Motor unit behavior of the lower trapezius and serratus anterior in individuals with scapular dyskinesis

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Article

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Abstract

Scapular dyskinesis results from weakness of the lower trapezius and serratus anterior, but no studies have investigated the motor unit (MU) behavior required for muscle exertion. This study aimed to classify scapular dyskinesis into raising (SDR) and lowering (SDL) phases and investigated the MU behaviors of the lower trapezius and serratus anterior. Fifty healthy young subjects underwent a scapular dyskinesis test and were divided into Normal, SDR, and SDL groups. The subjects performed submaximal voluntary contractions of the lower trapezius and serratus anterior, and surface electromyography signals were decomposed into the MU action potential amplitude (MUAP$_\text{AMP}$), mean firing rate (MFR), and recruitment threshold (RT). The average MUAP$_\text{AMP}$ and MFR and the slopes and y-intercepts of the linear MUAP$_\text{AMP}$-RT and MFR-RT were compared. The MUAP$_\text{AMP}$-RT slopes in the lower trapezius ($p = 0.049, r = 0.420$) and serratus anterior were smaller ($p = 0.010, r = 0.490$) and the MFR-RT y-intercept in the serratus anterior was lower ($p = 0.004, r = 0.540$) in the SDR group than in the Normal group. Differences in other parameters between the SDL and Normal groups were not significant. Lower trapezius and serratus anterior MU behavioral changes may cause scapular dyskinesis in the raising phase.

Introduction

Scapular dyskinesis is a general term for alterations in normal scapular kinematics and loss of normal scapular motion control and is characterized by decreased upward rotation and posterior tilt, increased internal rotation, excessive elevation, and rapid downward rotation during upper-limb raising and lowering [1, 2]. The patterns of scapular kinematics alterations vary in the raising and lowering phases [3] but most often appear in the lowering phase [4, 5]. Scapular dyskinesis interferes with stable kinematics of the humeral head in the scapular glenoid fossa [6, 7] and has been implicated in shoulder disorders [1, 8]. It is known that some healthy individuals also have scapular dyskinesis [9, 10]. However, a recent systematic review reported that scapular dyskinesis is a risk factor for shoulder disorders [11]. Therefore, correcting scapular dyskinesis is important in the treatment and prevention of shoulder disorders [12].

Scapular dyskinesis involves weakening of the periscapular muscles [1]. The lower trapezius and serratus anterior are of particular interest in scapular kinematics [13, 14], and many reports have shown a relationship between lower trapezius and serratus anterior weakness and reduced muscle activity in scapular dyskinesis [15–19]. Against this background, exercise therapy, primarily for strengthening the lower trapezius and serratus anterior, has been recommended for correcting scapular motion; however, a recent systematic review did not find sufficient evidence to support that recommendation [20]. Significant differences in the muscle thickness of the lower trapezius or serratus anterior between those with and without shoulder pain also have not been demonstrated [21].

The motor unit (MU) is the final common pass for conveying motor commands from the central nervous system to the effector, and muscle strength depends on the number, size, and firing rate of the recruited MU (MU behavior) [22, 23]. Although the role of the nervous system in muscle exertion has long been recognized, there have been no reports on its role in the lower trapezius or serratus anterior. Although
many studies have focused on muscle strength [17, 19] and muscle activity [3, 18, 24], it is unclear whether the nervous system that coordinates them, especially the MU behavior (the smallest basic unit of movement), is changed in those with scapular dyskinesis. MU behavior is not always constant and varies with age [25, 26], sex [27, 28], and the presence of a musculoskeletal disorder [29, 30], and those with scapular dyskinesis may also have characteristic MU behavior.

Advances in measurement and analysis technology have made non-invasive measurement of MU possible [31, 32]. This technique may enable clarifying the MU behaviors of the lower trapezius and serratus anterior, which has not previously been possible. The scapular motion is thought to require complex neuromuscular control [5], but the reality of this process remains unclear. Determining if MU alterations affecting the lower trapezius and serratus anterior exist in individuals with scapular dyskinesis would support the involvement of neuromuscular control in scapular motion and may provide useful information for understanding the pathology of scapular dyskinesis and for developing exercise therapies.

The study aim was to evaluate the MU behavioral characteristics of the serratus anterior and lower trapezius in individuals with scapular dyskinesis and advance our understanding of scapular dyskinesis pathology. We also examined the differences in neuromuscular control between separate groups of individuals with scapular dyskinesis appearing in the raising phase (SDR) and lowering phase (SDL) [4]. We hypothesized the following: 1) individuals with scapular dyskinesis will have MU behaviors in the lower trapezius and serratus anterior different from those of individuals without scapular dyskinesis, and 2) MU behavior will differ between individuals with SDR and SDL.

