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RESEARCH ARTICLE

Excitability of the infraspinatus, but not the middle deltoid, is affected by shoulder elevation angle

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Abstract Although both the rotator cuff and deltoid muscle serve as shoulder abductors, they play different roles in shoulder movement. While the deltoid is a primary abductor, the rotator cuff is a stabilizer. They have different anatomic structures for force production and demonstrate different neuromuscular control at different shoulder angles, as measured by electromyographic activity. Corticospinal excitability may be associated with different neuromuscular control of the deltoid and rotator cuff at different angles. The purpose of this study was to investigate how shoulder joint position influences the corticospinal excitability of the deltoid and rotator cuff muscles. Transcranial magnetic stimulation was used to measure the corticospinal excitability of the middle deltoid and infraspinatus at 0° and 90° of arm elevation. Three parameters, a plateau value, exponential parameter, and threshold, were calculated from the input–output curve of the corticospinal pathway. The plateau value of the infraspinatus was significantly higher at 90° of arm elevation, while there is no difference in the excitability in the middle deltoid between elevation angles. The plateau value of the middle deltoid at 90° was 5 % lower than that at 0°, but the plateau value of infraspinatus at 90° was 55 % higher than that at 0°. This suggests that the modulation of excitability varies with shoulder angle and reveals different neurological mechanism for the roles of the deltoid and rotator cuff.

Keywords Corticospinal excitability · Rotator cuff · Deltoid · Shoulder

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Introduction

The human shoulder complex sacrifices stability in exchange for a large range of motion necessary for reaching and hand manipulation at different positions. Due to the inherent lack of stability provided by the bony, ligamentous, and capsular structures, dynamic control of the muscles plays an important role in stabilizing the shoulder during motion (Donatelli 2004; Myers and Lephart 2000). The rotator cuff muscles, including the supraspinatus, infraspinatus, teres minor, and subscapularis, serve as the chief stabilizers of the shoulder joint, while the deltoid provides most of the torque necessary for motion (Kronberg et al. 1990; Poppen and Walker 1978; Yamaguchi et al. 2000).

Although both muscle groups contribute to arm elevation, cadaver and computer models show that the deltoid produces greater force and torques at higher elevation angles, but the rotator cuff provides a relatively consistent force throughout the range of motion (Yanagawa et al. 2008; Payne et al. 1997). The relatively constant force of the rotator cuff pulls the humeral head into the glenoid fossa and helps to stabilize the glenohumeral joint (Lee et al. 2000). Imbalance between the forces of the rotator cuff and deltoid may lead to injury and pain (Michener et al. 2003).

Dissimilar patterns of force production result from different anatomic structures and neuromuscular control. The efficiency of muscles at varying joint angles is determined by the moment arms of these muscles. The rotator cuff muscles maintain a constant moment arm throughout the range of motion, which provides a biomechanical advantage for stability (Otis et al. 1994; Liu et al. 1997). The deltoid has a shorter moment arm, but as the shoulder elevates to higher angles, the moment arm of the deltoid increases (Otis et al. 1994; Liu et al. 1997).

Electromyographic (EMG) activity of the rotator cuff and deltoid also demonstrates different neuromuscular control of shoulder movement between the two muscle groups. During arm elevation, the rotator cuff muscles are initially activated above 20 % of maximum voluntary contraction (MVC) and the activity is fairly consistent throughout elevation (Alpert et al. 2000; Kronberg et al. 1990). The peak of activity occurs between 30° and 60° of elevation and decreases slightly at higher elevation angles. The activity of the deltoid is lower at the initial range of motion and increases as the arm moves higher, with the peak around 90° of elevation (Alpert et al. 2000; Kronberg et al. 1990).

These differential patterns of control of the rotator cuff and deltoid, revealed by EMG, may be modulated by corticospinal tracts. The descending commands from primary motor cortex contain the signals necessary for joint movement and individual muscle force production (Kakei et al. 1999; Gritsenko et al. 2011). The spinal cord may also play an important role in coordination of motor patterns (Bizzi et al. 2000). Transcranial magnetic stimulation (TMS) has been used to investigate corticospinal excitability during different tasks. The excitability would be regulated according to different tasks and synergy patterns (Devanne et al. 2002; Ginanneschi et al. 2005; Lemon et al. 1995). For example, while the position of the shoulder influences the cortical excitability of the abductor digiti minimi, it does not affect the excitability of the first dorsal interosseous, possibly due to different muscle functions (Dominici et al. 2005; Ginanneschi et al. 2005). Due to the different roles played by the rotator cuff and deltoid in shoulder movement, the excitability of these muscles may be influenced by shoulder angles in different ways.

