angle and height of the load cell were adjusted to the appropriate angle being tested and then zeroed. For external rotation, the shoulder was slightly abducted and the elbow flexed to  $90^\circ$ . A towel was placed under the arm to help prevent the subject from abducting their arm during the MVC. If the arm did abduct, the towel would fall to the ground and the MVC was repeated. The height of the load cell and foot positions of the subjects was marked for each abduction angle and external rotation so the position can be replicated in the ramp contraction trials and when the protocol was repeated after the suprascapular nerve block.

Subjects were given two attempts for each MVC position with a two minutes rest between each attempt. If the MVC was performed incorrectly, feedback was given to the subject and a third MVC taken. The first 2.5 s and the last one second of force data were removed. The mean of the remaining 1.5 s was averaged and used as subject's MVC for force and EMG. For the middle deltoid MVC, the MVC that resulted in the highest EMG amplitude was used for EMG normalization. The MVC with the largest force for each humeral elevation angle was considered for further analysis and MVC force normalization. The mean of the two MVCs after the nerve block were used to determine the subject's post-block MVC.

### 2.4. Ramp contraction protocol

Following the collection of all MVCs, a ramp contraction protocol was performed. The ramp contractions were performed at a loading rate of 15 N/s up to 60% of the subject's MVC. The subjects performed three trials at each of the following angles of shoulder elevation in the scapula plane:  $30^\circ$ ,  $60^\circ$  and  $90^\circ$ . The subjects stood

with their feet in the foot positions marked for each during the MVC collection trials and the load cell at the marked heights (Fig. 1). The order that the angles were tested was block randomized. A total of nine ramp contractions, three at each angle were collected.

An LCD monitor presented visual feedback of force output that consisted of three lines. All lines were represented on a graph covering approximately half the monitor. Subject force output was represented with a dynamic red line across the width of the graph and the required loading rate was presented by two limit green lines across the width of the graph. The limit lines were separated by a space representing 10 N. The limit lines would move up the graph at rate of 15 N/s (Phillips and Karduna, 2017) at the onset of the trial from a point representing –40 N. Sixty percent force MVC for the angle under testing was represented with a static white line across the width of the graph. The display of the feedback graph was reset after each trial.

Subjects were instructed to completely relax the arm prior to the start of the trial, but to gradually increase the force applied on the load cell to keep the dynamic force line between the two moving limit lines. Subjects were given practice attempts until they could successfully keep the dynamic force line between the limit lines for the duration of the trial. If the dynamic force line dramatically left the boundaries set by the limit lines, the trial was repeated. Each trial was separated by a one minute rest period and a two minutes rest period was given between elevation angle changes. Subjects were encouraged to keep their elbow straight throughout the trial and abduct so their arm would elevate in the scapula plane, if it were able to move.

Following the collection of all ramp contractions, a suprascapular nerve block was performed. External rotation MVCs were taken at five minutes, ten minutes and then every two minutes. Once two external rotation MVCs were recorded below 50% preblock external rotation MVC, the protocol would be repeated.

### 2.5. Suprascapular nerve block procedure

A suprascapular nerve block was performed by a single board certified anesthesiologist. The subject was seated for the procedure

with the head flex slightly to the contralateral side. Ultrasound imaging was used to visualize the scapula notch where the suprascapular nerve travels. The ultrasound gel served as a conductive medium and surface preparation. A 3.5 in. 23 ga quince needle was advanced toward the scapular notch in a medial to lateral direction using an in plane technique. The advancing needle was observed on the ultrasound until it reached the scapula notch. At this point the lidocaine and epinephrine (1.5%, 1:200,000, 5 ml) was injected. The needle was removed and the subject was allowed to remain seated for 5 min.

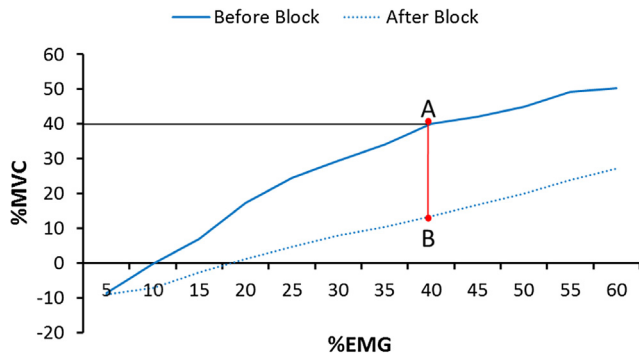
### 2.6. Data analysis

Electromyography amplitude was smoothed using a running 300 ms RMS window. EMG data were normalized to the highest EMG recorded for position targeting the anterior, middle and posterior deltoid. Force data were normalized to the peak force at each angle. To quantify the effect of the suprascapular nerve block on the middle deltoid EMG amplitude and %MVC, the program searched for EMG amplitude between 10% and 55%, in 5% increments, and extracted the associated %MVC force level. The mean of the three trials for each humeral elevation angle, before and after the suprascapular nerve block, was calculated.