## Methods

### Subjects

A total of 50 healthy 20–28-year-old adults enrolled at Hiroshima International University participated in this study [25 males: age 21.8 ± 2.3; height 1.71 ± 0.05 m; weight 63.4 ± 7.6 kg; Body Mass Index (BMI) 21.5 ± 2.0 kg/m²; 25 females: age 21.2 ± 1.4 years; height 1.59 ± 0.05 m; weight 49.9 ± 4.7 kg; BMI 19.8 ± 1.4 kg/m²]. A convenient sampling method was used to recruit the subjects. Subjects with no history of shoulder trauma or shoulder pathology and with completely active glenohumeral elevation were included. Participants with current pain or surgery in the neck or upper-limb, BMI > 25 kg/m² (WHO standards for overweight) [33], neurological abnormality or excessive kyphosis or scoliosis of the thoracic spine, and athletes or people who regularly engage in strenuous exercise were excluded. Subjects gave written informed consent after receiving a detailed explanation of the purpose, potential benefits, and risks involved in the participation prior to this study. The experimental procedures used in this study 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).

### Evaluation of scapular dyskinesis
The scapular dyskinesis test (SDT) was performed to determine if scapular dyskinesis was present. Male subjects were asked to remove their shirts, and female subjects were asked to wear halter tops. The subjects performed five repetitions of maximal bilateral raising to lowering of their arms in the sagittal and scapular planes using the thumbs-up position. The same operation was then performed by grasping dead weights. The weights were 1.4 kg for those with body weights < 68.1 kg and 2.3 kg for those with body weights > 68.1 kg. The movement speed was standardized at 3 s for both raising and lowering. A video camera (iPhone 11 pro, Apple, USA) was used to capture the scapular motion from behind. An examiner (first author) played back the recorded video and rated scapular motion as normal motion, subtle dyskinesis, and obvious dyskinesis in both the raising and lowering phases. The evaluation criteria were those reported by McClure et al. [34]. Scapular dyskinesis was evaluated in both the dominant and non-dominant 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 evaluation criteria were those reported by McClure et al. [34]. The inter-rater agreement was 70% in the raising phase and 80% in the lowering phase, and the kappa coefficient was 0.41 in the raising phase and 0.63 in the lowering phase.

The SDT results are shown in Fig. 1. Fourteen subjects who were rated as having normal motion in both the raising and lowering phases were defined as the Normal group. Nine subjects who were rated as having obvious dyskinesis in the raising phase were defined as the SDR group. Eleven subjects who were rated as having obvious dyskinesis in the lowering phase were defined as the SDL group (Fig. 1 & Table 1).

<table>
<thead>
<tr>
<th>Subject characteristics</th>
<th>Normal group (n = 14)</th>
<th>SDR group (n = 9)</th>
<th>SDL group (n = 11)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>7 males,</td>
<td>6 males,</td>
<td>8 males,</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>7 females</td>
<td>3 females</td>
<td>3 females</td>
<td></td>
</tr>
<tr>
<td>Right-handed (n)</td>
<td>12</td>
<td>9</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Age (year)</td>
<td>21.9 ± 1.9</td>
<td>21.4 ± 2.2</td>
<td>21.6 ± 1.0</td>
<td>0.567</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.64 ± 0.09</td>
<td>1.68 ± 0.07</td>
<td>1.67 ± 0.08</td>
<td>0.589</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>53.6 ± 7.2</td>
<td>60.2 ± 9.0</td>
<td>57.9 ± 7.7</td>
<td>0.168</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>19.79 ± 1.36</td>
<td>21.33 ± 2.17</td>
<td>20.66 ± 1.41</td>
<td>0.267</td>
</tr>
</tbody>
</table>

BMI, body mass index; SDR, scapular dyskinesis that appears in the raising phase; SDL, scapular dyskinesis that appears in the lowering phase.

Three-dimensional scapular motion
To present objective data on the scapular motion, a 6-degrees-of-freedom electromagnetic tracking device (Liberty, Polhemus, Colchester, VT, USA) [120 Hz] and Motion Monitor software (Innovative Sports Training, Chicago, IL, USA) were used to calculate the three-dimensional scapula motion. The local coordinate system and rotation sequence for the scapula, humerus, and trunk segments were as described in a previous study [35].

