THE EFFECTS OF EXERCISE TRAINING ON SHOULDER NEUROMUSCULAR CONTROL

by

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DISSERTATION ABSTRACT

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The human shoulder complex relies on the sensorimotor system to maintain stability. The sensorimotor system includes sensory feedback, control of the central nervous system and motor output. Exercise is considered an important part of shoulder rehabilitation and sports training to help improve control of the sensorimotor system. However, few studies have investigated the effect of exercise on the sensorimotor system.

The first study of this dissertation explored the central control of the deltoid and rotator cuff (infraspinatus). Although both the deltoid and infraspinatus contribute to shoulder abduction, the results from this study showed that the modulation of their corticospinal excitability was affected differently by elevation angle. This could be explained by the fact that they play different roles at the shoulder: the deltoid is a prime mover while the infraspinatus is a stabilizer.

The second study of this dissertation investigated scapular proprioception, which has not been assessed in previous studies. The findings of this study demonstrated that joint position sense errors of the overall shoulder joint mainly came from the glenohumeral joint. Scapular proprioception may need to be tested separately in addition to overall shoulder proprioception.

In the third study, the effect of the exercise on shoulder sensorimotor system was investigated by measuring shoulder kinematics, shoulder joint position sense and cortical excitability before and after a four-week exercise training program. This protocol included strengthening and neuromuscular exercises targeting rotator cuff and scapular muscles. After the training protocol, although strength increased overall, the only observed sensorimotor adaptations were a decrease in upper trapezius activation and a decrease in the corticospinal excitability of the supraspinatus. There were no changes in other key parameters.

Exercises focusing on specific muscles, combined with low-intensity closed-chain exercises, were not found to improve shoulder joint position sense or scapular kinematics. Combined with the findings of the decrease in corticospinal excitability of the supraspinatus and no change in muscle activity of the rotator cuff, it appears that while the exercises increased rotator cuff strength, these gains did not transfer to an increase in muscle activation during motion.

This dissertation includes previously published co-authored material.

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CHAPTER I

INTRODUCTION

The shoulder complex consists of the clavicle, scapula and humerus. It 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. The rotator cuff muscles, including the supraspinatus, infraspinatus, teres minor, and subscapularis, serve as the chief stabilizers of the glenohumeral joint, while the deltoid provides most of the torque necessary for glenohumeral motion. Therefore, the coordination of the deltoid and the rotator cuff muscles is essential for smooth glenohumeral movement (Donatelli 2004). In addition, the scapula moves simultaneously with humeral motion. The scapula is controlled by the muscles around it, including the trapezius and serratus anterior (Kibler 1998; Ludewig and Reynolds 2009; Mottram 1997; Ludewig and Cook 2000). Impairment in neuromuscular control of the scapulothoracic muscles may lead to injury and pain (Michener et al. 2003; Myers et al. 2006; Ludewig and Cook 2000). Consequently, rehabilitation programs aim to restore the normal neuromuscular control of the rotator cuff and scapulothoracic muscles in order to help decrease pain and improve shoulder function (McClure et al. 2004). Although rehabilitation programs have moderate success in decreasing pain and improving shoulder function (Michener et al. 2004), it is still unknown if they serve to improve neuromuscular control of the shoulder muscles. Therefore, the goal of this dissertation was to investigate the effect of exercise training on the neuromuscular control of shoulder complex. Since most of studies examined the muscle activity during the selective exercises in healthy subjects, this dissertation would examine the mechanism of the exercise effect in healthy subjects.

Deltoid and Rotator Cuff Muscles

During arm elevation, the deltoid generates the majority of the force and torque required to move the upper extremity (Yanagawa et al. 2008). However, the deltoid also applies a large amount of anterior and superior shear forces to the glenoid, which may translate the humeral head in an anterior or superior direction. In contrast, the rotator cuff muscles produce compressive forces to center the humeral head in the glenoid fossa (Lee et al. 2000; Yanagawa et al. 2008) as well as generate inferior and posterior shear forces, which counterbalances the deltoid shear force (Halder et al. 2001; Yanagawa et al. 2008). The balance and coordination between the deltoid and rotation cuff muscles is essential for normal shoulder function and may help protect the joint from injuries. If the rotator cuff force is insufficient, the deltoid anterior and superior shear forces could result in excessive anterior and superior translation of the humeral head (Morrey et al. 1998; Poppen and Walker 1978).

During arm elevation, the relative contribution of the deltoid and rotator cuff muscles varies due to change in moment arms. The moment arms of these muscles at different joint angles determine their efficiency and their role of the muscles in shoulder movement at different joint angles. The rotator cuff muscles maintain a long moment arm throughout the range of motion, which provides a biomechanical advantage for stability. In addition, the moment arm of the rotator cuff is greater than that of the deltoid in the range from 0° to 60° of arm elevation, thus the rotator cuff muscles are more effective abductors in this early range of motion. As the shoulder elevates to higher angles, the moment arm of the deltoid increases. Therefore, the deltoid can produce higher levels of torque at higher elevation angles (Otis et al. 1994; Liu et al. 1997). Moreover, during the early phases of elevation, because of the deltoid insertion angle on the humerus, the deltoid produces an upward shear force to the humeral head. Therefore, the rotator cuff muscles also provide a counterforce to prevent the humeral head from superior translating and help center the humeral head within the glenoid fossa at the beginning of arm elevation (Inman et al. 1944; Morrey et al. 1998).

Similar to the results of studies investigating forces and moment arms, the electromyographic (EMG) activity of rotator cuff muscles is higher in the initial range of elevation and that of deltoid is higher in the later range of motion (Inman et al. 1944; Alpert et al. 2000). The rotator cuff muscles are initially activated above 20% of maximum voluntary contraction and the activity stays around the same level throughout the range of motion. The peak of the activity occurs at about 30 to 60 degrees of elevation and the activity decreases slightly at the end ranges. The activity of the deltoid is lower at the initial range of motion and increases while the arm moves higher with the peak around 90 degrees of elevation (Alpert et al. 2000; Kronberg et al. 1990).

Therefore, because of the coordination of the deltoid and rotator cuff muscles, the humeral head shows little motion with respect to the humeral fossa during arm movement in healthy subjects. Studies investigating humeral head translation in healthy subjects with anterior-posterior radiographs have demonstrated that at the beginning of arm elevation, the position of the humeral head is just below the center of the glenoid. However, as the arm is elevated, and the humeral head becomes centered on the glenoid fossa. The excursion of the head is about 1 mm in the range of 0° to 120° motion (Yamaguchi et al. 2000; Paletta et al. 1997; Deutsch et al. 1996).

In subjects with shoulder impingement syndrome, the humeral head migrates superiorly during arm elevation, compared with that of healthy subjects (Yamaguchi et al. 2000; Deutsch et al. 1996). The excessive superior translation of the humeral may result in the impingement of the subacromial tissue, including the supraspinatus, subacromial bursa and long head of biceps tendon. One of the factors contributing to the excessive superior translation is the imbalance of the deltoid and the rotator cuff muscles. In cadaver models, loss of part or all of the rotator cuff increases the humeral superior translation during simulation arm elevation (Sharkey and Marder 1995). In vivo studies also demonstrate increased superior humeral head translation during arm elevation after a rotator cuff fatigue protocol (Chen et al. 1999) or a suprascapular nerve block (San Juan et al. 2013). Therefore, rehabilitation exercises for shoulder impingement syndrome contain exercises aiming to restore the normal relationship between the deltoid and rotator cuff (Greenfield et al. 2004; Reinold et al. 2009).

Scapular Kinematics and Muscles

The synchronous movement between the glenohumeral and scapulothoracic joint has been widely investigated (Inman et al. 1944; Karduna et al. 2001; Lukasiewicz et al. 1999; Ludewig and Cook 2000). This so-called scapulohumeral rhythm was first introduced by Inman et al. (1944). This historical study stated that after the initial 60 degrees of flexion and 30 degrees of abduction of the humerus, the scapula rotated upwardly as the range of flexion and abduction increased with the 1:2 ratio of scapulothoracic upward rotation to the glenohumeral motion (Inman et al. 1944). Recently by using motion tracking system, other investigators found the scapulothoracic motion is three-dimensional movement and it demonstrates posterior tilt, upward rotation, and external rotation during arm elevation (McClure et al. 2006; Lukasiewicz et al. 1999; Ludewig and Cook 2000). Upward rotation of the scapula can elevate the lateral acromion while scapular posterior tilting lifts the anterior acromion during arm elevation (Ludewig and Cook 2000; Kamkar et al. 1993). These movements move the acromion away from the humeral head to prevent impingement of the subacromial tissue and also orient the glenoid fossa for optimal contact of the humeral head (Levangie and Norkin 2001; Kibler 1998). Subjects with impingement syndrome demonstrate insufficient upward rotation and posterior tilt during shoulder movement (Ludewig and Cook 2000).

Scapular movement is controlled by the muscles connecting the axial skeleton to the scapula. The appropriate pattern of the scapulothoracic muscles activation is important for the scapula to perform precision movement and maintain stability of shoulder complex. In the early phases of arm elevation, the upper trapezius and serratus anterior are the principal rotators. After passing the middle phase of glenohumeral elevation, the lower trapezius and serratus anterior increase their contribution with decreasing activation of upper trapezius (Bagg and Forrest 1986, 1988). Therefore, during arm elevation, the muscular recruitment patterns are starting by the upper trapezius, followed by the serratus anterior and finally the lower trapezius (Moraes et al. 2008). Subjects with shoulder impingement syndrome showed late recruitment of all the scapulothoracic muscles during arm elevation (Moraes et al. 2008). Altered scapulothoracic muscle activation, including increased upper and lower trapezius activity and decreased serratus anterior activity, has been demonstrated in subjects with shoulder impingement syndrome (Ludewig and Cook 2000; Lin et al. 2011). Therefore, rehabilitation program for shoulder injuries usually include exercise programs focusing on restoring scapular control and the balance between the scapulothoracic muscles (Roy et al. 2009; Reinold et al. 2009).

Shoulder Exercise

Exercise is an important part of rehabilitation programs for shoulder impingement syndrome. Various exercises have been used, including range of motion exercise (Conroy and Hayes 1998), progressive resistance training in different direction of shoulder motion (Lombardi et al. 2008), motor control retraining (Worsley et al. 2013; Roy et al. 2009), rotator cuff strengthening (Bennell et al. 2010; Brox et al. 1993; Brox et al. 1999; Ludewig and Borstad 2003) and scapular stability exercise (Bennell et al. 2010; Brox et al. 1993; Brox et al. 1999; Haahr et al. 2005; Conroy and Hayes 1998). Systematic reviews and meta-analysis have concluded that exercise is an effective treatment to reduce pain and improve function in patients with shoulder dysfunction (Gebremariam et al. 2013; Marinko et al. 2011; Hanratty et al. 2012; Littlewood et al. 2012; Abdulla et al. 2015).

Since rotator cuff and scapulothoracic muscles play an important role in shoulder stability, exercises to strengthen rotator cuff and scapulothoracic muscles are recommended for shoulder injuries (Cricchio and Frazer 2011; Reinold et al. 2009). Those exercises are performed with the shoulder movements in which the rotator cuff and scapulothoracic muscles show high muscle activity. It also has been emphasized that the movements selectively activate the rotator cuff and scapulothoracic muscles with low activation levels of the deltoid, upper trapezius or pectoralis major in order to restore the balance and coordination between muscles (Reinold et al. 2004; Reinold et al. 2007; Decker et al. 2003; Ellenbecker and Cools 2010). However, while most of the studies focused on pain and function improvement (Bennell et al. 2010; Brox et al. 1993; Brox et al. 1999; Ludewig and Borstad 2003), only a few studies examined whether the neuromuscular control changes during the movement after the training, which is the rationale behind the exercises. Although in general, exercises lead to an increase of shoulder muscles strength (Wang et al. 1999; McClure et al. 2004; Padua et al. 2004), there is no change in the scapular kinematics after the exercise training (McClure et al. 2004; Hibberd et al. 2012). Only one study investigated scapulothoracic muscle activation during movement after exercise and showed the ratio of upper trapezius to serratus anterior decreased after training (De Mey et al. 2012). It is currently unknown whether rotator cuff and scapulothoracic muscle strengthening exercise result in neuromuscular adaptations during dynamic movement.

Proprioception

Proprioception is peripheral afferent input providing information about joint position sense, kinesthesia and sensation of resistance. The afferent inputs originate from receptors, include muscle spindle and Golgi tendon organs in the musculotendinous structures and the mechanoreceptors on the joint capsule, ligament and tissue around the joint (Riemann and Lephart 2002b). Proprioception is involved in three levels of motor control in the central nervous system: spinal, brain stem and cortical levels (Riemann and

Lephart 2002b; Myers and Oyama 2009). At the spinal level, reflex arcs have been found between the shoulder capsule and shoulder muscles, which may contribute to joint stabilization (Borsa et al. 1994). At the brain stem, integrated with visual and vestibular, proprioception is used to control automatic movement, including modulating muscle tone, balance and posture, as well as the sensitivity of muscle spindle (Riemann and Lephart 2002b). Moreover, the mechanoreceptors may terminate at somatosensory cortex (Tibone et al. 1997) and this conscious awareness of proprioception may also be associated with motor plan and strategy (Myers and Oyama 2009). Therefore, the central nervous system needs the proprioception input to regulate the neuromuscular control to help maintain functional joint stability.

Subjects with shoulder impingement syndrome (Machner et al. 2003; Anderson and Wee 2011), anterior glenohumeral dislocation history (Smith and Brunolli 1989), and shoulder instability (Lephart et al. 1994) have demonstrated proprioception deficits when compared to the uninjured shoulder. In addition to directly affect passive stability, it is possible that injured or loose ligaments, capsules, and muscles can also affect the proprioception afferent input. Proprioception deficits may result in impaired neuromuscular control, which could ultimately lead to muscle imbalance and joint instability. The microinjuries resulting from joint instability can aggravate these proprioception deficits. This vicious cycle may be a factor in the development of chronic shoulder pain and the high recurrent rate of shoulder dislocation (Lephart and Henry 1996).

It has been postulated that exercise can enhance proprioception by modulating the sensitivity of the muscle spindle or learning to pay more attention to the joint position

(Swanik et al. 1997; Ashton-Miller et al. 2001). Several studies have investigated the effect of the exercises on shoulder proprioception in healthy subjects, including open-chain exercise (Rogol et al. 1998; Padua et al. 2004; Salles et al. 2015), closed-chain exercise (Rogol et al. 1998; Padua et al. 2004), plyometric training (Heiderscheit et al. 1996; Swanik et al. 2002), and proprioceptive neuromuscular facilitation (Padua et al. 2004). However, the results of the exercise training are not consistent, even in the same type of exercises (Padua et al. 2004; Salles et al. 2015; Swanik et al. 2002; Heiderscheit et al. 1996; Rogol et al. 1998).

Most of the exercises mentioned above are advanced exercises for athletic training. Only one study studied specific exercises targeting the rotator cuff and scapulothoracic muscles with open-chain exercises (Padua et al. 2004). However, in clinical practice, rehabilitation exercises typically contain both open-chain and closed-chain exercises (Cricchio and Frazer 2011; Reinold et al. 2009). Therefore, it is still unknown if the exercises for the rotator cuff and scapulothoracic muscles improved the proprioception.

Corticospinal Excitability

When shoulder neuromuscular control is investigated in the fields of biomechanics, orthopaedic rehabilitation, and sports, the focus is generally on kinematics and EMG. These parameters represent how the shoulder complex is controlled during movement as the result of motor command execution. Corticospinal excitability, which has been widely examined in patients with neurological disorders, has also been recently applied in biomechanics, orthopaedic rehabilitation, and sports fields (Tsao et al. 2011a; Fisher et al. 2013; Kidgell and Pearce 2011). Corticospinal excitability represents the efficacy of neural transmission along the corticospinal pathway, from the primary motor cortex, through the spinal cord and to the muscle (Kidgell and Pearce 2011). Changes in corticospinal control are associated with inter-joint torque reaction (Gritsenko et al. 2011) and different task execution (Obata et al. 2009). In addition, different proprioceptive inputs at different joint position also influence the corticospinal excitability (Dominici et al. 2005). As mentioned previously, the deltoid and the rotator cuff muscles play different roles in dynamic stability and their contributions vary with arm elevation angles. It is possible that the corticospinal excitability of the deltoid and rotator cuff muscles changes at different arm elevation angles. The first study of this dissertation have explored the central control of the deltoid and rotator cuff (infraspinatus). The details are in Chapter II and have been published in volume number 233 (6) of the journal *Experimental Brain Research* in Jun 2015. Andrew Karduna and Anita Christie are co-authors.

In addition to neurological impairment, orthopaedic injury and pain can also affect corticospinal excitability. For example, in subjects with non-traumatic shoulder instability, the lower trapezius demonstrates lower excitability when compared to healthy controls (Alexander 2007). Also, experimental tonic muscle pain over the first dorsal interosseum results in inhibition of cortical and spinal excitability (Le Pera et al. 2001) Similarly, experimentally-induced acute low lumbar pain is associated with different effects on trunk muscles. The deep abdominal muscles, such as the transversus abdominis, showed reduced corticospinal excitability. In contract, more superficial muscles, such as the lumbar erector spinae and external oblique abdominis, demonstrated increased excitability (Tsao et al. 2011b). In addition to kinematics and EMG measurements, which demonstrate the overall motor strategy, corticospinal excitability is another promising parameter to investigate the details about how the deltoid and rotator cuff muscles are controlled from the primary motor cortex through the spinal cord to the muscle (Kobayashi and Pascual-Leone 2003).

While consistent evidence suggests that motor skill training is associated with increased excitability (Jensen et al. 2005), the effects of strength training on corticospinal excitability are still not well known and may depend on the muscles and training task (Griffin and Cafarelli 2007; Beck et al. 2007). For hand muscles and the biceps brachii, the corticospinal excitability decreases after resistance training (Carroll et al. 2002; Jensen et al. 2005). For the anterior tibialis, the corticospinal excitability increases after strength training (Griffin and Cafarelli 2007). The training of neuromuscular control may be associated with both motor learning and strength training. The control and firing pattern may be directly re-learned consciously, which involves increases in strength and motor learning. Since it is associated with a learning process, excitability may increase after training. It has been shown that changes in excitability are correlated with a motor learning effect (Jensen et al. 2005), so that changes in excitability after training may be correlated with changes of rotator cuff EMG. After repetitive practice, the conscious movement patterns may become automatic (Pascual-Leone et al. 1995), thus changing the EMG pattern of rotator cuff activation.

Conclusion

Shoulder proprioception and neuromuscular control has been widely investigated and altered proprioception and neuromuscular control also has been found in subjects with shoulder dysfunction. The control of central nervous system, corticospinal excitability, may be also influenced. To restore the balance of muscles and normalize the motion pattern, the strengthening exercises for rotator cuff and scapulothoracic muscles are an essential part in rehabilitation treatment. Although during these strengthening exercises, selective rotator cuff and scapulothoracic muscles demonstrate high muscle activation with lower activation of deltoid and pectoralis major, only few studies investigated the effect of these exercises on proprioception and neuromuscular control. The effect of the exercises on corticospinal excitability is still unknown.

CHAPTER II

EXCITABILITY OF THE INFRASPINATUS, BUT NOT THE MIDDLE DELTOID, IS AFFECTED BY SHOULDER ELEVATION ANGLE

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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 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 is 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, the middle deltoid contributes more in the middle range of motion while 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.

Methods

Subjects

Seventeen healthy subjects (7 male and 10 female; 20.4 ± 1.7 y; 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 mid-way 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 (10-1000Hz), 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 maximum voluntary contraction (MVC) of the middle deltoid and rotator cuff was measured separately at 0° and 90° of arm elevation for seven seconds. 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 70mm 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 worn by the subject. A support arm was used to hold the coil at the same position throughout the testing protocol (Figure 2.1). 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 (ie, where the response amplitude did not increase with increasing stimulation intensity). The stimulation interval was 10 to 15 seconds. 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.

