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Comparison of Supraspinatus Muscle Architecture During Three Different Shoulder Strengthening Exercises Using Ultrasonography

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Abstract

Background: Strengthening the supraspinatus is an important aspect of a rehabilitation program for subacromial impingement and tendinopathy. Many authors recommended empty-can (EC), full-can (FC), and prone full-can (PFC) exercises to strengthen the supraspinatus. However, no ultrasonography study has yet investigated supraspinatus muscle architecture (muscle thickness; MT, pennation angle; PA, fiber bundle length; FBL) in relation to supraspinatus strengthening exercises.

Objects: The purpose of this study was to compare the architecture (MT, PA, and FBL) of the supraspinatus muscle during three different types of exercises (EC, FC, and PFC) using diagnostic ultrasound.

Methods: Participants performed three different exercises: (A) EC; the arm was maintained at 60° abduction with full internal rotation in the sitting position, (B) FC; the arm was maintained at 60° abduction with full external rotation in the sitting position, and (C) PFC; the arm was maintained at 60° abduction with full external rotation in the prone position. Ultrasonography was used to measure the MT, PA and FBL of the supraspinatus. One-way repeated analysis of variance with Bonferroni's post-hoc test was used to compare between the three exercises and the initial position of each exercise.

Results: Compared with each initial position, the FC exercise showed the greatest mean difference in muscle architecture properties and the PFC exercise showed the least mean difference.

Conclusion: The findings suggest that the FC exercise position may have an advantage in increasing the amount of contractile tissue or producing muscle power and the PFC exercise position may be useful in a rehabilitation program because it offers the advantage of maintaining the muscle architecture properties.

Key Words: Rehabilitation; Rotator cuff; Shoulder; Sonography.

Introduction

Rotator cuff muscles play an important role in the stabilization of the glenohumeral joint and the translation of the humeral head during shoulder strengthening exercises (Escamilla et al, 2009). Glenohumeral joint instability and rotator cuff tears lead to subacromial impingement syndrome contributing to the most common cause of shoulder pain (Burke et al, 2002). Several authors have found that weakness and imbalance in the rotator cuff muscles resulted in mechanical compression of the subacromial structures between the coracoacromial arch and the greater tuberosity of the humeral head (Burke et al, 2002;

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Takeda et al, 2002). Among the rotator cuff muscles, the supraspinatus is an effective shoulder abductor muscle during arm elevation, and it is involved in subacromial impingement (Burke et al, 2002; Gates et al, 2010). Strengthening the supraspinatus is an important aspect of a rehabilitation program for subacromial impingement and tendinopathy (Malanga et al, 1996).

Many authors recommended empty-can (EC), full-can (FC), and prone full-can (PFC) exercises to strengthen the supraspinatus (Malanga et al, 1996; Takeda et al, 2002). The supraspinatus showed a similar amount of activity during these three types of shoulder strengthening exercises, as measured by electromyography (EMG) (Reinold et al, 2007). While all three exercises produced similar amounts of supraspinatus activity, Reinold et al (2007) reported that the FC exercise produced significantly less activity of the deltoid muscles and may be the optimal position to recruit the supraspinatus muscle for rehabilitation and testing. However, several studies have found inconsistent EMG activity results among EC, FC, and PFC exercises. Townsend et al (1991) reported that the EC exercise shows high EMG activity in comparison to the FC and PFC exercises, but Blackburn et al (1990) found that the PFC exercise showed high EMG activity and was beneficial for strengthening the supraspinatus. In addition, Kelly et al (1996) reported similar EMG activity between the EC and FC exercises, but not the PFC exercise. These inconclusive EMG activity results can be attributed to several factors, such as the subjects' characteristics, the testing procedure used, and the EMG analysis. Therefore, other contributing factors should be considered to determine which of these three types of exercises are most appropriate for supraspinatus rehabilitation.

Muscle architecture properties, such as muscle thickness (MT), fiber bundle length (FBL), and pennation angle (PA), can be used to determinate muscle function and force production, which form the basis for physiological movement (Fukutani and Kurihara, 2015; Lieber and Friden, 2001). Morse et al (2008) suggested that physiological muscle architecture, especially PA, is a better index for determining muscle force than anatomical muscle architecture. Thus, in the fields of physical therapy, structural analysis of the physiological muscle architecture is an important factor for enhancing human performance. The use of ultrasonography to measure changes in the architectural parameters of human skeletal muscles is well established (de Boer et al, 2008; Ikai and Fukunaga, 1968). However, no ultrasonography study has yet investigated supraspinatus muscle architecture (MT, PA, and FBL) in relation to supraspinatus strengthening exercises.