The subjects raised their upper-limb (measurement limb) to the maximum along a plane positioned 40° anteriorly (scapular) from the frontal plane. After sufficient practice, movements were performed in 10 consecutive trials, with each raising and lowering unified for 3 s. Five trials were arbitrarily selected from eight trials, excluding the first and last of ten 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 humeral elevation relative to the thorax, and the average value from the five trials was considered representative for each participant.

**Measurement of the MU**

**Surface electromyography signal recording**

Before attaching the surface electromyography (sEMG) electrodes, a participant’s skin was wiped with alcohol and rubbed with an abrasive skin preparation gel. Four differential sEMG signals were recorded from the lower trapezius and serratus anterior using a wireless array sensor consisting of four pins (Trigno Galileo Sensor; Delsys Inc., Natick, MA, USA). The lower trapezius was attached to the middle point between the spinous process of the seventh cervical vertebra and trigonum scapula [36], and the serratus anterior was attached to the middle point between the leading edge of the latissimus dorsi and trailing edge of the pectoralis major on the seventh rib [37]. Voluntary contraction of each muscle was encouraged before attaching, and contraction was confirmed. Another wireless array sensor (Trigno Avanti Sensor; Delsys Inc., Natick, MA, USA) was attached near the Galileo sensor as a sensor for visual feedback from trapezoidal contraction, as described below [31, 38]. The sensors were attached by two experienced physical therapists (first & third authors). sEMG signals were sampled at 2000 Hz with onboard 20–450 Hz filtering and streamed to EMGworks (Delsys Inc., Natick, MA, USA), where baseline noise and signal-to-noise ratio were monitored in real-time during data collection to confirm high sEMG signal quality.

**Measurement of maximal voluntary contraction**

First, maximal voluntary contractions of the lower trapezius and serratus anterior were performed. To measure the lower trapezius, the participants lay prone with the upper-limb abducted in line with the muscle fibers (approx. 145°). From this position, the upper-limb was lifted toward the ceiling with maximum force and the thumbs-up. The participants were cautioned beforehand to avoid compensatory trunk rotation and extension, abduction, adduction, and horizontal extension of the upper-limb. The serratus anterior were placed in a seated position with the feet on the ground, and the hip and knee joints were set at 90°. The upper-limb was raised to 130° in the sagittal plane with maximum protraction of the
shoulder girdle. The participants were warned beforehand to avoid compensations, such as elevation of the shoulder girdle, and anterior tilt of the trunk. These positions have been validated to produce the maximum sEMG activity of the primary agonist and least involvement of surrounding muscles with sEMG [39]. The measurements were taken after oral explanation and sufficient practice before the measurement. The maximal voluntary isometric contraction (MVC) was performed for 5 s, two trials each, and the EMG signal was recorded by the Trigno Avanti Sensor.

**Task movement (Fig. 2, informed consent was obtained from the subject shown in the image.)**

A trapezoidal contraction task for each muscle was used. A computer monitor was placed 80–100 cm in front of the subjects. On this monitor, the target values of muscle activity to perform trapezoidal contraction and sEMG root mean square (RMS) values (window length 0.25s) were obtained from the lower trapezius and serratus anterior [31, 38]. The target level for both the lower trapezius and serratus anterior was 70% MVC, with a ramp-up phase of 5 s, a plateau phase of 20 s, and a ramp-down phase of 5 s. Each performed the task movement in the posture in which the MVC was measured. Participants performed trapezoidal contraction tasks at various force levels, including 30% and 50% prior to measurement and were given time to become accustomed to the task movements. If the RMS value clearly deviated from the target value, the measurement was repeated. Measurements were taken until two successful trials were obtained, with sufficient rest periods between measurements.

**Decomposition of the MU**

Neuromap software (Delsys Inc., Natick, MA, USA) was used to extract the firing trains of the individual MU from the four channels of sEMG activity. The accuracy of the decomposition was calculated using the decompose–synthesize–decompose–compare method [32, 40]. To exclude MU with low decomposition accuracy from the analysis, only those with accuracy > 85% were used. To analyze the action potential amplitude and firing properties of the MU, the following five items were examined [41, 42]: 1) MU action potential amplitude (MUAP<sub>AMP</sub>), calculated as the maximum amplitude of the positive and negative peaks of the MUAP detected from the four sEMG channels; 2) MU recruitment threshold (RT), calculated as the sEMG level at which the MU began to fire; 3) mean firing rate (MFR) of the MU, calculated from the inverse of the interpulse intervals between MU firings during the plateau phase of the trapezoidal contraction; 4) the slope and y-intercept of a linear regression of MUAP<sub>AMP</sub> and RT (MUAP<sub>AMP</sub>-RT slope, MUAP<sub>AMP</sub>-RT y-intercept) that was used to clarify the relationship between MUAP<sub>AMP</sub> and RT; and 5) the slope and y-intercept of a linear regression of MFR and RT (MFR-RT slope, MFR-RT y-intercept) used to clarify the relationship between MFR and RT.

