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Original Article

Neural Drive and Motor Unit Characteristics of the Serratus Anterior in Individuals With Scapular Dyskinesis

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Abstract

Objective: Scapular dyskinesis is one of the causes of shoulder disorders and involves muscle weakness in the serratus anterior. This study investigated whether motor unit (MU) recruitment and firing property, which are important for muscle exertion, have altered in serratus anterior of the individuals with scapular dyskinesis. **Methods**: Asymptomatic adults with (SD) and without (control) scapular dyskinesis were analyzed. Surface electromyography (sEMG) waveforms were collected at submaximal voluntary contraction of the serratus anterior. The sEMG waveform was decomposed into MU action potential amplitude ($MUAP_{AMP}$), mean firing rate (MFR), and recruitment threshold. MUs were divided into low, moderate, and high thresholds, and MU recruitment and firing properties of the groups were compared. **Results**: High-threshold $MUAP_{AMP}$ was significantly smaller in the SD group than in the control group. The control group also exhibited recruitment properties that reflected the size principle, however, the SD group did not. Furthermore, the SD group had a lower MFR than the control group. **Conclusions**: Individuals with scapular dyskinesis exhibit altered MU recruitment properties and lower firing rates of the serratus anterior; this may be detrimental to muscle performance. Thus, it may be necessary to improve the neural drive of the serratus anterior when correcting scapular dyskinesis.

Keywords: EMG Decomposition, Motor Unit, Scapular Dyskinesis, Serratus Anterior, Shoulder

Introduction

Various musculoskeletal disorders can develop as a consequence of cumulative mechanical stress on joint components because of abnormal motion[1]. In addition to having many degrees of freedom, the shoulder joint has the largest range of motion in the human body. Its control mechanisms are complex; however, the prevalence of shoulder pain is high[2]. Scapular dyskinesis is defined as the alteration of normal scapular kinematics[3]. Many forms of scapular dyskinesis exist, such as decreased upward rotation and posterior tilt and increased internal rotation and elevation[3]. This abnormal motion increases mechanical stress on the shoulder components, increasing the risk of shoulder injury[4]. Therefore, correcting scapular dyskinesis is important for the prevention and treatment of shoulder injuries.

The serratus anterior is one of the most important muscles involved in scapular stabilization[3]. Decreased strength[5,6] and electromyography (EMG) activity[7,8] of the serratus anterior have been reported in individuals with shoulder pain and scapular dyskinesis. However, according to Seitz et al.[9], there was no significant difference in terms of the thickness of the serratus anterior among those with and without scapular dyskinesis. Moreover, there is inadequate evidence to support the efficacy of scapular stabilization exercises in correcting scapular motion[10]. Taken together, these reports complicate the pathogenesis of scapular dyskinesis and can hinder clinical decision making. Therefore, further research

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is warranted to understand its pathogenesis.

The force exerted by a muscle must consider both morphological and neural factors[11]. A motor unit (MU) is the smallest basic unit of movement which comprises a single motor neuron along with the group of muscle fibers it innervates[12]. Increased excitatory synaptic input to the motor neuron pool results in the orderly recruitment of MUs with larger diameter muscle fibers, action potential amplitude, and twitch forces[13-16]. Furthermore, the recruited MUs exhibit different firing properties, depending on their size[17]. The recruitment and firing properties of such MUs are evaluated in terms of the recruitment threshold. Low-threshold MUs have low amplitudes and high firing rates, whereas high-threshold MUs have high amplitudes and low firing rates[18]. Notably, the amplitude of high-threshold MUs is correlated with muscle strength[19]. Furthermore, older adults with presarcopenia do not exhibit hierarchical firing[20]. Other changes in MU recruitment and firing properties have been reported in patients both with and without disorders[21,22]. Considering that the weakness of the serratus anterior is closely related to scapular motion, patients with scapular dyskinesis may exhibit altered MU recruitment and firing properties of the serratus anterior, leading to characteristically reduced muscle strength and EMG activity.

MU recruitment and firing properties can be evaluated using surface EMG decomposition (dEMG). Recent improvements in algorithms have made it possible to apply this to dynamic movement tasks[23], expanding the scope of research to a wide variety of populations, muscles, and movements[24-28]. Applying this algorithm to the serratus anterior can potentially help determine how the neuromuscular system is involved in scapular dyskinesis and provide new insights for strengthening and other exercises in clinical practice.

Although scapular dyskinesis also exists in asymptomatic individuals[29,30], most studies have focused on symptomatic individuals. However, pain can be a confounding factor affecting EMG activity and maximal muscle strength[5,8,31]. Furthermore, since asymptomatic scapular dyskinesis may lead to shoulder injury in the future[4], preventive measures is also crucial for this population. Thus, the purpose of this study was to clarify the MU recruitment and firing properties of the serratus anterior in individuals with asymptomatic scapular dyskinesis. We hypothesize that, in patients with scapular dyskinesis, high-threshold MU has a small amplitude and does not exhibit hierarchical firing in the serratus anterior.

