EFFECT OF THREE DIFFERENT SCAPULAR POSITIONS ON ISOMETRIC STRENGTH AND MUSCLE ACTIVITY RATIO OF SERRATUS ANTERIOR IN SUBJECTS WITH SCAPULAR WINGING

[1]Ki-Seok Nam

ABSTRACT-- *The purpose of this study was to compare the isometric strength of serratus anterior at three different scapular positions (retracted, neutral and protracted) and electromyography activity ratio of upper trapezius to serratus anterior and upper trapezius to lower trapezius during isometric arm elevation between the subjects with and without scapular winging. Thirty-three subjects with scapular winging and thirty-three subjects without scapular winging were recruited for this study. This study showed that isometric strength of serratus anterior was significant decreased in subjects with scapular winging group than without scapular winging group (p<.05). In both of subjects with and without scapular winging groups, isometric strength of serratus anterior showed significant difference at scapular positions (p<.05). Isometric strength of serratus anterior was strongest in retracted scapular position (p<.05). Electromyography activity ratio of upper trapezius / serratus anterior was significantly higher in subjects with scapular winging than subjects without scapular winging (p<.05). Based on these findings in this study, the isometric strength of serratus anterior in retracted scapular position was strongest in both of subjects with and without scapular winging group. The higher upper trapezius/serratus anterior of electromyography activity ratio in subjects with scapular winging than in subjects without scapular winging implies that upper trapezius muscle is used more dominantly among scapular upward rotators during shoulder elevation in subjects with scapular winging.*

Keywords-- *Electromyography, Scapular winging, Serratus anterior, strengthening exercise*

---

[1]Department of Physical Therapy, Yeungnam University College, Daegu, Korea,170 Hyunchung-ro, Nam-gu, Daegu 42415, Republic of Korea, seokah@hanmail.net, Tel. 82-53-650-9703. Fax. 82-53-629-5048

Received: 22 Feb 2019 | Revised: 13Mar 2019 | Accepted: 05 Apr 2020

I. INTRODUCTION

Scapular winging (SW) is classically defined prominence of scapular medial border raising from normal contact with the chest wall (Martin and Fish, 2008). SW presents the alternation in anatomical position and motion of scapular in static and dynamic condition (Kibler et al., 2013). Static SW is caused by articular or bone deformity and dynamic SW is caused by neuromuscular impairment. SW in dynamic condition can be observed during resistance exercise of upper extremity (Hamano et al., 2012; Wilk et al., 2002).

Normal function of the serratus anterior (SA) muscle is essential in maintaining proper scapulohumeral rhythm during arm elevation (Decker et al., 1999; Mueller et al., 2013; Wiater, and Flatow, 1999; Yano, 2010). SA weakness is lead to change the scapular position (superior elevation and medial translation, inferior pole is rotated medially) and finally in change functional scapular motion. Abnormal position and movement result in alternation of scapulohumeral rhythm in glenohumeral joint and impingement syndrome (Cools et al., 2003; Ludewig and Cook, 2000; Ludewig and Reynolds, 2009). The patients with SW present pain, fatigability, and disability of upper limb function (Wiater and Flatow, 1999; Kisner and Colby, 2017). Principal dysfunctions have trouble to generation of power, elevation the arm over 120° and a generally unstable shoulder (Hamano et al., 2012; Ludewig et al., 2004).

It was reported that alternation of muscle length and direction around shoulder lead to change intermuscular relationship and muscle recruitment pattern (Mottram, 1997; Sahrmann, 2002). Smith et al (2002) compared the isometric strength of arm elevation at three scapular positions, and isometric strength decreased in protracted scapular position compared with the neutral scapular position and reduced in retracted scapular position relative to the neutral scapular position. Garner and Shim (2008) reported that protraction force was the strongest in retracted position of the scapula in healthy subjects. Although many studies have reported measurements of strength at shoulder joint, those studies did not considered the role of scapular position or performed at only neutral position (Wilk et al., 2002; Myers et al., 2006). To our knowledge, no study compared the SA isometric strength at the scapular position between the subject with and without SW group.