**Statistical analysis**

**Comparison of scapular motion**
Statistical Parametric Mapping (SPM) was performed to compare scapular motions in each group. The main effect of each group (Normal, SDR, SDL) on the scapulothoracic rotations was assessed by a One-Way ANOVA SPM(t). When the main effect of the group was observed, post hoc tests were applied.

**Reliability analysis**

To interpret the study results more carefully, we calculated the reliability of the MU parameters of the lower trapezius and serratus anterior and verified the measurement method's robustness. Ten males and 10 females were randomly selected from among the participants, and two successful trials of each task were analyzed. Intraclass correlation coefficients (ICCs) were calculated for the following items: average of MUAP<sub>AMP</sub> and MFR for all MUs, MUAP<sub>AMP</sub>-RT slope and y-intercept, and MFR-RT slope and y-intercept. ICC values were interpreted according to the following criteria: slight (ICC ≤ 0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (ICC > 0.80) [43]. The average of MUAP<sub>AMP</sub> and MFR was calculated for each 10% RT of the MU, and the Pearson product-moment correlation and Spearman rank correlation were used to analyze the correlation between the first trial and the second trial.

**Comparison of action potential amplitude and firing properties of the MU**

The Shapiro–Wilk test was performed to check the normality for the average of the MUAP<sub>AMP</sub>, MFR, MUAP<sub>AMP</sub>-RT slope and its y-intercept and the MFR-RT slope and its y-intercept. When normality was found, the Levene test was performed, One-way ANOVA was used when equal variances were confirmed, and Welch's analysis of variance was performed when unequal variances were found. If normality was not confirmed, the Kruskal–Wallis test was performed. When a main effect of a group (Normal, SDR, SDL) was observed, post hoc tests were applied. As the effect sizes for comparisons among the three groups and for multiple comparisons, $\eta^2$ (small, < 0.06; medium, 0.06–0.14; and large, > 0.14) and $r$ (small, < 0.30; medium, 0.30–0.50; large, > 0.50) were calculated [44, 45].

When significant differences were found in the above parameters, additional analyses were performed to more specifically determine at which RTs the differences were found. MU in each group (Normal, SDR, SDL) were divided on the basis of RT as follows: <20%, 20–40%, > 40%. MUAP<sub>AMP</sub> and MFR were averaged for each MU group and compared between groups (Normal, SDR, SDL). A two-sample $t$-test or Mann–Whitney $U$-test was performed individually for groups that differed significantly in multiple comparisons. The $d$ (small, < 0.20; medium, 0.20–0.50; large, > 0.80) [44, 45] or $r$ (as above) was calculated as the effect size.

MATLAB (R2021b; MathWorks Inc, Natick, MA, USA) was used for SPM, and SPSS Statistics 28 (IBM Japan, Tokyo, JP) was used for other statistical analyses. The level of significance was set at $p = 0.05$.

**Results**
One subject in the SDL group was excluded from the analysis because the sEMG data could not be successfully decomposed. One male subject in the SDL group had his non-dominant limb as the measurement limb. All other subjects used their dominant limb as the measurement limb.

Three-dimensional scapular motion

One-way ANOVA SPM results are shown in Supplementary Fig. S1 online. There was a main effect of the group for external rotation at 30° to 120° for the raising phase and 120° to 50° for the lowering phase. Post hoc test results showed that the SDR group had a smaller external rotation than the Normal group at 60° to 120° of the raising phase and 120° to 70° of the lowering phase. The SDL group had a smaller external rotation from the raising start to 120° in the raising phase and from 120° to 110° of the lowering phase. There were no significant differences between the SDR and SDL groups.

There was a main effect of the group for upward rotation from the raising start to 100° in the raising phase and from 110° to 20° in the lowering phase. Post hoc test results showed that upward rotation was smaller in the SDR group than in the Normal group from the raising start to 90° in the raising phase and from 110° to 20° in the lowering phase. The SDL group had smaller upward rotation from the raising start to 40° in the raising phase and from 70° to 20° in the lowering phase. There were no significant differences between the SDR and SDL groups.

There was a main effect of the group for posterior tilt from the raising start to 110° in the raising phase and from 120° to 20° in the lowering phase. Post hoc test results showed that the posterior tilt was smaller in the SDR group than in the Normal group from the raising start to 100° in the raising phase and from 110° to 20° in the lowering phase. The SDL group had smaller upward rotation from the raising start to 70° in the raising phase and from 90° to 20° in the lowering phase. There were no significant differences between the SDR and SDL groups.