Materials and Methods

Participants

This study included 49 healthy adults (age, 20–28 years) who were enrolled at Hiroshima International University (25 men, 24 women). Participants with $18<BMI<25$ and fully capable of raising their upper limbs were included in the study. The exclusion criteria were as follows: current pain or surgery in the neck or upper limb, neurological abnormalities, and athletes or those who regularly engage in strenuous exercise. Furthermore, individuals with excessive thoracic kyphosis (>50°)[32,33] and those with a previous diagnosis of scoliosis were excluded, considering the influence of spinal alignment on scapular motion. Thoracic kyphosis was measured by a physical therapist (MK) with 4 years of clinical experience who visually screened spinal alignment and used an inclinometer when necessary.

Evaluation of scapular motion

Scapular motion was evaluated using the scapular dyskinesis test[34,35]. Participants performed five repetitions of full bilateral flexion and abduction in the thumbs-up position. This was performed again while grasping the dead weights, which were determined based on the participant's body weight[34]. A video camera (iPhone 11 pro, Apple, USA) was used to capture scapular motion from behind. An examiner (MK) played back the recorded video and rated the scapular motion as normal, subtle, or obvious. Participants evaluated as obvious were assigned to the scapular dyskinesis (SD) group. Obvious dyskinesis was operationally defined as a clearly apparent dysrhythmia or winging of at least 2.54 cm in at least 3 out of 5 trials of either flexion or abduction. Dysrhythmia was defined as premature or excessive scapular protraction or elevation, nonsmooth motion, or rapid downward rotation motion during arm lowering. Winging was defined as a motion in which the medial border and/or inferior angle of the scapula was posteriorly away from the thorax. Normal motion was operationally defined as no evidence of abnormality; such patients were placed in the control group. Individuals with subtle dyskinesis, defined as winging or dysrhythmia that was mild, questionable, or not consistently present, were excluded. Scapular dyskinesis was evaluated in both the dominant and nondominant limbs. If scapular dyskinesis was bilateral or absent, the dominant limb was used for measurement; if scapular dyskinesis was present on one side, the limb on the scapular dyskinesis side was measured. The interrater agreement was 80%, kappa coefficient was 0.63, and intra-rater reliability, which was calculated using the kappa coefficient, was 0.77. This reliability was mostly consistent with that observed in previous studies[34,35]. After the scapular dyskinesis test, 13 and 20 participants were classified into the control and SD groups, respectively. The sample size was determined by referring to previous studies[22,36] comparing similar parameters.

Scapular motion was further quantified by three-dimensional motion analysis. Three-dimensional motion of the scapula was measured using the 6-degrees-of-freedom electromagnetic tracking device (Liberty, Polhemus, Colchester, VT, USA) [120 Hz][37]. After SDT, sensors were attached to the subject's sternum, acromion, and humerus. To link the sensors to the local coordinate system, digitization was performed using a stylus on the bony landmarks recommended by the International Society of Biomechanics (ISB)[38]. The participants raised their unilateral upper limb (measurement limb) to the maximum along a plane positioned 40° anteriorly (scapular) from the frontal plane in the standing position. After sufficient practice, movements were performed in 10 consecutive trials, with each raising and lowering unified for 3 s. The 3D data obtained were imported into Motion Monitor, and joint angles were calculated. The following joint angles were calculated using Euler angles for the rigid models of the thorax, humerus, and scapula. Scapula orientation relative to the thorax (+ internal / − external rotation, + downward / − upward rotation, + posterior / − anterior tilt) and humerus orientation relative to the thorax (humerothoracic) (+ depression / − elevation) were determined. Five trials were arbitrarily selected from eight trials (excluding the first and last of 10 consecutive trials). Each scapula angle (internal/external rotation, upward/downward rotation, and anterior/posterior tilt) was calculated in 10° increments from 20° to 120° and 120° to 20° of humerothoracic elevation (the angles at the start and end of the elevation were also calculated), and the average value from the five trials was considered representative for each participant.

Procedure

After skin conditioning with alcohol and an abrasive skin preparation gel, a 4-pin array sensor (diamond-shaped at 5-mm intervals) (Trigno Galileo Sensor; Delsys Inc., Natick, MA, USA) was attached at the midpoint between the leading edge of the latissimus dorsi and trailing edge of the pectoralis major on the 7th rib[39]. Voluntary contraction of the serratus anterior muscle was encouraged and confirmed before attachment. Another wireless array sensor (rectangular shape at 10-mm intervals) (Trigno Avanti Sensor; Delsys Inc., Natick, MA, USA) was attached near the Galileo sensor for visual feedback from trapezoidal contraction. Two experienced physical therapists (MK & RK) attached the sensors. Surface EMG (sEMG) waveforms were sampled at 2222 Hz with onboard 20–450 Hz filtering and streamed to EMGworks (Delsys Inc., Natick, MA, USA).