Recent researchers have considered to identify not only amplitude of electromyography (EMG) activity in each muscle but also interaction between serratus anterior (SA), upper trapezius (UT) and lower trapezius (LT) during arm elevation (Cools et al., 2004; Ludewig et al., 2004; Martin and Fish, 2008). Therefore, the purpose of this study was to compare the isometric strength of SA at the three different scapular positions (retracted, neutral and protracted position) between the subject with and without SW group. And we also compared EMG activity ratio of UT/SA and UT/LT during isometric arm elevation between the subject with and without SW group.

II. MATERIAL AND METHODS

Subjects

Sixty-six participants (14 men, 52 women) were recruited (Table 1). We use a scapulometer to detect the subjects with and without SW. To measure SW, the subject maintains stand up posture and flexed elbow joint in 90° and the forearm was neutral rotation. A cuff weighing 5% of the subject's body weight was placed in the wrist (Weon et al., 2011). And the examiner stands behind the patient and places the four pads of the scapulometer on the posterior thoracic wall medial to the vertebral border of the scapula, with the sliding board at the level of the inferior angle of the scapula. Holding the scapulometer in place with one hand, the examiner moves the sliding board anteriorly until it touches the inferior angle of the scapula. A ruler on the fixed board measures the posterior displacement of the inferior angle of the scapula from the thoracic wall. The subjects with SW was confirmed by a distance of at least 2 ㎝ between the thoracic wall and the inferior angle of the scapula, and the subject without SW was less than 1 ㎝ measured using a scapulometer. Weon et al. (2011) demonstrated the test–retest reliability of the scapulometer for measuring SW. The interclass correlation coefficient was 0.97 (95% confidence interval: 0.87–0.99), and the standard error of the measurement was 0.1 cm.

Participants were excluded according to following criteria; 1) limited shoulder motion 2) gross instability of the shoulder 3) signs and symptoms of cervical pain 4) adhesive capsulitis 5) thoracic outlet syndrome 6) a current complaint of numbness or tingling in the upper extremity 7) history of shoulder injury or surgery 8) participation in overhead sports at a competitive level 9) upper limb strength training for more than 5 hour per week.

Investigators of this study explained the procedure to the subjects in detail and all subjects signed written informed consent prior to experiment. This study was approved by the Yonsei University Wonju Institutional Review Board, in accordance with the ethical standards.

Table 1: Descriptive data for subjects (N=66)

Parameter	With SW (n_1=33, M=7, F=26)	Without SW (n_2=33, M=7, F=26)
Age (years)	26.6 ± 3.1 [a]	25.9 ± 2.7
Weight (kg)	62.2 ± 4.1	64.6 ± 3.9
Height (cm)	158.2 ± 2.8	161.2 ± 2.2
Amount of SW (mm)	23.7 ± 1.9	7.1 ± 2.8

[a]Mean±SD

M: male

F: female

SW: scapular winging

Measurement of Isometric Strength of Serratus Anterior

The SA isometric strength for scapular protraction were assessed using Biodex Dynamometer System 4 Pro (Biodex Medical Systems, Inc., Shirley, NY, USA) and Closed Kinetic Chain Attachment. Subjects were placed sitting with upright seat that is adjustable to accommodate subject according to the body dimension and fixed using thigh, pelvic and trunk strap to prevent compensative movement. Arm bar was placed in horizontally forward and length of arm bar was adjusted according to arm length of each subject. Measurement position of arm was 90° forward flexion in shoulder joint, full extension in elbow joint, thumb up position. For protraction trials, SA muscle strength was measured in a retracted, neutral, and protracted position. Neutral position was selected around center between retracted and protracted position. Protracted position was set up a little back position of full protraction of scapula. Retracted position was set up a little front position of full retraction of scapula. Test order was randomly selected to minimize the effect of fatigue and learning.