Reliability of the MU measurement method

ICC results are shown in Supplementary Table S1 online. The average MUAP\textsubscript{AMP} and MUAP\textsubscript{AMP}-RT slope of the lower trapezius were almost perfect, and the average MFR was substantial, whereas the MUAP\textsubscript{AMP}-RT y-intercept and the MFR-RT slope and y-intercept were only fair to slight. The serratus anterior was almost perfect to substantial for all variables.

The results of the correlation analysis are shown in Supplementary Fig. S2 online. Both MUAP\textsubscript{AMP} and MFR showed strong correlations between the first and second trials.

Comparison of action potential amplitude and firing properties of the MU

The results of the action potential amplitude and firing properties of MU are shown in Table 2, 3 and Fig. 3, 4. For the lower trapezius, 200 MUs were used for analysis in the Normal group, 126 in the SDR group, and 152 in the SDL group. ANOVA showed the group as the main effect and large effect sizes for
MUAP<sub>AMP</sub> (p < 0.001, η<sup>2</sup> = 0.418) and the MUAP<sub>AMP</sub>-RT slope (p = 0.021, η<sup>2</sup> = 0.227) (Table 3). The MUAP<sub>AMP</sub> post hoc test results showed that the MUAP<sub>AMP</sub> was significantly greater in the Normal group than in the SDR group (p = 0.003, r = 0.550) and significantly greater in the SDL group than in the SDR group (p < 0.001, r = 0.630) (Fig. 3a). The MUAP<sub>AMP</sub>-RT slope was significantly greater in the Normal group than in the SDR group (p = 0.049, r = 0.420) and significantly greater in the SDL group than in the SDR group (p = 0.026, r = 0.460) (Fig. 3b). Comparison of the MU groups summarized by RT showed that MUAP<sub>AMP</sub> was greater in both the Normal and SDL groups than the SDR group at all RTs (Fig. 3c.d).

### Table 2

Results of one-way ANOVA of motor unit parameters in Lower Trapezius

<table>
<thead>
<tr>
<th></th>
<th>Normal group</th>
<th>SDR group</th>
<th>SDL group</th>
<th>p-value</th>
<th>Effect size η&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Effect size r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lower Trapezius</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUAP&lt;sub&gt;AMP&lt;/sub&gt; (mV)</td>
<td>0.275 ± 0.084</td>
<td>0.166 ± 0.054</td>
<td>0.308 ± 0.061</td>
<td>&lt;.001**</td>
<td>.418++</td>
<td>-</td>
</tr>
<tr>
<td>MFR (pps)</td>
<td>16.425 ± 2.028</td>
<td>18.827 ± 1.683</td>
<td>16.962 ± 3.060</td>
<td>.062</td>
<td>.169++</td>
<td>-</td>
</tr>
<tr>
<td><strong>Linear MUAP&lt;sub&gt;AMP&lt;/sub&gt;-RT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope (mV·%MVC&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.010 ± 0.003</td>
<td>0.007 ± 0.002</td>
<td>0.010 ± 0.003</td>
<td>.021*</td>
<td>.227++</td>
<td>-</td>
</tr>
<tr>
<td>y-intercept (mV)</td>
<td>0.067 ± 0.048</td>
<td>0.032 ± 0.013</td>
<td>0.069 ± 0.053</td>
<td>.122</td>
<td>.131†</td>
<td>-</td>
</tr>
<tr>
<td><strong>Linear MFR-RT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope (mV·%MVC&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>-0.477 ± 0.118</td>
<td>-0.436 ± 0.103</td>
<td>-0.441 ± 0.131</td>
<td>.494</td>
<td>-</td>
<td>.246++</td>
</tr>
<tr>
<td>y-intercept (mV)</td>
<td>27.615 ± 3.146</td>
<td>27.482 ± 2.729</td>
<td>27.292 ± 4.328</td>
<td>.975</td>
<td>.002</td>
<td>-</td>
</tr>
</tbody>
</table>

ANOVA, analysis of variance; MUAP<sub>AMP</sub>, motor unit action potential amplitude; MFR, mean firing rate; RT, recruitment threshold

Data are shown as the mean ± standard deviation. *p < .05, **p < .01, † medium effect size, ‡‡ large effect size
Table 3
Results of one-way ANOVA of motor unit parameters in Serratus Anterior

