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Coordination of the Sub-Regions of the Supraspinatus and Deltoid Muscles During Shoulder Scaption: a Shear Wave Elastography Study

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SUMMARY

Background. Understanding the functional role of the supraspinatus (SSP) and deltoid muscles during shoulder motion is a basis for understanding rotator cuff pathology and for the development of appropriate rehabilitation protocols. The purpose of this study was to elucidate the coordination, focusing on activation timing, of the sub-regions of the SSP muscle and of the middle region of deltoid muscle during scapular plane abduction (scaption) using shear wave elastography (SWE).

Methods. Twelve healthy male volunteers without any restrictions in their shoulder joints, altered posture or scapulothoracic dyskinesis were recruited to this study. Participants were instructed to sit on a chair with their back against the back-rest. Measurements of the non-dominant arm were obtained at rest and during isometric contraction at a neutral position and every 15° interval from 30° to 150° during scaption. Muscle activity was defined as the difference in SWE-measured stiffness between resting outcomes and those measured during muscle contraction (ΔE = stiffness during contraction – stiffness at rest).

Results. The anterior-middle sub-region of the SSP muscle and the middle region of the deltoid muscle presented a mountain-shape type curve with peaks at 60° (146.2 ± 26.6 kPa) and at 90° (142.0 ± 25.9 kPa), respectively. The anterior-superficial sub-region of SSP muscle peaked at 30° (102.1 ± 27.4 kPa), linearly decreasing thereafter.

Conclusions. The anterior-superficial sub-region of the SSP muscle showed activity during initial range of motion, while the anterior-middle sub-region showed activity at early mid-range. On the contrary, the middle region of the deltoid muscle showed increased SWE-measured activity at late mid-range. A more refined approach focusing on the muscles sub-regions may lead to improved rehabilitation protocols.

KEY WORDS

Coordination; deltoid; shear-wave elastography; sub-region; supraspinatus.

BACKGROUND

The rotator cuff muscles are crucial in limiting translation of the humeral head on the glenoid fossa, induced by the contraction of the deltoid muscle, and provide glenohumeral joint congruency by joint compression during shoulder motion (1-3). The middle region of deltoid muscle is the prime mover and migrates the humeral head superiorly on the glenoid fossa, while the SSP muscle predominantly applies joint compression during scapular plane abduction (scaption) (1, 3). Kinematic and electromyography (EMG) studies have investigated the coordination of the deltoid and SSP muscles during shoulder scaption motion (4, 5), and showed that the activation timing between the SSP muscle and the middle region of the deltoid muscle differed, and normal motion was not achieved with a pathological SSP muscle (6).

Recent cadaveric studies have demonstrated that the SSP muscle has a complex morphology (7-10). Roh *et al.* divided the SSP muscle into anterior and posterior regions, based on their attachment to different sections of the internal tendon, and suggested that the anterior region is responsible for force production while the posterior region for an adjustment of tension (7). Kim *et al.* subdivided the anterior and the posterior regions into superficial, middle and deep sub-regions each based on fiber bundle arrangement (8). EMG studies have evaluated the functions of the morphologically divided regions (11, 12). EMG data were obtained from the anterior and posterior regions suggesting that the anterior region was a mover and the posterior region acted as stress control for the anterior region (11, 12). Understanding the functional roles of these sub-regions in relation to deltoid muscle activity will complement our understanding of shoulder motion and function.

Shear wave elastography (SWE) is an ultrasound technique that has been implemented to obtain quantitative estimations of tissue shear modulus, as a surrogate for tissue stiffness. Sasaki *et al.* reported a linear relationship between muscle shear modulus and tetanic muscular force produced by electrical stimulation *in vivo* (13). During passive muscle stretching, Koo et al. showed that the SWE elasticity increased when the muscle was being stretched and that the SWE elasticity was linearly correlated with passive resistance force (14). Hoshikawa et al., using SWE, demonstrated the different behavior of three partitions of infraspinatus muscle during scaption *in vivo* (15). Hatta *et al.* demonstrated that the four subregions of SSP muscle and five subregions of deltoid muscle presented distinct characteristics during passive motion using SWE *in vitro* (16,17). The functions of the sub-regions of the SSP and infraspinatus muscles in previous studies using ultrasound elastography are summarized in **table I**. These studies

Table I. Functions of the sub-regions of the infraspinatus and supraspinatus muscles in previous studies using ultrasound elastography. (**a**) Infraspinatus muscle. (**b**) Supraspinatus muscle.