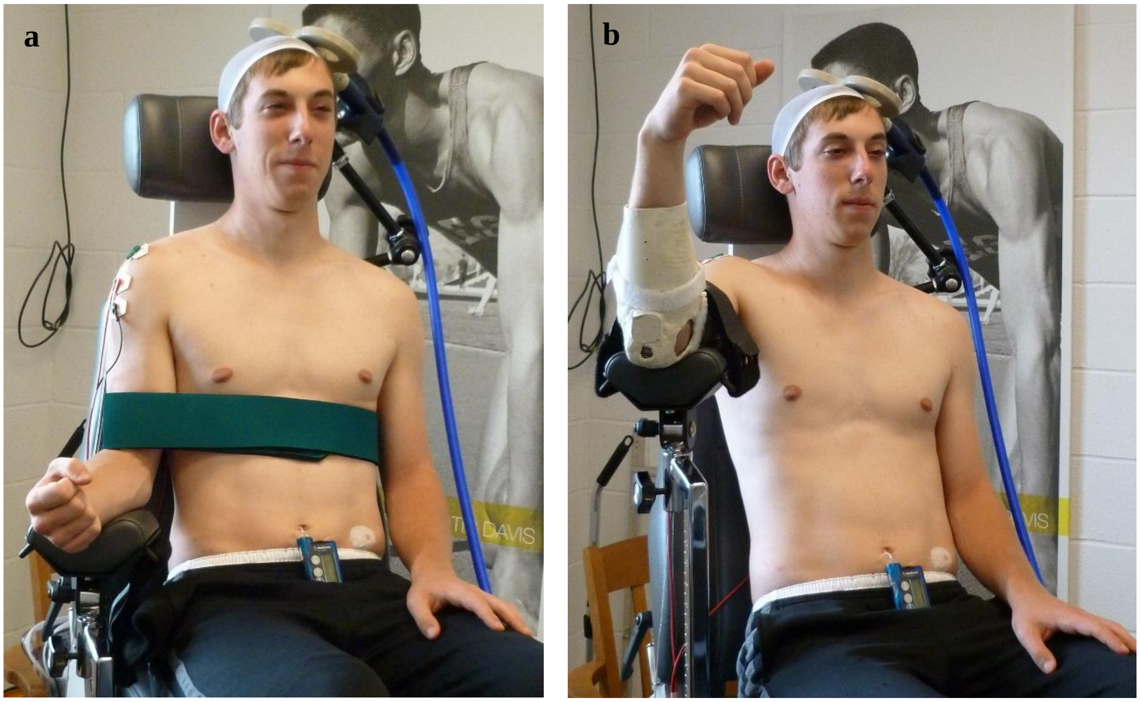

Figure 2.1. The testing position. During TMS test, the subject was seated with head support. The coil was held by a support arm. (a) The arm was at 0° of elevation. The elbow was supported at 90° of flexion. (b) The arm was supported at 90° of elevation. The elbow was also supported at 90° of flexion with elbow splint

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 (Figure 2.1).

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).

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

Where MEP(s) is the amplitude of motor evoked potential, $\mathrm{MEP}_{\mathrm{max}}$ 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 $\mathrm{MEP}_{\mathrm{max}}$. The peak slope of the curve occurs at S_{50} and is defined by the relationship: $\frac{\mathrm{m\ x\ MEP_{max}}}{4}$ (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) (Figure 2.2). Three parameters, $\mathrm{MEP}_{\mathrm{max}}$, 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 two seconds 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.

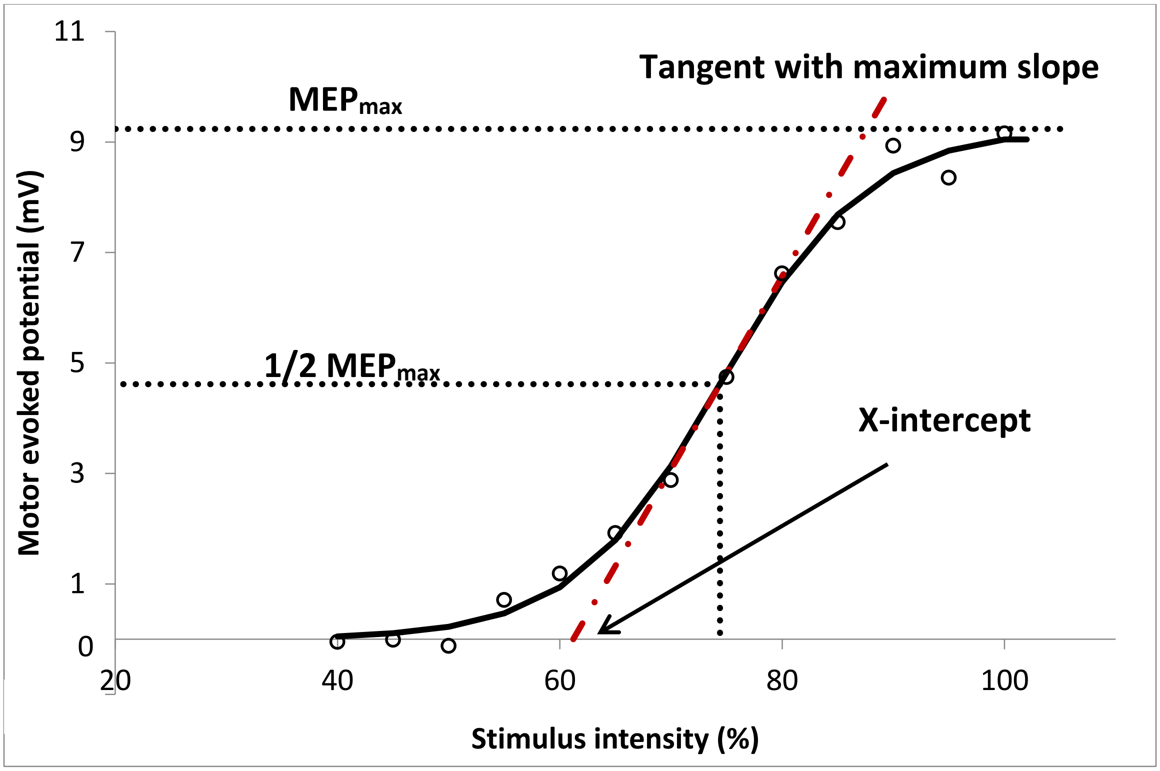

Figure 2.2. The example of motor evoked potential data at different intensity fit with the Boltzmann equation. The peak slope of the function happens at S_{50} where the motor evoked potential (MEP) is 50% of estimated plateau (MEP_{max}). The threshold of the curve is the x-intercept of tangent at S_{50}

Statistical analysis

A paired *t* test was used to assess the difference of the three parameters, $\mathrm{MEP}_{\mathrm{max}}$, *m*, and x-intercept threshold between 0° and 90° of arm elevation for each muscle. A paired *t* test was also used to also 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 ($\mathrm{MEP}_{\mathrm{max}}$, *m*, and x-intercept threshold) for the middle deltoid were not significantly different between 0° and 90° of arm elevation ($p = 0.51$, $p = 0.15$ and $p = 0.34$ respectively). For the infraspinatus, MEPmax 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 ($p = 0.19$ and $p = 0.78$) (Figure 2.3).

The percentage change of $\mathrm{MEP}_{\mathrm{max}}$ from 0° to 90° of arm elevation was significantly different between the middle deltoid and infraspinatus. While the $\mathrm{MEP}_{\mathrm{max}}$ of the middle deltoid at 90° was 5% lower than that was at 0°, that of infraspinatus at 90° was 56% higher than that at 0° ($p = 0.01$). The percentage change of the exponential parameter and intercept was not significantly different ($p = 0.91$ and $p = 0.41$) (Table 2.1). Table 2.2 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.

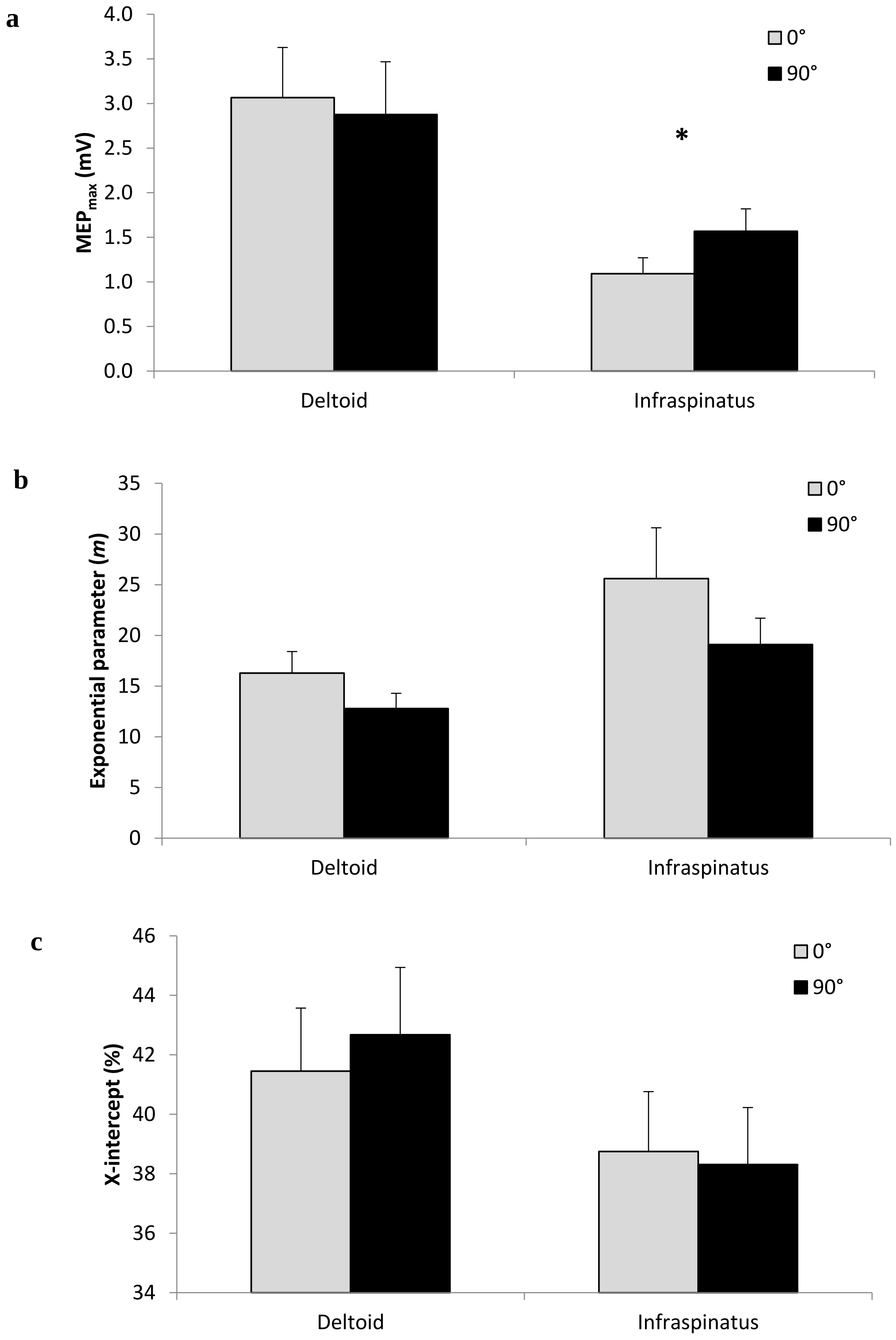

Figure 2.3. Comparison of (a) plateau value (MEP$_{max}$), (b) exponential parameter (*m*), and (c) x-intercept between humeral elevation angles.*$p < 0.05$

Table 2.1. 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	Infraspinatus	*p*
	Mean (SD)	Mean (SD)	
MEP_{max} (%)	-4.9 (36.2)	56.3 (72.6)	0.01
Slope (%)	-4.7 (49.2)	-2.6 (53.0)	0.91
Threshold (%)	3.6 (13.9)	0.1 (14.2)	0.41

Table 2.2. Mean and standard deviation for root mean square of maximum voluntary contraction (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 was calculated from the window of 90 ms before the stimulus was applied.

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 (56%) than that at 0°.

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 motorneuron 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; Heckman et al. 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 2.2, 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 if one muscle was disproportionally recruited, we calculated the ratio between the amplitude of the motor evoke potential (MEP) of the deltoid and infraspinatus at the intensity where the optimal spot was found (averaged across 5 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 re-ran 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.

Bridge

This dissertation focused on shoulder the sensorimotor system, including sensory afferent, central nervous system, and motor output. The study in Chapter II investigated the modulation of the central nervous system, which involved the coordination between muscle groups. The next study in Chapter III is about the coordination between joints in the sensory system, focusing on the contribution of proprioception errors of individual joints to the errors of the overall shoulder complex.

CHAPTER III

SCAPULAR PROPRIOCEPTION

Introduction

The shoulder complex consists of the clavicle, scapula and humerus. The joints of shoulder complex coordinate to generate a large range of motion necessary for reaching and hand manipulation at different positions. However, due to the inherent lack of stability provided by the bony, ligamentous, and capsular structures, the control from the sensorimotor system is essential for providing dynamic stability (Donatelli 2004; Myers and Lephart 2000). The sensorimotor system includes the sensory pathway, motor efferent and central nervous system (Riemann and Lephart 2002a). The central nervous system, including the spinal cord, brain stem and cerebral cortex, integrates afferent input to regulate neuromuscular control (Myers and Lephart 2000). Besides input from the visual and vestibular systems, the central nervous system relies on proprioception information to maintain functional joint stability. Proprioception originates from Golgi tendon organs, muscle spindle, and the mechanoreceptors on the muscle, tendon, joint capsule, ligament and tissue around the joint (Riemann and Lephart 2002b). There are three submodalities of proprioception: joint position sense (JPS), kinesthesia and sensation of resistance (Riemann and Lephart 2002a).

For shoulder joint, JPS has been tested with several different models. The paradigms of active or passive repositioning with passive positioning have been widely used (Lephart et al. 2002; Wassinger et al. 2007; Sole et al. 2015). In these paradigms, the arm of the subject was passively moved to the target position. The repositioning was performed either passively or actively. Other studies used the paradigm of active joint position sense, in which subject actively moved to the target position and actively reproduced the target angle (Suprak et al. 2006; Iida et al. 2014; Salles et al. 2015). Specific motion in different planes has been selected to test JPS, including internal and external rotation (Salles et al. 2015; Sole et al. 2015; Iida et al. 2014), elevation in different planes (Suprak et al. 2006; Wassinger et al. 2007), and functional movement (Barden et al. 2004; Tripp et al. 2007). Since most functional activities involve muscle contraction, the active joint position sense may be better to present the afferent input necessary for functional activities (Suprak et al. 2006). For the testing motion, the internal and external rotation mainly comes from glenohumeral joint and is not a functional movement for the general population. Testing the elevation may be a more appropriate protocol that for representing functional activities.

Most of the studies investigating shoulder JPS have treated the shoulder complex as a single joint and only measured the motion of the humerothoracic joint (HT) (Lephart et al. 2002; Wassinger et al. 2007; Sole et al. 2015; Iida et al. 2014; Salles et al. 2015; Suprak et al. 2006). However, the coordination between glenohumeral (GH) and scapulothoracic (ST) joints has been emphasized in both clinical practice (Kibler 1998) and research investigation (McClure et al. 2006; Ludewig and Cook 2000; Ludewig and Reynolds 2009; Inman et al. 1944). During arm elevation, the classic study demonstrated the ST joint contributes one third of the range of motion of the HT joint (Inman et al. 1944) and recent studies found three-dimensional scapular motion of upward rotation, posterior tilt and external rotation (Karduna et al. 2000; McClure et al. 2006). Only four studies have been found to investigate the JPS of the ST joint. Tripp et al. (2006; 2007) tested the effect of fatigue and testing position on multijoint position reproduction acuity of the throwing motion. They used three-dimensional variable errors scores which combined the errors in different direction to represent the overall JPS for each joint. Two other studies specifically measure the scapular JPS in scapular elevation/depression and protraction/retraction (Deng and Shih 2015; Guo et al. 2011). It is still unknown whether the JPS errors of GH and ST joints contribute to the JPS errors of HT joint in function movements.

In healthy subjects, it has been shown that JPS errors of the HT joint decreased as the target angles approached to 90° of arm elevation (Suprak et al. 2006). The JPS errors of the elbow have showed the same pattern (King et al. 2013). Therefore, the purpose of this study is to investigate the JPS errors of the GH and ST joints at different elevation angles and to examine whether both errors of the GH and ST joints contribute to the errors of the HT joint. We hypothesized that both errors of the GH and ST joints follow the same pattern as those of the HT joint and both the errors of the GH and ST joints are correlated with the errors of the HT joint.

Methods

Subjects

Fifty-one healthy subjects (21 males and 30 females; 7 left-handed and 44 right-handed) with an average age of 21.1 ± 3.4 years, average body weight of 66.7 ± 14.0 kg, and average body height of 168 ± 9 cm were recruited for this study. Anyone with a history of shoulder or neck disorders in three years was excluded. The study was approved by the Office for Protection of Human Subjects at the University of Oregon and all subjects signed an informed consent form.

Instrumentation

Thoracic, scapular and humeral kinematics were sampled at 120 Hz with a magnetic tracking device (Polhemus Liberty, Colchester, VT), which included a transmitter, three sensors, and a digitizer. The sensors were mounted on the manubrium of the sternum, the flat area of the acromion, as well as on the distal humerus via a custom-molded Orthoplast™ cuff and Velcro™ strap (Suprak et al. 2006; Ludewig and Cook 2000). The transmitter was positioned posterior to the subject and at the height of the subject's shoulders. The subject sat on an ergonomically designed kneeling chair (Better Posture Kneeling Chairs, Jobri® , Konawa, OK) and fitted with a head mounted display (Z800, eMagine, Bellevue, WA). The display blocked the visual feedback for the shoulder motion as well as displayed the target angle and real-time HT angle of the subject (Figure 3.1).

Anatomic landmarks were palpated and digitized, using the standards recommended by the International Society of Biomechanics (ISB) (Wu et al. 2005). The thoracic anatomic coordinate system was derived from T8, xiphoid process, C7, and the jugular notch. The digitization points for the scapula were the root of the scapular spine, inferior angle of the scapula, and laterodorsal point of acromion. The humeral coordinate system was defined with the second option in the ISB proposed standard, which includes the center of the humeral head, medial epicondyle, lateral epicondyle, ulnar styloid process and medial styloid process (Wu et al. 2005). The center of the humeral head was calculated using a least squares algorithm and was defined as the point that moved the least during several small arcs of motion (Harryman et al. 1992).

Figure 3.1. Sensor placement and testing position.

Protocol

JPS was tested with an active position reproduction and on the dominant shoulder. The protocol was modified from the work of King and Karduna (2014). There were three target positions of HT elevation in the scapular plane (50°, 70°, and 90°). Each target position was repeated four times, resulting in 12 trials. The order of the trials was randomized and there was a five-second break between each trial during testing. The subject was instructed to practice at least three sets of three successive arm elevations in the scapular plane to help become familiarized with the motion. The scapular plane was chosen because JPS errors were not found to vary between planes (Suprak et al. 2006) and most functional arm movements occur in this plane.

LabVIEW (Version 2012, National Instruments, Austin, TX) was used to control visual and auditory guides during testing. At the beginning of the trial, a black screen was displayed and the subject was asked to relax with the arm at their side. Two white lines then were shown on the black screen indicating the boundary of the predetermined target position (±1° from the target). For all target angles, the white lines were always set at the same position of the screen. The subject was instructed to elevate the arm with the elbow extended and thumb pointing up. A dynamic red line, representing the real-time HT angles of the subject, appeared on the screen when the subject was within 10 degrees of the target. Additionally, when the subject deviated more than five degrees from the scapular plane (35 degrees anterior to the frontal plane), a vertical green line would appear on the side of the screen, which prompted the subject to move away from the line and back into the scapular plane (Figure 3.2).

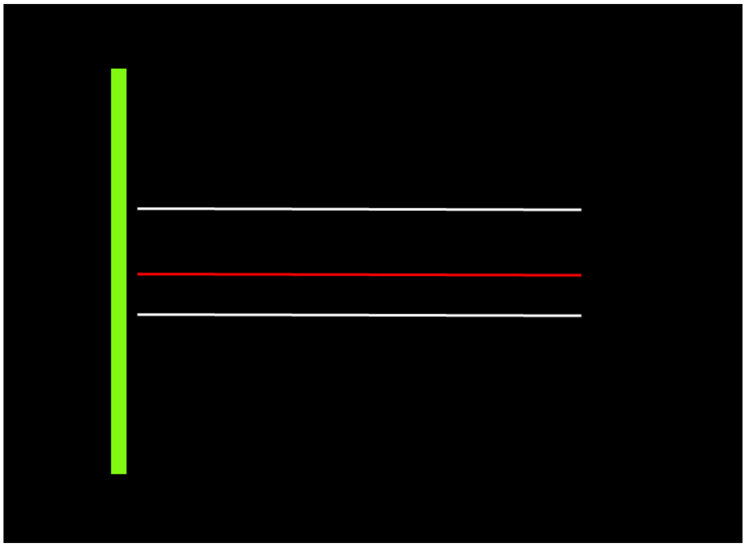

Figure 3.2. The target shown in the head mounted display. The white lines indicate the target. The red bar represents the real-time humerothoracic elevation angle. If the testing arm is right arm, in this example, the appearance of the left green bar indicates the arm deviates from the scapular plane to the midline.