<table>
<thead>
<tr>
<th></th>
<th>Normal group</th>
<th>SDR group</th>
<th>SDL group</th>
<th>p-value</th>
<th>Effect size η²</th>
<th>Effect size r</th>
</tr>
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<tbody>
<tr>
<td><strong>Serratus Anterior</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUAP&lt;sub&gt;AMP&lt;/sub&gt; (mV)</td>
<td>0.179 ± 0.072</td>
<td>0.105 ± 0.063</td>
<td>0.183 ± 0.09</td>
<td>.056</td>
<td>.175 † †</td>
<td>-</td>
</tr>
<tr>
<td>MFR (pps)</td>
<td>17.254 ± 2.153</td>
<td>13.879 ± 3.824</td>
<td>17.270 ± 1.407</td>
<td>.069</td>
<td>.277 † †</td>
<td>-</td>
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<tr>
<td><strong>Linear MUAP&lt;sub&gt;AMP&lt;/sub&gt;-RT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope (mV•%MVC&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.009 ± 0.004</td>
<td>0.004 ± 0.003</td>
<td>0.007 ± 0.003</td>
<td>.014 *</td>
<td>.248 † †</td>
<td>-</td>
</tr>
<tr>
<td>y-intercept (mV)</td>
<td>0.013 ± 0.043</td>
<td>0.017 ± 0.026</td>
<td>0.042 ± 0.079</td>
<td>.686</td>
<td>-</td>
<td>.131 †</td>
</tr>
<tr>
<td><strong>Linear MFR-RT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope (mV•%MVC&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>-0.491 ± 0.178</td>
<td>-0.380 ± 0.137</td>
<td>-0.370 ± 0.113</td>
<td>.266</td>
<td>-</td>
<td>.461 † †</td>
</tr>
<tr>
<td>y-intercept (mV)</td>
<td>27.839 ± 3.515</td>
<td>22.215 ± 5.069</td>
<td>25.623 ± 2.605</td>
<td>.006 **</td>
<td>.288 † †</td>
<td>-</td>
</tr>
</tbody>
</table>

ANOVA, analysis of variance; MUAP<sub>AMP</sub>, motor unit action potential amplitude; MFR, mean firing rate; RT, recruitment threshold

Data are shown as the mean ± standard deviation. * p < .05, ** p < .01, † medium effect size, † † large effect size

For the serratus anterior, 163 MUs were used for analysis in the Normal group, 85 in the SDR group, and 129 in the SDL group. The ANOVA results showed a main group effect and large effect sizes for the MUAP<sub>AMP</sub>-RT slope (p = 0.014, η² = 0.248) and MFR-RT y-intercept (p = 0.006, η² = 0.288) (Table 3). The post hoc test results showed that the MUAP<sub>AMP</sub>-RT slope was significantly greater in the Normal group than in the SDR group (p = 0.010, r = 0.490) (Fig. 4a). The MFR-RT y-intercept was significantly greater in the Normal group than in the SDR group (p = 0.004, r = 0.540) (Fig. 4b). There was a medium effect size between the Normal and SDL groups (p = 0.138, r = 0.340), although the difference was not significant (Fig. 4b). In a comparison of the MU groups summarized by RT, MUAP<sub>AMP</sub> was significantly greater in the Normal group for MU medium thresholds (20–40%), and there was a medium effect difference for MU high thresholds, although the difference was not significant (Fig. 4c). MFR was significantly different between the low threshold (> 20%) and medium threshold (20–40%) MU groups, but the low threshold only showed a small effect size. The high threshold (> 40%) MU group showed a moderate MFR effect size difference, but it was not statistically significant (Fig. 4d).
Discussion

This study characterized the MU behavior of the lower trapezius and serratus anterior in individuals with scapular dyskinesis. The results showed differences in the MU behaviors of the lower trapezius and serratus anterior between the SDR and Normal groups, but there was no significant difference between the SDL and Normal groups. The lower trapezius and serratus anterior are important in scapular motion, but the MU behaviors showed phase-dependent changes in scapular dyskinesis. Although our hypothesis was partially rejected, the study results are important contributors to our understanding of the scapular dyskinesis pathology.

This study used SDT for grouping, which is a simple method for visually evaluating scapular motion that has superior reliability [34] and validity [46]. This study also showed reliability consistent with that of previous studies [34]. In three-dimensional scapular motion, upward rotation, external rotation, and posterior tilt were larger in the Normal group than in the other two groups with scapular dyskinesis, consistent with previous studies [46, 47].