Received: 22 Feb 2019 | Revised: 13Mar 2019 | Accepted: 05 Apr 2020

Value of isometric strength was recorded and calculated automatically by Biodex Advantage Software program Version 4 (Biodex Medical Systems, Inc., Shirley, NY, USA). Calibration of the Biodex dynamometer was performed according to the specifications outlined by the manufacturer's service manual.

EMG Recording and Data Analysis

Noraxon TeleMyo 2400T (Noraxon TeleMyo 2400T, Noraxon Inc., Scottsdale, AZ, U.S.A.) was used to measure SA, UT and LT muscle activity. EMG electrodes were attached to trapezius upper fibers, trapezius lower fibers and SA. For the SA muscle, the electrodes were placed vertically along the mid-axillary line at 6-8 rib levels (Ekstrom et al., 2005). Electrodes of trapezius upper fiber were placed at 2 ㎝ lateral of intermediate location between 7th cervical spinous process and lateral tip of acromion in shoulder 90° abduction position. Electrodes of trapezius low fiber is placed at an oblique vertical angle to a point 5 ㎝ inferomedial from the root of the scapula spine (Cram et al., 1998).

Preparation of the electrode sites involved shaving and cleaning the skin with rubbing alcohol (Cram et al., 1998). Disposable silver/silver chloride surface electrodes were positioned at an inter-electrode distance of 2 ㎝. The reference electrode was attached on the seventh cervical vertebra. The subjects were asked to perform MVIC in manual muscle test positions specific to each muscle. To measure the MVIC of SA maximum resistance was applied over the hand and at the elbow with the subject in the supine position (Ekstrom et al., 2005). Measurement of LT MVIC was performed with the shoulder rotation externally and the arm overhead and lined up with the muscle fibers of the LT while resistance was applied distal to the elbow in prone lying position (Ekstrom et al., 2005). The UT was tested with the shoulder abducted to 90°, and the head in a neutral position. Resistance was applied to downward on the shoulder (Ekstrom et al., 2005).

After MVIC testing, subjects were instructed to sit on Biodex Dynamometer System Pro and set the arm bar in 120° flexion of shoulder joint to measure EMG activity of SA, UT and LT during isometric upper extremity elevation. To avoid any compensatory strategy, the trunk and lower extremities were fixed on the equipment with the velcro and belts. Researcher commanded a "Start" signal to a subject and then subjects lifted their arm upwardly with maximum effort for 5 seconds. In order to prevent fatigue, relaxation time was provided about 1 minute between trials.

The EMG signal was then digitally analyzed in the MyoResearch Master Edition 1.06 XP software (Noraxon Inc., Scottsdale, AZ, U.S.A). The raw EMG signals were collected 16 bit analog-digital converted by 1000 ㎐ sampling rate. The sampled raw data were digitally filtered 30~400 Hz using band-pass filter and removed 60 ㎐ with notch filter. The raw data were processed into the root mean square (RMS) for analysis. For normalization, the each MVIC was collected for a period of 5-seconds and the mean values from the middle 3-seconds were averaged to calculate the mean value. Each mean muscle activity of SA, UT and LT were measured during 5-seconds isometric arm elevation and then normalized the data of the middle 3-seconds of the 5-seconds contraction by 100% MVIC method, and EMG activity ratio (UT/SA) were also calculated.

Statistical analysis

Demographic data including sex, age, height, and weight were analyzed using descriptive statistics. Average of three trial was used for the data analysis. In this study, a mixed model analysis of variance (ANOVA) (between: group, within: position) was used to determine difference of isometric strength of SA in 90° shoulder flexion at the three scapular positions between the subjects with SW and the subjects without scapular wining group. If a significant effect was observed, post hoc Bonferroni correction was used. A independent-t test was used to compare difference of EMG activity ratio of UT/SA and UT/LT between groups. All analyses were performed using SPSS 18.0 (SPSS Inc, Chicago, IL, USA), and p-value<0.05 was set for statistical significance.