Participants were asked to perform maximal voluntary contraction (MVC) on the serratus anterior while seated with their feet on the ground. The hip and knee joints were at 90°, whereas the upper limb was raised to 125° in the sagittal plane with maximum protraction of the shoulder girdle. The participants were warned beforehand to avoid compensation, such as elevation of the shoulder girdle and anterior tilt of the trunk. The MVC was performed for 5 s, with two trials each, and the sEMG waveform was recorded using a Trigno Avanti sensor. The 50% MVC target for trapezoidal contraction based on the peak root mean square (RMS) values recorded during MVC was projected on a computer monitor placed in front of the participants. The participants performed the trapezoid task using the RMS value (window length 0.25 s) of the sEMG waveform of the serratus anterior as a reference[24,40]. In the trapezoid task, sEMG activity was increased to the desired level by flexing the upper limb to 125° and protracting the shoulder girdle during the 5-s ramp-up phase, where it was held for 20 s, after which the sEMG activity level was reduced to baseline by lowering the upper limb over 5 s (Figure 1). After approximately 15 minutes of explanation and practice trials of the task movement, all participants were able to perform the movement. Measurements were taken after a 15-min rest period following the practice trial. If the RMS value deviated from the target value, the measurement was repeated. Sufficient rest periods (5 min) between measurements.

Data analysis

Neuromap software (Delsys Inc., Natick, MA, USA) was used to extract the firing trains of the individual MUs from the four sEMG activity channels. The decomposition accuracy was calculated using the decompose–synthesize–decompose–compare method. The analysis included only MUs with an accuracy of >90%, and the following items were calculated: 1) MU action potential amplitude ($\mathrm{MUAP}_{\mathrm{AMP}}$), calculated as the maximum amplitude of the positive and negative MUAP peaks detected from the four EMG channels; 2) recruitment threshold (RT), calculated as the EMG level at which the MU began to fire; and 3) mean firing rate (MFR), calculated from the inverse of the interpulse intervals between MU firing during the plateau phase of the trapezoidal contraction. Based on their RTs, all MUs were classified as either L-RTs (<15%), M-RTs (15%–30%), or H-RTs (>30%)[20].

Statistical analysis

Normality of all variables was examined with the Shapiro-Wilk test.

Demographic data, maximum RMS values during serratus anterior MVC, mean relative activity in serratus anterior trapezoidal contraction (20s plateau phase), and RT (total, L-RT, M-RT, H-RT) were compared using a two-sample t-test or Mann–Whitney U test.

Two-way analysis of variance (ANOVA) was performed to compare scapular motion (internal/external rotation, downward/upward rotation, anterior/posterior tilt) between the groups, in each of the raising and lowering phases. The between-participant factor was the groups (control and SD), and the within-participant factor was the humerothoracic elevation angle (raising phase: start, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, 120°; lowering phase: 120°, 110°, 100°, 90°, 80°, 70°, 60°, 50°, 40°, 30°, 20°, end). The main effect of the groups and the interaction between the groups and elevation angle were examined.

Two-way ANOVA with group (control, SD) and RT (L-RT, M-RT, H-RT) as factors was performed for $\mathrm{MUAP}_{\mathrm{AMP}}$ and MFR. If an interaction or main effect was observed, a one-way ANOVA or Kruskal–Wallis test was performed for each group for the three RTs (L-RT vs. M-RT vs. H-RT). Tukey's test or the Steel–Dwass test was used for post-hoc tests. Two-sample t-test or Mann–Whitney U-test was used for intergroup comparisons (control vs. SD) for each RT.

When performing two-way ANOVA, *partial eta square* (ηp^2) was calculated as the effect size (small, 0.01–0.06; medium, 0.06–0.14; and large, >0.14). When performing two-sample