The purpose of the study was to investigate how shoulder elevation angles influence the corticospinal excitability of the deltoid and rotator cuff muscles. Because the middle deltoid is the primary abductor and the infraspinatus is the only rotator cuff muscle accessible with superficial EMG electrodes, we chose to assess these two muscles in the present study. In addition, since the middle deltoid contributes more in the middle range of motion, the infraspinatus maintains fairly constant activation throughout the range. We therefore hypothesized that the corticospinal excitability of the middle deltoid at 90° of arm elevation would be higher than that at 0° and that there would be no difference between the excitability of the infraspinatus between 0° and 90° of arm elevation. We also hypothesized that the change in excitability of the deltoid from 0° to 90° of arm elevation would be larger than that of infraspinatus.

Materials and methods

Subjects

Seventeen healthy subjects (seven males and ten females; 20.4 ± 1.7 year; 68 ± 15 kg; 1.7 ± 0.1 m) without neck or upper extremity neuromuscular or neurological disorders were recruited to participate in this study. All subjects signed an informed consent form before participation. The study was approved by the Office for Protection of Human Subjects at the University of Oregon.

EMG

Surface EMG of the infraspinatus and middle deltoid was recorded with superficial EMG electrodes (Bio Protech Inc, Wonju si, Gangwon-do, Korea). The electrodes were placed midway along the scapular spine just inferior to the posterior deltoid for the infraspinatus and the lateral aspect of the arm approximately 3 cm below the acromion for the middle deltoid (Cram et al. 1998). The Myopac Jr. (Run Technologies, Mission Viejo, CA) was used to collect raw EMG data. This unit provided signal amplification, band-pass filtering (10–1000 Hz), and a common mode rejection ratio of 110 dB. Output from the Myopac was linked to an analog to digital board, and data were collected at a frequency of 5000 Hz. Customized LabVIEW (National Instruments, Austin, TX) programs were used for data collection and analysis.

The EMG of the MVC of the middle deltoid and rotator cuff was measured separately at 0° and 90° of arm elevation for 7 s. The EMG of the middle deltoid MVC was measured by having the subject push up into arm elevation. The resistance was applied over the distal humerus, close to the elbow. The EMG of the infraspinatus MVC was measured by having the subject push into external rotation with 90° of elbow flexion. The resistance was over the distal forearm, close to the wrist (Alpert et al. 2000).

TMS

A stimulator (Magstim200, Magstim Co., Whitland, UK) with a 70-mm figure of eight stimulation coil was used to provide single-pulse stimulation. The coil was placed approximately 3.5 cm lateral to the vertex of cranium (Alexander 2007). It was moved to find the optimal spot for both the middle deltoid and infraspinatus, where the sum of the evoked response from the middle deltoid and infraspinatus was the largest. Once the optimal spot was found, the position of the coil was marked on a wig cap

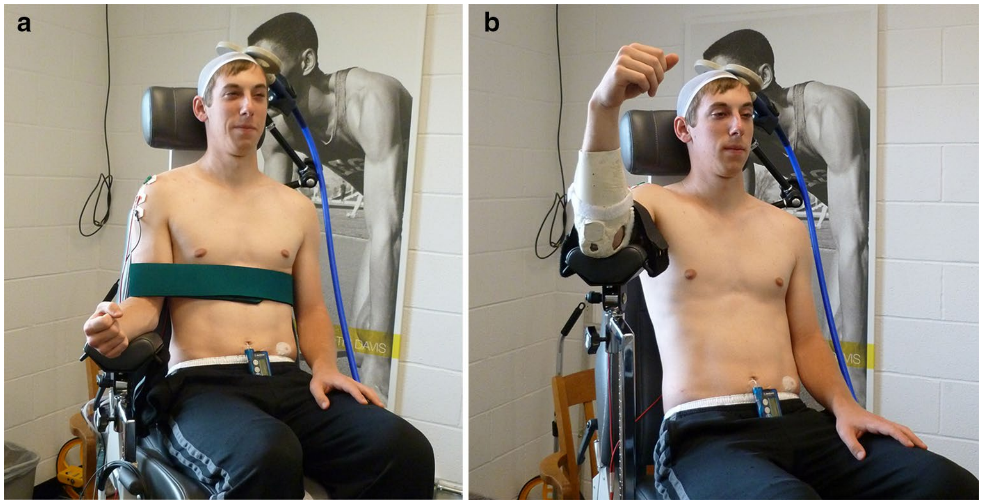

Fig. 1 During TMS test, the subject is seated with head support, the coil is held by a support arm, **a** the arm is at 0° of elevation, the elbow is supported at 90° of flexion, **b** the arm is supported at 90° of elevation, and the elbow is also supported at 90° of flexion with elbow splint