(a)

Author (year)	Measurements	Tasks	Function		
			sub-regions		
			superior	middle	inferior
Hoshikawa *et al.* (2021)	Shear wave elastography	Scaption	Force production at end-range of scaption	Force production throughout scaption initiator of scaption	Force production at end-range of scaption dynamic tenodesis at initial-range of scaption
Yuri *et al*. (2021)	Shear wave elastography	Sidelying external rotation	Force production at end-range of external rotation	Force production at mid-range of external rotation	force production at initial-range of external rotation
Kuwahara *et al.* (2017)	Strain elastography	External rotation in 70° abduction and 30° of horizontal abduction	Abductor	External rotator	External rotator abductor

(b)

Author (year)	Measurements	Tasks	Function					
			Sub-Regions					
			Anterior			Posterior		
			Superficial	Middle	Deep	Superficial	Middle	Deep
Yuri *et al.* (2017)	Strain elastography	External rotation in 90° abduction	Force production for abduction	Force production for abduction	Force production for abduction	Maintain tension	Maintain tension	Force production for abduction and external rotation
Kuwahara *et al*. (2017)	Strain elastography	External rotation in 70° abduction and 30° of horizontal abduction	Abductor					External rotator

suggest the feasibility of SWE to elucidate the distinct behaviors of the subregions of the SSP and deltoid muscles during scaption. Different muscle activation timing during scaption motion would lead to sub-region specific therapeutic strategies in degenerated or pathological muscles. The purpose of this study was to elucidate the coordination, focusing on activation timing, of the sub-regions of the SSP muscle and the middle region of the deltoid muscle during scaption using SWE. Outcomes from this process would provide an in-depth understanding of the contribution of the sub-regions and muscles to the shoulder scaption motion.

MATERIALS AND METHODS

Participants

A power analysis was performed *a-priori* to calculate the sample size needed for one-way analysis of variance (ANOVA) with repeated measures [effect size = 0.25, α error = 0.05, power = 0.8] using G* power 3.1 software (Heinrich Heine University, Duesseldorf, Germany) (18). Thus, twelve healthy male volunteers without any restrictions in their shoulder joints, altered posture or scapulothoracic dyskinesis were recruited to this study after approval by our Institutional Ethics Review Board, which was met the ethical standards of the journal (19). Their mean age, body weight, and height were 20 ± 1 years old, 60 ± 3 kg and 170 ± 4 cm, respectively. Written informed consent was obtained from all participants.

Experimental protocol

Participants were instructed to sitting on a chair with their back against the back-rest and hip and knee angle at 90° without pelvic posterior tilt. Investigator then checked the participants posture with their arm by side whether there are scapula dyskinesis, thoracic kyphosis and forward head (20). Before the measurement, participants were instructed warm-up exercises and stretching as well as scapular stabilizing muscles for muscular imbalance correction (21). Shoulder (SSP and middle region of the deltoid muscle) measurements of the non-dominant arm were obtained at rest and during isometric contraction at a neutral position and every 15° interval from 30° to 150° during scapular plane abduction (scaption). A custom-built fixture was designed to allow for resting of the arm at each shoulder interval, while also allowing for active measurements. Resting measurements were obtained by having the participants place their arm at specific intervals on the fixture; active isometric contraction measurements were obtained by moving the fixture back from the resting position and instructing the participants to hold their arm against gravity in the air (**figure 1**). Arm postures, muscular conditions (at rest, during contraction), and sub-regions of muscle were randomized. An Aixplorer ultrasound system (Supersonic Imagine, Aix-en-Provence, France) and a 15-4 MHz linear array probe (SL 15-4) were used to obtain shear modulus (kPa), as a surrogate for stiffness. The anterior-superficial and anterior-middle sub-regions of the SSP muscle, as determined by Kim (8), and the middle region of the deltoid muscle were identified based on their distinct muscle fiber orientations using B-mode imaging (**figure 2**). One investigator (K.H.) obtained a continuous SWE imaging video for each sub-region of muscle, then three random images were chosen from the video for analysis and circular regions of interest (ROI) of 4 mm in diameter were positioned center of muscle fiber each sub-region of muscle to obtain stiffness outcomes while looking at the B-mode maps. This process was repeated for each arm position. Muscle activity values were defined as the difference in stiffness outcomes between the active muscle contractions and the stiffness values at rest (ΔE = stiffness during contraction – stiffness at rest) (15, 22). Muscle activity values were obtained for each shoulder position.

