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Scapular kinematic and shoulder muscle activity alterations after serratus anterior muscle fatigue

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1 Title page

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3 fatigue

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25

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28 **Abstract**

29 Background: Although the serratus anterior muscle has an important role in scapular movement,
30 no study to date has investigated the effect of serratus anterior fatigue on scapular kinematics
31 and shoulder muscle activity. The purpose of this study was to clarify the effect of serratus
32 anterior fatigue on scapular movement and shoulder muscle activity.

33 Methods: The study participants were 16 healthy men participated in this study. Electrical
34 muscle stimulation was used to fatigue the serratus anterior muscle. Shoulder muscle strength
35 and endurance, scapular movement, and muscle activity were measured before and after the
36 fatigue task. The muscle activity of the serratus anterior, upper and lower trapezius, anterior
37 and middle deltoid, and infraspinatus muscles were recorded and the median power frequency
38 of these muscles was calculated to examine the degree of muscle fatigue.

39 Results: The muscle endurance and median power frequency of the serratus anterior muscle
40 decreased after the fatigue tasks, whereas the muscle activities of the serratus anterior, upper
41 trapezius, and infraspinatus muscles increased. External rotation of the scapula at the shoulder
42 elevated position increased after the fatigue task.

43 Conclusion: Selective serratus anterior fatigue due to electric muscle stimulation decreased the
44 serratus anterior endurance at the flexed shoulder position. Furthermore, the muscle activities
45 of the serratus anterior, upper trapezius, and infraspinatus increased and the scapular external
46 rotation was greater after serratus anterior fatigue. These results suggest that the rotator cuff

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47 and scapular muscle compensated to avoid the increase in internal rotation of the scapula caused

48 by the dysfunction of the serratus anterior muscle.

49 **Level of evidence:** Basic Science, Kinesiology Study

50 **Key words:** Shoulder, Scapula, Fatigue, Serratus anterior muscle, Biomechanics,

51 Rehabilitation

52

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53 Introduction

54 The shoulder complex consist of the scapula, humerus, and clavicle, and the scapula upwardly
55 and externally rotates and posteriorly tilts during shoulder elevation.^{28,30} This coordinated
56 movement is controlled by the neuromuscular function and capsular ligaments.²² Dysfunction
57 of the control system alters the scapular movement and might cause a shoulder disorder.
58 Previous studies reported that the scapular movement during shoulder elevation changed in
59 people with subacromial impingement syndrome,^{27,29} rotator cuff tear,³⁷ or shoulder
60 instability.^{37,41}

61 Shoulder muscle activity plays an important role in controlling scapular movement, and
62 the dysfunction of these muscles might be a factor that changes scapular movement. Previous
63 studies found decreased activity of the serratus anterior muscle²⁷ and increased activity of the
64 upper trapezius muscle^{10,27} in subacromial impingement syndrome. Furthermore, the serratus
65 anterior and the upper and lower trapezius muscles work as a force couple for upward rotation
66 of the scapula. Decreased activity of the serratus anterior muscle relative to the upper trapezius
67 muscle associated with the change in scapulohumeral rhythm and the decrease in scapular
68 upward rotation during shoulder elevation were found in people with impingement
69 syndrome.^{19,36} These findings in previous studies suggested that the change in muscle activity
70 of the serratus anterior was related to the change in scapular movement. In addition, it was
71 proposed in the consensus statement from the scapular summit also proposed that the serratus

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anterior is one of the causes of scapular dyskinesis²⁴ and is one of the target muscles for its rehabilitation.¹² However, the cause-consequence relationship between the dysfunction of the serratus anterior muscle and abnormal scapular movement is unknown.