This present study aimed to compare the architecture (MT, PA, and FBL) of the supraspinatus muscle during three different types of exercises (EC, FC, and PFC) using diagnostic ultrasound. We hypothesized that EC, FC, and PFC would influence the mean difference of MT, PA, and FBL.

Methods

Subjects

Based on pilot data, a priori power analysis with G-Power software ver. 3.1.5 (Franz Faul, University of Kiel, Kiel, Germany) was performed to calculate the sample size. A pilot study with five subjects was used to achieve a effect size of 1.72, an alpha level of 5%, and a statistical power of 80%. In the present study, the estimated sample size was 10. Sixteen healthy male subjects participated in the study. Inclusion criteria for this study was active, right-handed participants so as to optimize the data processing time (by asking participants their preferred hand for writing) (de Castro et al, 2014). Exclusion criteria were the presence of any pain, any previous or current rotator cuff pathology (test for subacromial impingement), glenohumeral joint instability (tests for anterior and posterior apprehension to determine instability) (Kim et al, 2015), and engaging in regular physical activity more than three times a week (to avoid a possible influence of physical training on the participants' performance) (de Castro et al, 2014). The study protocol and informed consent document were approved by the Yonsei University Wonju Institutional Review Board (Approval number: #1041849-201502-BM-014-02). The characteristics of the subjects are shown in Table 1.

Ultrasonography

An ultrasound scanner with 7.5 ㎒ linear transducer (SonoAce x8, Medison Co, Ltd, Seoul, Korea) was used to measure the MT, PA, and FBL of the supraspinatus muscle. Using the protocols recommended by Kim et al (2010), supraspinatus architecture images were taken. Kim et al, (2010) reported a strong correlation for the intra- and inter-rater reliability of FBL measurements (above .85, respectively) and PA measurements (above .80, respectively), with no significant difference between the two ($p<.001$). As the present study used a different type of ultrasound machine than was used by Kim et al (2010), intra-reliability was calculated to compare this study's findings with the results from the previous study. We used the intra-class correlation coefficient [ICC (3,1)] to calculate the intra-rater reliability of MT, PA, and FBL in three different contracted positions (EC, FC, and PFC exercises), and we found excellent intra-rater reliability (ICC=.98, .99, .85, respectively). To ensure the consistency of the measurements, one physical therapist (O.B.L.), who was trained to administer the supraspinatus ultrasound imaging protocol, took all of the images. The mid-point muscle belly and the anterior part of the supraspinatus were imaged in two different positions: relaxed 0° abduction (the arm resting at the side and the palm facing inward or outward) and isometric contracted 60° abduction (Kim et al, 2015). An inclinometer was used to ensure an accurate 60° abduction position. The mid-point of the muscle belly (sagittal scans) was observed to capture MT (Katayose and Magee, 2001). The anterior part of the supraspinatus (longitudinal panoramic scan) was used to capture PA and FBL (Kim et al, 2015). All of the images were saved for the analyses.

Table 1. General characteristics of the study subjects (N=16)

Characteristics	Mean±SD[a]
Age (year)	24.5±1.7
Height (㎝)	175.3±3.7
Weight (㎏)	74.4±11.4
BMI[b] (㎏/㎡)	24.1±3.3

[a]standard deviation, [b]body mass index.

Procedures

All of the volunteer subjects were randomly assigned an order for the three different exercises (EC, FC, and PFC) (Forbush et al, 2013). The exercise order was generated using Randomization.com (accessed at http://www.randomization.com on April 4, 2015). One researcher (I.Y.M.), who was trained in the protocols for all three types of exercises, instructed all of the subjects in how to perform the exercises. The subjects were asked to do each of the three exercise positions in the order randomized for their session. Each position was resisted using a dumbbell that weighed approximately 5% of the each individual's body mass index (BMI) (ranging from 1 ㎏ to 1.5 ㎏) (de Castro et al, 2014). When applying resistance using a dumbbell, a proper hold time (5 sec) was used in order to capture three ultrasound images. Each subject was securely strapped to a chair and/or a table to prevent any compensatory movement. To maximize the data processing time, only the right arm was tested (de Castro et al, 2014). One minute of rest was provided between the exercise sets to prevent the carry-over effect. To investigate the mean difference of muscle architecture (MT, PA, and FBL), the average of three images in resting and isometric contracted positions was measured. Resting average is the average of three images shot in the sitting or prone positions before applying the three different exercises (EC, FC, and PFC). The isometric contracted average is the average of three images shot during the three different exercises (EC, FC, and PFC). The mean difference of muscle architecture (MT, PA, and FBL) indicates the amount of mean change between the isometric contraction and resting positions, respectively. The three exercise positions are described below.