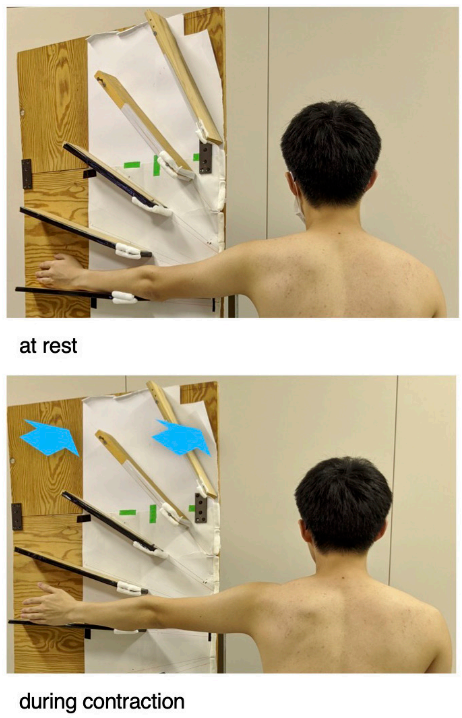

Figure 1. A resting position was attained by having the participants place their arm at specific intervals on the fixture; active isometric contraction measurements were obtained by moving the fixture buck from the resting position and instructing them to hold their arm against gravity in the air, at every 15° intervals from 30° to 150° during abduction in scapular plane (scaption).

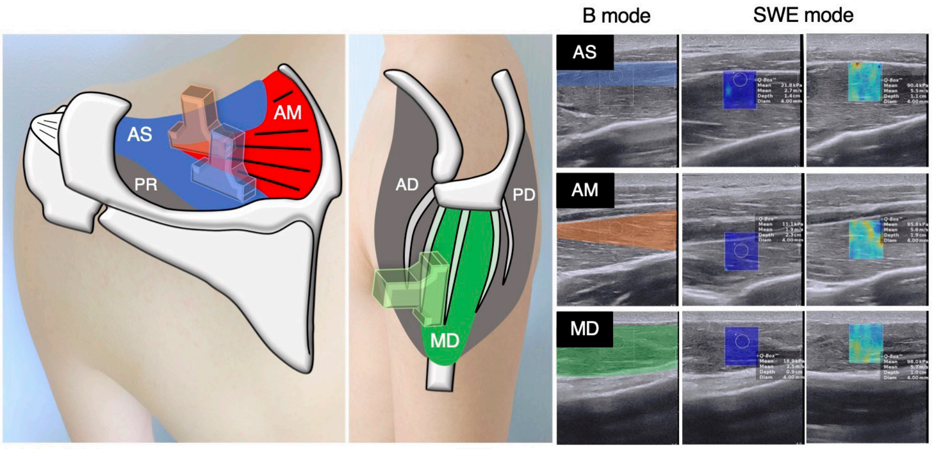

Figure 2. Probe orientations for the anterior-superficial (AS) sub-region, anterior-middle (AM) sub-region of the supraspinatus muscle and middle region of the deltoid muscle (MD). PR; posterior region of the supraspinatus muscle, AD; anterior region of the deltoid muscle, PD; posterior region of the deltoid muscle.