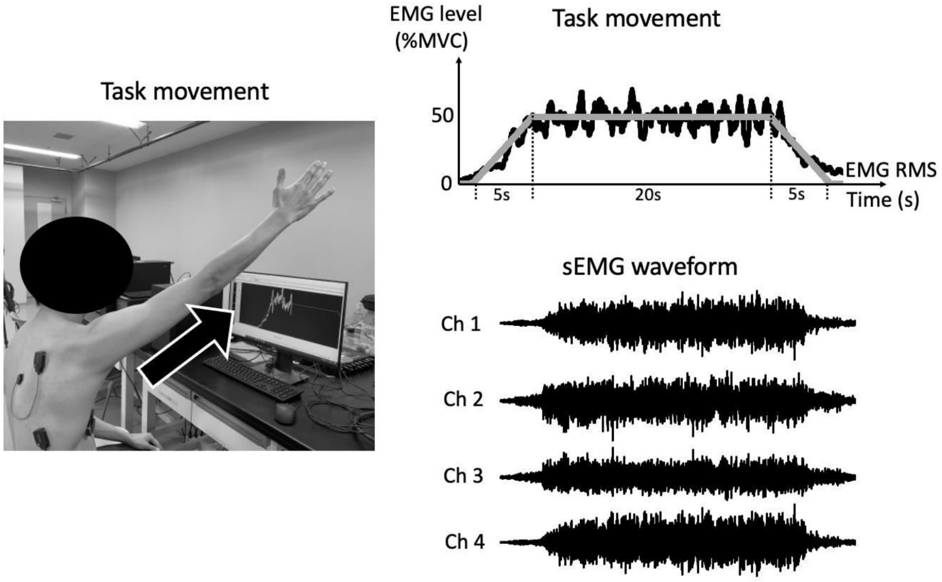

Figure 1. Participants performed trapezius contractions at a 50% EMG level of the maximal voluntary contraction of the serratus anterior. The serratus anterior muscle was contracted by flexing the upper limb to 125° and protracting the shoulder girdle. There was feedback of the RMS values of the serratus anterior EMG in real time during trapezoidal contraction. The sEMG waveforms obtained for the four channels were used for the MU analysis. sEMG, surface electromyography; RMS, root mean square.

Table 1. Demographic information of study participants.

	Control group (n = 13)	SD group (n = 19)	*p*-value
Sex (male/female)	7/6	13/6	0.473
Right-handed (n)	12	19	0.406
Age (year)	22.0 ± 1.9	21.5 ± 1.71	0.671
Height (m)	1.64 ± 0.09	1.68 ± 0.08	0.234
Weight (kg)	54.1 ± 7.6	59.4 ± 8.6	0.081
BMI	20.0 ± 1.23	21.0 ± 1.90	0.072

Mean ± SD; BMI, body mass index; SD, scapular dyskinesis.

t-tests and Mann–Whitney U-tests, *d* (small, 0.20–0.50; medium, 0.50–0.80; large, >0.80) and *r* (small, 0.30–0.50; medium, 0.50–0.80; large, >0.80) were calculated as effect sizes, respectively. SPSS Statistics 28 (IBM Japan, Tokyo, JP) was used for all statistical analyses. Statistical significance was set at $p = 0.05$.

Results

One participant in the SD group was excluded because MU data could not be obtained, and data from 13 participants in the control group and 19 participants in the SD group were finally analyzed. There were no significant differences in the demographic data for each group (Table 1).

Data on the dominant arm side were collected from all subjects. There were no significant differences in the RMS values of the serratus anterior MVC ($p = 0.650$, $r = 0.081$) and relative activity during trapezoidal contraction ($p = 0.862$, $d = 0.003$). A total of 93 MUs were obtained from the control group and 94 from the SD group. The SD group had a significantly smaller total RT than the control group ($p = 0.018$, $r = 0.174$) (Supplementary Table 1).

The data and statistical results of scapular motion are shown in Supplementary Figure 1 and Supplementary Table 2. Two-way ANOVA indicated that the groups have significant main effects on scapular upward rotation (raising: $p < 0.001$,

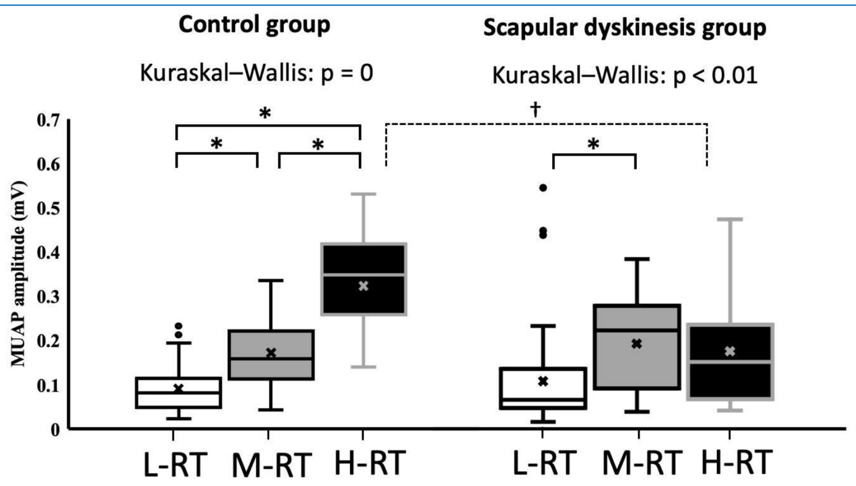

Figure 2. Motor unit action potential amplitude in the control and scapular dyskinesis groups. The motor unit action potential (MUAP) amplitude at each recruitment threshold (RT) is shown as a box-and-whisker diagram. Asterisks (*p <0.01) indicate significant differences in the Steel–Dwass test. Daggers ($^{\dagger}p$ <0.01) indicate significant differences in the two-sample t-test between groups. $MUAP_{AMP}$, motor unit action potential amplitude; L-RT, motor units recruited at 0%–15% of maximal voluntary contraction (MVC); M-RT, motor units recruited at 16%–30% of MVC; H-RT, motor units recruited at 31%–50% of MVC.