The subject was instructed to elevate the arm until the red line was positioned between the white lines, with no green line displayed. After the subject had maintained the red line between the white lines for one second, the target disappeared and only a black screen was left. For the rest of the trial, the display remained black, thus removing all visual feedback. The subjects were instructed to hold their arms at the target position and memorize their arm position (three seconds) until they heard the verbal instruction from the computer indicating that they should return the arm to the side. After relaxing the arm at the side for two seconds, another verbal cue from the computer prompted the subjects to reposition their shoulder to the target position without any visual guide. When the subjects believed the target had been reached, they indicated by pushing the button on a wireless trigger with their contralateral hands. This would trigger the computer to instruct the subjects to relax their arm to the side, at which point the trial ended. Between the trials, a blue screen was displayed with a countdown timer and instruction to keep the arm on the side during the break. No feedback related to the accuracy of performance was provided to the subjects.

Data reduction

HT and GH and ST motion was calculated. Based on the ISB standard, for HT and GH motion, the following Euler sequence was used: plane of elevation, elevation and axial rotation. Because the plane of elevation and axial rotation were controlled, only the errors of elevation were considered for the HT and GH joints. For the ST joint, because it is hard to constrain the scapular motion in one dimension, we chose to use the helical angle to represent ST motion. The helical angle is the rotation angle about the helical axis (Woltring et al. 1985). Although the helical axis is not aligned with the anatomic axes, the helical angle can represent the ST three-dimensional angular motion.

The HT and GH elevation angles of the subject at the presented target position during the holding time (three seconds) were averaged (θ_p). The repositioned elevation angle was the angle at the moment that the subject pushed the trigger (θ_r). For the HT and GT elevation angles, the errors (θ_e) is the difference between the angles at the present target position and repositioned position ($\theta_e = \theta_r - \theta_p$).

The rotation matrix of ST joint at the presented target position and at the midpoint of the holding time was recorded (R_p). The rotation matrix of the ST joint was also recorded at the moment that the trigger was pushed (R_r). The error of the scapular helical angle (θ_e) was derived from the rotation matrix at the repositioned position with respect to that at presented target position ($R_{pr} = R_p^{-1} \bullet R_r$).

Constant and variable errors were calculated to represent accuracy and precision of JPS respectively (King et al. 2013; Schmidt and Lee 2005), where *n* is number of repetition for each target angle, which is four in this present study.

$$\text{Constant error } (\theta_m) = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e)$$

$$\text{Variable error } = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e - \theta_m)^2}$$

Statistical analysis

A one way repeated-measure analysis of variance (ANOVA) was used to examine the difference of errors between the elevation angles for each joint. The dependent variables are the constant and variable errors at different angles. The independent variable is angle, which has three levels: 50°, 70°, and 90°. If there was an effect of angle, post hoc polynomial contrasts were conducted to test whether the trends were linear. The significant level was set at 0.05.

A Multiple regression model was run to investigate the contribution of the GH and ST constant errors to the HT constant errors at each elevation angle. Unique variance (ΔR^2) was also calculated to show the variance of the HT errors that was explained by only either the GH errors or ST errors.

Results

There was a significant effect of angle on the constant errors of the HT joint ($p < 0.001$) and GH joint ($p < 0.001$) (Figure 3.3). The linear contrasts revealed significant linear decreases in the constant errors of the HT joint ($p < 0.001$) and GH joint ($p < 0.001$) as the target angle increased. However, the constant errors of the ST joint were around 3° at each target angle and the effect of angle on the constant errors of the ST joint was not significant ($p = 0.45$). There was no significant effect of angle on the variable errors of the three joints (Figure 3.4).

The results of the multiple regression are shown in Table 3.1. At each angle, the model with the predictors of the GH and ST constant errors was significant and explained more than 76% of variance in the constant errors of the HT joint. Of two predictors, GH joint had a stronger predictive relationship with HT joint than did ST joint, based on standardized regression coefficient (β) and ΔR^2. At the target position of 70°, the ST joint was not significant predictive of HT joint. In all the target angles, for each 1° increase in the GH constant error, there was an increase in the constant error of the HT joint, which ranged from 1.1° – 1.2°. At lower target angle (50°), the increase of ST constant errors increased the errors of HT joint while at higher target angle (90°), the increase of ST errors reduced the errors of HT joint.

Discussion

We investigated the JPS of the HT, GH and ST joints at different target angles during elevation in the scapular plane and examined the contribution of the GH and ST joints to the errors of the HT joint. We hypothesized that the errors of the GH and ST joints would decrease as the target angles approach to 90° of arm elevation and both errors of GH and ST joints would predict the errors of HT joint. The results partially supported our hypotheses. The constant errors of GH joint were reduced from 3.9° to 1.5° as the targets increased from 50° to 90° of arm elevation, which followed the pattern of the HT joint (5.4° to 1.4°). However, the constant errors of the ST joint maintained constant around 3° at different elevation angles. In addition, there is no angle effect on the variable errors of the three joints, which is the same as the results of a previous study from our lab (Suprak et al. 2006). For the regression models, the constant errors of the HT joint were significantly predicted by the GH and ST joints at each angle while the GT joint explained most of the variation of the HT joint, especially at higher angles.

When the shoulder complex was treated as one joint (HT) and the shoulder JPS was examined at different elevation angles, it has been found that the JPS error was smallest at 90° of arm elevation, compared to lower elevation angles (Hung and Darling 2012; Suprak et al. 2006). The decrease of the JPS errors with arm elevation target angles is a linear relationship (Suprak et al. 2006). The elbow joint demonstrated the same pattern (King et al. 2013). In the present study, the results of the HT joint confirmed the

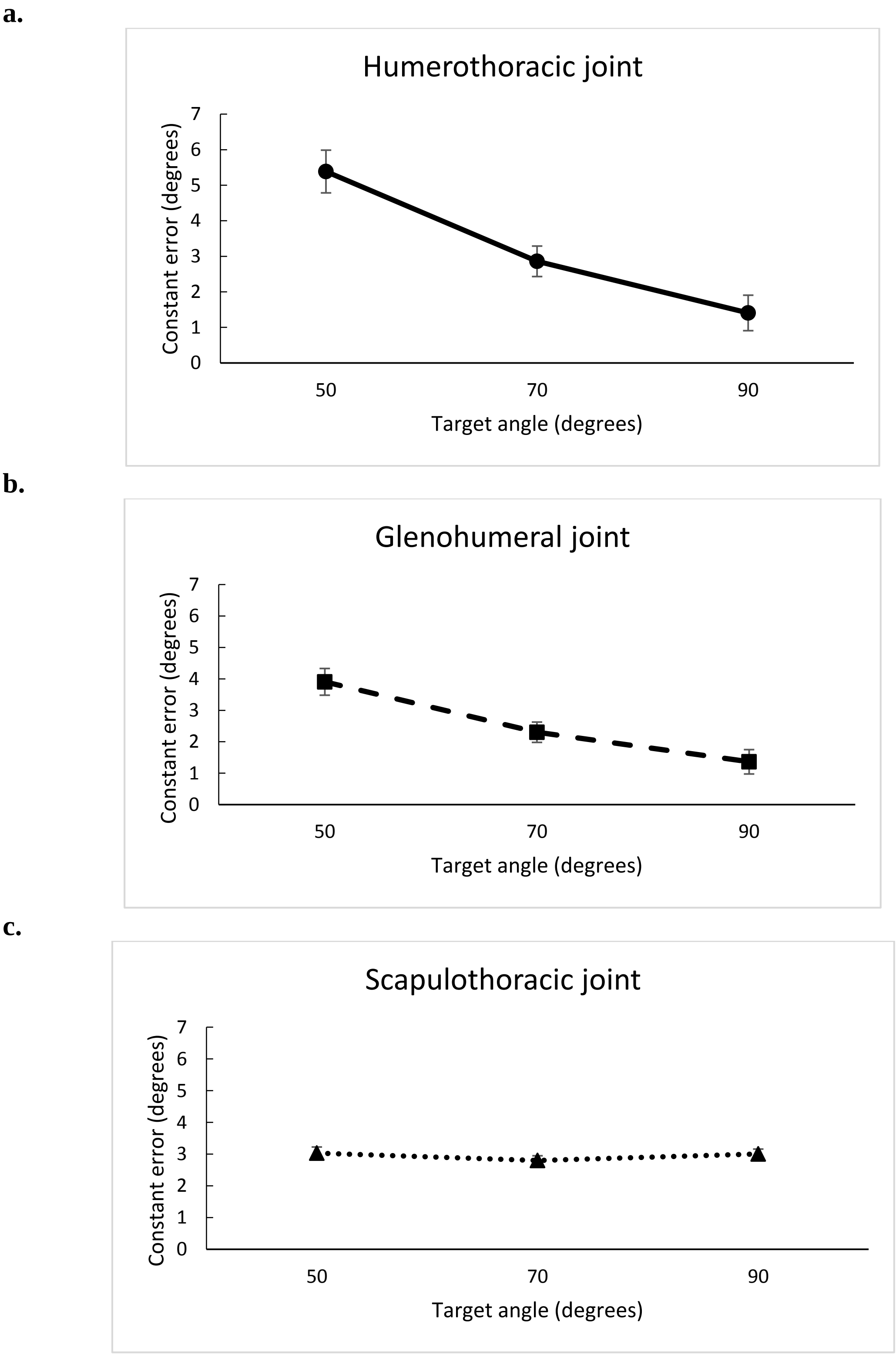

Figure 3.3. Constant errors of a) humerothoracic joint, b) glenohumeral joint, and c) scapulothoracic joint

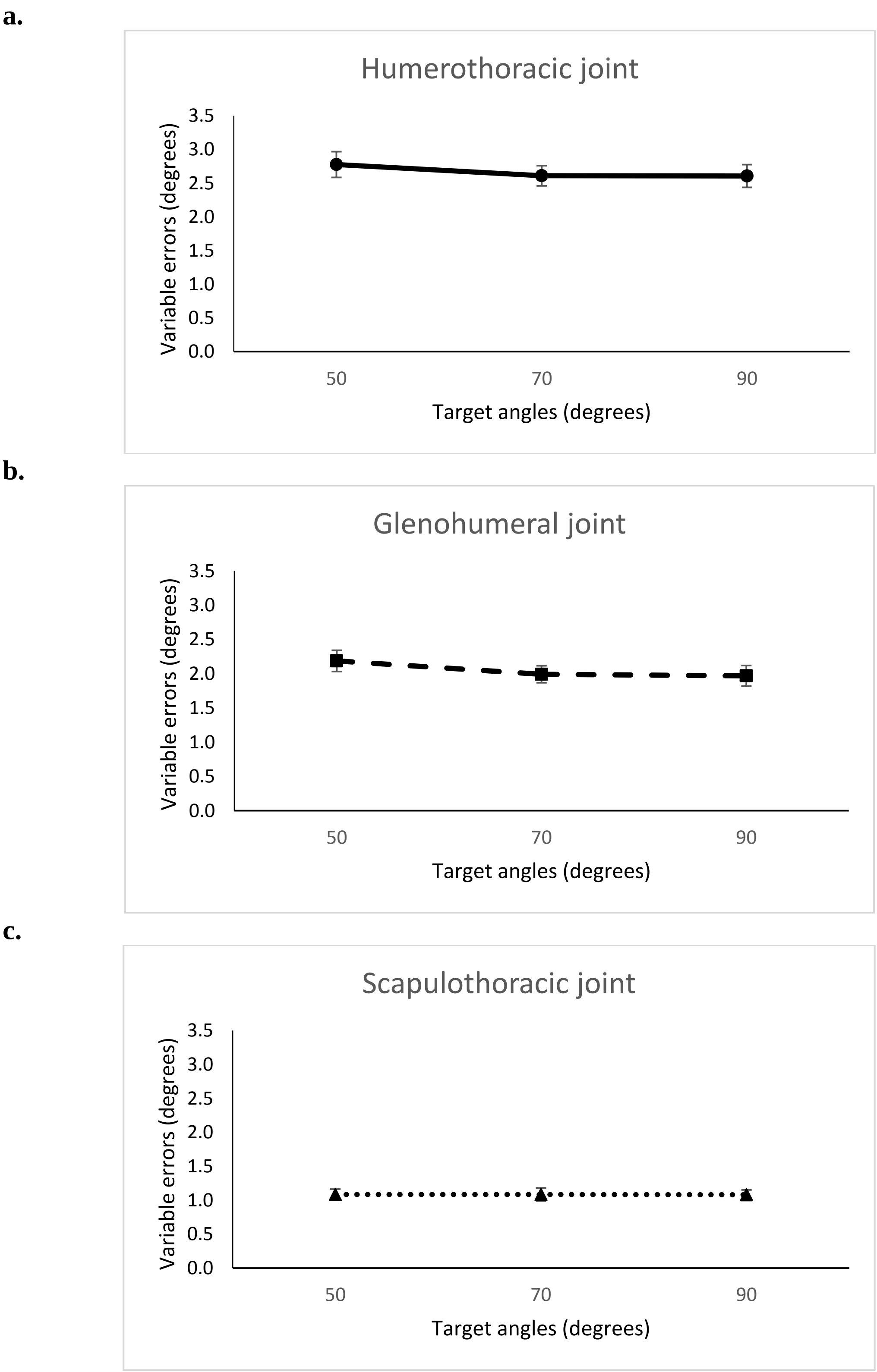

Figure 3.4. Variable errors of a) humerothoracic joint, b) glenohumeral joint, and c) scapulothoracic joint

Table 3.1. Results of multiple regression

	b	β	p	ΔR^2	Sig of ΔR^2
Errors of HT at 50° ($R^2 = 0.89$, $p < 0.001$)					
Error of GH at 50°	1.08	0.76	< 0.001	0.48	< 0.001
Error of ST at 50°	1.00	0.32	< 0.001	0.08	< 0.001
Errors of HT at 70° ($R^2 = 0.76$, $p < 0.001$)					
Error of GH at 70°	1.16	0.88	< 0.001	0.76	< 0.001
Error of ST at 70°	0.40	0.14	0.06	0.02	0.06
Errors of HT at 90° ($R^2 = 0.79$, $p < 0.001$)					
Error of GH at 90°	1.14	0.88	< 0.001	0.77	< 0.001
Error of ST at 90°	-0.49	-0.14	0.03	0.02	0.03

findings of Suprak et al. (2006) and Hung and Darling (2012). The GH joint also showed the same pattern. Errors of the GH joint significantly predicted those of the HT joint and explained most of the variability of the HT joint. The observed pattern of the HT joint may arise from the GH joint. The mechanism of this pattern is still not clear, but it may be due to the increase of the muscle activation level during arm elevation. Muscle spindles are the main contributing resource of the JPS (Proske and Gandevia 2012) and the sensitivity of the muscle spindles is associated with the level of the muscle contraction (Poppele and Quick 1985). It also has been found that external load improved the JPS (Suprak et al. 2007). Therefore, the decrease of the errors may be due to the increase of muscle activation from the beginning to the 90° of arm elevation.

The other possible mechanism of this phenomenon may be that the central nervous system utilizes some other intrinsic coordinate systems in addtion to muscle spindles. Chapman et al. (2009) tilted subjects backward when testing shoulder JPS. They found the effect of the arm orientation with respect to the trunk is more dominant than the effect of the gravity, which triggered different levels of muscle activation. The central nervous system may use a Bayesian inference process to reposition the arm when lacking major input signals, such as visual input in the present study (Gritsenko et al. 2007; King and Karduna 2014). It may be that the central nervous system tends to return the arm to the position where it is most likely to be positioned (King and Karduna 2014). It has been found that non-human primates performed tasks close to the chest and mouth for 50% of the time (Graziano et al. 2004). Therefore, the arm would overshoot toward the head at the lower targets but the accuracy is better at the target of 90°, which is around the level of the mouth. However, this hypothesis still needs more experimental models.

The errors of the ST joint did not decrease with increases in elevation angle, which did not support our hypothesis. This may be due to structural differences between the GH and ST joints. Unlike the GH joint, the ST joint is a so-called pseudo-joint without real joint structure. The muscles of the GH joint generate torque against the gravity to move the humerus (Yanagawa et al. 2008), but the muscles wrapping around the scapula coordinate to move and rotate the scapula along the thoracic cage (Johnson et al. 1994). The upper trapezius elevates and retracts the scapula. The lower trapezius stabilizes the scapular rotation axis and upward rotates the scapula while the serratus anterior substantially contributes to scapular upward rotation and posterior tilt (Ludewig and Braman 2011; Johnson et al. 1994). Therefore, although in general the activation of the scapular muscles increases with the arm elevation, the timing and activation level is different in each muscle (Phadke and Ludewig 2013; Bagg and Forrest 1986). Therefore, the effect of muscle contraction on the accuracy of the scapular JPS may not be as strong as that of the GH joint. In addition, the ST joint is at the dorsal side of the human body, so the Bayesian inference process may not be applied to the ST joint. As a result, there is no angle effect on the errors of the ST joint.

The multiple regression models demonstrated that relationship between the HT, GH and ST errors varies with elevation angles. At 50° of arm elevation, because of the collinearity between the GH and ST joints ($r = 0.42$, $p = 0.002$), the ΔR^2 of the GH and ST errors is low. However, the model combining both the GH and ST errors can explain 89% of variation of the HT errors. At higher target angles (70° and 90°), the GH errors account for almost all of the variation of the HT errors. Although the predictive relationship between the HT and ST joint is close to significant level at the target of 70° and is significant at the target of 90°, the relationship between the ST and HT joint is weak according to standardized regression coefficient (β) and ΔR^2. Although the scapular movement contribute to overall shoulder movement (McClure et al. 2006; Ludewig and Cook 2000; Ludewig and Reynolds 2009; Inman et al. 1944), the weak relationship and varied prediction direction (increasing HT errors at lower angle but decreasing HT errors at higher angle) indicates a dissociation between the JPS errors of the HT joint and ST joints.

For all target angles, for each 1° increase in the GH constant error, there was an increase in the constant error of the HT joint, which ranged from 1.1° – 1.2°. Therefore, when the JPS of the HT joint is examined, the results mainly represent the GH errors, especially at higher angles. Since the proprioception deficits has been demonstrated in the patients with shoulder impingement syndrome (Machner et al. 2003; Anderson and Wee 2011), anterior glenohumeral dislocation history (Smith and Brunolli 1989), and shoulder instability (Lephart et al. 1994), future studies may need to investigate the proprioception of scapula in the patients with shoulder injuries. In the clinical setting, it may be hard to test the scapular JPS in the task of elevation. The scapular JPS could be tested separately with the movement of scapular elevation/depression and protraction/retraction (Deng and Shih 2015).

Only two studies investigating JPS of multiple joints have been found. Tripp et al. (2006) investigated the end point acuity and the JPS of individual joints of upper extremity at the positions of arm-cock and ball-release in overhead-throwing athletes. They found no clear pattern of principle component analysis showing that the errors of individual joints contribute to the end point acuity. They found when all the variance was pooled, the proximal joints (ST and GH joints) accounted for more variance than the distal joints (elbow and wrist joints). The difference between the study of Tripp et al. (2006) and the present study may be due to different statistical models and different movements used for the test. In the present study, we restricted elevation to the scapular plane with thumb pointing upward while Tripp et al. (2006) used the movements of arm-cock and ball-release, which involve more joints and degrees of freedom.

King and Karduna (2014) tested JPS with targets involving both elbow and shoulder flexion. They found that end point acuity improved at the targets where the hand was closer to the head. Although they presented the targets according to the angles of the shoulder and elbow, which is different from the present study, they found, for the JPS errors of the shoulder (the proximal joint), did not depend on the angles but there was angle effect on the elbow (the distal joint). Their results are similar to our finding that there is no angle effect on the ST joint (the proximal joint) but the JPS errors of the GH joint (the distal joint) depended on the target angle. The mechanism of this phenomenon still needs more investigation with the JPS testing protocol involving multiple joints.