The program searched the ramp force data before the nerve block for the first instance that the subject reached one of the pre-determined force level values between 10% and 55% MVC, in 5% increments. The middle deltoid EMG amplitude for each level was extracted and the mean of three trials was calculated. The EMG value for each force level was then used to search the middle deltoid EMG amplitude data in the ramp trials after the nerve block, and extracted the corresponding force level. The difference between the force level at the same middle EMG amplitude represented the contribution of the suprascapular muscle (Fig. 2). This value was then divided by the sum of pre-block force level (10%–55%) and baseline force on the load cell due to the weight of the arm to determine the percent contribution of the suprascapular at each force level. Baseline force was calculated with anthropometric measurements (Winter, 2005) and normalized to MVC. This was repeated for each humeral elevation angle: 30°, 60° and 90°.



**Fig. 1.** Experimental setup. (1) Monitor giving feedback on loading rate, (2) surface electrodes on anterior, middle and posterior deltoid, (3) load cell, (4) markings on floor for positioning.



**Fig. 2.** A schematic plot to demonstrating the calculation of supraspinatus contribution. The difference between A and B for the same EMG amplitude, measured at 40% MVC before the block, represents the contribution of the supraspinatus muscle to elevation torque. The difference was then divided by the sum of A and normalized baseline resting force at the load cell (calculated from anthropometry). Analysis is performed only when both lines are greater than 0% MVC.

$$\% \text{ supraspinatus} = \frac{A - B}{A + C} \times 100$$

where A is pre-block force level (10% to 55%), B is the post block force for the same deltoid EMG amplitude and C is the baseline force of the arm. The magnitude of C was inconsistent when measured directly from the load cell. This was because subjects either completely relaxed causing the elbow to flex, or did not relax completely at the shoulder. C was therefore calculated using anthropometric equations (Winter, 2005). For this same reason, the calculation was only performed when forces measured at the load cell were positive for both curves. All forces were normalized to MVC values.

### 2.7. Statistical analysis

Statistical analysis was performed using SPSS version 22.0 (SPSS Inc., Chicago, IL). To quantify the effects of the suprascapular nerve block on MVC forces, a paired *t* test was conducted on each MVC position: external rotation and maximal abduction force at each elevation angle (30°, 60° and 90°).

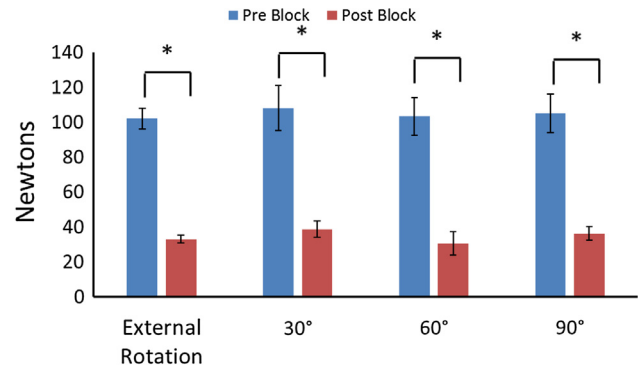
A 2-way repeated ANOVA was conducted to determine the effect of %MVC force level (10%:55% in 5% increments) and humeral elevation angle (30°, 60° and 90°) on the percent contribution of the supraspinatus during isometric ramp contractions. 95% confidence intervals are reported for main effects or total data in the absence of statistical significance.

## 3. Results

Two subjects were removed from the analysis, thus reducing the total subjects analyzed to seven as reported in subject demographics. One subject was removed because he was unable to activate his deltoid above 20% MVC after the nerve block. The second subject was removed based on a clinical observation of an unusual scapula position by the doctor and not completing the MVC procedure correctly after the nerve block.

### 3.1. Maximal voluntary contractions

Subjects demonstrated a significant reduction in the blocked condition for all MVCs. For external rotation, 30° elevation, 60° elevation and 90° elevation there was a 68%, 64%, 71% and 66% reduction respectively ( $p \leq .001$  for all tests) (Fig. 3).