Empty-can exercise position

The EC exercise position was performed with the subjects sitting in a chair. Each subject's trunk was securely strapped to the chair to prevent compensatory movement. A target bar was located at the level of the 60° abduction position, which was determined to be an accurate angle during the contracted position. Before elevating their arm, the subjects were instructed to rest their arm at their side and position their thumb inward to capture the resting position images. They were then instructed to maintain their arm at 60° abduction in the scapular plane (30° anterior to the frontal plane), with full internal rotation. The thumb was pointing toward the floor (Figure 1A). The subjects maintained this position as much as possible to capture the images against the downward resistance applied by the dumbbell (5% of BMI) (Jobe and Moynes, 1982).

Full-can exercise position

The FC exercise position was performed with the subjects sitting in a chair. Each subject's trunk was securely strapped to the chair to prevent compensatory movement. A target bar was located at the level of the 60° abduction position, which was determined to be an accurate angle during the contracted position. Before elevating their arm, the subjects were instructed to rest their arm at their side and position their thumb outward to capture the resting position images. They were then asked to maintain their arm at 60° abduction in the scapular plane (30° anterior to the frontal plane), with full external rotation. The thumb was pointing toward the ceiling (Figure 1B). The subjects maintained this position as much as possible to capture the images against the downward resistance applied by the dumbbell (5% of BMI) (Kelly et al, 1996).

Prone full-can exercise position

The PFC exercise position was performed with the subjects lying in a prone position on a bed. Each subject's trunk was securely strapped to the bed to prevent compensatory movement. A target bar was located at the level of the 60° abduction position, which was determined to be an accurate angle during the contracted position. Before elevating their arm, the subjects were instructed to rest their arm at their side and position their thumb outward to capture the resting position images. They were then asked to maintain their arm at 60° abduction with full external rotation in the horizontal plane. The thumb was pointing toward up (Figure 1C). The subjects maintained this position as much as possible to capture the images against the downward resistance applied by the dumbbell (5% of BMI) (Blackburn et al, 1990).

Data management

We palpated the supraspinatus muscle examining

Figure 1. Three exercise positions (A: empty-can, B: full-can, C: prone full-can).

the acromion and the spine of the scapula. These landmarks helped determine the proper probe positioning (Figure 2). MT was measured as the distance between the superficial surface of the muscle and the supraspinatus fossa at the mid-point of the muscle belly (sagittal scan) (Figure 3A). FBL was measured as the linear distance between the medial and the lateral attachment sites, and PA was measured as the angle between the fiber bundle and its attachment to the intramuscular tendon (longitudinal panoramic scan) (Kim et al, 2015) (Figure 3B).

Statistical analysis

The one-sample Kolmogorov-Smirnov test was performed to determine if the continuous data approximated a normal distribution; all of the variables were confirmed as normally distributed. A repeated measure one-way analysis of variance was performed for all the measured mean variables (MT, PA, and FBL) to compare the variables among the three different shoulder exercises (EC, FC, and PFC). The statistical significance level was set at $\alpha=.05$. The variables that showed significant differences were followed up with pairwise comparisons. A post-hoc analysis was performed using Bonferroni correction to compare the significant difference (.05/3=.017). Statistical analysis was performed using SPSS ver. 21.0 (SPSS Inc., Chicago, IL, USA).

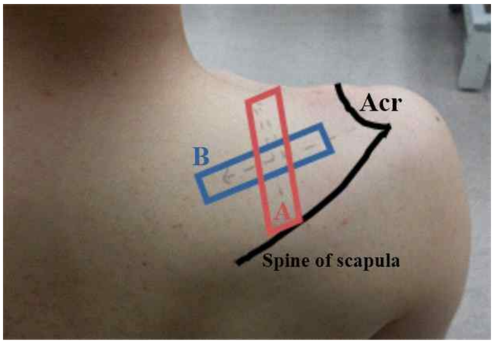

Figure 2. Ultrasound probe positioning (right shoulder in the resting position, Acr: acromion; A: sagittal ultrasound probe positioning for the MT images; B: longitudinal panoramic ultrasound probe positioning for the PA and FBL images).