There are limitations in the present study. First, we chose to use the helical angle to represent the three-dimensional scapular movement. Although it reduces the number of the variables for the scapular movement, the helical angle does not represent the scapular movements observed in the clinic, such as upward/downward rotation, protraction/retraction or tipping. Therefore, the scapular JPS errors in the present study do not represent the errors in any specific plane. The subject population is another limitation. The subjects in the present study were young and healthy. The results may not be generalized to the population that is older or with shoulder injuries.

Conclusion

The results of the present study show that the HT constant errors decrease as the target elevation angle increases. While the GH joint demonstrates the same pattern, the ST constant errors did not depend on the target angle. At each target angle, the GH errors accounted for most of the variance of the HT errors, especially at higher elevation angles. Therefore, the HT errors are chiefly dependent on the GH joint. It may be necessary to test the JPS of the scapula separately in addition to the assessment of overall shoulder JPS, since the assessment of scapular kinematics is important in the evaluation of the patients with shoulder injuries. Future work may still need to investigate the JPS involving multiple joints to provide better understanding of coordination and compensation between joints.

Bridge

In this chapter, we have explored scapular proprioception at different elevation angles and the relationship of proprioception errors between individual joints and overall shoulder joint. This testing protocol for the shoulder proprioception will be used in the third study, which investigated the effect of exercise on the sensorimotor system.

CHAPTER IV

THE EFFECTS OF EXERCISE ON SHOULDER KINEMATICS AND ELECTROMYOGRAPHY

Introduction

The shoulder complex consists of the glenohumeral, acromioclavicular, sternoclavicular and scapulothoracic joints. Although the shoulder has a large degree of mobility, there is little stability from the bony, ligamentous, and capsular structures. Thus, coordination between joints is necessary for smooth, efficient and stable shoulder movement. Dynamic control of the humeral and scapular muscles plays an important role in stabilizing the shoulder during motion (Ludewig and Reynolds 2009).

During arm elevation, the deltoid generates the majority of the force and torque required to move the upper extremity (Yanagawa et al. 2008). The deltoid also applies large amount of anterior and superior shear forces to the glenoid, which may translate the humeral head in an anterior or superior direction. In contrast, the rotator cuff muscles produce compressive forces to center the humeral head in the glenoid fossa (Lee et al. 2000; Yanagawa et al. 2008) as well as generate inferior and posterior shear forces, which counterbalance the deltoid shear force (Halder et al. 2001; Yanagawa et al. 2008). The balance and coordination between the deltoid and rotation cuff muscles is essential for normal shoulder function and may help protect the joint from injuries. If the rotator cuff force is insufficient, the deltoid superior shear forces could result in excessive anterior and superior translation of the humeral head, which has been demonstrated in cadaver (Sharkey and Marder 1995), fatigue (Sharkey and Marder 1995) and nerve block models (San Juan et al. 2013). The excessive superior translation of the humeral may result in the impingement of the subacromial tissue, including the supraspinatus, subacromial bursa and long head of biceps tendon, which is called shoulder impingement syndrome (Neer 1972; Deutsch et al. 1996; Yamaguchi et al. 2000).

The scapulothoracic joint moves synchronously with the glenohumeral joint (Inman et al. 1944; Karduna et al. 2001; Lukasiewicz et al. 1999; Ludewig and Cook 2000). Investigators have found that the scapula demonstrates posterior tilting, upward rotation, and external rotation during arm elevation (McClure et al. 2006; Lukasiewicz et al. 1999; Ludewig and Cook 2000; Karduna et al. 2001). Upward rotation of the scapula can elevate the lateral acromion, while scapular posterior tilting lifts the anterior acromion during arm elevation (Ludewig and Cook 2000; Kamkar et al. 1993). These motions move the acromion away from the humeral head to prevent impingement of the subacromial tissue and also orient the glenoid fossa for optimal contact of the humeral head (Levangie and Norkin 2001; Kibler 1998). Scapular movement is controlled by the muscles connecting from the axial skeleton to the scapula. The appropriate pattern of scapulothoracic muscles activation is important for the scapula to perform precision movements and maintain stability of shoulder complex (Ludewig and Cook 2000; Ludewig and Reynolds 2009).

Subjects with shoulder impingement syndrome have demonstrated insufficient scapular upward rotation and posterior title during shoulder movement and have also shown altered scapulothoracic muscle activation, including increased upper trapezius activity and decreased lower trapezius and serratus anterior activity (Ludewig and Cook 2000; Lin et al. 2011). Late recruitment of all the scapulothoracic muscles during arm elevation also has been demonstrated in patients with shoulder impingement syndrome (Moraes et al. 2008).

Since rotator cuff and scapulothoracic muscles play an important role in shoulder stability, exercises to strengthen the rotator cuff and scapulothoracic muscles are recommended for shoulder injuries (Cricchio and Frazer 2011; Reinold et al. 2009). These exercises are performed with shoulder movements in which the rotator cuff and scapulothoracic muscles show high muscle activity. It also has been emphasized that the movements selectively activate the rotator cuff and scapulothoracic muscles with low activation levels of the deltoid, upper trapezius or pectoralis major in order to restore the balance and coordination between these muscles (Reinold et al. 2004; Reinold et al. 2007; Decker et al. 2003; Ellenbecker and Cools 2010). However, while most of the studies focused on pain and function improvement (Bennell et al. 2010; Brox et al. 1993; Brox et al. 1999; Ludewig and Borstad 2003), only a few studies have examined whether the neuromuscular control changes during the movement after the training, which is the rationale behind the exercises. Although in general exercises lead to an increase of shoulder muscles strength (Wang et al. 1999; McClure et al. 2004; Padua et al. 2004), there are no reported change in the scapular kinematics after the exercise training (McClure et al. 2004; Hibberd et al. 2012). Only one study has investigated scapulothoracic muscle activation during movement after exercise and showed that the ratio of upper trapezius to serratus anterior activity decreased after training (De Mey et al. 2012). It is currently unknown whether rotator cuff and scapulothoracic muscle strengthening exercise result in neuromuscular adaptations during dynamic movement.

Therefore, the purpose of this study was to investigate the effect of exercise on shoulder kinematics and muscle activity. We hypothesized that after strength training of the rotator cuff and scapulothoracic muscles, the activation of rotator cuff, lower trapezius and serratus anterior would increase during arm elevation while the activation of deltoid and upper trapezius would decrease or remain the same during arm elevation.

Methods

Subjects

Thirty-six healthy subjects were recruited from the University of Oregon. Subject exclusion criteria for the study were as follows: 1) prior shoulder and cervical surgery; 2) presence of shoulder and neck pain and injuries; 3) history of cervical or shoulder pain or pathology in past 3 years; 4) a concussion within the past 12 months or a history of 3 or more concussions; 5) brain injury and neurological impairment; 6) history of seizures; 7) taking anti-seizure and anti-depressive medication; 8) pacemaker and other magnetic implant; 9) pregnancy and 10) participation on a NCAA sports team. The study was approved by the Office for Protection of Human Subjects at the University of Oregon and all subjects signed an informed consent form.

Procedure

Subjects were randomly assigned into either a control or training group during their first visit to the lab. The age, height and weight of subjects in both groups were similar, with no significant between-group difference (Table 4.1). Shoulder kinematics and electromyography (EMG) of the dominant arm were assessed at baseline and 4-5 weeks later for both groups. For the control subjects, these were the only two visits to the lab and they were asked to maintain their normal activity level between visits. For the subjects in the training group, there were two additional visits for exercise intensity evaluation, and 12 visits for exercise training. Intensity evaluation, 10 repetition maximum (RM), was assessed before the start of exercise training and between the sixth and seventh visits.

Table 4.1. Subject characteristics: means (standard deviations)

	Training (n = 18)	Control (n = 18)	*p*
Age (y)	20.3 (1.9)	21.1 (3.9)	0.42
Height (cm)	167 (10)	168 (10)	0.77
Weight (kg)	67.3 (12.3)	65.8 (14.0)	0.73
Sex	9M, 9F	8M, 10F	
Dominant side	16R, 2L	16R, 2L	

* Independent *t* test was used to examine the difference between groups. M: male, F: female. R: right-hand dominant, L: left-hand dominant.

Kinematics

Thoracic, scapular and humeral kinematics were sampled at 120 Hz with a magnetic tracking device (Polhemus Liberty, Colchester, VT), which included a transmitter, three sensors, and a digitizer. The sensors were mounted on the manubrium of the sternum, the flat area of the acromion, as well as on the distal humerus via a custom-molded Orthoplast^{TM} cuff and Velcro^{TM} strap (Suprak et al. 2006; Ludewig and Cook 2000). The transmitter was positioned posterior and contralateral to the testing arm of the subject. The subject sat on an ergonomically designed kneeling chair (Better Posture Kneeling Chairs, Jobri® , Konawa, OK) (Figure 4.1).

Anatomic landmarks were palpated and digitized, using the standards recommended by the International Society of Biomechanics (ISB) (Wu et al. 2005). The thoracic anatomic coordinate system was derived from T8, C7, the xiphoid process and the jugular notch. The digitization points for the scapula were the root of the scapular spine, inferior angle of the scapula, and laterodorsal point of acromion. The humeral coordinate system was defined with the second option in the ISB proposed standard, which includes the center of the humeral head, medial epicondyle, lateral epicondyle, ulnar styloid process and medial styloid process (Wu et al. 2005). The center of the humeral head was calculated using a least squares algorithm and was defined as the point that moved the least during several small arcs of motion (Harryman et al. 1992).

After the digitization and calibration process, the kinematics data were converted from sensor coordinate systems to anatomic coordinate systems. Humerothoracic and scapulothoracic motion was calculated. Based on the ISB standard, for humerothoracic motion, the following Euler sequence was used: plane of elevation, elevation and axial rotation. For scapulothoracic motion, the Euler sequence was posterior/anterior tilting, upward/downward rotation, and internal/external rotation (Wu et al. 2005).

EMG

The Myopac Jr (Run Technologies, Mission Viejo, CA) was used to collect raw EMG data of the middle deltoid, supraspinatus, infraspinatus, upper trapezius, lower trapezius, and serratus anterior. This unit provided signal amplification, band pass filtering (10 – 1000Hz), and a common mode rejection ratio of 110 dB. Output from the Myopac was linked to an analog to digital board and data were sampled at 1000 Hz.

Customized fine-wire electrodes were used for supraspinatus and infraspinatus. The fine-wire electrodes were prepared with a two-inch hypodermic needle with 25 Ga (Covidien/Kendall Monoject™ hypodermic needle, Minneapolis, MN) and four 22 cm long wires. The wires were 200 μm diameter, Stablohm 800, annealed, and HPN-green insulation. The four wires were spun and twisted together and different length of hooks were formed at the tips of the wires. The green insulation of the tips of the hooks was removed for recording, but only two of the four wires were used to record EMG. The other two hooks of the wires helped anchor the electrodes in the muscles. For the supraspinatus, the electrodes were inserted at 2.5 cm above the midpoint of scapular spine and to the bottom of the supraspinous fossa (Perotto et al. 2005). For the infraspinatus, the fine-wire electrodes were inserted at the midpoint of the inferior angle of scapula and the midpoint of scapular spine and to the bottom of infraspinous fossa (Geiringer 1999). To confirm the fine-wire stayed in the supraspinatus, muscle contraction of the upper trapezius and supraspinatus in shoulder shrug and abduction with arm at the side was tested before and after the TMS testing. If the EMG amplitude of supraspinatus in shrug and abduction is similar, which implied the fine-wire electrodes were in upper trapezius, instead of supraspinatus, the data would not be used in data calculation.

The middle deltoid, upper trapezius, lower trapezius and serratus anterior were measured with surface EMG electrodes (Bio-protech Inc, Wonju si, Gangwon-do, Korea). The electrodes of middle deltoid were placed at the lateral aspect of the arm approximately 3 cm below the acromion for the middle deltoid (Cram et al. 1998). The electrodes for upper trapezius were attached to the midpoint of the acromion and C7 (Cools et al. 2003; Hsu et al. 2009). The electrodes of lower trapezius were placed at the midpoint of the root of the scapular spine and T7 (Cools et al. 2003; Hsu et al. 2009). For the serratus anterior, the electrodes were attached on the midaxillary line and in front of latissimus dorsi when the arm was flexed at 90°. (Ludewig and Cook 2000).

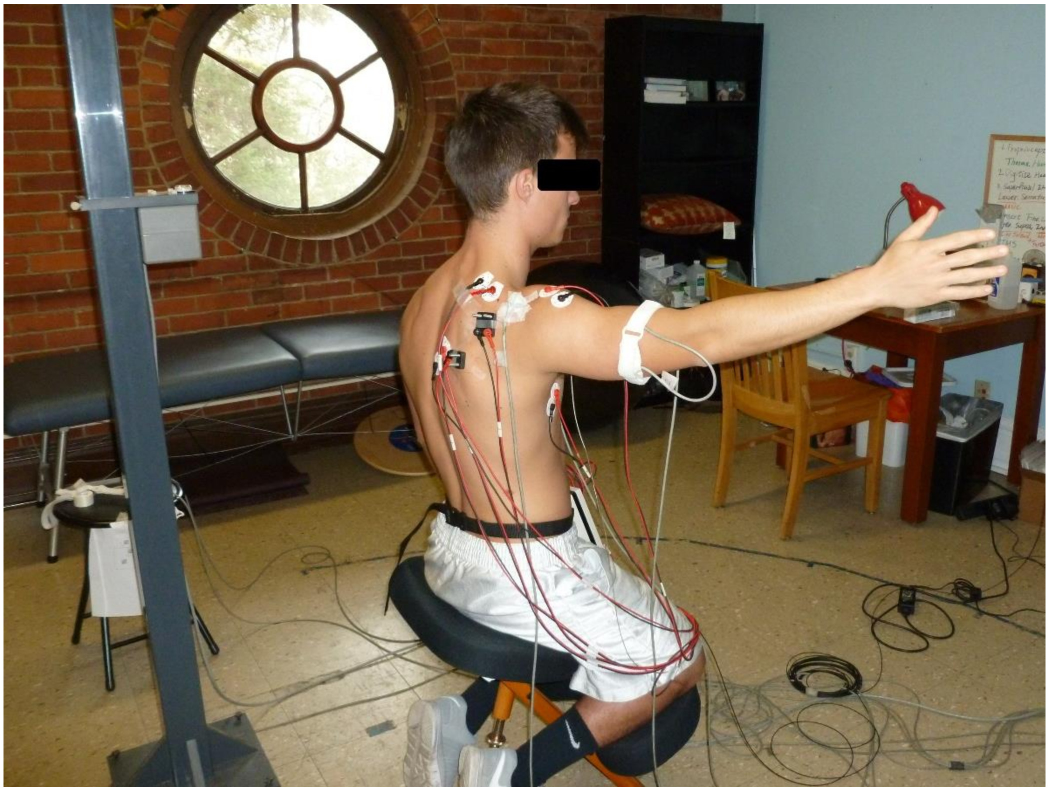
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Figure 4.1. The testing position and the sensor placement

<u>Forces and EMG of maximum voluntary contraction</u>

Three trials of maximum voluntary contraction (MVC) during a five-second contraction were conducted in a specific testing position for each muscle. There were approximately 30 seconds of rest between trials and one minute of rest between muscles.

The force during the MVC was also measured simultaneously. The MVC of the middle deltoid, supraspinatus and upper trapezius was measured with abduction in the scapular plane at 90° of humeral elevation with neutral position in axial rotation (Reinold et al. 2007; Ludewig and Cook 2000). The resistance was applied on the wrist by a load cell (Lebow, Troy, MI) mounted on the wall and the load cell measured the elevation force simultaneously. For other measures of MVC forces, a handheld dynamometer micro FET2 (Hoggan Scientific, Salt lake city, UT) was used and positioned at the wrist joint. The infraspinatus MVC was tested by resisted external rotation with arm at the side and 90° of elbow flexion (Alpert et al. 2000). The lower trapezius MVC was tested in a prone position with horizontal abduction in 120° of elevation in line with the fibers of the lower trapezius and the thumb pointing upward (Ekstrom et al. 2005). For the serratus anterior, the MVC was measured with 135° of abduction in the scapular plane (Ekstrom et al. 2005).

The amplitude of MVC was calculated by taking the root mean square (rms) of the middle 1.5 seconds of the muscle contraction. The maximum rms of the three MVC EMG was used for normalization. For the force measured by the load cell, the force was calculated by the mean of the middle 1.5 seconds of the muscle contraction. The dynamometer recorded the peak force of the muscle contraction. The MVC force measures were average across three trials.

Testing protocol

After MVC testing, the subjects were instructed to perform three arm elevation trials in the scapular plane. To maintain humeral elevation in the scapular plane, the subjects were asked to point their hand to a pole 1.5 meters away or a target they found on the wall. The speed of the movements was control by a metronome. Each elevation trial was performed for eight seconds, four-second ascending and four-second descending. The subject was allowed to practice for three to five trials to help become familiarized with the motion. A customized LabVIEW program (Version 2012, National Instruments, Austin, TX) was used to collect the shoulder kinematics and EMG during arm elevation. The kinematics and EMG data were synchronized.

Exercise training

The subjects in the control group were instructed to maintain their normal activities of daily living while the subjects in the training group were trained three times per week for four weeks with an average duration of 30 minutes per session. All training sections were supervised to ensure compliance with the training protocol. The subjects in the training group performed strengthening and neuromuscular exercises to target the rotator cuff and scapulothoracic muscles.

The strengthening exercises included full can, sidelying external rotation, diagonal exercise, prone full can at 100° of abduction (Figure 4.2, Table 4.2). These exercises were chosen due to that those exercises could specifically generate higher level of muscle activation (Reinold et al. 2009; Reinold et al. 2007). The exercise intensity, 10 RM, was tested before the first visit of the exercise training and measured again in the third week, before the seventh training section. The strengthening training consisted of three sets of 10 repetitions using variable resistance: one set at 50% of the 10 RM, one at 75% of the 10 RM, and one at 100% of the 10 RM (Padua et al. 2004).

The neuromuscular training consisted of the following upper extremity weight-bearing exercises: push-up with plus and push-up position on an exercise ball. These exercises have been shown to facilitate the co-contraction of shoulder muscles as well as strengthen the serratus anterior (Myers and Oyama 2009; Ubinger et al. 1999). For the push-up with plus, the subjects were instructed to push up and protract their shoulder with a straight elbow for 15 – 40 repetitions, depending on the subject's ability. If the subjects were not able to perform the regular push-up, they started with the push-up with a quadruped position and then progressed to the push-up on toes. For the push-up position on an exercise ball, subjects maintained the push-up position with their hands on an exercise ball for five repetitions with 15 seconds for each repetition. The push-up position on the ball was from a quadruped position to a push-up position on toes to a single-arm push-up position (Padua et al. 2004) (Figure 4.2, Table 4.2). A wobble board was used if the subject was unable to maintain their position on the ball. The interval between sets were one minutes. There was a rest period of three minutes between each exercise.

Data reduction

For scapular kinematics, anterior/posterior tilt, upward/downward rotation, internal/external rotation, were calculated at 30°, 60°, 90°, and 120° (McClure et al. 2006; Ludewig and Cook 2000). The root mean square EMG data were normalized by the MVC amplitude and calculated over three 30° increments of motion during arm elevation from 30° to 120°, including 30° - 60°, 60° - 90°, and 90° - 120° (Reddy et al. 2000).

Table 4.2. Exercises for four-week exercise training

Exercise	**Target**	**Reference**
Full can	Supra	Reinold et al. (2007)
Prone full can	Supra, infra, LT	Reinold et al. (2007), Cools et al. (2007)
Sidelying external rotation	Infra, LT	Reinold et al. (2004), Cools et al. (2007)
Diagonal exercise	Sub, LT, SA, TM	Decker et al. (2003), Myers et al. (2005)
Push-up with plus	Sub, SA, proprioception	Decker et al. (2003), Ludewig et al. (2004), Rogol et al. (1998)
Push-up position on an exercise ball	Shoulder stability Cocontraction	Ubinger et al. (1999)

Supra, supraspinatus; infra, infraspinatus; sub, subscapularis; TM, teres minor; LT, lower trapezius; SA, serratus anterior

Figure 4.2. The exercises for rotator cuff and scapulothoracic muscles. a) full can, b) prone full can, c) sidelying external rotation, d) diagonal exercise, e) push up with plus and f) push-up position on an exercise ball

Statistical analysis

A three-way, mixed-effects analysis of variance (ANOVA) was used to examine the effect of exercise on shoulder kinematics. Angle (30°, 60°, 90°, and 120°) and time (pre-training and post-training) were the within subject effect. The between-subject effect was group (control and training groups).