Statistical analysis

SPSS statistical software (version 24.0; SPSS, Chicago, IL, USA) was used for all the statistical analyses. Mean (SD) stiffness values across the twelve participants for each sub-region and shoulder position were computed. Intra-observer reliability of three images between twelve participants for each muscular sub-region and scaption angle was examined using intraclass correlation coefficient ($ICC_{1,3}$). Reliability was classified as poor (less than 0.50), moderate (between 0.50 and 0.75), good (between 0.75 and 0.90), and excellent (greater than 0.90) (23). One-way ANOVA with repeated measures were used to evaluate differences in measurement outcomes among nine angles of scaption in each sub-region. Paired Student's t-test with Bonferroni revision was used as *post-hoc* analysis to identify levels of difference among scaption angles when warranted. Statistical significance was set as $p < 0.05$.

RESULTS

$ICC_{1,3}$ values among overall measurements were > 0.910, indicating excellent reliability. **Figure 3** shows the quantitative stiffness outcomes (rest, contraction, and activity value) for each muscle sub-region at various scaption angles. Example SWE images during contraction are also shown for reference. Activity values for the anterior-middle ($p < 0.001$, $F = 57.062$) and anterior-superficial ($p < 0.001$, $F = 41.301$) sub-regions of the SSP muscle and the middle region of the deltoid muscle ($p < 0.001$, $F = 29.449$) were influenced variously by scaption angle. Mean (SD) stiffness values (rest, contraction, and activity value) across the twelve participants for each sub-region and shoulder position and statistical outcomes for *post-hoc* test are shown in **table II**.

Activity outcomes of the anterior-middle sub-region of the SSP muscle (**table II a**) increased from 30° up-to 60° of scaption, reaching a value of 146.2 ± 26.6 kPa. Activity of this muscle sub-region linearly decreased after 60° with increasing elevation angles, resulting in a stiffness value of 43.2 ± 21.3 kPa at 150°. The peak stiffness value at 60° was significantly higher than the values measured at all other angles ($p < 0.002$), except at 45° ($p = 0.244$). At angles > 75°, the activity values of this sub-region continued to decrease with significant differences between the activity values at adjacent arm position ($p < 0.004$), except between 105° and 120° ($p = 0.059$). Values obtained at 105° and higher scaption angles were significantly lower than that at 30° ($p < 0.019$).

On the other hand, muscle activity outcomes of the anterior-superficial sub-region of the SSP muscle (**table II b**) were highest at 30° (102.1 ± 27.4 kPa) and linearly decreased with increasing shoulder angle position. The peak stiffness value at 30° was significantly higher than the values measured at all other angles ($p < 0.029$). There were no statistical differences between the activity values at adjacent arm position at angles > 90° ($p > 0.394$).

Finally, activity values of the middle region of the deltoid muscle (**table II c**) showed a prominent mountain-shape with peaks of 142.0 ± 25.9 kPa at 90°. The peak value was significantly higher than the values at all other angles ($p < 0.007$). The activity values of this region decreased with significant differences between values at adjacent arm position from 90° to 135° ($p < 0.038$), while there was no significant difference between 135° and 150° measured outcomes ($p = 0.155$). Outcomes at 135° and 150° were higher than the lowest value of 63.1 ± 22.7 kPa observed at 30°, but not significant.