**Fig. 3.** Change in maximal voluntary measured force after the suprascapular nerve block.

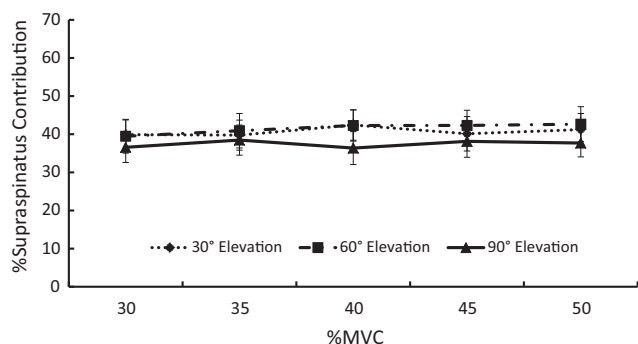
### 3.2. Supraspinatus contribution to abduction in the scapular plane

A positive force value was present for all subjects in the non-blocked and blocked conditions from 30% to 50% MVC. The interaction between humeral elevation angle and load was not significant,  $p = .23$ . The main effect of angle ( $p = .67$ ) and load ( $p = .13$ ) was not significant (Fig. 4). The supraspinatus contributes 40%, 95% CI [32%–48%], when data are collapsed across angles and loads.

## 4. Discussion

The purpose of the study was to determine the contribution of the supraspinatus muscle to external force production. We hypothesized that the supraspinatus contribution will decrease with increasing humeral elevation and %MVC. The suprascapular nerve block resulted in a significant reduction in external rotation MVC and at each angle of abduction in the scapular plane. A similar drop in MVC was seen at each humeral elevation angle. This resulted in a significant decrease in MVC for a given a specific level of deltoid EMG amplitude (%MVC) after the suprascapular nerve block. The criteria for an effective block was a minimum drop of 50% in external rotation. This indicates that all subjects experience an effective suprascapular nerve block. The drop in MVC shoulder elevation torque is greater than was reported in a previous nerve block study (Howell et al., 1986) but the external rotation reduction was slightly less (McCully et al., 2007).

The data do not support our hypothesis – the contribution of the supraspinatus did not change significantly for either angle or %MVC. These results indicate that the supraspinatus contributes between 32% and 48% (95% confidence interval) of the torque needed to elevate the shoulder. This amount is still more than is



**Fig. 4.** Percent contribution of the supraspinatus to the %MVC at each. Error bars are standard error of the mean.

predicted by a computational and cadaveric model (Wuelker et al., 1994; Yanagawa et al., 2008). These models predicted that the deltoid is the prime mover with the supraspinatus contributing mainly to compressive forces at the glenohumeral joint. These results also do not perfectly agree with Howell et al., (1986) where the supraspinatus contributes 50% at maximum contraction. However, Howell et al., (1986) used a maximal isokinetic contraction while we used sub-maximal isometric ramp contractions. This could account for the potential differences. Our result is also consistent with the cross-sectional area of the two muscles. The deltoid is substantially larger than the supraspinatus and capable of producing more force (Aluisio et al., 2003; Bouaicha et al., 2016).

We did not find any effect of elevation angle in the present study. The deltoid has a larger moment arm at higher elevation than the supraspinatus. But the deltoid's moment arm will decrease while the supraspinatus' will increase with decreasing elevation (Ackland et al., 2008). This study lacks the statistical power to detect if a difference is present. A post hoc power analysis indicated a small angle effect size of 0.26 which is much smaller than expected. A sample of 25 would be needed to achieve a power of 0.8. Even though this study lacks the power to detect a difference, this technique would be valuable to researchers investigating the role of the supraspinatus in the future.

It is not clear how much the supraspinatus should contribute to shoulder elevation. Quantifying non-pathological mechanical contribution of the supraspinatus may be useful in diagnosing shoulder dysfunction and improve treatment plans. Current supraspinatus rehabilitation focuses on reducing the activation of surrounding musculature to isolate the supraspinatus and reduce superiorly directed forces at the glenohumeral joint (Boettcher et al., 2009; Reinold et al., 2007; Yasojima et al., 2008). Basing rehabilitative exercises solely on activation patterns may not optimize supraspinatus behavior, prevent injury or promote recovery.

This study has a number of limitations. Subjects in this study were young and asymptomatic with no history of upper extremity injury or pathology. The assumption is that the supraspinatus is functioning normally. The results can only be applied to this population. The suprascapular nerve block will paralyze both the supraspinatus and infraspinatus muscles. The infraspinatus may contribute a small proportion of the elevation torque.

In calculating the supraspinatus contribution, only middle deltoid EMG amplitude was used. EMG data from the anterior and middle deltoid, also collected in this study, can be incorporated into computational modelling to determine the contribution of the supraspinatus. Modelling results can then be compared to the results of this study. The method of calculation was not able to determine supraspinatus contribution for 0%–29% MVC. A positive force (upward directions) on the load cell was needed to complete the calculation. This was because subjects that completely relaxed prior to the start of each trial bent their elbow and other subjects did not completely relax so that not all the weight of the arm was measured by the load cell. It is for the same reason that baseline force was calculate from anthropometry. Lastly, isometric ramp contractions were used to establish the MVC and EMG curve. Ramp isometric contractions may not represent the concentric and eccentric functioning at the shoulder.

### Conflict of interest statement

The authors have no conflicts of interest to disclose.

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