Some studies investigated the effect of muscle dysfunction caused by acute muscle fatigue on the scapular movement to clarify the relationship between shoulder muscle activity and scapular movement.^{7,14,32} A previous study of serratus anterior fatigue and scapular movement, a previous study examined the effect of a push-up plus task on muscle activity and scapular movement and found an increase in scapular internal rotation and decrease in posterior tilt during scapular plane elevation. However, electromyographically, fatigue of the serratus anterior and upper and lower trapezius and infraspinatus muscles was seen in this study.⁵ Therefore, the relationship between selective fatigue of the serratus anterior and changes in scapular kinematics is unknown, whereas the effect of selective muscle fatigue on scapular kinematics should be elucidated to further develop our knowledge of the shoulder complex.

Many previous studies evaluated 3-dimensional scapular motion during only shoulder elevation. However, it is possible that muscle endurance at the shoulder elevated position is important for evaluating shoulder function because some shoulder functional tests apply muscle endurance at the shoulder elevated position, which is impaired in people with shoulder disease.^{8,39}

The purpose of this study was to investigate the effect of selective fatigue of the serratus

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- 91 anterior on muscle activity and scapular movement. We hypothesized that scapular upward
- 92 rotation increased at the shoulder elevated position after the fatigue task due to the
- 93 compensatory increase in muscle activity of the upper trapezius.
- 94

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95 **Materials and Methods**96 **Participants**

97 This study was a controlled experimental study. The study participants were 16 men (mean age,
98 25.6 ± 3.4 years; mean height, 172.4 ± 5.4 cm; mean weight, 66 ± 7.2 kg) who were students
99 from our institution. At the time of recruitment, the participants confirmed that they did not
100 meet the exclusion criteria, which included present or history of orthopedic or nervous system
101 disease in the upper limb, athletes, or persons who perform perform any extensive exercise, and
102 female gender. Before the experiment, no participants were excluded. The aim and procedure
103 of this study was explained to all participants, each of whom provided informed consent. The
104 sample size was calculated based on a 2-way analysis of variance (ANOVA) with repeated
105 measures (effect size = 0.25, α error = 0.05, power = 0.8) using G*Power 3.1 (Heinrich Hein
106 University, Düsseldorf, Germany) before the participants were recruited and showed that a
107 group size of 10 subjects was required for this analysis to enable the detection of statistical
108 significance. Therefore, 16 healthy men were recruited for this study.

109

110 **Experimental procedures**

111 The dominant and non-dominant upper limb was identified as the control and fatigue limb,
112 respectively. The participants performed maximal isometric shoulder flexion at 90° and then
113 kept their arm at shoulder flexion at 90° to measure the shoulder muscle strength and endurance,

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respectively. Scapular kinematics and electromyography (EMG) measurements were collected during the muscle endurance test. The participants underwent the fatigue task for 25 minutes. Muscle strength and endurance, scapular movement, and muscle activity were measured again after the fatigue task.

Fatigue task

The fatigue task consisted of electric muscle stimulation of the serratus anterior muscle using musculoskeletal electric stimulator (EU-910, Ito Co. Ltd., Tokyo, Japan) to induce selective muscle fatigue. Participants sat on a stool and skin was shaved and cleaned to reduce the skin resistance. Bipolar electrodes (2 cm × 2 cm) were attached to the skin over the lower parts of the serratus anterior with tape at level of the sixth rib on the midaxillary line along the leading edge of the latissimus dorsi muscle. The motor point of the lower parts of the serratus anterior muscle was interposed between these electrodes to activate this muscle as much as possible. A high-voltage pulsed current with a 50-μs pulse width and 100-Hz frequency was used in this study. During the initial 5 minutes of muscle stimulation, the intensity was gradually increased to the maximum level that each subject could tolerate and then sustained for the following 20 minutes. The average voltage intensity was about 30 V. Fatigue induced by electrical muscle stimulation was applied in previous studies and acute loss of muscle strength after electrical muscle stimulation was reported.^{6,35,38} Fatigue indicates the condition of muscle fatigue induced

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133 by electrical muscle stimulation using a musculoskeletal electric stimulator.