Table 2. Two-way ANOVA for motor unit action potential amplitude and mean firing rate.

	Group		Main effect		Interaction
	Control	SD	Group	RT	Group × RT
$MUAP_{AMP}$ (mV)					
L-RT	0.090 ± 0.059	0.107 ± 0.107	*$p = 0.016$ $^{\dagger}\eta p^2 = 0.031$	**$p < 0.001$ $^{\dagger\dagger\dagger}\eta p^2 = 0.257$	**$p < 0.001$ $^{\dagger\dagger}\eta p^2 = 0.097$
M-RT	0.174 ± 0.075	0.192 ± 0.109			
H-RT	0.323 ± 0.109	0.175 ± 0.131			
MFR (pps)					
L-RT	18.85 ± 4.28	16.77 ± 4.96	*$p = 0.023$ $^{\dagger}\eta p^2 = 0.028$	**$p < 0.001$ $^{\dagger\dagger\dagger}\eta p^2 = 0.373$	$p = 0.626$ $\eta p^2 = 0.005$
M-RT	13.91 ± 4.49	13.15 ± 4.68			
H-RT	9.12 ± 4.94	6.79 ± 4.38			

*ANOVA, analysis of variance; MFR, mean firing rate; $MUAP_{AMP}$, motor unit action potential amplitude; SD, scapular dyskinesis; RT, recruitment threshold. L-RT, motor units recruited at 0%–15% of maximal voluntary contraction (MVC); M-RT, motor units recruited at 16%–30% of MVC; H-RT, motor units recruited at 31%–50% of MVC; ηp^2, partial eta square; *p <0.05; **p <0.01; † small effect size; †† medium effect size; ††† large effect size.*

$\eta p^2 = 0.063$; lowering: $p < 0.001$, $\eta p^2 = 0.063$), external rotation (raising: $p < 0.001$, $\eta p^2 = 0.111$; lowering: $p < 0.001$, $\eta p^2 = 0.111$), and posterior tilt (raising: $p < 0.001$, $\eta p^2 = 0.093$; lowering: $p < 0.001$, $\eta p^2 = 0.085$) angles, all of which were smaller in the SD group than in the control group.

Two-way ANOVA for $MUAP_{AMP}$ revealed an interaction between group and RT ($p < 0.001$, $\eta p^2 = 0.097$) (Table 2). Kruskal–Wallis for RT showed a main effect for both groups (control $p = 0$, SD $p < 0.001$), with post-hoc tests showing significant differences in all combinations for the control group, but only between L-RT and M-RT for the SD group (Figure 2). Significant differences between the groups at each RT were found only for H-RT ($p < 0.001$, $d = 1.254$), with $MUAP_{AMP}$ being significantly greater in the control group than in the SD group (Figure 2). Two-way ANOVA for MFR showed a main effect for each group ($p = 0.023$, $\eta p^2 = 0.028$) and RT (p < 0.001, np2 = 0.373), but no interaction ($p = 0.736$, $\eta p^2 = 0.005$) (Table 2). One-way ANOVA for RT showed a main