III. RESULTS

The SA isometric strength between the subjects with and without SW group at the scapular positions is present in Table 2 and Figure 1. For the isometric strength of SA, the main effects were significant for group (F=9.75, p=0.00) and position (F=61.46, p=0.00). There was no significant group-by-position interaction effect (F=0.06, p=0.92) in the isometric strength of SA.

Isometric strength of SA was significantly weaker in subjects with SW than without SW group (p=0.00). In both groups, isometric strength of SA showed significant difference between all scapular positions (retracted-protracted (p=0.00), protracted-neutral (p=0.00), neutral-retracted (p=0.00)). Isometric strength of SA in retracted scapular position was strongest (Table 2, Figure 1).

Received: 22 Feb 2019 | Revised: 13Mar 2019 | Accepted: 05 Apr 2020

The EMG activity ratio of UT/SA and UT/LT between the subjects with and without SW group is present in Table 3 and Figure 2. The EMG activity ratio of UT/SA in subjects with SW group was significantly higher than in subjects without SW group (p=0.03). The EMG activity ratio of UT/LT between the subjects with and without SW group was no significant difference (p=0.62).

Table 2: Comparison of the isometric strength of SA at the three scapular positions (unit: N·m)

GROUP	Positions of Scapula			F(p)		
	Retracted	Neural	Protracted	Group	Position	Group*Position
With SW	31.64±9.07	23.20±7.80	11.19±4.17	9.75(0.00)	61.46(0.00)	0.06(0.94)
Without SW	37.11±15.96	27.39±13.01	15.92±8.25			

[a]Mean±SD

SA: serratus anterior

SW: scapular winging

* $p<0.05$

Table 3: Comparison of the EMG activity ratio of UT/SA and UT/LT

Ratio	Group		p
	With SW	Without SW	
UT/SA	1.05 ± 0.45[a]	0.83 ± 0.33	0.03*
UT/LT	1.49 ± 0.42	1.42 ± 0.62	0.62

[a]Mean±SD

SW: scapular winging

UT/SA: upper trapezius / serratus anterior

UT/LT: upper trapezius / lower trapezius

* $p<0.05$

Received: 22 Feb 2019 | Revised: 13Mar 2019 | Accepted: 05 Apr 2020

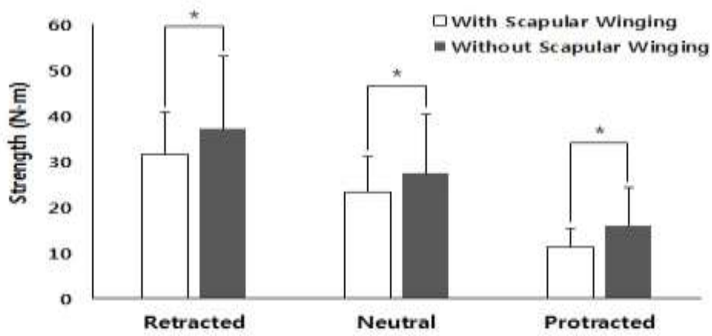

Figure 1: Comparison of the isometric strength of serratus anterior at the three scapular positions (mean ± SD) ($^{*}p$<0.05)

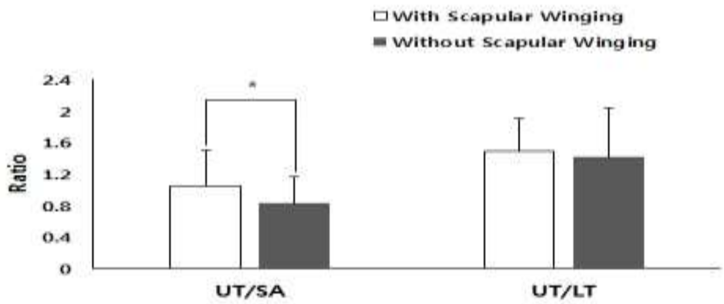

Figure 2: Comparison of the EMG activity ratio of UT/SA and UT/LT

(mean ± SD) ($^{*}p$<0.05)