Results

Muscle thickness

Significant difference were found in the MT among the three different shoulder exercises (Wilks' Lambda=.363, $F_{2,14}$=12.295, p=.001) (Table 2). The FC exercise showed significantly greater MT in comparison to the EC and PFC exercises (p=.002, p=.001), and the EC exercise showed significantly greater MT in comparison to the PFC exercise (p=.013).

Fiber bundle length

Significant differences in FBL were observed among the three different shoulder exercises (Wilks' Lambda=.247, $F_{2,14}$=21.381, p<.001) (Table 2). FBL was significantly shorter for the EC and PFC exercises in comparison to the FC exercise (p<.001, p<.001). However, no significant difference in the FBL was found between the EC and PFC exercises (p=.087).

Pennation angle

Statistically significant differences were found for PA (Wilks' Lambda=.191, $F_{2,14}$=29.657, p<.001) (Table 2). The PA was significantly greater for the FC exercise in comparison to the EC and PFC exercises (p<.001, p<.001). Whereas, there were no significant difference in the PA between the EC and PFC exercises (p=.196).

Discussion

This is the first study to quantify MT, PA, and FBL following three different isometric exercises (EC, FC, and PFC) that are used for supraspinatus rehabilitation. Significant differences among MT, PA, and FBL were observed in the FC exercise position; the PFC exercise position showed the least difference among the three muscle architecture properties. These findings support our hypotheses that these three types of exercises can have an effect on the mean difference of the supraspinatus muscle.

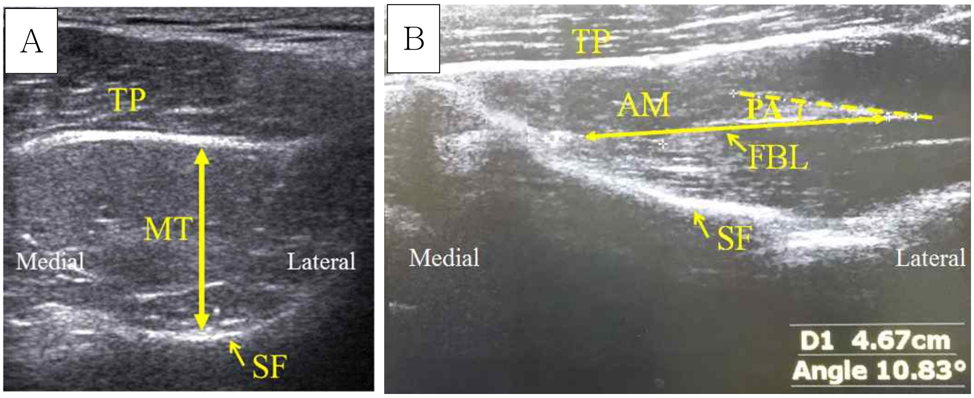

Figure 3. Ultrasound scans of the right supraspinatus in the resting position. (A) sagittal scan, (B) longitudinal scan (MT: muscle thickness, SF: supraspinous fossa, TP: trapezius, AM: middle region of anterior part, PA: pennation angle, FBL: fiber bundle length).

Among the three exercise positions, the FC exercise was found to have the greatest increase in MT, while the least increase in MT was observed in the PFC exercise, and a statistically significant difference was found for each of the other exercise positions. MT is commonly used to predict muscle hypertrophy, which is defined by muscle activity (Farthing and Chilibeck, 2003). Changes in MT can be used to indicate changes in the electrical activity of a muscle. McMeeken et al (2004) showed a positive linear relationship between MT and electrical activity in the transversus abdominis muscle. O'Hagan et al (1995) reported that the type of isometric resistance training increases MT and muscle strength. Thus, EC, FC, and PFC exercises allowed for the contraction of the supraspinatus muscle, and MT increased in comparison to the initial (resting) position. In the EC exercise position, the scapula gradually tilted anteriorly (sagittal plane) and internally rotated (transverse plane), which contributes to scapular protraction and reduces the subacromial space width (Thigpen et al, 2006). Smith et al (2006) reported that this scapular kinematic difference reduced the activity and strength of the supraspinatus muscle. In addition, the internal rotation of the humeral head causes greater tuberosity under acromion impacts, thereby decreasing supraspinatus activity (Escamilla et al, 2009). In our data, the prone position showed the least amount of supraspinatus contraction. The anterior part of the supraspinatus was found to have a weak rotator force at 60° during glenohumeral elevation (Otis et al, 1994). This change may be ideal for PFC as a low-impact exercise. In contrast, Worrell et al (1992) found the greatest EMG activity in the PFC exercise position, and Reinold et al (2007) showed a similar amount of muscle activity among the three types of exercises. To address the discrepancies of supraspinatus EMG activity, this study chose to examine the glenohumeral elevation angle and the anterior and posterior portions of the