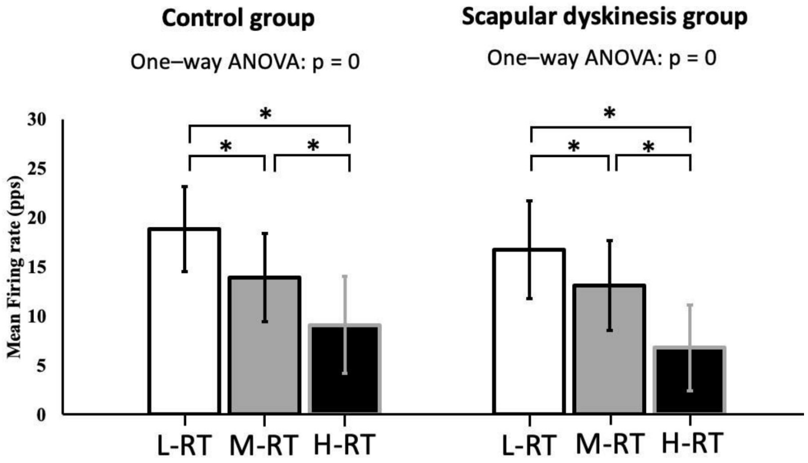

Figure 3. Mean firing rates in the control and scapular dyskinesis groups. The mean firing rate (MFR) at each recruitment threshold (RT) is shown as a box-and-whisker diagram. Asterisks (*$p < 0.01$) indicate significant differences in the Turkey test. MFR for each RT are shown. Both the groups exhibited hierarchical firing patterns. MFR, mean firing rate; L-RT, motor units recruited at 0%–15% of maximal voluntary contraction (MVC); M-RT, motor units recruited at 16%–30% of MVC; H-RT, motor units recruited at 31%–50% of MVC.

effect for both groups, and the post-tests showed significant differences for all combinations (Figure 3).

Discussion

The SD group had a smaller amplitude of MUs recruited after 30% of the MVC than the control group, confirming the hypothesis. Contrary to the hypothesis, the SD group showed a hierarchical firing pattern, but the firing rate was lower than that of the control group.

This study used SDT for grouping. Lopes et al.[41] used SDT and assigned 19 of 53 participants to the SD group. Burn et al.[42] demonstrated that SD was present in 33% of non-overhead athletes. Of the 49 participants in this study, 20 were assigned to the SD group, which is generally consistent with the prevalence of SD obtained in previous studies[41,42]. In the three-dimensional scapular motion, upward rotation, external rotation, and posterior tilt were also greater in the control group than in the SD group, objectively demonstrating the validity of the grouping.

Although dEMG has been used for a variety of muscles, this study is the first to use it for the serratus anterior. The location of the sEMG sensor has been shown in previous studies low likelihood of crosstalk[43]. The upper limb flexion of 125° used in the task movement ellicited the highest EMG activity in the serratus anterior and lowest EMG activity in the surrounding muscles[44]. This position also showed no significant difference in amplitude between the EMG activity of the serratus anterior recorded with intramuscular versus surface electrodes[43]. Therefore, we believe that this was the most appropriate position for promoting EMG activity in the serratus anterior. Although many studies have provided feedback force data[19,45], for this study, trapezoidal contraction tasks have been performed using feedback from sEMG activities. The main actions of the serratus anterior, scapular upward rotation and protraction[46], also involves muscles other than the serratus anterior. In individuals with scapular winging, there is increased muscle activity around the scapula rather than around the serratus anterior during scapular protraction[47]. Therefore, the sEMG activity of the target serratus anterior might not be sufficiently high if there was feedback from the force data. Feedback of sEMG activity was used to promote the maximum activity of the serratus anterior. Isometric contractions alone were not sufficient to accomplish the task movements in this study, and some dynamic contractions were included. Algorithms for the decomposition of dynamic tasks have already been established[23]. Furthermore, only MUs with high decomposition accuracy, wherein the agreement between the original sEMG waveform and reconstructed sEMG waveform exceeded 90%, were analyzed[23,40]. Due to the lack of previous studies analyzing MU in the serratus anterior, we were unable to collate the results; nevertheless, we believe that the measurement method was valid for the reasons listed above.

Herein, the SD group showed a decrease in RT width, a decrease in the amplitude of high threshold (30%-50% MVC) MUs, and a lower overall firing rate. This result suggests that the SD group shifts the recruitment of MUs to a lower threshold and is unable to recruit more tractional MUs. This may be due to atrophy of muscle cross-sectional area and type II muscle fibers, and reduced neural drive to the MU pool. Trevino et al.[48] reported that the muscle cross-sectional area was correlated with MUAP_{AMP}. In older adults, whose skeletal muscle is reduced compared with that in younger adults, MU recruitment shifts to a lower threshold and MUAP_{AMP} is also reduced[21]. Furthermore, the magnitude of MUAP_{AMP} also correlates with muscle fiber size[14,49]. However, Seitz et al.[9] reported no significant differences in the thickness of the serratus anterior, suggesting that morphological factors alone does not explain. A lower firing rate suggests a reduction in neural drive, which may be underlain by prolonged afterhyperpolarization (AHP)[50] and a decrease in persistent inward currents (PIC)[51]. This may have prevented a sufficient increase in spinal cord excitability, negatively affecting the increase in synaptic drive in anterior horn cells of the spinal cord and inhibiting the recruitment of larger sized MUs. Such abnormalities in the neuromuscular system may counteract the muscular exertion of the serratus anterior and lead to reduced strength and activity of the serratus anterior. Further research is needed to verify this.