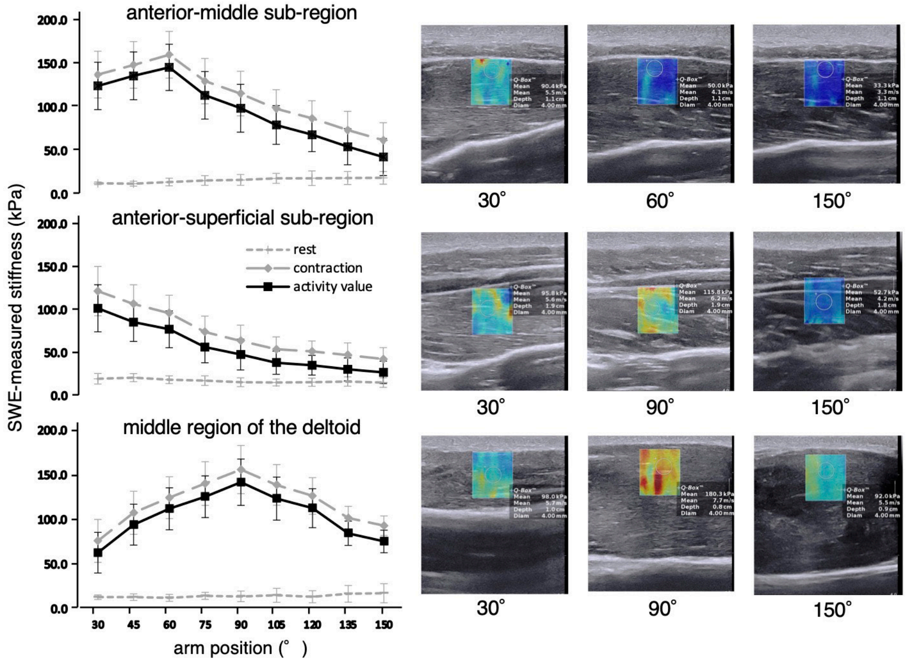

Figure 3. SWE-measured stiffness outcomes (rest, contraction, activity) and example images from the single participant for each muscle sub-region during contraction at various scaption angles.

Table II. Mean (SD) values for SWE-measured stiffness at the various arm positions and conditions (rest, contraction and activity value). (**a**) Anterior-middle sub-region of the supraspinatus muscle. (**b**) Anterior-superficial sub-region of the supraspinatus muscle. (c) Middle region of the deltoid muscle.

(a)

	30°	45°	60°	75°	90°	105°	120°	135°	150°	*p*-value
Activity value	124.8 (27.2)	136.4 (27.4)	146.2 (26.6)	114.1* (27.3)	99.2* (27.5)	80.0*# (22.3)	68.8# (19.5)	55.1*# (20.8)	43.2*# (21.3)	*: significantly lower than the value at adjacent arm position (p < 0.004) #: significantly lower than the value at 30° (p < 0.019)
Rest	13.0 (1.5)	12.6 (2.8)	14.5 (4.3)	16.3 (5.6)	16.9 (6.2)	18.7 (5.7)	18.8 (8.4)	19.1 (7.5)	19.3 (7.3)	
Contraction	137.9 (26.9)	149.0 (26.8)	160.7 (26.0)	130.3 (26.0)	116.1 (25.6)	98.7 (21.8)	87.7 (20.2)	74.2 (21.5)	62.5 (20.1)	

(b)

	30°	45°	60°	75°	90°	105°	120°	135°	150°	*p*-value
Activity value	102.1 (22.4)	85.9 (22.4)	77.6 (21.5)	56.8 (18.2)	48.2# (18.0)	38.7# (13.5)	35.8# (11.5)	30.9# (13.4)	27.4# (13.0)	#: no statistical difference between the values at adjacent arm position (p > 0.394)
Rest	20.0 (6.2)	21.3 (4.7)	18.9 (4.5)	17.8 (5.6)	15.9 (5.1)	15.7 (4.0)	16.0 (4.7)	16.8 (5.4)	15.6 (5.6)	
Contraction	122.1 (28.7)	107.2 (22.3)	96.4 (20.8)	74.6 (18.3)	64.2 (18.3)	54.4 (14.3)	51.7 (12.2)	47.7 (14.1)	43.0 (13.3)	

(c)

	30°	45°	60°	75°	90°	105°	120°	135°	150°	*p*-value
Activity value	63.1# (22.7)	94.5 (22.9)	112.2 (23.5)	125.8 (23.4)	142.0 (25.9)	123.7* (24.1)	112.9* (21.8)	84.0*# (13.6)	75.7# (12.6)	*: significantly lower than the value at adjacent arm position ($p < 0.038$) #: no statistical difference between the values ($p > 0.155$)
Rest	13.2 (2.6)	13.3 (3.7)	12.5 (3.9)	14.8 (3.9)	14.2 (5.9)	15.4 (7.9)	13.7 (6.7)	17.0 (9.3)	17.7 (10.7)	
Contraction	76.3 (24.0)	107.8 (24.1)	124.7 (23.4)	140.5 (24.5)	156.2 (27.0)	139.0 (22.7)	126.7 (20.5)	101.9 (13.2)	93.3 (10.9)	