UT/SA: upper trapezius / serratus anterior

UT/LT: upper trapezius / lower trapezius

IV. DISCUSSION

This study is unique to measure the isometric strength of SA at different scapular positions in subjects with and without SW. Some previous studies have been conducted to measure the strength of SA and shoulder girdle muscle by various maneuver, but they didn't consider the scapular position and the subjects were healthy individuals (Cools et al., 2002; Garner and Shim, 2008; Smith et al., 2002; Wang et al., 2006). Cools et al (2002) measured unilateral, isokinetic strength of protraction in healthy subjects. They didn't consider the scapular position to measure the SA strength in scapular plane. Although Garner and Shim (2008) measured bilateral isometric protraction strength at three scapular positions (retracted, neutral and protracted), the subjects were healthy individuals. As a result, the measured protraction force was strongest at the retracted scapular position as similar to the findings of this study. Their peak protraction force in protracted position (951 N) is 85 % of retracted position (1117 N). The results of this study showed that the isometric strength of SA in protracted position is 35 % (in subject with SW) and 42 % (in subject without SW) of retracted position. It is the reason of different ratio between Garner's study and this study that Garner and Shim (2008) measured bilateral strength of protraction in healthy subject and this study conducted to measure the unilateral strength of protraction in subject with and without SW.

A muscle's ability to generate force depends on the length at which the muscle is held with maximum force delivered near the muscle's normal resting length that is generally in middle range of motion. However, the findings of this study, as well as the results of previous studies (Garner and Shim, 2008; Contemori, 2019) showed that the strength of SA was strongest in the retracted scapular position that is most lengthened of SA muscle. The reason of this result may be described as the relationship between strength and length of muscle that is called the length-tension relationship. Muscles that tend to be lengthened muscles such as SA, gluteus medius and gluteus maximus are capable of generating substantial tension at the appropriate point in the range that is named positional strength (Carrie and Lori, 2005; Ellenbecker et al., 2015). It is considered that the positional strength of SA is retracted scapular position. The muscle that generates the greatest tension at its longest length and generates the least tension when tested at a shortened length. When the lengthened muscle is placed in a shortened position, the myofilaments in each sarcomere are excessively overlapped and thus cannot develop maximal tension (Sahrmann, 2002). Therefore SA strength test should be performed at multiple points in the range to determine whether the SA is positionally weak throughout the range (Hall Carrie and Thein Brody, 2005).

In current study, measurement position of SA strength was 90° forward flexion in shoulder joint, full extension in elbow joint, thumb up position. Wang et al (2006) and Garner and Shim (2008) were also used such posture for measurement of SA strength. Methods for measuring SA strength mentioned in many studies (protraction in scapular plane, protraction in shoulder 90° flexion in sagittal plane, and protraction in shoulder 90° flexion and 105° horizontal adduction of shoulder joint) (Cools et al., 2002; Garner and Shim, 2008; Wang et al., 2006). Among them, protraction in shoulder 90 degree used the most common for measurement of SA strength. Therefore, this study used such method. Although other methods were known to be effective, it is not recommended to measure the strength of SA muscle. Since, other muscles are also activated as an agonist during arm elevation. That is, it is difficult to focus solely on SA muscle in those methods.