Considering the above factors, improving the neural drive in the serratus anterior could be key to the treatment of scapular dyskinesis. Selkowitz et al[52]. reported higher activity in the tensor fascia and lower activity in the gluteus medius and gluteus maximus in patients with patellofemoral pain (PFP) than in healthy participants during hip abduction exercise. This suggests the need to activate the gluteus medius and gluteus maximus prior to therapeutic exercise in patients with PFP. The same is true for correcting scapular motion. Some exercises that increase the activity of the serratus anterior, include push-up plus[53] and scapular punch[54]. These were proposed based on a study that reported higher activity in the serratus anterior using electromyography. However, this study was conducted in healthy participants; it is unknown whether the same applies to individuals with scapular dyskinesis, wherein the neural drive of the serratus anterior is reduced. Kim et al.[47] have shown that individuals with scapular winging, versus healthy participants, have lower serratus anterior activity during scapular protraction and higher activity in the pectoralis major, deltoid, and upper trapezius. Furthermore, our results suggested that exercises that recruit high-threshold MUs are needed in individuals with SD. High-intensity resistance training is recommended to improve MUAP_{AMP}[45]. Muscle contraction at relatively low activity levels has previously been recommended for shoulder rehabilitation[55]. However, intervention studies have not provided sufficient evidence to correct scapular motion[10]. From this study, it is possible that a load setting of at least 30% MVC is necessary to promote neural drive in the anterior serratus; however, further research is needed to establish a specific method.

This study had several limitations. First, as a cross-sectional study, the causal relationship between scapular dyskinesis and changes in MU recruitment and firing properties could not be determined. Second, the effect of subcutaneous fat could not be considered, and the MUAP_{AMP} size has been reported to affect subcutaneous fat thickness[56]. Nevertheless, participants with $18<\text{BMI}<25$ were included, and there were no significant differences in physical characteristics between the groups. Finally, this study was conducted in healthy young adults. Therefore, caution should be exercised when extrapolating the results of this study to other populations.

In conclusion, individuals with scapular dyskinesis had altered MU recruitment pattern during submaximal contraction of the serratus anterior, especially with reduced MUAP_{AMP} that recruited at a higher threshold. Furthermore, the MU firing rate was also decreased. This may be detrimental to the muscle exertion of the serratus anterior, suggesting a neuromuscular mechanism in the pathogenesis of scapular dyskinesis. Thus, it may be necessary to improve neural drive of the serratus anterior before performing scapular stabilization exercises.

Ethics approval

The experimental procedures were conducted in accordance with the Declaration of Helsinki and were approved by the Medical Research Ethics Committee for Humans at Hiroshima International University (No. 22–006).

Consent to participate

Before participation, the purpose, potential benefits, and risks involved in the study were explained to the participants, and written informed consent was obtained.

Author's contributions

M.K. and N.K. conceived and designed research; M.K., R.K. and D.Y. performed experiments; M.K. and D.K. analyzed data; M.K., Y.I. and N.K. interpreted results of experiments; M.K. prepared figures; M.K. drafted manuscript; M.K., Y.I. and N.K. edited and revised manuscript; M.K., Y.I., R.K., D.K., D.Y. and N.K. approved final version of manuscript.

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Supplementary Table 1. Information on MVC and number of motor units.