For shoulder EMG, because we were concerned with differences in pre-training EMG between groups, a two-way ANCOVA was run to test the difference of the post-training EMG between groups. The pre-training EMG amplitudes at different levels of elevation were averaged for each muscle and the averaged pre-training EMG amplitude was used as covariance. The dependent variable was the EMG of the post-training test. The within-subject effect was angle range, including 30° - 60°, 60° - 90°, and 90° - 120°. The between-subject effect was group (control and training groups). When there was an interaction effect, pairwise comparisons were conducted to examine difference between groups.

The changes in the MVC force from the first visit to the second visit were calculated. An independent *t* test was used to examine the difference of the change scores in the MVC forces between groups. The significant level was set at 0.05 for all analyses.

Results

All the subjects in the control group completed two shoulder kinematics and EMG assessments. One subject in the training group did not finish the exercise training and the second shoulder kinematics and EMG assessment due to personal reasons. Other subjects in the training group completed all the training sections and two assessments. In one subject in the control group and one in the training group, it was found that the fine-wire electrodes of the supraspinatus had likely slid into the upper trapezius in the post-training test. This assertion was based on the comparison of the supraspinatus EMG between the two testing contraction: shoulder shrug and abduction with arm at the side. The data of these subject were not included in the analysis.

For MVC force measures, there were significant differences of the changes after the training between the control and training groups in the forces of the elevation at 90°, external rotation with arm at the side, and horizontal abduction in 120° of elevation (p = 0.026, p = 0.019 and p = 0.004 respectively). No difference between groups was found in the force of 135°of elevation (p = 0.918) (Figure 4.3)

For scapular kinematics (anterior/posterior tilt, upward/downward rotation, internal/external rotation), the three-way ANOVA showed that although there was a significant angle effect ($p < 0.05$), there was no significant difference in either three-way interaction (angle x time x group) or two-way interaction of group and time, angle and group, and time and angle ($p > 0.05$) (Figure 4.4).

For the EMG measures, the ANCOVA showed there was no significant interaction effect of group and angle effect in the deltoid, supraspinatus and infraspinatus ($p > 0.05$) (Figure 4.5). There was an angle effect (p = 0.022) and there was a group difference in the upper trapezius EMG after four weeks (p = 0.004) with no interaction of angle and group (p =0.16). The group effect of the serratus anterior after four week was close to the significance level (p = 0.056) with no interaction effect (p = 0.14) and no angle effect (p = 0.12). There was an angle effect of the lower trapezius (p = 0.003) but there was no interaction of angle and group ($p > 0.05$), no angle effect ($p > 0.05$) and no group effect ($p > 0.05$) for other EMG measures (Figure 4.6).

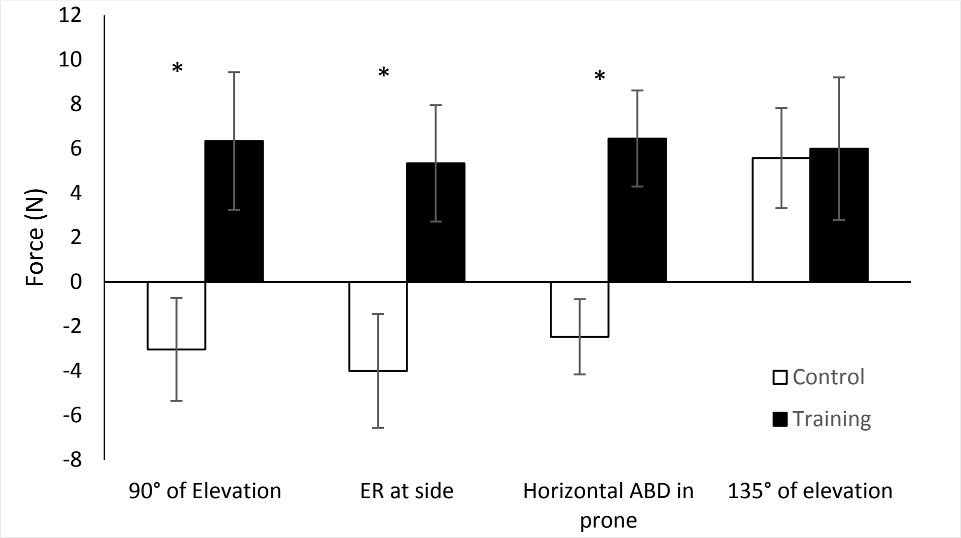

Figure 4.3. The changes of the forces from pre-training to post-training in control and training groups. The maximum voluntary contraction (MVC) forces of deltoid, supraspinatus and upper trapezius was measured with abduction (ABD) in the scapular plane at 90° of elevation with neutral position in axial rotation. The infraspinatus MVC force was by resisted external rotation with arm at the side. The lower trapezius MVC was tested in a prone position with horizontal ABD in 120° of elevation. The serratus anterior MVC was measured with 135° of ABD in the scapular plane.

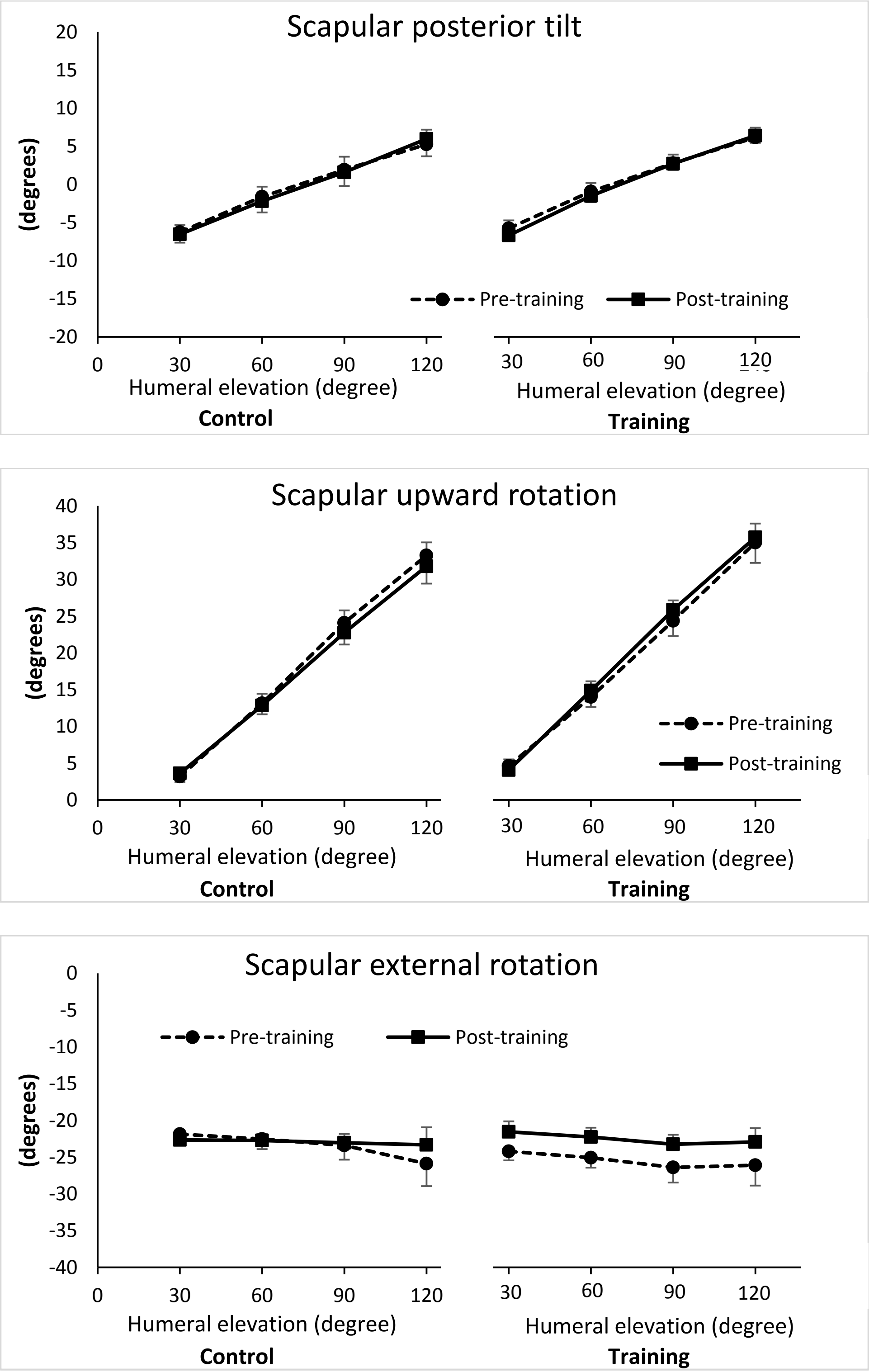

Figure 4.4. The scapular kinematics of the pre-training and post-training in the control and training group. a) scapular anterior/posterior tilt, b) upward/downward rotation, c) internal/external rotation

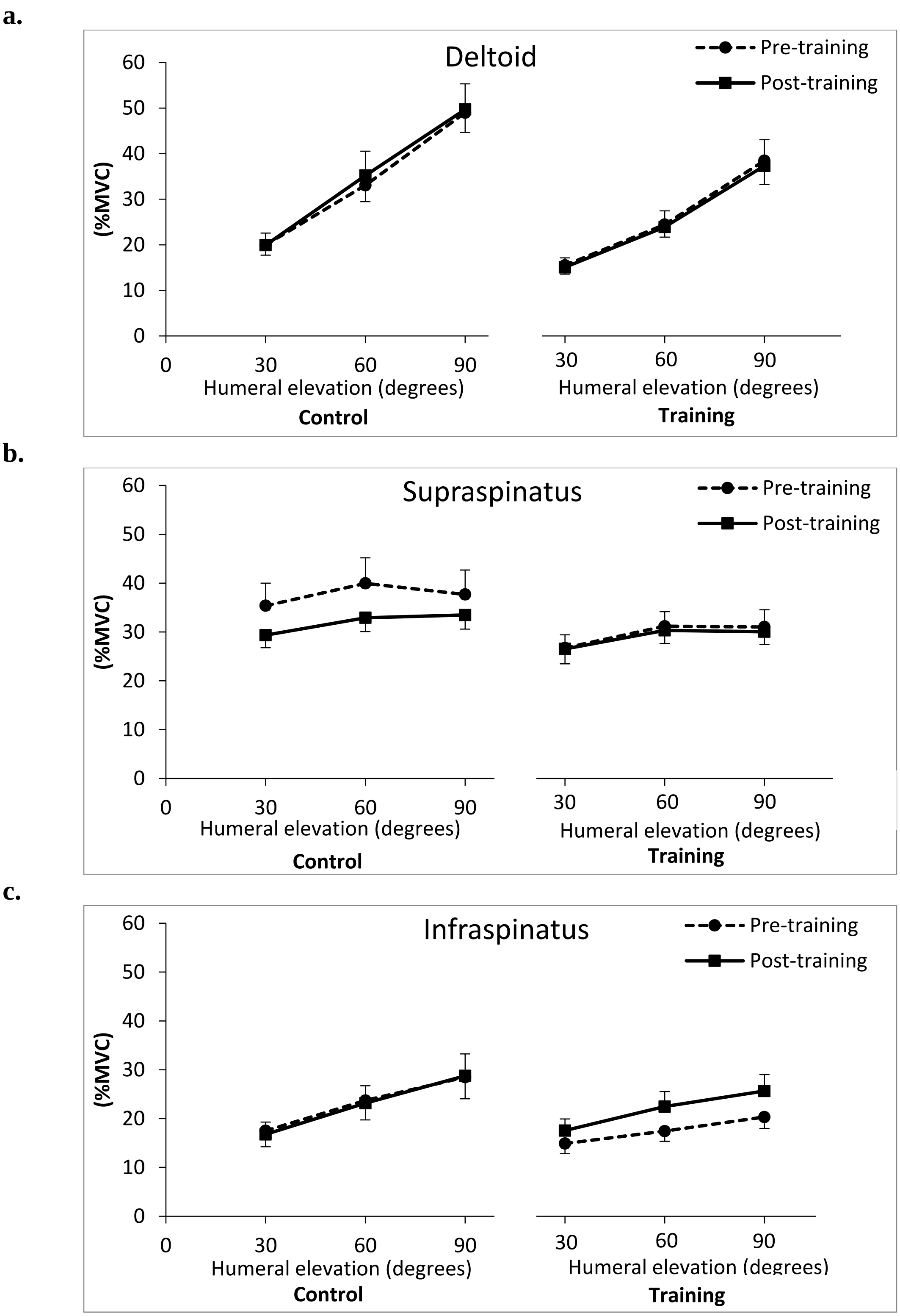

Figure 4.5. The electromyography of the deltoid and rotator cuff muscles of pre-training and post-training in the control and training groups. a) deltoid, b) supraspinatus, and c) infraspinatus. MVC: maximum voluntary contraction.

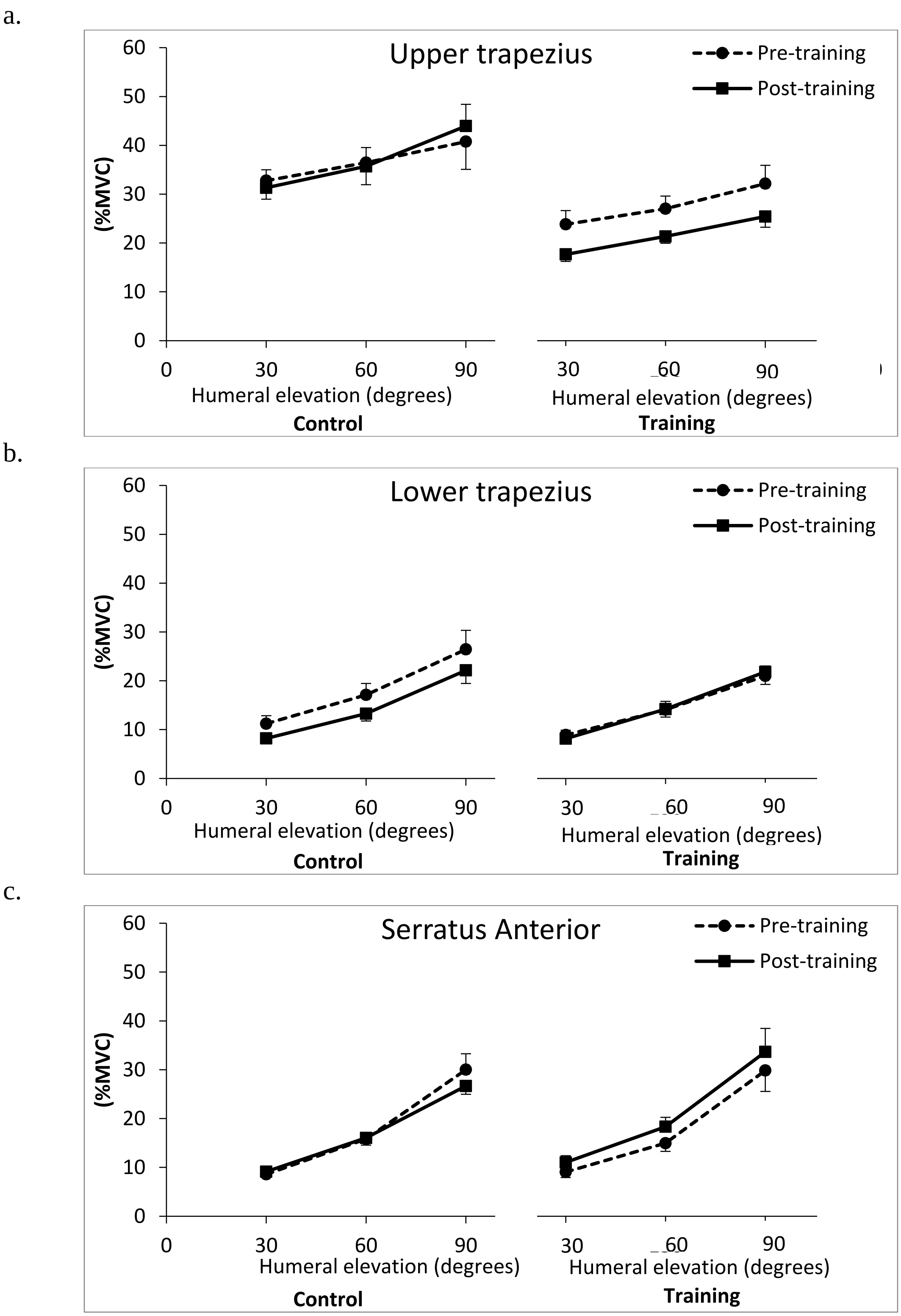

Figure 4.6. The electromyography of the scapulothoracic muscles of pre-training and post-training in the control and training groups. a) upper trapezius, b) lower trapezius, and c) serratus anterior. MVC: maximum voluntary contraction.

Discussion

Strengthening and neuromuscular control training for the rotator cuff and scapulothoracic muscles is an essential part of shoulder rehabilitation. Although many studies have investigated which exercises induced high EMG of rotator cuff and scapulothoracic muscles (Reinold et al. 2009; Reinold et al. 2007), only a few studies examined the effect of the exercise on the shoulder neuromuscular control, including shoulder kinematics and EMG (McClure et al. 2004; Hibberd et al. 2012; De Mey et al. 2012). Therefore, in the present study, healthy young subjects were trained with strengthening and neuromuscular control exercises for rotator cuff and scapulothoracic muscles over a four week period. By comparison with the subjects in the control group, the subjects receiving the four-week exercise demonstrated significant increases in most of the force measures, significant decrease in EMG of upper trapezius and a trend of increasing EMG of the serratus anterior, while there was no difference in scapular kinematics and the EMG of the deltoid and rotator cuff muscles.

In the present study, we included full can, prone full can and sidelying external rotation exercises to strengthen the supraspinatus and infraspinatus muscles, as well as used closed-train exercise to facilitate cocontraction. Although the forces during elevation and external rotation at side significantly increased, compared to that of the control subjects, the activation of the supraspinatus and infraspinatus during arm elevation did not change after training. The supraspinatus and infraspinatus are stabilizers of the glenohumeral joint and also serve as an abductors and external rotators (Sangwan et al. 2015). We selected exercises to train the supraspinatus and infraspinatus to become a stronger abductors and external rotators and also used closed-chain exercise to induce cocontraction of all the muscles around the shoulder. However, the training effect did not transfer to their roles as the stabilizer during the open-chain arm movement: the supraspinatus and infraspinatus did not contribute more during arm elevation even though they become stronger. This result shows the difficulty in changing the activation pattern of the rotator cuff in the healthy subjects. The present study is the first study investigating the muscle activation of the rotator cuff muscles after exercise. Future work should examine the effect of exercises in the subjects with shoulder injuries. Because exercise reduces pain and increases strength of weak muscles (McClure et al. 2004), the activation of rotator cuff may change with the removal of pain inhibition.

Patients with shoulder impingement syndrome demonstrate greater upper trapezius activation and less lower trapezius and serratus anterior activation (Struyf et al. 2011; Lin et al. 2011; Ludewig and Cook 2000; Diederichsen et al. 2009). Greater upper trapezius activation is believed to compensate for less serratus anterior activation because serratus anterior substantially produce scapular upward rotation and posterior tilt (Johnson et al. 1994; Ludewig and Reynolds 2009).We found after a four-week exercise training program, the activity of upper trapezius decreased significantly and there was a trend of increasing serratus anterior throughout the arm elevation. This is similar to the findings of De Mey et al. (2012). They found the activity of upper trapezius decreased during arm elevation with a decreased ratio of upper trapezius activation to serratus anterior activation after a six-week scapular muscle rehabilitation for overhead athletes with shoulder impingement syndrome. Therefore, the shoulder strengthening exercise not only can decrease pain and improve function, but also can also change the activation patterns of the scapulothoracic muscles. The activation patterns of scapulothoracic muscles, less upper trapezius and greater serratus anterior activation, during the exercise training can be transferred to functional shoulder movement, such as arm elevation in this present study.

Altered scapular kinematics is one of the factors identified as contributing to shoulder impingement syndrome (Michener et al. 2003) and has been found in subjects with shoulder impingement syndrome (Lukasiewicz et al. 1999; Ludewig and Cook 2000; Hebert et al. 2002), especially in the patients with visible scapular dyskinesis (Lawrence et al. 2014a; Lopes et al. 2015). The altered scapular kinematics in subjects with shoulder impingement syndrome includes less scapular upward rotation and external rotation (Timmons et al. 2012). Exercises were thought to restore normal shoulder kinematics by increasing upward rotation and external rotation. However, in healthy subjects, although strengthening exercises changed the coordination of the scapulothoracic muscle activity, the changes of the activation patterns of scapulothoracic activation did not change the shoulder kinematics. In previous studies, exercise also failed to change the scapular kinematics to more upward rotated and external rotated during the shoulder movement. Wang et al. (1999) trained healthy subjects with the strengthening exercise for scapular retractors and elevators as well as shoulder abductors and external rotators, and found that the scapula showed less upward rotation and less superior translation at 90° of shoulder abduction although the strength increased after six-week exercise training. The difference in the effect of exercise between the present study and the study of Wang et al. may result from different exercise training and different assessments of kinematics.