In the EMG analysis, EMG activity of SA, UT and LT were measured and was calculated the relative ratio of UT/SA and UT/LT. Previous studies have reported that UT, LT, and SA muscles were the agonist muscles of scapular movement during arm elevation and solely related to upward rotation of scapula without any co-activation of other muscles (Borstad and Ludewig, 2002; Bech et al., 2017). SA muscle was generated with resistance given during upward rotation of the scapula with the shoulder flexed. LT muscle activity decreased below 90° of shoulder flexion and progressively increases over 90° of shoulder flexion. UT muscle was less than 10% of maximal muscle activity during mid-range of shoulder elevation, and showed higher muscle activity in end-range of shoulder elevation (Moon et al., 2013). Furthermore, it is reported that the abnormal movement was associated with imbalance between muscles more than muscle weakness (Sahrmann, 2002). According to Ludewig and Cook (2000), high ratio of UT/SA contributes to abnormal movement pattern during shoulder elevation. That is, increased activation of the UT may contribute to abnormal scapulohumeral rhythm and SW. Reduced activity in the SA and LT muscles during shoulder flexion were also believed to affect the abnormal scapular movement pattern (Cools et al., 2004; Cools et al., 2007). If the SA muscle does not upward rotate the scapula sufficiently, then the activation of the UT muscle may be increased. The increased UT muscle activation can cause stress on the acromioclavicular joint (Johnson et al., 1994) and the deficient control of scapula by SA muscle can create stress at the glenohumeral joint (Sahrmann, 2002).

Based on our finding, EMG activity ratio of UT/SA was significantly different between groups. That is, the muscle activity of UT in SW group was significantly higher than in subjects without SW group. Comparing our results about UT/SA with previous studies, there are similar findings. Huang et al. (2013) compared muscle activation ratio of UT/SA during forward flexion in subject with and without impingement syndrome according to the contraction type (concentric, eccentric, and isometric contraction). As a result, they found that the ratio of UT/SA showed nearly 0.6 in normal subject and 0.7-0.8 in subject with impingement syndrome during isometric shoulder forward flexion. The other several studies presented a little different result about the ratio of UT/SA. Martin et al. (2008) and Ludewig et al. (2004) found ratios of nearly 0.3 on stable and unstable surfaces during maintaining push-up plus posture. Pirauá et al. (2014) measured muscle activation ratio of UT/SA of 0.5-1 according to electrode attached sites of SA muscle and different according to the exercise surface (stable, unstable) during push-up exercise in subject with SW. Differences of UT/SA may be explained by discrepancies in exercise methods, contraction type and electrode sites of the SA muscle. That is, the higher activation of UT means abnormal state of

Received: 22 Feb 2019 | Revised: 13Mar 2019 | Accepted: 05 Apr 2020

scapular motion which is resulted from the weakened SA. Specifically, when the movement is performed in the same range of motion, decreased activity of one muscle can give rise to increased activity of another muscle to achieve the same range of motion (Jonkers et al., 2003; Kang et al., 2019). Page et al. (2010) reported in his study that synergistic muscles can affect each other by working together through movement. Furthermore, it is also reported that reduced activation of SA in persons with shoulder pain was combined with the increased muscle activity of UT, which is known as a compensatory strategy (Martin, 2008). Thus, the activity ratio of UT/SA was significantly high in SW.

This study was to compare the isometric strength of SA at three different scapular positions (retracted, neutral and protracted position) and EMG activity ratio of UT/SA and UT/LT during isometric arm elevation between the subject with and without SW. We found that the isometric strength of SA was significant decreased in subjects with SW group than without SW group. In both of subjects with and without SW groups, isometric strength of SA showed significant difference according to the retracted, neutral, and protracted scapular positions. Isometric strength of SA showed strongest in retracted scapular position. And also, the results of this study demonstrated that the EMG activity ratio of UT/SA was significantly higher in subject with SW than subject without SW, but UT/LT was no significant difference between two groups.

Based on these findings in this study, the isometric strength of SA in retracted scapular position was strongest in both of subjects with and without SW group. And the result of higher UT/SA of EMG activity ratio in subjects with SW than in subjects without SW implies that UT muscle use more dominantly among scapular upward rotators during shoulder elevation in subjects with SW.

REFERENCES

1. Bech KT, Larsen CM, Sjogaard G, Holtermann A, Taylor JL, Sogaard K. Voluntary activation of the trapezius muscle in cases with neck/shoulder pain compared to healthy controls. J Electromyogr Kinesiol. 2017;36:56-64.
2. Borstad JD, Ludewig PM. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. Clin Biomech (Bristol, Avon). 2002;17(9-10):650-659.
3. Contemori S, Panichi R, Biscarini A. Effects of scapular retraction/protraction position and scapular elevation on shoulder girdle muscle activity during glenohumeral abduction. Hum Mov Sci. 2019;64:55-66.