Although not significant, the stiffness at rest of each muscle sub-region changed at various scaption angles. The resting values of the anterior-middle sub-region of the SSP muscle was lowest at 45° and tended to increase from 60° to 90°, remaining almost constant from 105° with increasing elevation angle. Similarly, the resting values of the middle region of the deltoid muscle was lowest at 60° and then tended to increase with increasing elevation angle. On the other hand, the resting values of the anterior-superficial sub-region of the SSP muscle tended to decrease from 30° to 90° and constant with higher angles.

DISCUSSION

The purpose of this study was to elucidate the behaviors, focusing on activation timing, of the SSP muscle sub-regions and the middle region of the deltoid muscle during scaption motion using SWE. Results showed activity values of the anterior-middle sub-region of the SSP muscle to present a mountain-shape pattern with a peak at 60° and linearly decreasing outcomes with increasing elevation angles. Similarly, the middle region of the deltoid muscle showed a mountain-shape behavior with a peak at 90° but this region continued to show statistically equivalent and higher stiffness values at end-range. On the contrary, the anterior-superficial sub-region of the SSP muscle showed a peak value at 30° with linearly decreasing outcomes until 90° of scaption motion.

Previous EMG studies showed the SSP and deltoid muscles during scaption motion to present a mountain-shape activation pattern with peaks at 60° and 90°, respectively (4, 5). EMG studies, since the sub-regions of the SSP muscle are so small and not be able to identify each sub-region due to not only difficulty in anatomical orientation but mutual interference, there has been only one study that revealed the functions of the anterior and posterior region of the SSP muscle using fine-wire EMG electrodes (24). Tthe placement of the electrode was performed under assistance of ultrasound B-mode at and inserted into the center of the SSP muscle, indicating that activation values were obtained solely from the anterior-middle sub-region of the SSP muscle. The results from these studies are consistent with our SWE outcomes from the anterior-middle sub-region of the SSP muscle and middle region of the deltoid muscle. The SSP and the deltoid muscles exert unique forces in the humeral head with scaption motion; activation of the SSP muscle results in a compressive force on the humeral head against the glenoid fossa, with a peak at 60°; while activation of the deltoid muscle, with a peak at 90°, will create a force on the humeral head inducing superior subluxation (1, 3). Therefore, the relationship, measured using SWE in the current study, between the anterior-middle sub-region of the SSP muscle and middle region of the deltoid muscle aligns well with these previous studies, indicating that these regions have a major significant role at 60° and 90° of scaption motion, respectively.

On the other hand, the activation timing of the anterior-superficial sub-region of the SSP muscle was different from that of anterior-middle subregion. The highest activity value in anterior-superficial sub-region was observed at 30°, resulting in a mean value of < 125 kPa. Activity values gradually decreased from 30° to 90°, with minor changes thereafter and up-to 150°. The anterior-superficial sub-region of the SSP muscle may play a major role at 30° of scaption. To our knowledge, this is the first study reporting high activity values in anterior-superficial sub-region of the SSP muscle at lower scaption angles.

Previous SWE studies demonstrated a linear relationship not only between stiffness and active contractile force, but a linear relationship between stiffness and passive stretching force (13, 14). As muscle is stretched, it will tend to increase its passive resistance to deformation. Thus, the stiffness at rest can indicate the length of muscle. Stiffness at rest from the anterior superficial sub-region was highest at 30° and then gradually decreased up-to 90° in this study. This indicates that the anterior superficial sub-region was gradually shortened with increasing elevation angles and approaching the resting length. The resting values of the anterior-middle sub-region of the SSP muscle and middle region of the deltoid muscle were lowest at 45° and 60°, respectively, and increased thereafter with increasing elevating angle, *i.e.*: with a decrease in muscle length. These outcomes suggest that the muscular length positioned at 45° corresponded to the resting length for the anterior-middle sub-region of the SSP muscle and the muscular length at 60° corresponded to the resting length for the middle region of the deltoid muscle. It is important to note that the force generated by skeletal muscles will be the summation of active and passive components. Therefore, the higher activity outcomes of the anterior-superficial sub-region of the SSP muscle from 30° to 90° could mainly not only be a result of active muscle contraction but a result of the tension produced by passive stretching, and values from 90° to 150° could indicate a major role of active muscle contraction. Activity values of the anterior-middle sub-region of the SSP muscle and middle region of the deltoid muscle were a result of mainly active muscle contraction. To utilize the passive stretching force, even it is small, is reasonable for small volume muscle, such as the anterior-superficial sub-region of the SSP.