Other studies also showed no effect of shoulder rehabilitation or strengthening exercise on scapular kinematics in patients with shoulder impingement syndrome

(McClure et al. 2004) or overhead athletes (Hibberd et al. 2012). However, Worsley et al. (2013) included motor control retraining of scapula for subjects with shoulder impingement syndrome and found scapular upward rotation and posterior tilt increased significantly after a ten-week treatment. Therefore, in addition to stretching and strengthening exercises, the training for controlling or being aware of scapular position may be necessary for patients with shoulder dyskinesis.

There are some limitations in the present study that must be addressed. The first is that since the population of subjects in the present study was young and healthy, the results may not be generalized to the population which is older or with injuries. Also, measurements of fine-wire EMG did not show good reliability (Jonsson and Bagge 1968; Morris et al. 1998), which may contribute to measurement errors. Some of the subjects complained of discomfort and mild pain (2 – 3 in numeric rating scale) during the arm elevation trials. The fine-wire may have influenced the muscle activation patterns. The duration of the exercise was four weeks, which may not be sufficient to induce neuromuscular changes for kinematics and rotator cuff EMG patterns. Finally, we did not measure subscapularis, since the shoulder injuries affect supraspinatus and infraspinatus more. Future research may need to investigate the effect of exercise on subscapularis.

Conclusion

After a four-week training protocol focusing on shoulder strengthening and neuromuscular control, strength was increased overall. However, with a decrease in EMG activity, the upper trapezius was the only muscle demonstrating a change in activation during motion (there was a trend of an increase for the serratus anterior). Of particular interest is that while the exercise succeeded in increasing rotator cuff strength, these gains did not transfer to an increase in muscle activation during motion. Thus, the benefits of this exercise program on joint stability are questionable. Additionally, there were no changes in scapular kinematics after the exercise protocol, demonstrating the difficulty in changing this movement pattern in healthy subjects. Future work should focus on the effects of exercise in the subjects with shoulder injuries.

Bridge

This chapter (Chapter IV) is a part of the third study in this dissertation, which investigated the effect of the exercise on the sensorimotor system. The sensorimotor system consists of the sensory afferent, control of the central nervous system, and motor output. We investigated changes of motor output, including kinematics and muscle activation in this chapter. In the next chapter (Chapter V), the focus is on the effect of exercise on the sensory system (proprioception).

CHAPTER V

THE EFFECTS OF EXERCISE ON SHOULDER PROPRIOCEPTION

Introduction

Proprioception is peripheral afferent input providing information about joint position sense (JPS), kinesthesia and sensation of resistance. The afferent inputs originate from receptors, including muscle spindles and Golgi tendon organs in the musculotendinous structures as well as the mechanoreceptors in the joint capsule, ligament and tissue surrounding the joint (Riemann and Lephart 2002b). Proprioception is involved in reflex arcs contributing to joint stabilization (Borsa et al. 1994) and automatic movement (Riemann and Lephart 2002b) as well as motor planning and strategy (Myers and Oyama 2009).

For the shoulder complex, due to the inherent lack of stability provided by the bony, ligamentous, and capsular structures, proprioception input is essential for the central nervous system to regulate the neuromuscular control in order to maintain functional joint stability. Subjects with shoulder impingement syndrome (Machner et al. 2003; Anderson and Wee 2011), anterior glenohumeral dislocation history (Smith and Brunolli 1989), and shoulder instability (Lephart et al. 1994) have demonstrated proprioception deficits when compared to their uninjured shoulder. In addition to directly affect passive stability, it is possible that injured or loose ligaments, capsules, and muscles also affect the proprioception afferent input. Proprioception deficits may result in impaired neuromuscular control, which could ultimately lead to muscle imbalance and joint instability. The microinjuries resulting from joint instability can aggravate these proprioception deficits. This vicious cycle may be a factor in the development of chronic shoulder pain and the high recurrent rate of shoulder dislocation (Lephart and Henry 1996).

It has been postulated that exercise can enhance proprioception by modulating the sensitivity of the muscle spindle or learning to pay more attention to the joint position (Swanik et al. 1997; Ashton-Miller et al. 2001). Several studies have investigated the effect of the exercises on shoulder JPS in healthy subjects, including open-chain exercise (Rogol et al. 1998; Padua et al. 2004; Salles et al. 2015), closed-chain exercise (Rogol et al. 1998; Padua et al. 2004), plyometric training (Heiderscheit et al. 1996; Swanik et al. 2002), and proprioceptive neuromuscular facilitation (Padua et al. 2004). However, the results of exercise training are not consistent, even with the same type of exercises (Padua et al. 2004; Salles et al. 2015; Swanik et al. 2002; Heiderscheit et al. 1996; Rogol et al. 1998).

Most of the exercises used in previous studies are advanced exercises for athletic training. In the treatment of shoulder impingement syndrome or instability, the exercises to strengthen rotator cuff and scapulothoracic muscles are recommended for shoulder injuries (Cricchio and Frazer 2011; Reinold et al. 2009). In order to restore the balance and coordination between muscles, those exercises are performed with shoulder movements in which the rotator cuff and scapulothoracic muscles show high muscle activity and the shoulder movements which selectively activate the rotator cuff and scapulothoracic muscles with low activation levels of the deltoid, upper trapezius or pectoralis major (Reinold et al. 2004; Reinold et al. 2007; Decker et al. 2003; Ellenbecker and Cools 2010). However, to our knowledge, only one study used specific exercises targeting the rotator cuff and scapulothoracic muscles with open-chain exercises (Padua et al. 2004). However, in clinical practice, rehabilitation exercises typically contain both open-chain and closed-chain exercises (Cricchio and Frazer 2011; Reinold et al. 2009).It is still unknown if strengthening exercises for rotator cuff and scapulothoracic muscles improved the shoulder proprioception.

Previous studies have investigated JPS using the positions of internal and external rotation (Padua et al. 2004; Salles et al. 2015; Swanik et al. 2002; Heiderscheit et al. 1996; Rogol et al. 1998). Although this testing position, which limited the shoulder motion to one-dimension and is easier to test, is a functional position for overhead athletes, it blocks the scapular movement and is not functional motion for general population. Therefore, the purpose of the present study was to examine the effects of the rotator cuff and scapulothoracic muscle strengthening exercises on shoulder proprioception during an arm elevation motion. The proprioception of humerothoracic (HT), glenohumeral (GH) and scapulothoracic (ST) would be examined. It was hypothesized that the JPS errors of HT, GH and ST joints would decrease after the rotator cuff and scapulothoracic muscle strengthening exercise training.

Methods

Subjects

Thirty-six healthy subjects were recruited from the University of Oregon. The details of the subject exclusion criteria were described in the subject section of Chapter IV. The study was approved by the Office for Protection of Human Subjects at the University of Oregon and all subjects signed an informed consent form.

Procedure

Subjects were randomly assigned into either a control or training group during their first visit to the lab. The age, height and weight of subjects in both groups were similar, with no significant between group difference. The characteristics of the subjects were described in Chapter IV (Table 4.1). The shoulder proprioception of the dominant arm was assessed at baseline and 4-5 weeks later for both groups. For the control subjects, these were the only two visits (for proprioception assessment) and they were asked to maintain their normal activity level between the visits. For the subjects in the training group, there were two additional visits for exercise intensity evaluation, and 12 visits for exercise training. Intensity evaluation, 10 repetition maximum (RM), was assessed before the start of exercise training and between the sixth and seventh visits.

Exercise training

The subjects in the control group was instructed to maintain their normal activities of daily living while the subjects in the training group were trained three times per week for four weeks with an average duration of 30 minutes per session. All training sections were supervised to ensure compliance with the training protocol. The subjects in the training group performed strengthening and neuromuscular exercises to target the rotator cuff and scapulothoracic muscles, including full can, sidelying external rotation, diagonal exercise, prone full can at 100° of abduction, push-up with plus and push-up position on an exercise ball (Reinold et al. 2009; Reinold et al. 2007; Myers and Oyama 2009; Ubinger et al. 1999; Padua et al. 2004). The details of the exercise training were described in the exercise training section of Chapter IV.

JPS measurement

JPS was tested with an active position reproduction task on the dominant shoulder. There were three target positions of HT elevation in the scapular plane (50°, 70°, and 90°). Each target position was repeated four times, resulting in 12 trials. JPS of HT and GH and ST joints was measured with a magnetic tracking device (Polhemus Liberty, Colchester, VT). The subject was fitted with a head mounted display (Z800, eMagine, Bellevue, WA). The display blocked the visual feedback for the shoulder motion as well as displayed the target angle and real-time HT angle of the subject. The visual and auditory guides during testing motion were controlled by a customized LabVIEW program (Version 2012, National Instruments, Austin, TX). Constant and variable errors were calculated to represent accuracy and precision of JPS respectively (King et al. 2013; Schmidt and Lee 2005). The details of the JPS measurement and calculation were described in Chapter III.

Force measurement

To confirm the effect of the exercise, the forces of maximum voluntary contraction (MVC) of rotator cuff and scapulothoracic muscles were measured. Three trials of MVC force measure during a five-second contraction were conducted in a specific testing position for each muscle including 90° of abduction in scapular plane, external rotation with arm at the side, horizontal abduction in 120° of elevation, and 135° of elevation in the scapular plane. The forces were average across three trials. The details of force measurement were described in Chapter IV.

Statistical analysis

The change scores of the constant errors, variable errors and force measures from pre-training to post-training were calculated. An independent *t* test was used to examine the differences of the force change scores between two groups. A two-way, mixed-effects analysis of variance (ANOVA) was used to examine the effect of exercise on the shoulder proprioception. The dependent variables were the change scores of the constant and variable errors of different joints. Angle was within subject effect. Angle had three levels: 50°, 70°, and 90°. The between-subject effect was group, control and training groups. If there was an interaction effect, pairwise comparisons were conducted. The significant level was set at 0.05.

Results

All the subjects in the control group completed two JPS assessments. One subject in the training group did not finish the exercise training and the second JPS assessment due to personal reasons. Other subjects in the training group completed all the training sections and two JPS assessments.

For MVC force measures, significant differences of the change after the training between the control and training groups were found in the forces of external rotation with arm at the side and horizontal abduction in 120° of elevation ($p = 0.011$ and $p = 0.001$ respectively). There was no difference between groups in the elevation forces at 90° and 120°of elevation ($p = 0.065$ and $p = 0.872$ respectively) (Figure 5.1).

The average of the plane of elevation was 36.7° in the pre-training test and 36.6° in the post-training test. For constant errors of the HT joint, there was no significant group by angle interaction (*p* = 0.80) as well as within-subject effect of angle (*p* = 0.43) and between-subject effect of group (*p* = 0.43). For GH constant errors, there was also no significant interaction effect (*p* = 0.93), angle effect (*p* = 0.71) and group effect (*p* = 0.30). For ST constant errors, there was also no significant interaction effect (*p* = 0.66), angle effect (*p* = 0.32) and group effect (*p* = 0.23) (Figure 5.2).

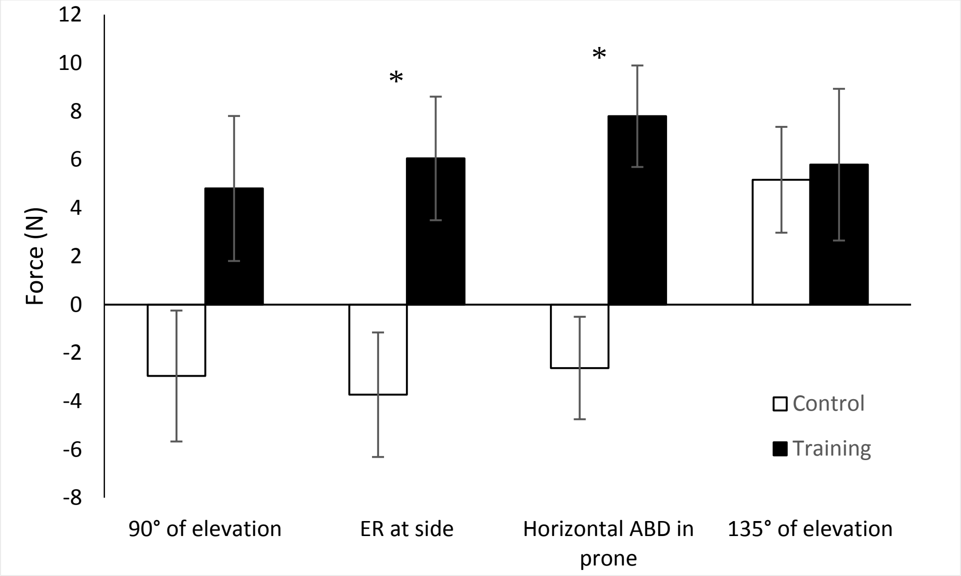

Figure 5.1. The changes of the forces from pre-training to post-training in control and training groups. The maximum voluntary contraction (MVC) forces of deltoid, supraspinatus and upper trapezius was measured with abduction (ABD) in the scapular plane at 90° of elevation with neutral position in axial rotation. The infraspinatus MVC force was by resisted external rotation with arm at the side. The lower trapezius MVC was tested in a prone position with horizontal ABD in 120° of elevation. The serratus anterior MVC was measured with 135° of ABD in the scapular plane.

For the variable errors, in HT joint, there was no significant interaction of group and angle (*p* = 0.18) as well as within-subject effect of angle (*p* = 0.93) and between-subject effect of group (*p* = 0.29). For GH constant errors, there was also no significant difference in interaction effect (*p* = 0.33), angle effect (*p* = 0.97) and group effect (*p* =

0.84). For ST constant errors, there was also no significant difference in interaction effect (*p* = 0.70), angle effect (*p* = 0.80) and group effect (*p* = 0.94) (Figure 5.3).

Discussion

It has been recommended that rehabilitation programs include exercises to restore the sensorimotor control of the patients with shoulder injuries (Borsa et al. 1994; Reinold et al. 2009; Myers et al. 2006). Exercises with active contraction are considered more appropriate for proprioceptive training because the muscle spindles and golgi tendon organs are stimulated during active contraction (Röijezon et al. 2015). Since JPS is important for shoulder neuromuscular control, we examined the effect of the four-week rotator cuff and scapulothoracic muscle strengthening exercises on shoulder JPS in the healthy subjects. After four weeks, although the changes of the forces of external rotation and horizontal abduction in prone in the training group was significantly more than those of the control groups, there were no significant differences in the changes of constant errors and variable errors between the control and training groups. For the constant errors, the HT and GT errors increased in the post-test in both control and training groups while the changes of ST errors were small in both groups, within ±1°. For the variable errors, the changes of HT, GH and ST joints in both groups after four weeks were small, within ±1°. The results showed that JPS did not improve after the four-week training and thus did not support our hypothesis.

In previous studies, the effects of open-chain and closed-chain exercises on JPS were not consistent. For the open-chain exercise, Rogol et al. (1998) and Salles et al. (2015) trained the healthy subjects with exercises involving multiple joints and big

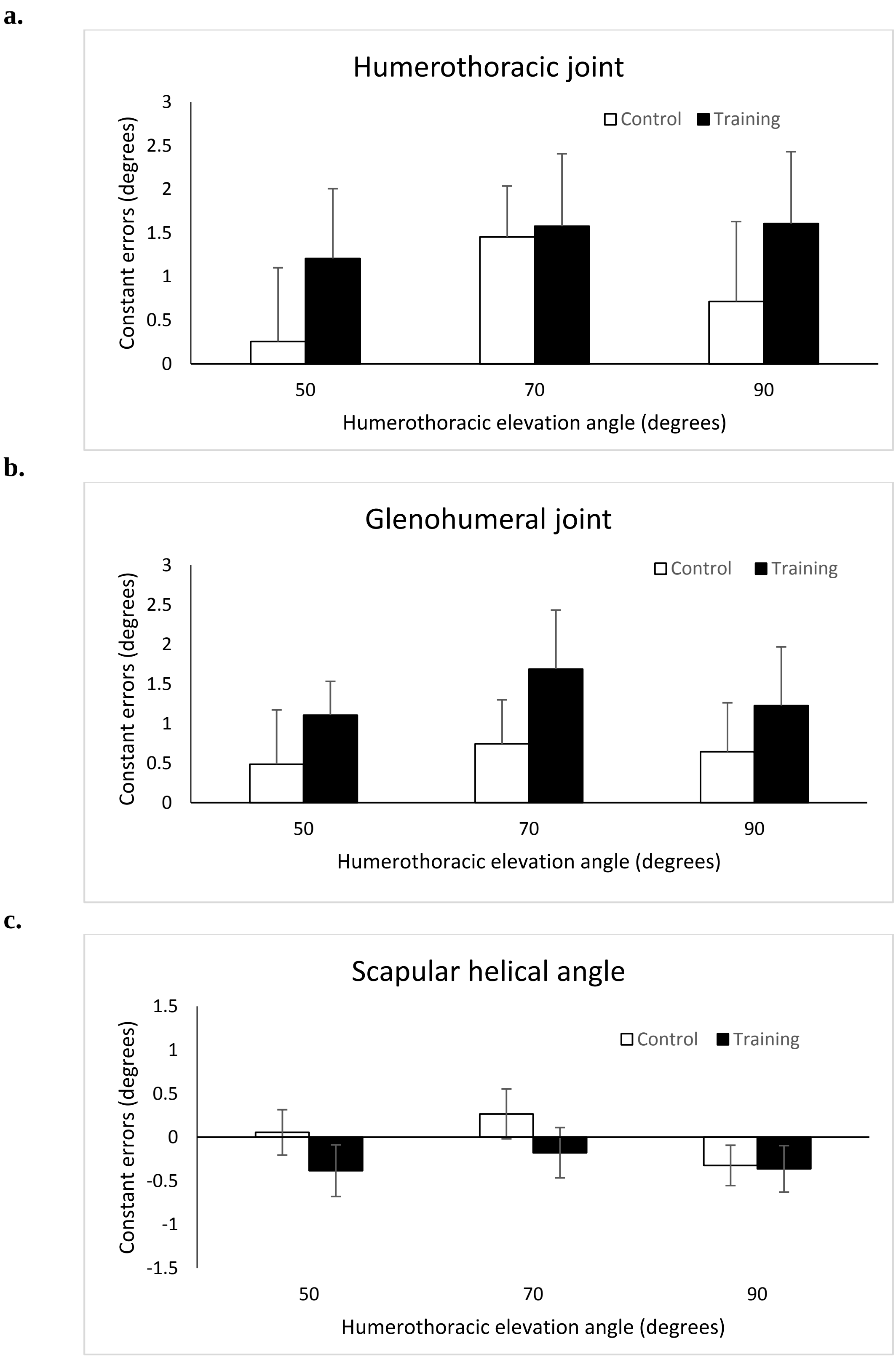

Figure 5.2. The changes of the constant errors after the exercise training in (a) humerothoracic joint, (b) glenohumeral joint, and (c) scapulothoracic joint.