Received: 22 Feb 2019 | Revised: 13Mar 2019 | Accepted: 05 Apr 2020

4. Cools A, Declercq G, Cambier D, Mahieu N, Witvrouw E. Trapezius activity and intramuscular balance during isokinetic exercise in overhead athletes with impingement symptoms. Scand J Med Sci Sports. 2007;17(1):25-33.
5. Cools AM, Witvrouw EE, De Clercq GA, Danneels LA, Willems TM, Cambier DC, et al. Scapular muscle recruitment pattern: electromyographic response of the trapezius muscle to sudden shoulder movement before and after a fatiguing exercise. J Orthop Sports Phys Ther. 2002;32(5):221-229.
6. Cools AM, Witvrouw EE, Declercq GA, Danneels LA, Cambier DC. Scapular muscle recruitment patterns: trapezius muscle latency with and without impingement symptoms. Am J Sports Med. 2003;31(4):542-549.
7. Cools J, Mentens N, Furet P, Fabbro D, Clark JJ, Griffin JD, et al. Prediction of resistance to small molecule FLT3 inhibitors: implications for molecularly targeted therapy of acute leukemia. Cancer Res. 2004;64(18):6385-6389.
8. Cram JR. Introduction to surface electromyography: Aspen publishers; 1998.
9. Decker MJ, Hintermeister RA, Faber KJ, Hawkins RJ. Serratus anterior muscle activity during selected rehabilitation exercises. Am J Sports Med. 1999;27(6):784-791.
10. Ekstrom RA, Soderberg GL, Donatelli RA. Normalization procedures using maximum voluntary isometric contractions for the serratus anterior and trapezius muscles during surface EMG analysis. J Electromyogr Kinesiol. 2005;15(4):418-428.
11. Ellenbecker TS, Sueyoshi T, Bailie DS. Muscular activation during plyometric exercises in 90 degrees of glenohumeral joint abduction. Sports Health. 2015;7(1):75-79.
12. Garner BA, Shim J. Isometric shoulder girdle strength of healthy young adults. Clin Biomech (Bristol, Avon). 2008;23(1):30-37.
13. Hall Carrie M, Thein Brody L. Therapeutic exercise, Moving toward Function. A Wolters Kluwer Company Lippincott Williams & Wilkim. 2005;31:255-263.
14. Hamano T, Mutoh T, Hirayama M, Uematsu H, Higuchi I, Koga H, et al. Winged scapula in patients with myotonic dystrophy type 1. Neuromuscul Disord. 2012;22(8):755-758.
15. Huang H-Y, Lin J-J, Guo YL, Wang WT-J, Chen Y-J. EMG biofeedback effectiveness to alter muscle activity pattern and scapular kinematics in subjects with and without shoulder impingement. J Electromyogr Kinesiol. 2013;23(1):267-274.
16. Johnson G, Bogduk N, Nowitzke A, House D. Anatomy and actions of the trapezius muscle. Clin Biomech

(Bristol, Avon). 1994;9(1):44-50.