An evaluation of MU behavior with trapezoidal contractions has been performed on a variety of muscles, including the vastus lateralis [25, 30], first dorsal interosseous [48, 49], biceps brachii [32], tibia anterior [50, 51], and triceps surae [51, 52]. This is the first study to apply the decomposition technique to the lower trapezius and serratus anterior. Generally, MVC measurements are performed in the position of Manual Muscle Testing (MMT) reported by Kendall [53]. Additionally, Ekstrom et al. [39] reported that the MMT position was the least of the surrounding muscle activity and produced higher sEMG activity of the primary agonist than that of all other positions. Therefore, we believe that the methods used in this study were valid for the task movement to determine the MU behavior of the individual muscle (lower trapezius and serratus anterior). In the reliability analysis of the measurement method, MUAP\textsubscript{AMP} and MFR were both highly correlated between the first and second trials. The ICCs also showed moderate to high reliability for most parameters, with particularly high reliability for the parameters that showed significant group differences in this study.

MUAP\textsubscript{AMP} correlates with the MU size and its component muscle fiber size [54, 55]. Additionally, the slope regressed on RT (MUAP\textsubscript{AMP}-RT slope) represents the magnitude of MUAP\textsubscript{AMP} relative to the force level. The SDR group may not be able to recruit larger-size MUs in the lower trapezius and serratus anterior. The inability to recruit larger-size MUs can have a major effect on muscle strength [23, 42]. Furthermore, the MFR-RT y-intercept of the serratus anterior was smaller in the SDR group than in the Normal group. This result can be interpreted as a failure to compensate for the inability to recruit larger-size MUs by the firing rate. In particular, the amplitudes and firing rates of MU recruited at medium and high thresholds tended to be lower. These are similar to the amount of muscle activity required during upper-limb raising [56], which may cause problems in producing adequate muscle tension to stabilize the scapula during raising. The results support the importance of the lower trapezius and serratus anterior in scapular motion from a neurophysiological perspective. The weakness of the lower trapezius and serratus anterior and their
inadequate activation associated with scapular dyskinesis may explain why the MU behavior is the final common pass.

On the other hand, the SDL group was not significantly different from the Normal group in the lower trapezius. The MFR-RT y-intercept for the serratus anterior was smaller in the SDL group than the Normal group, with a moderate effect size difference (not significant). This result suggests that the scapular dyskinesis that appears in the upper-limb lowering phase cannot be explained by changes in MU behavior in the lower trapezius and serratus anterior. Neuromuscular control differs between the upper-limb raising and lowering phases, and the scapular dyskinesis during the lowering phase may be related to impairment other than MU behavior. Many previous studies [19, 46, 57, 58] have analyzed SDR and SDL as one group, but it is possible that they have different mechanisms, suggesting the need for a clearly differentiated analysis. It would be useful for future studies to focus on other neurophysiological factors to determine what is responsible for the scapular dyskinesis that appears in the lowering phase.

The present study results can be used to understand the pathology of scapular dyskinesis and to establish a treatment for the disorder. This study shows that we should focus not only on treatment for anatomical and kinematics factors as previously reported, but also on the behavior of the central nervous system, especially the MU, which controls movement. Individuals who have scapular dyskinesis from the raising phase may require treatment strategies that bring the MU behavior closer to that of the Normal group as the recruitment size of MU of the lower trapezius and serratus anterior and the firing rate to the serratus anterior may be reduced. High-intensity resistance training may be recommended for MU size [59, 60], but it is unclear if it can be applied to the lower trapezius and serratus anterior. Treatment to improve the firing rate has not been reported to date. Further investigation is needed for scapular dyskinesis that appears in the lowering phase, and similar treatment strategies cannot be used for all cases. Future efforts are needed to properly classify scapular dyskinesis, elucidate the mechanisms of each disorder, and develop and test the efficacy of treatments.

One limitation of this study is that it was conducted in healthy young adults. Caution should be applied when extrapolating our results to different populations as MU behavior has been reported to change with age [25, 26]. Second, the kinematic data showed less scapular motion in the SDL group than in the Normal group during the raising phase. There was a gap between the visual and objective evaluations. The SDL group also included subjects who had subtle dyskinesis in the raising phase, which may have affected the objective data. Therefore, the SDL group results should be interpreted with caution, but the inter-rater reliability of the SDT results was consistent with that of previous studies. Third, the sex ratio varied by group. Differences in MU behavior between the sexes have also been observed [27, 28]. Sex differences in MU behavior in the lower trapezius and serratus anterior are unknown, but it is possible that differences in sex ratio may have influenced the results. Fourth, the effect of subcutaneous fat could not be considered. The size of the MUAP\textsubscript{AMP} has been reported to affect subcutaneous fat thickness [61]. Measurement of subcutaneous fat using ultrasound imaging equipment could not be performed in this study. However, subjects with a BMI > 25 kg/m\textsuperscript{2} were excluded, and there were no significant differences in physical characteristics among the groups. Finally, the movement tasks in this study were different.
from actual upper-limb raising, so it is not clear how the results of this study will apply to upper-limb raising. The decomposition of MUs in dynamic repetitive movements has been reported by De Luca et al. [32] but further research is needed to apply it to upper-limb raising to lowering.