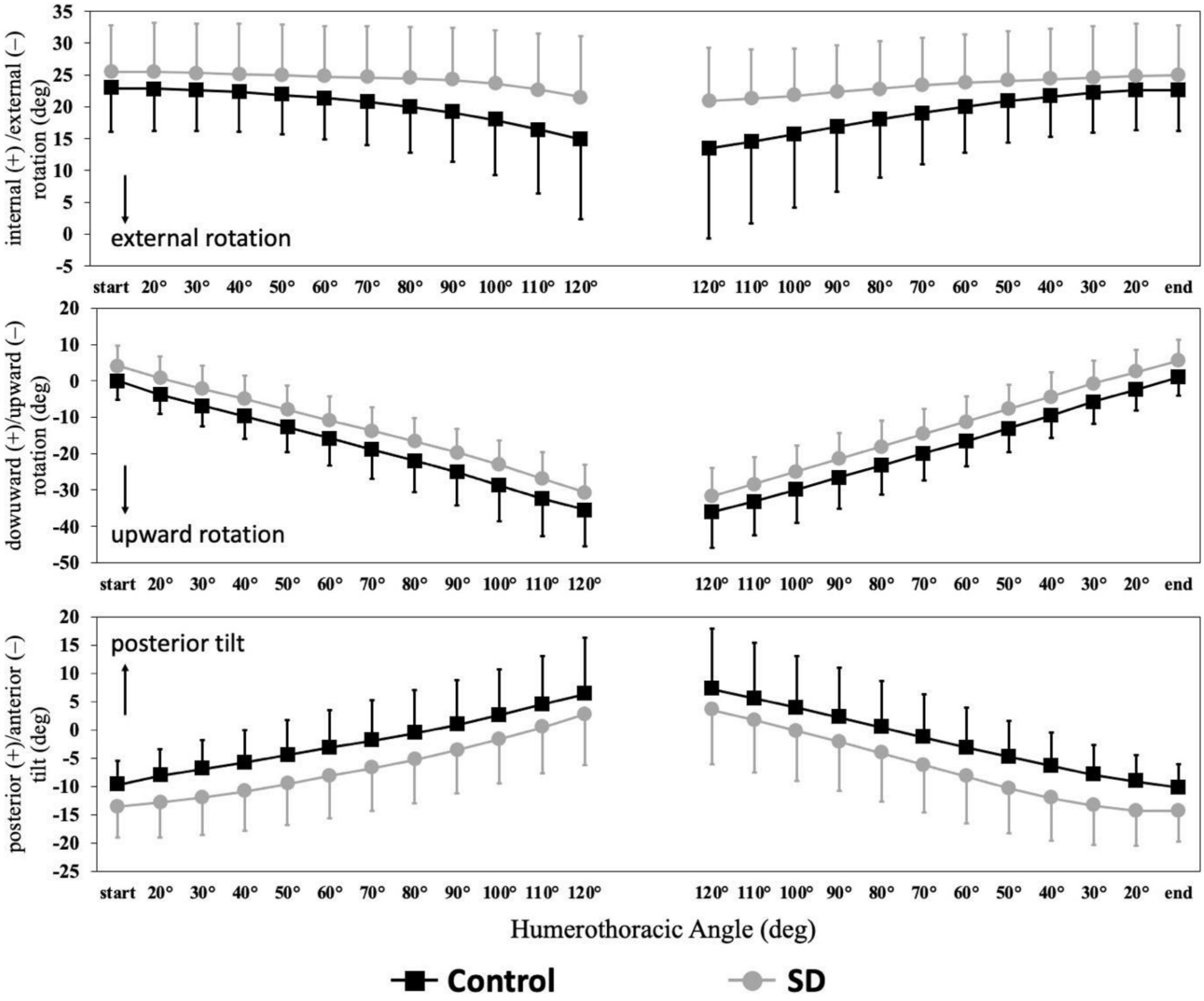
	Control group	SD group	*P*-value	Effect size
MVC (mV)	0.30 ± 0.11	0.31 ± 0.21	0.650	$r = 0.081$
50% MVC task (%)	46.7 ± 1.9	46.8 ± 3.0	0.862	$d = 0.003$
RT range (%)				
Total	21.7 ± 10.8	18.5 ± 10.7	*0.018	†$r = 0.174$
L-RT	9.8 ± 4.3	10.5 ± 3.0	0.370	†$r = 0.163$
M-RT	23.6 ± 4.6	23.7 ± 4.0	0.836	$r = 0.025$
H-RT	35.0 ± 5.0	38.7 ± 5.9	0.055	††$r = 0.318$

MVC, Peak RMS (root mean square) of the serratus anterior EMG (electromyography) during MVC (maximum voluntary contraction). 50% MVC task, relative activity of serratus anterior during trapezoidal contraction in plateau phase. RT range, mean ± standard deviation of RT; MU, motor unit; RT, recruitment threshold, SD, scapular dyskinesis; L-RT, motor units recruited at 0%–15% of MVC; M-RT, motor units recruited at 16%–30% of MVC; H-RT, motor units recruited at 31%–50% of MVC; ηp^2*, partial eta square;* *$p < 0.05$*; † small effect size; †† medium effect size; ††† large effect size.*

Supplementary Table 2. Results of two-way ANOVA in scapular motions.

	Phase	Main effect				Interaction	
		Group		Elevation angle		Group × elevation angle	
		p	ηp^2	p	ηp^2	p	ηp^2
Internal/External rotation	raising	*<0.001	††0.063	0.058	†0.051	0.991	0.008
	lowering	*<0.001	††0.063	*0.007	††0.068	0.969	†0.011
Downward/Upward rotation	raising	*<0.001	††0.111	*<0.001	†††0.702	1.000	0.001
	lowering	*<0.001	††0.111	*<0.001	†††0.735	1.000	0.000
Posterior/Anterior tilt	raising	*<0.001	††0.093	*<0.001	†††0.331	1.000	0.001
	lowering	*<0.001	††0.085	*<0.001	†††0.366	1.000	0.002

ANOVA, analysis of variance; ηp^2*, partial eta square;* *$p < 0.01$*; † small effect size; †† medium effect size; ††† large effect size.*



Supplementary Figure 1. Comparison between groups in three scapular motions. The black line denotes the control group, and the gray line denotes the SD group. The vertical axis indicates the angle of each scapulothoracic rotation, and the horizontal axis indicates the angle of humerothoracic raising. There was a significant group main effect for all scapular motions. SD, scapular dyskinesis.