134

135 **Muscle strength and endurance**

136 The muscle strength of shoulder flexion was measured in both upper limbs using the handheld
137 dynamometer (HHD) (Mobile, SAKAI Medical Co. Ltd., Tokyo, Japan). The participant sitting
138 on a stool performed maximal isometric shoulder flexion for 3 seconds at 90° shoulder flexion
139 with the elbow in full extension and the forearm in a neutral position. The shoulder flexion
140 angle was confirmed by the investigator using the goniometer. The handheld dynamometer was
141 place on the distal radius, and maximal isometric strength of shoulder flexion was examined 3
142 times with optimal interval. The shoulder flexion strength was expressed as torque, the product
143 of the mean value of the 3 maximal isometric strength measurements and the length of upper
144 limb from the acromion of the scapula to the styloid process of the radius. The intraclass
145 correlation coefficient (1,3) values, which represent the reliability of muscle strength
146 measurement, fell within a range of 0.88 to 0.94. This value indicated “almost perfect”, meaning
147 high reliability according to the previous study.²⁵

148 The muscle endurance of shoulder flexion was measured in both upper limbs. The
149 participants kept their arms at 90° of shoulder flexion with the elbow in maximal extension and
150 the forearm in a neutral position holding a load, which was adjusted as 40% of the maximal
151 isometric strength of shoulder flexion mentioned above (Figure 1). Muscle endurance was

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represented as the maximum time that the participant could maintain his posture without deviating while holding the load. The investigator visually confirmed whether the participants could maintain the correct posture and even the slightest lowering of the flexed upper limb, flexion of the elbow, or compensation of the trunk was noted as a deviation from the correct posture. The evaluation of correct posture by the investigator using visual confirmation based on a previous study.³³ The maximum time for muscle endurance in each upper limb was examined once in a random order with optimal interval.

EMG protocol

Muscle activity was determined using surface EMG (TeleMyo2400; Noraxon, Scottsdale, AZ, USA) with sampling at 1500 Hz. The skin at the electrode sites was shaved and cleaned using scrubbing gel and alcohol. Disposable pre-gelled Ag-AgCl electrodes (Blue Sensor, Medicotest, Olstykke, Denmark) were placed over the anterior and middle deltoid, upper and lower trapezius, infraspinatus in the fatigued limb, and serratus anterior in the both limbs with a fixed 2.5-cm spacing parallel to the muscle fiber. According to previous studies, the electrode locations for the anterior and middle deltoid were defined as 4 cm below the distal clavicle²³ and the halfway point between the acromion of the scapula and the deltoid tuberosity of the humerus,⁹ respectively; those for the upper and lower trapezius were defined as the halfway point between the spinous process of the seventh cervical vertebra and the acromion of the

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scapula²³ and the halfway point between the spinous process of the seventh thoracic vertebra and the trigonum scapula,⁹ respectively; that for the infraspinatus was defined as the halfway point between the inferior angle of the scapula and the middle point between the acromion and the trigonum scapula;¹⁸ and that for the serratus anterior was defined as the halfway point between the leading edge of the latissimus dorsi and the trailing edge of the pectoralis major on the seventh rib¹⁵ (Figure 2).

The raw EMG signal during the muscle endurance test was recorded and analyzed for the first 3 seconds of every 10 seconds up to 53 seconds (i.e. 0–3 seconds; 10–13 seconds; 20–23 seconds; 30–33 seconds; 40–43 seconds; 50–53 seconds), and all participants maintained a flexed arm position without deviating their posture. The EMG signal of the maximal voluntary contraction (MVC) during the 3-second period for each muscle was obtained as described in previous studies.^{1,4} The raw EMG signals were processed using a bandpass filter and the root mean square (RMS) of the raw EMG signal was smoothed. The RMS amplitude of each muscle was normalized by the MVC of each muscle and the muscle activity was represented as percentage MVC. In addition, the median power frequency (MDPF) of the power spectrum was calculated for first 3 seconds during the muscle endurance test to analyze muscle fatigue. The decline in MDPF indicates muscle fatigue.