worn by the subject. A support arm was used to hold the coil at the same position throughout the testing protocol (Fig. 1). The stimulation was first decreased to the level where no response was found. Then, the stimulation intensity was increased in 5 % increments until the response saturated (i.e., where the response amplitude did not increase with increasing stimulation intensity). The stimulation interval was 10–15 s. Five stimuli were delivered at each stimulation intensity, as five stimuli have been demonstrated to be sufficient for reliable MEP amplitudes (Kamen 2004; Christie et al. 2007). While the stimulus was applied, the subject maintained an EMG amplitude of 10 % MVC of both the middle deltoid and infraspinatus (Griffin and Cafarelli 2007). Because the infraspinatus is an abductor and external rotator, the subject was instructed to perform an isometric contraction of arm elevation first to reach 10 % of deltoid MVC and then perform external rotation to reach 10 % of infraspinatus MVC. The root-mean-square of the EMG signal was displayed to provide real-time feedback.

Arm elevation angle

Corticospinal excitability of both muscles was measured at 0° and 90° of arm elevation in one visit and in the same experimental session. The order of testing (0° vs. 90°) was randomized. The same optimal spot was used for both angles. When the corticospinal excitability was measured at 0° of arm elevation, the arm was at the side with the forearm supported at 90° of elbow flexion. To examine the excitability at 90° of arm elevation, the arm was supported at 90° of arm elevation in the scapular plane with 90° of elbow flexion (Fig. 1).

Data processing and analysis

The peak-to-peak amplitude of the motor evoked potential (MEP) was measured. The background EMG amplitude before the artifact was subtracted from the MEP amplitude, and then, the MEP amplitude was averaged across the five trials at each intensity level. The curve of the relationship between stimulation intensity and the MEP amplitude was sigmoidal. The curve for each muscle from each individual subject was fit with the Boltzmann equation using a Levenberg–Marquardt algorithm (Devanne et al. 1997).

$$\mathrm{MEP}_{(s)} = \frac{\mathrm{MEPmax}}{1 + e^{m(S_{50}-s)}},$$

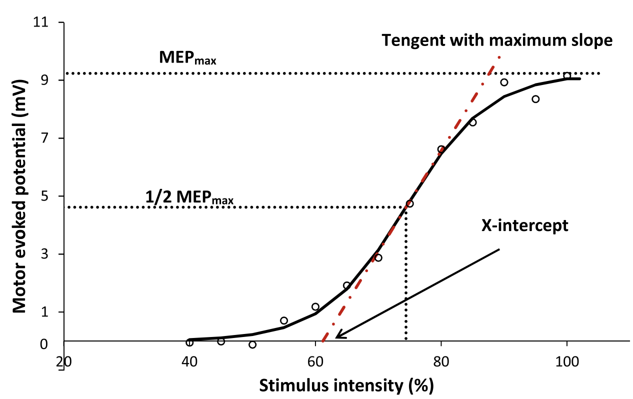

Fig. 2 The example of MEP data at different intensity fit with the Boltzmann equation. The peak slope of the function happens at S_{50} where the MEP is 50 % of estimated plateau (MEP_{max}). The threshold of the curve is the x-intercept of tangent at S_{50}