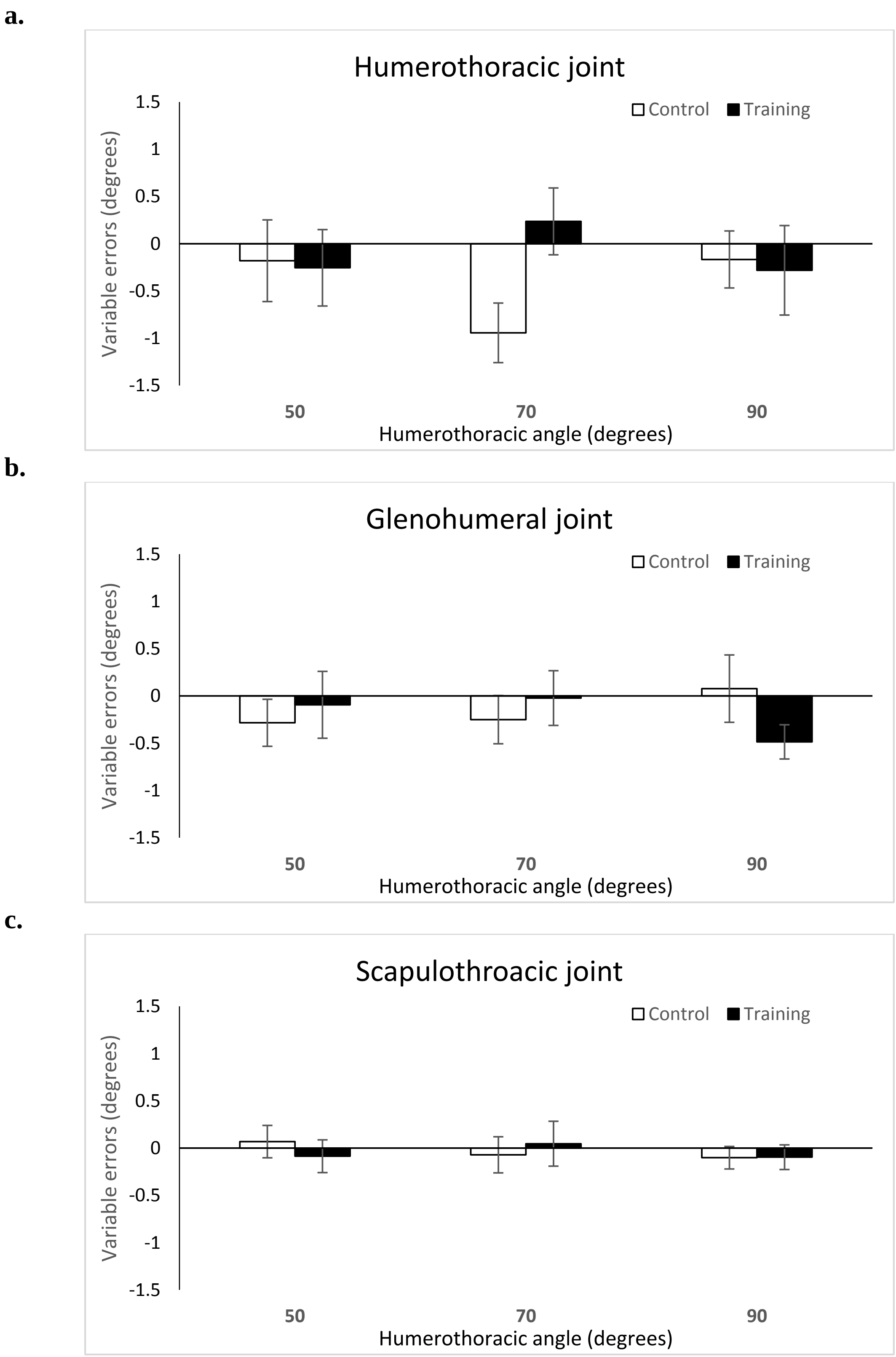

Figure 5.3. The changes of the variable errors after the exercise training in (a) humerothoracic joint, (b) glenohumeral joint, and (c) scapulothoracic joint.

muscle groups and they found the JPS improved after training. Rogol et al. (1998) trained the male healthy subjects with supine dumbbell press for six weeks. The JPS of the subjects improved after six-week training. Salles et al. (2015) also trained male healthy college subjects with the exercises of bench press, lat pull down, shoulder press and seated row. They found the JPS improved after training and the group training with higher intensity (eight to nine repetition maximum) showed less errors. However, Padua et al. (2004) chose the exercises targeting on rotator cuff and scapulothoracic muscles but found there was no effect of five-week open-chain exercises on JPS in healthy college-age subjects, although the average rotational torque significantly increased. In the present study, the four-week protocol combined closed-chain and open-chain exercises. It focused on strengthening all rotator cuff muscles with lower activation of deltoid and pectoralis major as well as strengthening lower trapezius and serratus anterior (Reinold et al. 2009; Cricchio and Frazer 2011). The JPS was not improved after the training. Considering the results of the present study and those of previous studies, the open-chain exercise involving multiple joints and large muscle groups with high intensity, such as the exercises used in the studies of Salles et al. (2015) and Rogol et al. (1998), may be more effective in improving JPS.

Although there were two closed-chain exercises in the present study, push up with plus and maintaining push-up position on the exercise ball, there was still no effect of these exercises on JPS. Closed-chain exercises are thought to train sensorimotor control for the athlete and shoulder instability (Borsa et al. 1994; Myers and Lephart 2000; Myers et al. 2006) but the effect of the closed-chain exercise is not consistent in different studies. While Rogol et al. (1998) found six-week standard push-up improved JPS in healthy subjects, Padua et al. (2004) found no changes in JPS after five weeks training with push-up position on the wobble board and exercise ball as well as using both arm to step up onto and down off a 12-inch box. Although our training protocol included push-up with plus, most female subjects started the push-up with plus in a quadruped position. Therefore, the weight bearing over shoulders was not as high as the intensity used by Rogol et al. (1998). Comparing push-up exercise with other closed-chain exercises on unstable surface, push-up exercise involved in dynamic multiple muscle contraction while closed-chain exercises on unstable surface may facilitate co-contraction as well as training feedback and feedforward motor control of shoulder (Lephart and Henry 1996; Partin et al. 1994). Therefore, according to the results of the present study and the previous studies, for proprioception training, the intensity of muscle contraction may be more important than the training of sensory feedback and feedforward during the exercise. However, further research is still needed to investigate which types of closed-chain exercise can efficiently improve JPS.

Although the strengthening exercises of rotator cuff and scapulothoracic muscles may not improve JPS in healthy subjects, there may be still an effect of strengthening exercise on JPS in subjects with shoulder injuries. Dilek et al. (2015) included rotator cuff strengthening and scapular stability exercises in the physical therapy program besides transcutaneous electrical nerve stimulation and hot pack for the patients with shoulder impingement syndrome. After 12 weeks, the JPS improved. However, Dilek et al. (2015) also found the improvement of JPS of the group with regular physical therapy was similar to that of the group trained with proprioceptive exercises, which were the closed-chain exercises with hands on different surface, in addition to physical therapy.

Naughton et al. (2005) trained patients with shoulder posterior dislocation with upper-body wobble board exercise. They found that patients improved in the movement discrimination test but there was no control group included. Therefore, since chronic pain and effusion may influence JPS centrally and peripherally (Röijezon et al. 2015), by reducing pain and decrease symptoms with exercises (Littlewood et al. 2012), JPS may be restored in patients with shoulder injuries. Future work is needed to investigate the mechanism of the improvement of JPS in the patients and whether the mechanism of improvement comes from the re-training of the sensorimotor system.

In the present study, we chose to test JPS in shoulder abduction in the scapular plane, while most previous studies used a protocol involving shoulder internal and external rotation. (Padua et al. 2004; Salles et al. 2015; Swanik et al. 2002; Heiderscheit et al. 1996; Rogol et al. 1998). This may be another reason that the results of this present study were different from the previous studies. Although internal and external rotation is a functional movement for some overhead athletes, it may not be functional for the general population. This testing position of internal and external rotation may also block the scapular movement and only test the GH joint. A systematic review and meta-analysis for the effects of shoulder injuries on proprioception showed the difference in JPS between subjects with shoulder injuries and healthy subjects were found in external rotation and abduction (Fyhr et al. 2015), especially at higher angle of abduction (Anderson and Wee 2011). Shoulder abduction requires the coordination of humerus and scapula. Thus, we tested the JPS of HT joint as well as the JPS of GH and ST joints. Although we did not find the difference in JPS after exercise training, future research may still need to investigate the effect of treatment on JPS in abduction.

The duration of the exercise training may help explain why we found no improvement after the training. Although some of the force measures increase after the training, training for four weeks may not be sufficient for sensory adaptions. Another limitation is that the subjects in the present study were young healthy students. The result of this present study may not be generalized to an older population.

Conclusion

After a four-week rotator cuff and scapular strengthening training protocol, involving both closed-chain and open-chain exercises, subjects did not demonstrate any improvement in JPS, compared to those in the control group. This is in contrast to previous studies (Rogol et al. 1998; Salles et al. 2015), which have demonstrated improvements with exercise including multiple big muscles and higher intensity. Therefore, the types and intensity of the exercise may explain why there was no improvement in JPS in the present study. Future work is needed to further investigate which types of exercise are more effective in improving JPS, and the mechanisms associated with those changes.

Bridge

This chapter (Chapter V) is the second part of the third study in this dissertation, which investigated the effect of the exercise on the sensorimotor system. The sensorimotor system consists of the sensor afferent, control of the central nervous system, and motor output. We presented the effect of the exercise on the sensory system, (joint position sense of shoulder). The next chapter (Chapter VI) explores the effect of exercise on the control of the central nervous system (corticospinal excitability).

CHAPTER VI

THE EFFECTS OF EXERCISE ON THE CORTICOSPINAL EXCITABILITY OF THE DELTOID AND SUPRASPINATUS

Introduction

The human shoulder complex relies on neuromuscular control to maintain stability because the bony congruence, ligament and capsule of the shoulder allows a large range of motion (Donatelli 2004; Myers and Lephart 2000). For the glenohumeral joint, neuromuscular control includes the coordination between deltoid and rotator cuff muscles (supraspinatus, infraspinatus, teres minor and subscapularis). While the deltoid generates most of the torque for motion, as well as a shear force pulling the humeral head upward, the rotator cuff muscles counterbalance the deltoid forces and stabilize the humeral head in the glenoid fossa. (Kronberg et al. 1990; Poppen and Walker 1978; Yamaguchi et al. 2000). The imbalance between the deltoid and rotator cuff muscles, such as a dominant deltoid and insufficient contribution from rotator cuff, may lead to pain and injuries (Chen et al. 1999; San Juan et al. 2013).

Altered neuromuscular control has been found in patients with shoulder injuries, including altered kinematics of the glenohumeral joint (Lawrence et al. 2014b), decreased deltoid and rotator cuff muscle activity (Reddy et al. 2000), and muscle weakness (Brox et al. 1997). Altered neuromuscular control may be associated with changes in central motor control. Ngomo et al. (2015) found a decrease in corticospinal excitability of the infraspinatus in patients with rotator cuff tendinopathy, suggesting that the corticospinal excitability of the rotator cuff muscles may be affected by pain and injury.

To restore shoulder neuromuscular control, exercise is an essential part of shoulder rehabilitation and sports training (Reinold et al. 2009; Myers and Lephart 2000; Myers et al. 2006). Although in general, these exercises serve to improve shoulder function and reduced pain (Gebremariam et al. 2013; Marinko et al. 2011; Hanratty et al. 2012; Littlewood et al. 2012; Abdulla et al. 2015), the effect of the exercise on neuromuscular system is still not fully understood. Only a few studies have investigated changes in strength (McClure et al. 2004; Wang et al. 1999), scapular kinematics (Hibberd et al. 2012; McClure et al. 2004) and scapular muscle activation (De Mey et al. 2012) after exercise training.

It is still unknown if shoulder exercise training changes the corticospinal excitability of shoulder muscles. Although the effect of strengthening exercises on the corticospinal excitability has been investigated, the results are not consistent (Carroll et al. 2002; Jensen et al. 2005; Beck et al. 2007). For the muscles of the upper extremity (finger abductors, wrist extensors and elbow flexors), the corticospinal excitability decreased or maintained the same after resistance training (Carroll et al. 2002; Jensen et al. 2005; Kidgell and Pearce 2010; Carroll et al. 2009; Hortobagyi et al. 2009). For the muscles of the lower extremity (knee extensors and ankle dorsiflexors), the corticospinal excitability increases after strength training (Griffin and Cafarelli 2007; Weier et al. 2012). These inconsistent results may result from different training protocols and testing of different muscle groups (Carroll et al. 2011). In addition, the muscle groups previously tested were at more distal limbs and the muscles providing movements. The results of these distal prime movers may not generalize to proximal joint stabilizers, such as the rotator cuff muscles at shoulder joint

Shoulder exercise is designed to restore neuromuscular control with shoulder movements in which the rotator cuff muscles show high muscle intensity and the movements that selectively activate the rotator cuff muscles, with low activation level of deltoid (Reinold et al. 2009; Reinold et al. 2007) or movements that facilitate cocontraction of the rotator cuff muscles (Lephart and Henry 1996). Because the goal of the exercise is to re-educate the rotator cuff muscles to contribute more during shoulder movement, the training may be associated with both motor learning and strength training. Since motor control training is associated with increased excitability (Jensen et al. 2005), the excitability of the rotator cuff muscles may increase after the shoulder exercise training.

Therefore, the purpose of this study is to investigate the effects of shoulder exercise on corticospinal excitability of the deltoid and rotator cuff muscle in healthy subjects. We chose a four-week exercise protocol that includes rotator cuff strengthening exercises and neuromuscular training. The exercises were selected to target the rotator cuff muscles. Supraspinatus is the rotator cuff muscle that is easiest to be impinged and injured. We hypothesized that after this protocol the corticospinal excitability of the supraspinatus would increase, while that of the middle deltoid would not change.

Methods

Subjects

Thirty-six healthy subjects were recruited from the University of Oregon. The details of the subject exclusion criteria were described in the subject section of Chapter

IV. The study was approved by the Office for Protection of Human Subjects at the University of Oregon and all subjects signed an informed consent form.

Procedure

Subjects were randomly assigned into either a control or training group during their first visit to the lab. The age, height and weight of subjects in both groups were similar, with no significant between-group difference. The characteristics of the subjects were described in Chapter IV (Table 4.1). The corticospinal excitability of the deltoid and supraspinatus of the dominant side were assessed at baseline and 4-5 weeks later for both groups. For the control subjects, these were the only two visits to the lab and they were asked to maintain their normal activity level between visits. For the subjects in the training group, there were two additional visits for exercise intensity evaluation, and 12 visits for exercise training. Intensity evaluation for 10 repetition maximum (RM) was assessed before the start of exercise training and between the sixth and seventh visits.

Electromyography

Customized LabVIEW programs (Version 2012, National Instruments, Austin, TX) were used for data collection and analysis. The Myopac Jr (Run Technologies, Mission Viejo, CA) was used to collect raw electromyographic (EMG) data. This unit provided signal amplification, band pass filtering (10 – 1000Hz), and a common mode rejection ratio of 110 dB. Output from the Myopac was linked to an analog to digital board and data were sampled at 5000 Hz. Customized fine-wire electrodes were used for the supraspinatus. The fine-wire electrodes were prepared with a two-inch hypodermic needle with 25 Ga (Covidien/Kendall Monoject™ hypodermic needle, Minneapolis, MN) and four 22 cm long wires. The wires were 200 μm in diameter, Stablohm 800, annealed, and HPN-green insulation. The four wires were spun and twisted together and different length of hooks were formed at the tips each wire. The green insulation of the tips of the hooks was removed for recording, but only two of the four wires were used to record EMG. The other two hooks of the wires helped anchor the electrodes in the muscle. The electrodes were inserted at 2.5 cm above the midpoint of scapular spine and to the bottom of the supraspinous fossa to measure supraspinatus EMG (Perotto et al. 2005). Surface EMG of the middle deltoid was recorded with superficial EMG electrodes (Bio-protech Inc, Wonju si, Gangwon-do, Korea). The electrodes were place on the lateral aspect of the arm approximately 3 cm below the acromion for the middle deltoid (Cram et al. 1998). To confirm that the fine-wire stayed in the supraspinatus, muscle contraction of the upper trapezius and supraspinatus were tested under two conditions before and after the transcranial magnetic stimulation (TMS) testing protocol: a) shoulder shrug and b) abduction with arm at the side. If the EMG amplitudes of supraspinatus in the shrug and abduction were similar, which implied the fine-wire electrodes were in upper trapezius, instead of supraspinatus, the data were not used in the analysis.

The force and EMG of the maximum voluntary contraction (MVC) of the middle deltoid and supraspinatus was measured simultaneously during abduction in scapular plane at 90° of arm elevation with neutral position in axial rotation for five seconds (Reinold et al. 2007; Ludewig and Cook 2000). Three trials were conducted with a rest of approximately 30 seconds between trials. The resistance was measured at the wrist joint by a load cell (Lebow, Troy, MI) mounted on the wall.

The amplitude of MVC EMG was calculated by taking the root mean square (rms) of the middle 1.5 seconds of the muscle contraction. The maximum rms of the three MVC trials was used for normalization during TMS measurement. The mean of peak-to-peak amplitude of the middle 1.5 seconds of the muscle contraction was also calculated for normalization of data processing. The force was calculated by the mean of the middle 1.5 seconds of the muscle contraction. The MVC force measures were averaged across three trials.

Coil position

A magnetic tracking device (Polhemus Liberty, Colchester, VT) was used to provide real-time coil position with respect to the head as well as record the coil position. The device included a transmitter, two sensors, and a digitizer. One sensor was attached to the TMS coil via a customized bracket (Figure 6.1) and the other one was mounted on the forehead of subject, just above the glabella, via a custom-molded Orthoplast^{TM} cuff and Velcro^{TM} strap (Figure 6.2). To derive the anatomic coordinate system of the head, anatomic landmarks were palpated and digitized, including the tip of the nose and bilateral tragi. The Euler sequence of pitch, roll and yaw was used to calculate the orientation of the coil with respect to the head. Once the optimal position was found, the coil coordinate system with respect to the head coordinate system was recorded. The position and angles of the coil for the three axes of the head was derived and then was used to ensure that the coil was repositioned to the same spot and with the same angles after a break during the excitability measurement and during in the second visit of excitability of assessment.

Figure 6.1. The sensor attached to the coil with a customized bracket.

<u>TMS testing protocol and data analysis</u>

When the corticospinal excitability was measured, the subject was seated in a chair with a head support and the upper extremity supported at 90° of arm elevation in scapular plane, with neutral position in axial rotation (Figure 6.2). It has been showed another rotator cuff muscle, infraspinatus, demonstrated different corticospinal excitability at different elevation angles (Lin et al. 2015). Ninety degree of arm elevation was chosen because it is within a functional range of motion. A stimulator (MagStim200, Magstim Co., Whitland, UK) with a 70mm 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 the supraspinatus. Once the optimal spot was found, the position of the coil was marked on a wig cap worn by the subject and also recorded by the magnetic device. While the stimulus was applied, the subject was instructed to maintain an EMG amplitude of 10% MVC of the supraspinatus during shoulder abduction (Griffin and Cafarelli 2007). The resistance was applied at the distal humerus, close to the elbow. Responses of both the supraspinatus and deltoid were recorded. 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 raw data of the MEP amplitude were normalized by the peak-to-peak amplitude of the MVC EMG. The curve of the relationship between stimulation intensity and the motor evoked potential (MEP) amplitude was fit with the Boltzmann equation using a Levenberg-Marquardt algorithm (Devanne et al. 1997).

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

Three parameters, $\mathrm{MEP}_{\max}$, exponential parameter (*m*), and x-intercept threshold, were set as dependent variables and were used to represent the corticospinal excitability for each individual subject. If R^2 was below 0.75 during curving fitting, the data were excluded. Other details of the testing procedure and data processing were described in Chapter II and a previous study (Lin et al. 2015).

Exercise training

The subjects in the control group were instructed to maintain their normal activities of daily living while the subjects in the training group were trained three times per week for four weeks with an average duration of 30 minutes per session. All training sections were supervised to ensure compliance with the training protocol. The subjects in the training group performed strengthening and neuromuscular exercises to target the rotator cuff and scapulothoracic muscles, including full can, sidelying external rotation, diagonal exercise, prone full can at 100° of abduction, push-up with plus and push-up position on an exercise ball (Reinold et al. 2009; Reinold et al. 2007; Myers and Oyama 2009; Ubinger et al. 1999; Padua et al. 2004). The details of the exercise training were described in the exercise training section of Chapter IV.