Scapular movement

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190 Three-dimensional motion of the scapula and the humerus was measured during the muscle
191 endurance test using a 6-df electromagnetic tracking device (Liberty, Polhemus, Colchester, VT,
192 USA) at 120 Hz in the fatigued limb. This system consists of a transmitter, five sensors, and a
193 digitizing stylus operated by an electronic unit. The transmitter was fixed on a rigid wooden
194 board 40 cm from the floor and 30 cm behind the subjects. An electromagnetic field generated
195 by the transmitter was sensed by these sensors and the stylus. This electromagnetic field
196 represented the global coordinate system, with the X-axis pointing forward, Y-axis pointing
197 upward, Z-axis pointing to the right, and origin located at the transmitter. Next, the sensors were
198 attached to the bony landmarks of the subjects with tape. The thoracic sensor was placed on the
199 sternum just inferior to the jugular notch, the humeral sensor was placed on the middle point of
200 the humerus with a thermoplastic cuff, and the scapular sensor was placed on the flat surface of
201 the acromion. Based on these sensor placement, the local coordinate system of the thorax,
202 humerus, and scapula were established by digitizing each bony landmark.

203 All definitions of the local coordinate system agreed with the shoulder standardization
204 proposal of the International Society of Biomechanics.⁴³ The rotation of the distal coordinate
205 system was described with respect to the proximal coordinate system according to the Euler
206 angle of the International Society of Biomechanics. The kinematics of the scapula segment
207 relative to the thorax segment around the S_y -axis was defined as internal (positive) and external
208 (negative) rotation, that around the S_x -axis was defined as downward (positive) and upward

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209 (negative) rotation, that around the Sz-axis was defined as posterior (positive) and anterior
210 (negative) tilt, and that of the humerus segment relative to the thorax segment around the Hx-
211 axis was defined as elevation (positive) and depression (negative) based on the shoulder
212 standardization proposal of the International Society of Biomechanics (Figure 3). The
213 kinematics data of the scapula in the shoulder flexion position were analyzed every 10 seconds
214 from 0 to 50 seconds, and all participants maintained the flexed arm position without deviating
215 their posture.

216

217 **Data analysis**

218 The statistical analysis was performed using SPSS Statistical software (version 22; IBM,
219 Armonk, NY, USA). Shapiro-Wilk test was used to confirm normality distribution. For the
220 muscle strength and endurance and the MDPF of the bilateral serratus anterior muscles, two-
221 way ANOVA with repeated measures on two factors (time [two levels, pre-fatigue; post-
222 fatigue]) $\times$ (limb [two levels, fatigue limb; control limb]) was used to examine the effect of
223 serratus anterior muscle fatigue on each parameter. When a significant interaction was found, a
224 paired *t*-test for normal distribution or Wilcoxon signed rank test for non-normal distribution
225 for post hoc analysis was performed to compare the pre- and post-fatigue values of each limb.
226 The MDPF values of all muscles except the serratus anterior were compared between the pre-
227 and post-fatigue states using a paired *t*-test in the fatigued limb to confirm whether these

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228 muscles were fatigued due to the electric muscle stimulation. For the muscle activity and
229 scapular kinematics during the muscle endurance test, a two-way ANOVA with repeated
230 measures of two factors (time [pre- and post-fatigue]) $\times$ (seconds [six levels: 0, 10, 20, 30, 40,
231 50]) was used. When a significant main effect was found, Bonferroni comparison of the post
232 hoc test was performed to compare the pre- and post-fatigue in each muscle. The significant
233 main effect of seconds was ignored because the present study was interested in the comparison
234 of pre- and post-fatigue. In addition, for the amount of change in the muscle activity calculated
235 by subtracting pre-fatigue from post-fatigue in each muscle, a split-plot ANOVA with two
236 factors (muscle [six levels: anterior deltoid, middle deltoid, upper trapezius, lower trapezius,
237 infraspinatus, serratus anterior]) $\times$ (seconds (six levels: 0, 10, 20, 30, 40, 50]) was used to
238 determine which muscle was activated via serratus anterior fatigue though the muscle
239 endurance test. When a significant main effect was found, a Tukey comparison of the post hoc
240 test was performed to compare muscles. A confidence level of .05 was used in all of the
241 statistical tests.