Table 2. Mean difference between isometric contraction and resting positions among the three different exercises

Variables	Exercises		
	Empty-can	Full-can	Prone full-can
MT (㎝)	3.48±1.48[a,*]	4.26±1.37	1.99±1.06[*,†]
FBL (㎝)	2.27±1.11[*]	3.43±1.47	1.66±1.02[*]
PA (°)	4.65±2.80[*]	7.70±3.50	3.70±2.20[*]

[a] mean±standard deviation, [*] p<.017, significant difference from the full-can exercise, [†] p<.017, significant difference from the empty-can exercise.

supraspinatus. Many EMG studies have viewed the supraspinatus (anterior and posterior) as a whole, and the images in those studies were taken in the 100° horizontal abduction position.

The FBL showed a significant decrease in the FC exercise position in comparison to the EC and PFC exercise positions; no significant difference in the FBL was observed between the EC and PFC positions. The mean FBL decreased during isometric training with all of the exercise positions. Previous studies demonstrated that the FBL of the vastus lateralis decreased in different knee positions after active isometric contractions (Fukunaga et al, 1997). The FBL is the most important architectural parameter; it is affected by a decrease in the muscle contraction velocity or a decrease in the range of the muscle fiber excursion (Lieber, 1993). A more marked shortening of the FBL indicates an increase in the amount of contractile tissue. A large amount of contractile tissue and increased muscle contraction velocity were observed in the FC exercise position. These muscle architecture properties correspond with our previous data (MT), and they are of clinical interest to authors supporting the idea that the FC exercise is the best method for strengthening the supraspinatus muscle (Kelly et al, 1996). Khan et al (1999) suggested that the least or maintenance muscle architecture has the benefit of healing micro-trauma. A shortened FBL was found to be more difficult to repair, and it often results in ineffective outcomes for repairing rotator cuff tears (Meyer et al, 2012). Thus, the length of the FBL is an important predictor for surgical outcomes for micro-trauma muscle tears. In our data, the PFC exercise position showed the least amount of contractile tissue. Therefore, for patients that need a low loading healing advantage, the PFC exercise positions can be recommended for rehabilitation.

The FC exercise showed a significant increase in the PA in comparison to the EC and PFC exercises; moreover, no significant difference in PA was observed between the EC and PFC exercise positions. A larger PA provides evidence for effective supraspinatus muscle activation (Aagaard et al, 2001). The anterior part of the supraspinatus is a circumpennate muscle (Kim et al, 2015), which depends on the fiber length axis (force development) (Lieber, 1993). An increase in the MT and the cross-sectional area correlates with a greater FBL and a larger PA. A larger PA indicates muscle strengthening, which is reflected in a greater amount of force development (contractile tissue) (Aagaard et al, 2001). In our PA data, the FC exercise position was found to have a greater amount of force development, which is consistent with our previous data (MT and FBL). Thus, the FC exercise position may have an advantage over the EC and PFC exercises in terms of increases in the amount of contractile tissue (force development), thereby producing more muscle power.

This present study has several limitations. First, the current experiment is a cross-sectional design, which makes it difficult to observe the long-term effect of exercise. For example, Seynnes et al (2007) reported that muscle size increase might have occurred within three weeks of training. Second, the general characteristics of the subjects were limited to healthy males in their twenties. In future studies, a variety of subjects, such as people with shoulder pain, and subjects using their non-dominant arm, are needed to evaluate differences in muscle architecture properties. Finally, for within-subject designs there is a possibility of muscle fatigue during repetitive movements. Thus, a longer resting time between exercise sessions is needed to prevent a possible carry-over effect.

Conclusion

The present study investigated muscle architecture properties (MT, PA, and FBL) following three different isometric exercises (EC, FC, and PFC). During these three different isometric exercises, the mean difference of MT and PA showed a significant increase, and FBL showed a significant decrease. Furthermore, the FC exercise showed the greatest increase in MT and PA, and the PFC exercise showed the least increase in MT and PA. The greatest difference in the FBL data was observed for the FC exercise position, which is consistent with our previous data (MT and FBL), and FBL was found to decrease the least in the PFC exercise. From this finding, the FC exercise position may have an advantage in increasing the amount of contractile tissue or producing muscle power, and the PFC exercise position may be useful in a rehabilitation program because it offers the advantage of maintaining the muscle architecture properties.

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