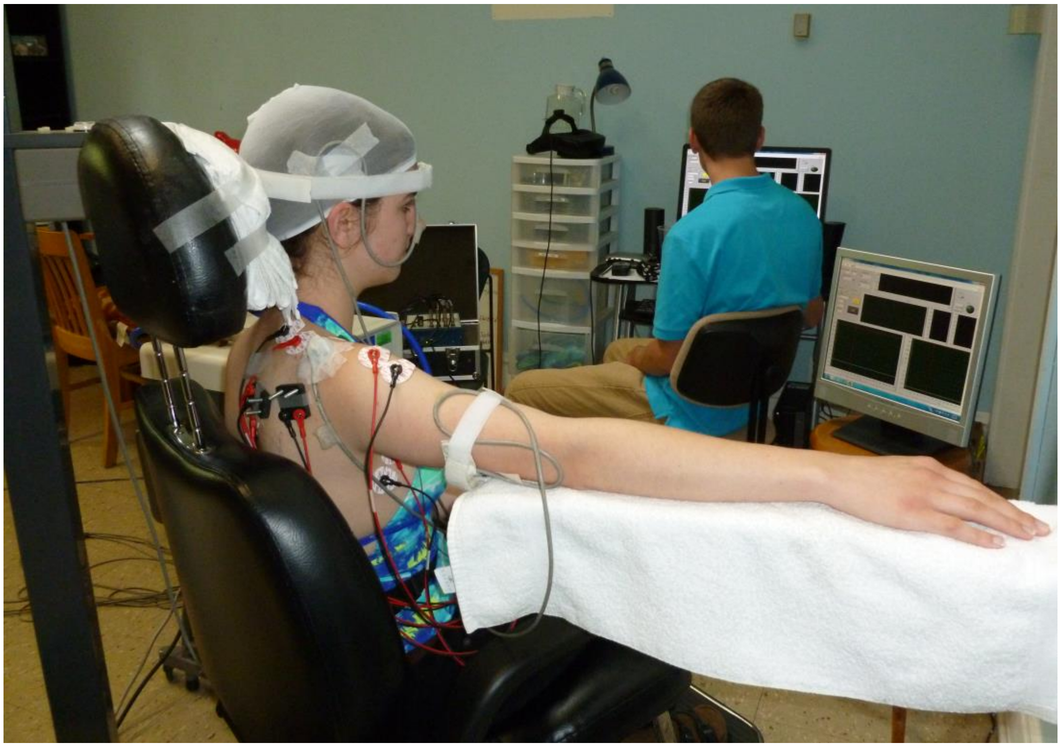

Figure 6.2. The testing position during TMS protocol. The subject was seated with head support and the arm was supported at 90° of arm elevation in scapular plane.

Statistical analysis

The changes of excitability from the first visit to the second visit were calculated for the force and excitability measures. An independent *t* test was used to assess the difference of the change scores in the force and excitability measures between groups. An independent *t* test was also run to examine the difference between groups in the pre-training test. The significant level was set at 0.05.

Results

All subjects in the control group completed two corticospinal excitability assessments. One subject in the training group did not finish the exercise training and the second corticospinal excitability assessment due to personal reasons. Other subjects in the training group completed all the training sections and two excitability assessments.

In one subject in the control group and one in the training group, it was found that the fine-wire electrodes of the supraspinatus had likely slid into the upper trapezius after the TMS testing protocol of the post-training test. This assertion was based on the comparison of the supraspinatus EMG between the two testing contraction: shoulder shrug and abduction with arm at the side. The data from these two subjects were excluded from the analysis. For the supraspinatus, the R^2 in three subjects in the control group and two subjects in the training group was below 0.75. For deltoid, R^2 of the three subjects in the control group was below 0.75. The data of these subjects were not included in the analysis.

For the pre-training assessment, there was no difference in the three excitability parameters and force measures between the two groups ($p > 0.05$) (Table 6.1). After the four-week training, the change of the elevation force in the training group was significantly more than that in the control group ($p = 0.026$) (Figure 6.3). For the excitability parameters, MEP_{max} in the training group decreased after the four-week training and the change of the training group was significantly different from that of the control group. However, there were no significant differences in the changes of m and x-intercept after the training between groups (Figure 6.4).

Table 6.1. Mean and standard deviation of the force measures and excitability parameters in the pre-training assessment

Parameter	Control	Training	*p*
Deltoid excitability			
MEP_{max} (MEP/MVC)	2.3 (2.3)	1.7 (0.9)	0.33
Exponential parameter (*m*)	14.3 (7.7)	18.8 (12.5)	0.25
X-intercept threshold (%)	46.6 (13.2)	41.9 (10.9)	0.29
Supraspinatus excitability			
MEP_{max} (MEP/MVC)	1.7 (0.7)	2.6 (1.7)	0.07
Exponential parameter (*m*)	19.8 (16.7)	18.5 (10.1)	0.82
X-intercept threshold (%)	50.2 (12.1)	45.2 (12.2)	0.29

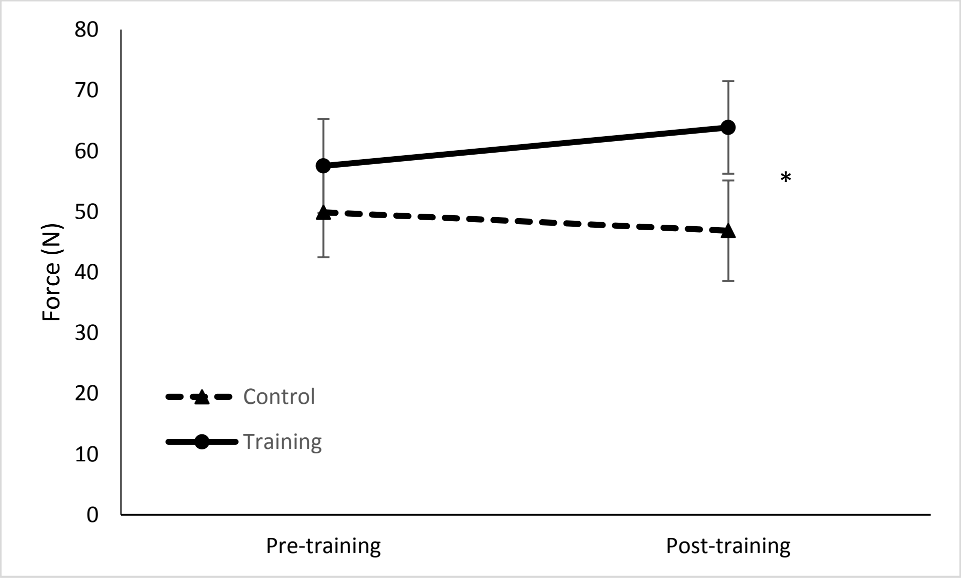

Figure 6.3. The changes of the elevation force from pre-training to post-training in control and training groups.

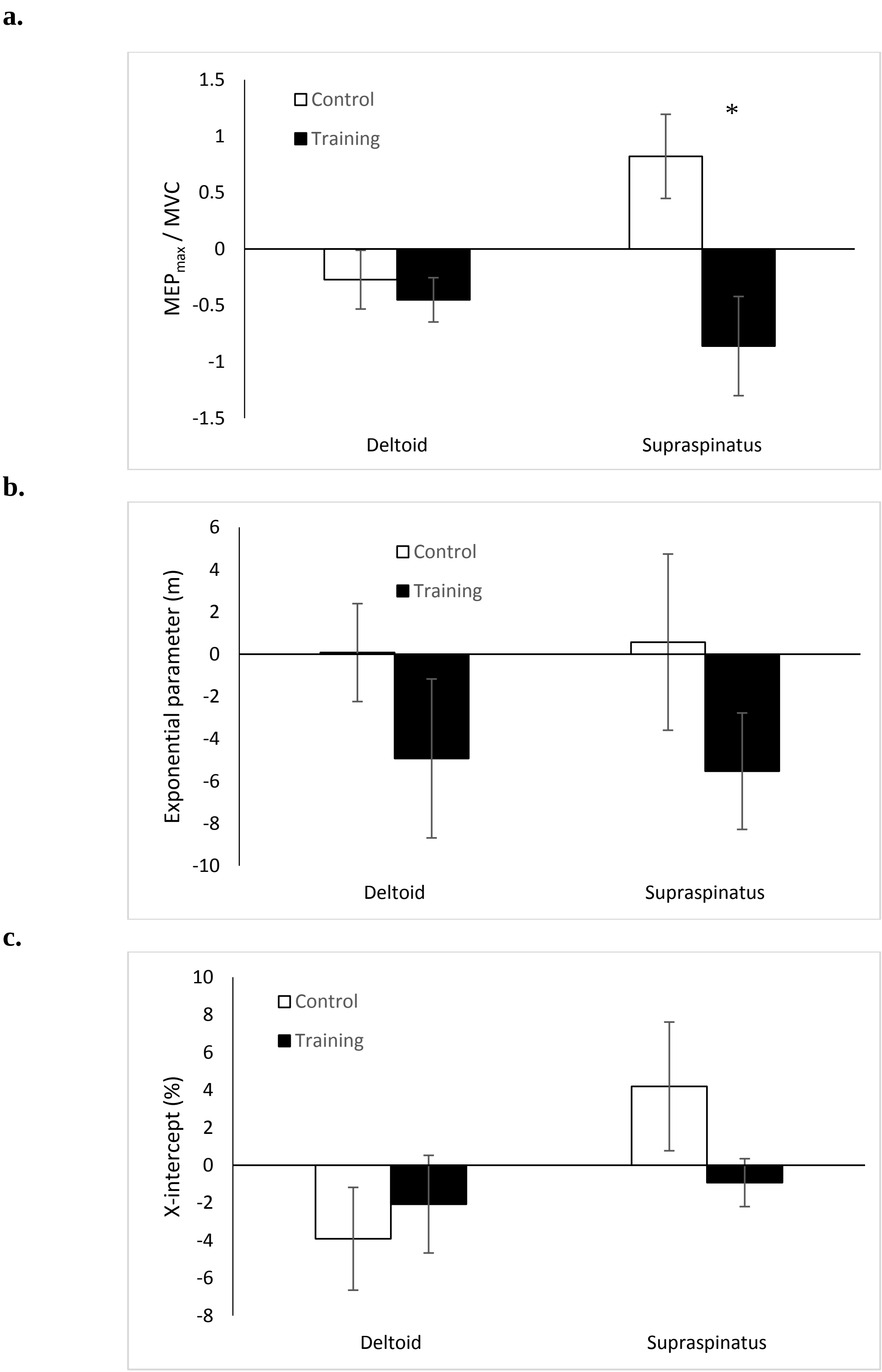

Figure 6.4. The changes of the three excitability parameters after the training of the deltoid and supraspinatus in the control and training groups. a) MEP$_{max}$, b) exponential parameter (*m*), and c) x-intercept threshold.

Discussion

While previous studies focused on the effects of strengthening exercise on the corticospinal excitability of the prime movers of distal limbs (e.g. finger abductors, wrist extensors and elbow flexors) the present study investigated the effects of the shoulder exercise training on rotator cuff muscles, which are shoulder joint stabilizers. Our hypothesis was after a four-week training protocol the corticospinal excitability of the supraspinatus would increase, while that of the middle deltoid would not change , which was not fully supported by the results. The MEP_{max} of the supraspinatus decreased and the excitability of the deltoid did not change after the training protocol.

According to cadaver and computer models, the supraspinatus works as an abductor as well as a humeral head stabilizer (Lee et al. 2000; Yanagawa et al. 2008). Since the supraspinatus tendon lies between humeral head and acromion (Brossmann et al. 1996), it is at risk of impingement and damage due to of excessive superior translation of humeral head (Graichen et al. 1999). The exercises associated with rehabilitation and sports training tend to focus on strengthening of the supraspinatus in order to facilitate a higher activation during shoulder movement (Reinold et al. 2009; Reinold et al. 2007). These strengthening exercises are usually performed with movements that produce high muscle activation of the supraspinatus and relative lower activation of the deltoid, such as full can, prone full can, and sidelying external rotation exercises (Reinold et al. 2007; Reinold et al. 2004).

Neuromuscular control exercises, such as push up with plus and push up on a unstable surface, are believed to facilitate co-contraction of the shoulder muscles and promote joint stability (Uhl et al. 2003; Dillman et al. 1994). Because of the anatomical complexity of the shoulder, it is impossible to isolate the activation of the rotator cuff muscles from that of deltoid. The results of the present study show that although the elevation strength increased after the exercise training, the corticospinal excitability of the deltoid remained the same, while that of supraspinatus decreased after the four-week exercise training. It is possible that exercises designed for the rotator cuff may mainly affect the rotator cuff muscles but have little effect on the central control of the deltoid.

In order to re-educate the muscles and increase the contribution of the rotator cuff muscles, strengthening and neuromuscular control training for the rotator cuff muscles was used. Jensen et al. (2005) found that the corticospinal excitability of the biceps increased after motor skill training but decreased after strength training. We therefore hypothesized that the corticospinal excitability of the supraspinatus would increase after the exercise training. However, the results do not support this hypothesis. The excitability of the supraspinatus decreased after the exercise training. Combined with the results of Chapter IV, in which the activation of the supraspinatus during arm elevation did not change, it is likely that the exercises used in the present study are only strengthening exercises and not involved the motor learning process.

There is evidence that injuries and pain can affect corticospinal excitability (Pelletier et al. 2015). Alexander (2007) found that in subjects with non-traumatic shoulder instability, the lower trapezius demonstrates lower excitability when compared to healthy controls. Ngomo et al. (2015) found that the excitability of the infraspinatus in patients with rotator cuff tendinopathy is lower than that of healthy subjects. The decrease of the excitability is correlated with the duration of the symptoms. Although the shoulder exercises used in the present study were not found to increase the excitability in healthy subjects, these exercises may still reverse the central change resulting from pain and injuries, since the shoulder exercises can decrease pain and improve function (McClure et al. 2004). Future work is needed to investigate the effect of shoulder exercise on the patient with shoulder injuries.

Although the effects of strengthening exercises have been previously investigated, the results are not consistent (Carroll et al. 2011). Among the studies targeting the muscles on lower extremity (tibialis anterior and rectus femoris), the excitability increased after a four-week training of isometric MVC (Griffin and Cafarelli 2007), ballistic strength training (Beck et al. 2007) and heavy load squat (Weier et al. 2012). For the muscles on upper extremity (first dorsal interosseous, extensor carpi radialis, and biceps brachii), the excitability did not change after a four-week isometric training (Hortobagyi et al. 2009; Kidgell and Pearce 2010), but decreased after four-week dynamic training with measurement in resting condition (Jensen et al. 2005) and during active contractions of more than 50% MVC (Carroll et al. 2009; Carroll et al. 2002). The results of the present study are similar to the studies of dynamic training for the upper extremity, although we did find difference in MEP_{max} during lower active contraction (10% MVC). This may be due to difference in the muscles tested. The mechanism of the decrease in the corticospinal excitability after strengthening training is not fully understood. It may be related to changes in the firing rate of the motoneurons or associated with a greater or longer after-hyperpolarisation in motoneurons after exercise training (Carroll et al. 2002).

In the present study, we did not measure the excitability at the spinal level, since it is difficult to directly simulate the suprascapular nerve. In previous studies of the upper extremity, the spinal reflex has not been measured. Carroll et al. (2002) found the MEP elicited by transcranial electrical stimulation decreased as that in the trials with TMS after strengthening training. It may suggest that the change in central nervous system happens at the subcortical level (spinal circuitry). However, Hortobagyi et al. (2009) was able to diminish the exercise training effect by using chronic low-frequency repetitive TMS applied on primary motor cortex. It also may suggest primary motor cortex is also involved in the central adaptation to the strengthening exercise.

There are some limitations to the present study. First, since the population of the subjects was young and healthy, the results may not be generalized to a population that is older or with injuries. Also, measurements of fine-wire EMG did not show good reliability (Jonsson and Bagge 1968; Morris et al. 1998), which may lead to measurement errors. Moreover, although none of the subjects complained of the fine-wire electrodes and could ignore the fine-wire electrodes during the contraction of 10% MVC, the fine-wire electrodes may still affect the MEP because the electrodes may still stimulate some receptors in the muscles.

Conclusion

Rotator cuff muscle exercises resulted in a decrease in corticospinal excitability of supraspinatus but no change in that of deltoid. This suggests that this training exercise mainly targeted rotator cuff muscles. However, these exercises, which designed to improve shoulder neuromuscular control, may be only strengthening exercises and not result in motor learning effect. Future work is needed to investigate the effects of exercise protocols on patients with shoulder injuries.

CHAPTER VII

FINAL CONCLUSIONS

General Summary of Findings

The joints of the shoulder complex work synergistically to generate a large range of motion necessary for reaching and hand manipulation at different positions. Control from the sensorimotor system is essential for providing dynamic stability (Donatelli 2004; Myers and Lephart 2000). Therefore, smooth and efficient coordination between joints relies on sufficient sensory feedback, appropriate control of central nervous system and precise movement patterns (Riemann and Lephart 2002a). For the glenohumeral joint, while the deltoid generates most of the torque necessary for motion as well as a shear force pulling the humeral head upward, the rotator cuff muscles counterbalance the deltoid forces and stabilize the humeral head in the glenoid fossa (Kronberg et al. 1990; Poppen and Walker 1978; Yamaguchi et al. 2000). The different roles of the deltoid and rotator cuff muscles may results from the anatomical difference in moment arms (Otis et al. 1994; Liu et al. 1997) and muscle activation patterns (Alpert et al. 2000; Kronberg et al. 1990). The findings of this dissertation demonstrated that the corticospinal excitability of the infraspinatus, but not the middle deltoid, is increased at 90° of arm elevation when compared to 0°, which may help explain the differences in the function of the deltoid and rotator cuff.

The coordination between the scapula and humerus has been widely investigated (McClure et al. 2006; Ludewig and Cook 2000; Ludewig and Reynolds 2009; Inman et al. 1944). However, most of the studies investigating shoulder JPS have treated the shoulder complex as a single joint (Lephart et al. 2002; Wassinger et al. 2007; Sole et al.

2015; Iida et al. 2014; Salles et al. 2015; Suprak et al. 2006). The results of the dissertation demonstrated that joint position sense errors of the overall shoulder complex are primarily associated with errors of the glenohumeral joint. Therefore, scapular proprioception may need to be tested in addition to the overall shoulder proprioception.

Exercise is an important part of shoulder rehabilitation and sports training but few studies have investigated the effect of exercise on the sensorimotor system (McClure et al. 2004; Hibberd et al. 2012; De Mey et al. 2012). In this dissertation, we designed a four-week strengthening and neuromuscular control training protocol targeting the rotator cuff and scapular muscles and investigated the effect of the exercise on the shoulder proprioception, scapular kinematics, shoulder muscle activation and corticospinal excitability. The results showed that although overall strength was increased, the exercise protocol did not affect all parts of the sensorimotor system. There was no effect of exercise on the shoulder joint position sense. Combined with the results of previous studies (Rogol et al. 1998; Salles et al. 2015), which have demonstrated that improvements with exercises including multiple big muscles and with higher intensity, the type and intensity of exercises may explain why we found no improvement in joint position sense in this dissertation.

Rotator cuff muscle exercises resulted in a decrease in corticospinal excitability of the supraspinatus, but no change in that of the deltoid. This suggests that this training exercise mainly targeted rotator cuff muscles. However, these exercises, which were designed to improve shoulder neuromuscular control, may only be strengthening exercises and not result in motor learning effect.

For shoulder muscle activation and kinematics, with a decrease in muscle activity, the upper trapezius was the only muscle to demonstrate a change in activation during motions (there was a trend of an increase for the serratus anterior). Combined with the findings of the corticospinal excitability, while the exercise succeeded in increasing rotator cuff strength, these gains did not transfer to an increase in muscle activation during motion. Thus, the benefits of this exercise program on joint stability are questionable. Additionally, there were no changes in scapular kinematics after the exercise protocol, demonstrating the difficulty in altering this movement pattern in healthy subjects.

Limitations and Future Directions of Research

There are some limitations to the present study. First, measurements of fine-wire EMG may not be reliable (Jonsson and Bagge 1968; Morris et al. 1998), which may lead to measurement errors. Moreover, some of the subjects complained of discomfort and mild pain (2 – 3 in numeric rating scale) during the arm elevation trials, which may have influenced the muscle activation patterns. For the corticospinal excitability measures, although none of the subjects complained of the fine-wire electrodes during the contraction of 10% MVC, the fine-wire electrodes may still affect the MEP because the electrodes may have stimulated some receptors in the muscles.

We chose a four-week duration due to the fact that the response of the central nervous system to the exercise happens within this time period (Jensen et al. 2005). However, it may not be sufficient for the adaption in proprioception, kinematics and muscle activation patterns. The duration of the exercise training may be another factor to help explain why we found no improvement after the training.

For the scapular proprioception, we chose to use the helical angle to represent the three-dimensional scapular movement. Although it reduces the number of the variables for the scapular movement, the helical angle does not represent the scapular movements observed in the clinic, such as upward/downward rotation, protraction/retraction or tipping. Therefore, the scapular JPS errors in the present study do not represent the errors in any specific plane.

Finally, the subject population is another limitation. The subjects in the present study were young and healthy. The results may not be generalized to the population that is older or with shoulder injuries. Future work is needed to investigate the effects of exercise protocols on patients with shoulder injuries, as well as which types of exercise are more effective in improving joint position sense and scapular kinematics.

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