Several studies have demonstrated that, in the setting of a rotator cuff tear, the superficial subregion of the SSP primarily atrophies, while the deep subregions mainly show fat infiltration (25, 26). Kim *et al.* showed that the fiber type distribution of the anterior superficial subregion was mainly comprised of Type II fibers, while that of the anterior middle was Type I (27). Those findings also support the different function observed between the superficial and middle subregions of the SSP muscle. Current rehabilitation protocols for shoulder related injuries were developed based on the coordinated function between the deltoid muscle and the anterior middle subregion of the SSP muscle; *e.g.* isometric exercise is conducted at 60° abducted position. In case with the superficial subregion atrophy, for example, the exercise should be conducted at 30° abducted position. The findings of the current study provide evidence to investigate the coordinated function between deltoid and anatomical subregions of the SSP muscle in pathological populations so that better rehabilitation protocols can be developed.

The presence of alterations in scapular position and in its movement patterns is could be related to various conditions altering the relationship between the glenohumeral and acromioclavicular joints, or which act on correct muscle activation and coordination. Since the scapular position on the dominant side is varied as Frizziero *et al*. pointed out in the various instrumental musicians (28), non-dominant side was selected for measurement in this study. We also checked the participants sitting posture with their arm by side whether there are scapula dyskinesis, thoracic kyphosis and forward head to prevent altering the muscle activation and coordination affected by posture (20). Before the measurement, participants were instructed the warm-up exercises and stretching as well as scapular stabilizing muscles for muscular imbalance correction (21).

There are several limitations in this study. First, we measured only two sub-regions of the SSP muscle as determined by Kim *et al*., who subdivided the anterior and the posterior regions into superficial, middle and deep sub-regions each (8). The selection on these regions was based on the anterior sub-region being responsible for force production and the posterior sub-region for an adjustment of tension on the tendon (8). Similarly, Roh *et al*. reported the anterior region to be responsible for contractile forces, while concluding that the posterior region could not generate large contractile loads (7). A study by Hatta *et al.* demonstrated that deep region of the anterior compartment of the SSP muscle, beneath the internal tendon, presented different stiffness outcomes compared to the superior region (16). Although the anterior region is responsible for the contractile properties of the muscle, there are still intrinsic differences between the superficial and deep sub-regions (10, 22, 26, 27). Since the purpose of this study was to elucidate the behaviors of the SSP sub-regions and the middle region of the deltoid muscle in relation to the contractile properties of the muscle during scaption motion, we only measured the anterior-superficial and anterior-middle sub-regions of the SSP muscle. Second, holding the arm against gravity was defined as isometric contraction corresponded to the manual muscle test grade 3 in this study. While this process could be considered as a weak static muscle contraction, it allowed for the evaluation of the individual SSP sub-regions during active muscle conditions. When the tasks of daily life is assumed, specific load should be applied using such as weighing scale method (29). Therapeutic strategies focusing on the specific activation timing of the sub-regions of the pathological SSP muscles will lead to better rehabilitation outcomes.

CONCLUSIONS

The anterior-superficial sub-region of the SSP muscle showed activity during initial range of motion, while the anterior-middle sub-region showed activity at early mid-range. On the contrary, the middle region of the deltoid muscle showed increased SWE-measured activity at late mid-range. A more refined approach focusing on the muscles sub-regions may lead to improved rehabilitation protocols.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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