Summary, the MU sizes in the lower trapezius and serratus anterior were smaller and the firing rate in the serratus anterior was lower in individuals with scapular dyskinesis in the upper-limb raising phase than in individuals with normal scapular motion. The weakness of the lower trapezius and serratus anterior muscles, which is believed to cause scapular dyskinesis, may be explained by changes in MU behavior. On the other hand, the MU behaviors of the lower trapezius and serratus anterior in individuals with scapular dyskinesis in the lowering phase did not differ significantly from those in individuals with normal scapular motion, suggesting that the SDL may not be due to changes in MU behavior. This study can be used as basic data for understanding the pathology of scapular dyskinesis and establishing treatment.

Declarations

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Author contributions

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

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References


**Figures**
Flow chart of scapular dyskinesis classification. Of the 50 subjects in the raising phase, 33 were classified as normal, 8 as subtle, and 9 as obvious. Of the 33 subjects evaluated as normal in the raising phase, 14 were normal, 12 were subtle, and 7 were obvious in the lowering phase. Of the eight subjects evaluated as subtle in the raising phase, four were Subtle, and four were obvious in the lowering phase. The nine subjects evaluated as obvious in the raising phase were classified as the scapular dyskinesis appearing in the raising phase (SDR) group, regardless of the results of the lowering phase. Of a total of 41 subjects evaluated as normal or subtle in the raising phase, a total of 11 subjects evaluated as obvious in the lowering phase were classified as the scapular dyskinesis appearing in the lowering phase (SDL) group. Of the 33 subjects who were evaluated as normal in the raising phase, 14 subjects who were also evaluated as normal in the lowering phase were classified as the normal group.
Figure 2

(a) Trapezoidal contraction of the lower trapezius. The participants lay prone with the upper-limb abducted in line with the muscle fibers (approx. 145°). From this position, the upper-limb was lifted toward the ceiling with thumbs-up while looking at the target and RMS values on the monitor. (b) Trapezoidal contraction of the serratus anterior. The upper-limb was raised to 130° in the sagittal plane in a seated position. From this position, the shoulder girdle was protracted while looking at the target and RMS values on the monitor. RMS, root mean square
Figure 3

Results of post hoc analysis for parameters that were significantly different in ANOVA in the lower trapezius (a, b). Show the results of post hoc analysis, and (c, d) show the average of MUAP\textsubscript{AMP} and MFR for the motor unit groups distinguished by RT (<20%, 20%–40%, >40%) for each group. Average MUAP\textsubscript{AMP} (a) and MUAP\textsubscript{AMP}-RT slope (b) had significant differences and large effect sizes between the Normal
Graph c shows that the MUAP_{AMP} is smaller at all RTs in the SDR group than in the other two groups. MUAP_{AMP}, motor unit action potential amplitude; MFR, mean firing rate; RT, recruitment threshold; SDR, scapular dyskinesis appearing in the raising phase; SDL, scapular dyskinesis appearing in the lowering phase. * \( p < .05 \), ** \( p < .01 \), † medium effect size, †† large effect size

Figure 4
Results of post hoc analysis for parameters that were significantly different in ANOVA on the serratus anterior (a, b). Show the results of post hoc analysis, and (c, d) show the average of MUAP_{AMP} and MFR for the motor unit groups distinguished by RT (<20%, 20%–40%, >40%), for each group. There was a significant difference in the MUAP_{AMP}-RT slope between the Normal group and SDR groups and a medium effect size. Graph c shows that the MUAP_{AMP} of the recruited motor units at 20%–40% and >40% is smaller in the SDR group than in the Normal group. Graph d shows that the firing rate of the recruited motor units, especially at 20%–40% and >40%, is lower in the SDR group than in the Normal group.

MUAP_{AMP}, motor unit action potential amplitude; MFR, mean firing rate; RT, recruitment threshold; SDR, scapular dyskinesis appearing in the raising phase; SDL, scapular dyskinesis appearing in the lowering phase. * p < .05, ** p < .01, † medium effect size, †† large effect size

**Supplementary Files**

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