17. Jonkers I, Stewart C, Desloovere K, Molenaers G, De Borre L, Spaepen A, editors. Relating knee kinematics, muscle lengthening profiles and spasticity level of the rectus femoris in children with cerebral palsy. International meeting of the European Society for Movement Analysis in Adults and Children, Date: 2003/09/11-2003/09/13, Location: Marseille; 2003.
18. Kang FJ, Ou HL, Lin KY, Lin JJ. Serratus Anterior and Upper Trapezius Electromyographic Analysis of the Push-Up Plus Exercise: A Systematic Review and Meta-Analysis. J Athl Train. 2019;54(11):1156-1164.
19. Kibler WB, Wilkes T, Sciascia A. Mechanics and pathomechanics in the overhead athlete. Clin Sports Med. 2013;32(4):637-651.
20. Kisner C, Colby LA, Borstad J. Therapeutic exercise: foundations and techniques: Fa Davis; 2017.
21. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther. 2000;80(3):276-291.
22. Ludewig PM, Hoff MS, Osowski EE, Meschke SA, Rundquist PJ. Relative balance of serratus anterior and upper trapezius muscle activity during push-up exercises. Am J Sports Med. 2004;32(2):484-493.
23. Ludewig PM, Reynolds JF. The association of scapular kinematics and glenohumeral joint pathologies. J Orthop Sports Phys Ther. 2009;39(2):90-104.
24. Martin RM, Fish DE. Scapular winging: anatomical review, diagnosis, and treatments. Curr Rev Musculoskelet Med. 2008;1(1):1-11.
25. Martins J, Tucci HT, Andrade R, Araujo RC, Bevilaqua-Grossi D, Oliveira AS. Electromyographic amplitude ratio of serratus anterior and upper trapezius muscles during modified push-ups and bench press exercises. J Strength Cond Res. 2008;22(2):477-484.
26. Moon S-J, Kim T-H, Roh J-S. A comparison of the serratus anterior muscle activity according to the shoulder flexion angles in a closed kinetic chain exercise and an open kinetic chain exercise. J the Kor Soc Phys Med. 2013;8(3):369-378.
27. Mottram SL. Dynamic stability of the scapula. Man Ther. 1997;2(3):123-131.
28. Mueller AM, Entezari V, Rosso C, McKenzie B, Hasebrock A, Cereatti A, et al. The effect of simulated scapular winging on glenohumeral joint translations. J Shoulder Elbow Surg. 2013;22(7):986-992.
29. Myers JB, Laudner KG, Pasquale MR, Bradley JP, Lephart SM. Glenohumeral range of motion deficits and posterior shoulder tightness in throwers with pathologic internal impingement. Am J Sports Med.

2006;34(3):385-391.

30. Page P, Frank C, Lardner R. Assessment and treatment of muscle imbalance: the Janda approach. J Orthop Sports Phys Ther. 2011;41(10):799-800.
31. Pirauá ALT, Pitangui ACR, Silva JP, dos Passos MHP, de Oliveira VMA, Batista LdSP, et al. Electromyographic analysis of the serratus anterior and trapezius muscles during push-ups on stable and unstable bases in subjects with scapular dyskinesis. J Electromyogr Kinesiol. 2014;24(5):675-681.
32. Sahrmann SA. Diagnosis and Treatment of Movement Impairment Syndromes. St. Louis: mosby; 2002.
33. Smith J, Kotajarvi BR, Padgett DJ, Eischen JJ. Effect of scapular protraction and retraction on isometric shoulder elevation strength. Arch Phys Med Rehabil. 2002;83(3):367-370.
34. Wang SS, Normile SO, Lawshe BT. Reliability and smallest detectable change determination for serratus anterior muscle strength and endurance tests. Physiother Theory Pract. 2006;22(1):33-42.
35. Weon J-H, Kwon O-Y, Cynn H-S, Lee W-H, Kim T-H, Yi C-H. Real-time visual feedback can be used to activate scapular upward rotators in people with scapular winging: an experimental study. J Physiother. 2011;57(2):101-107.
36. Wiater JM, Flatow EL. Long thoracic nerve injury. Clin Orthop Relat Res. 1999(368):17-27.
37. Wilk KE, Meister K, Andrews JR. Current concepts in the rehabilitation of the overhead throwing athlete. Am J Sports Med. 2002;30(1):136-151.
38. Yano Y, Hamada J, Tamai K, Yoshizaki K, Sahara R, Fujiwara T, et al. Different scapular kinematics in healthy subjects during arm elevation and lowering: glenohumeral and scapulothoracic patterns. J Shoulder Elbow Surg. 2010;19(2):209-215.