where $MEP_{(s)}$ is the amplitude of motor evoked potential, MEP_{max} is the estimated plateau of MEP amplitude, m is the exponential parameter of the equation determining the steepness of the curve, and S_{50} is the stimulus intensity where the MEP is 50 % of MEP_{max}. The peak slope of the curve occurs at S_{50} and is defined by the relationship: $\frac{m \times MEP_{max}}{4}$ (Carroll et al. 2001). The threshold of the curve is the x-intercept of the tangent to the function at S_{50}. The slope of this tangent is the maximal slope of the function (Carroll et al. 2001) (Fig. 2). Three parameters, MEP_{max}, m, and x-intercept threshold, were three dependent variables and were used to represent the corticospinal excitability for each individual subject, which provides more details of the excitability of the corticospinal tract than only applying the stimulation intensity at certain level of motor threshold (Devanne et al. 1997; Obata et al. 2009). The value of the x-intercept threshold is similar to the motor threshold (Ginanneschi et al. 2005) and represents the minimum stimulus intensity required to recruit the most excitable corticospinal motoneurons. The exponential parameter (m) decides the slope of the curve and indicates the recruitment increment of the corticospinal tract with the simulation increase. The MEP_{max}, which is the maximum response of the corticospinal neurons, represents the balance between the effects of excitatory and inhibitory neurons regulating the corticospinal tract (Devanne et al. 1997). The percentage change of the three parameters from 0° to 90° of arm elevation was calculated.

To examine the difference of MVC between angles, root-mean-square of MVC was calculated from the middle 2 s of the data. The root-mean-square of background EMG during the trial was also calculated from the window of 90 ms before the stimulus was applied.

Statistical analysis

A paired t test was used to assess the difference of the three parameters, MEP_{max}, m, and x-intercept threshold between 0° and 90° of arm elevation for each muscle. A paired t test was also used to examine the difference of the percentage changes from 0° to 90° of arm elevation between the middle deltoid and infraspinatus. For all analyses, the significant level was set at 0.05.

Results

All three parameters (MEP_{max}, m, and x-intercept threshold) for the middle deltoid were not significantly different between 0° and 90° of arm elevation ($p = 0.51$, $p = 0.1$, and $p = 0.34$, respectively). For the infraspinatus, MEP_{max} was significantly higher at 90° of arm elevation ($p = 0.01$), while there was no significant difference between angles for the exponential parameter and intercept ($p = 0.69$ and $p = 0.78$) (Fig. 3).

The percentage change of MEP_{max} from 0° to 90° of arm elevation was significantly different between the middle deltoid and infraspinatus. The MEP_{max} of the middle deltoid at 90° was 5 % lower than that at 0°, while infraspinatus at 90° was 55 % higher than that at 0° ($p = 0.01$). The percentage change of the exponential parameter and intercept was not significantly different ($p = 0.31$ and $p = 0.41$) (Table 1). Table 2 shows the root-mean-square of the background EMG with window of 90 ms before the stimulus and the EMG of MVC. Neither background EMG nor MVC was significantly different between angles.

Discussion

The middle deltoid and infraspinatus play different roles at the shoulder joint. While the infraspinatus serves as a stabilizer and has fairly constant activation during arm elevation, the middle deltoid is a primary mover and demonstrates more activity at the middle range of motion (Kronberg et al. 1990). However, the results of the present study show that the corticospinal excitability does not follow the EMG and force production patterns for these muscles. While there was no significant difference in excitability of the middle deltoid between angles, the MEP_{max} of the infraspinatus at 90° of elevation was significantly higher (55 %) than that at 0°.

Table 1 The comparison of the percentage changes from 0° to 90° of arm elevation between the middle deltoid and infraspinatus by using a paired t test

	Deltoid Mean (SD)	Infraspinatus Mean (SD)	p
MEP_{max} (%)	−4.9 (36.2)	56.3 (72.6)	0.01
Slope (%)	−6.1 (17.6)	−1.0 (13.6)	0.31
Threshold (%)	3.6 (13.9)	0.1 (14.2)	0.41

Table 2 Mean and standard deviation for root-mean-square of MVC of electromyography (EMG) and background EMG

Muscle	Angle	0°	90°	p
Deltoid	MVC	0.82 ± 0.59	0.62 ± 0.33	0.05
	Background EMG	0.09 ± 0.05	0.08 ± 0.04	0.27
Infraspinatus	MVC	0.44 ± 0.17	0.44 ± 0.26	0.96
	Background EMG	0.05 ± 0.01	0.05 ± 0.03	0.31

Background EMG is calculated from the window of 90 ms before the stimulus is applied

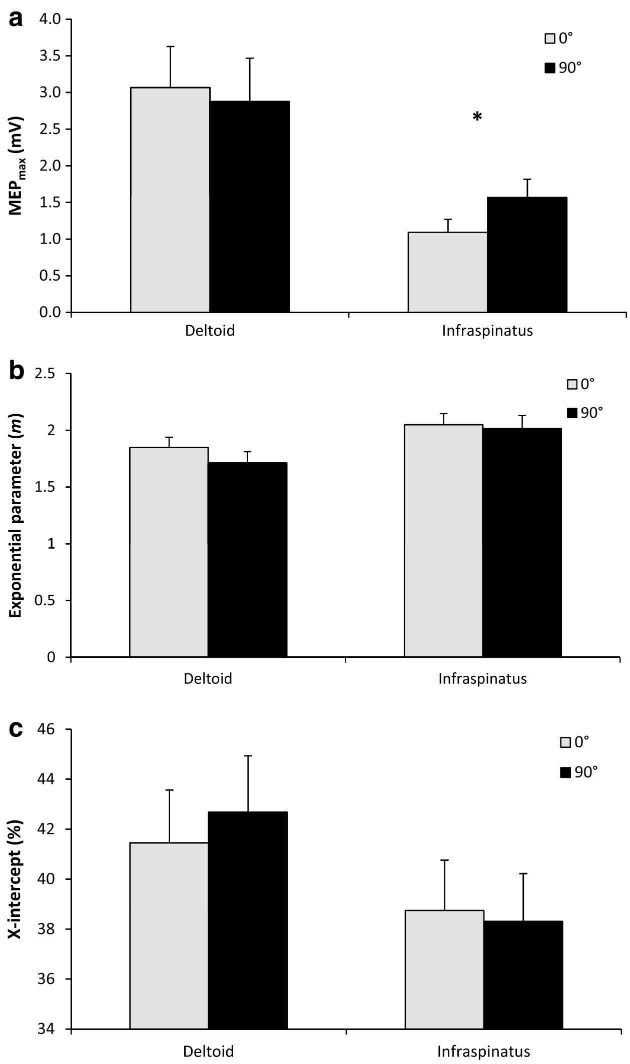

Fig. 3 Comparison of **a** plateau value (MEP_{max}), **b** exponential parameter (m), and, **c** x-intercept between humeral elevation angles.*$p < 0.05$

TMS has been widely used to study corticospinal excitability. The motor threshold may represent conductivity of ion channels on the membrane of corticospinal neurons and interneurons involving in the corticospinal tract, which is related to modulation of action potential generation (Ziemann et al. 1996). The exponential parameter (m) of the curve is related to the size of the subliminal fringe of corticospinal motor neurons and also the synchronization of motor unit discharge (Devanne et al. 1997). For both the middle deltoid and infraspinatus, the results of the present study demonstrated that elevation angle did not change the membrane excitability and the size of subliminal fringe. However, the MEP_{max} of infraspinatus was affected by elevation angle. The difference of MEP_{max} between angles provides evidence for different recruitment circuits at different angles (Ginanneschi et al. 2005).

In the present study, to represent the change of the excitability in the dynamic movement, we chose to measure the corticospinal excitability of the middle deltoid and infraspinatus under static conditions because the change of the muscle activation during movement may bias the change of the excitability. With control of the background activities at static condition, however, the patterns of motor cortex excitability do not follow the patterns of EMG and force production during dynamic elevation, which does not support our hypothesis. The reason may be due to that the excitability in static condition may not represent the excitability in dynamic motion (Forman et al. 2014). In the testing protocol, the subjects performed external rotation and arm elevation when the stimulus was applied for the purpose of standardizing background EMG activation. This testing protocol may be different from the task of arm elevation, which is dynamic elevation for both muscles. Since corticospinal excitability would be regulated for different tasks and torque production (Gritsenko et al. 2011; Pearce and Kidgell 2010), the results of the present study may not represent the actual corticospinal excitability which occurs during arm elevation.

The excitability of muscles involved in posture control would be modulated because of a change in static position (Kantak et al. 2013; Obata et al. 2009). The difference in the regulation of the corticospinal excitability of the middle deltoid and infraspinatus demonstrates different function for the infraspinatus and middle deltoid at different shoulder orientation. Specifically, while infraspinatus is a shoulder stabilizer, the primary role of the deltoid is as an arm abductor. The corticospinal excitability of the deltoid was not changed because the tasks of arm elevation at different elevation angles are the same for the deltoid. Although the infraspinatus performed arm elevation and external rotation at both angles, the corticospinal excitability of infraspinatus may have increased for the purpose of humeral head control at 90° of elevation due to the fact that the infraspinatus is a posterior rotator cuff muscle preventing anterior translation of the humeral head (Malicky et al. 1996). The results of the present study reveal different neurological regulation for the synergist muscles (deltoid and infraspinatus), at different angles.

Since we only applied single-pulse stimulation of TMS at primary motor area, the change of the excitability may be occurring either at cortical or at spinal motor neurons. Proprioceptive signals from the shoulder joint may alter the corticomotor excitability (Dominici et al. 2005) or spinal motoneuron excitability (Knikou and Rymer 2002). In addition, although the C3–C4 propriospinal system is less dominant in higher primates than in cats, a part of corticospinal excitability of the upper extremity for voluntary control is regulated by these premotoneurons (Pierrot-Deseilligny 2002). The infraspinatus is also modulated by the propriospinal system (Roberts et al. 2008). The background excitation of propriospinal neurons may be affected by peripheral inputs and the motor task (Iglesias et al. 2007; Giboin et al. 2012). The change of the peripheral input resulting from a change in joint angle may also influence the propriospinal system, ultimately altering the corticospinal excitability of infraspinatus. Moreover, the intrinsic electrical properties of the spinal motoneurons are mediated by neuromodulatory control through monoamines serotonin or norepinephrine, which regulate voltage-sensitive channels of calcium and sodium. These channels tend to remain open and generate persistent inward currents (PICs) (Heckmann et al. 2005, 2008). In the cat, PICs may amplify the synaptic input to the spinal motoneurons (Hultborn et al. 2003). Reciprocal inhibition also regulates PICs, and the amplitude of PIC changes at different joint angles (Hyngstrom et al. 2007). Therefore, joint angles may alter the intrinsic property of spinal motoneurons through PICs.

Several factors may also influence corticospinal excitability. Muscle stretch may change the excitability of the homonymous motoneuronal pool (Delwaide 1973) and may affect the excitability of the neuromuscular junction (Frigon et al. 2007). During arm elevation, the length of both the middle deltoid and infraspinatus is gradually shortened (Bechtol 1980; Ward et al. 2006). Since both muscles are shorter at 90° of arm elevation, the changes of muscle length would not be expected to contribute to the different effects of shoulder angle on their excitability. In addition, it has been mentioned that the activation of these muscles is different at different levels of elevation during arm movement (Alpert et al. 2000) and the slight change of background EMG may affect the excitability (Weber and Eisen 2002). Therefore, we measured the MVC of each muscle at 0° and 90° of elevation separately. Both middle deltoid and infraspinatus maintained 10 % of MVC when the stimulation was applied. In Table 2, although the difference of deltoid MVC between angles was close to significant level, the background EMG of both deltoid and infraspinatus during the trials was not significantly different between angles. Therefore, the background EMG during the trials may not contribute the difference of excitability between angles. Moreover, background activities only affect the threshold and slope of the curve but do not influence the plateau value (Devanne et al. 1997).

There are some limitations to the present study. One optimal spot was used for both deltoid and infraspinatus, where the sum of the evoked response from the middle deltoid and infraspinatus was the largest. In order to determine whether one muscle was disproportionally recruited, we calculated the ratio between the amplitude of the MEP of the deltoid and infraspinatus at the intensity where the optimal spot was found (averaged across five trials). The mean of this ratio was 2.2 with standard deviation of 2.0. However, we did note two outliers with higher ratios of 6.7 and 7.3. After removing those two subjects from the data set, the mean and standard deviation were reduced to 1.6 and 0.9, respectively. Therefore, for these 15 subjects, the optimal spot results in consistent recruitment of both muscles. To determine whether these outliers skewed our data, we reran our analysis with these subjects removed. This resulted in no changes in our statistical results. However, future work may need to investigate with separate spots for deltoid and infraspinatus. Moreover, we used MVC for normalization and found the statistic results were the same as the results of raw amplitude in mV. We therefore chose to report the raw data without normalization. We only assessed the excitability at two different shoulder angles in the scapular plane and fixed the elbow at 90° of flexion. Future work could test the excitability during dynamic motion to investigate the roles of deltoid and infraspinatus during the arm elevation.

Conclusion

The results of the present study demonstrate corticospinal excitability of the infraspinatus but not the middle deltoid is increased at 90° of arm elevation when compared to 0°. This suggests that although both muscles serve as shoulder abductors, the modulation of their excitability is affected differently by elevation angles. These findings provide additional evidence that the neurological modulation of the deltoid and rotator cuff is different, which is consistent with the fact that they play different roles and have different function at the shoulder.

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