242

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Results

Muscle strength and endurance

The muscle strength and endurance results are shown in Table 1. For muscle strength, two-way ANOVA showed no significant interaction or main effects. For muscle endurance, two-way ANOVA showed a significant interaction between time and limb and a significant main effect of time. A post hoc test indicated that the muscle endurance significantly decreased in the fatigued limb after the fatigue task ($P < .001$).

Muscle activity

The muscle activity and degree of change in all muscles during the muscle endurance test are shown in Figure 4. For muscle activity, two-way ANOVA showed significant main effects of time in the SA, UT, and ISP, while the muscle activity significantly increased after the fatigue task. For amount of change in muscle activity, two-way ANOVA showed a significant main effect of muscle ($F = 7.00$, $P < .001$). The post hoc test indicated that the amount of change in the muscle activity of the upper trapezius was significantly greater than that of the other muscles ($P < .001$ in all tests).

The MDPF values of the bilateral serratus anterior muscles and the other muscles are shown in Tables 1 and 2, respectively. For the MDPF of the serratus anterior, ANOVA showed a significant interaction, and then Wilcoxon signed rank test indicated a significantly decreased

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MDPF in the fatigued limb after the fatigue task ($P < .001$). The paired t -test indicated that the MDPF of the upper trapezius significantly increased only in the fatigue task.

Scapular movement

Scapular movement before versus after the fatigue task is shown in Figure 5. Two-way ANOVA showed no significant interaction and main effects in upward/downward rotation and posterior/anterior tilt. For internal/external rotation, there was no significant interaction ($F = 0.008$, $P = .99$); there was no significant main effect of seconds ($F = 0.68$, $P = .64$) but a significant effect of time ($F = 5.87$, $P = .02$). The post hoc test indicated that the external rotation after the fatigue task was significantly greater than that before it at all seconds ($P = .02$).

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273 Discussion

274 The present study investigated the effect of selective serratus anterior fatigue on muscle strength
275 and endurance, scapular movement, and muscle activity at the flexed shoulder position. The
276 results indicated no change in muscle strength but a significant change in muscle endurance.
277 Additionally, scapular movement and shoulder muscle activity were influenced by serratus
278 anterior muscle fatigue. However, our hypothesis that the increase in scapular upward rotation
279 was caused by compensatory activation of the upper trapezius muscle due to serratus anterior
280 fatigue was rejected because upper trapezius, infraspinatus, and serratus anterior muscle
281 activities were increased and the external rotation of the scapula was altered after the fatigue
282 task. To our knowledge, this is the first study to demonstrate the changes in muscle endurance,
283 scapular kinematics, and muscle activity following selective fatigue of the serratus anterior
284 muscle.

285 In this study, the serratus anterior muscle was fatigued using electrical stimulation and
286 muscle fatigue was confirmed electromyographically via measurement of MDPF. A previous
287 study indicated that the decline in MDPF was a sign of the physiological change in the muscle
288 due to fatigue such as the slowing of muscle fiber conduction velocity, synchronization of motor
289 units, and/or decreased firing frequency.⁴⁰ Here we stimulated the serratus anterior muscle using
290 a musculoskeletal electric stimulator, so the fatigue of the selective serratus anterior muscle
291 could have been caused by the electric muscle stimulation because the decreased MDPF of the

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292 serratus anterior only occurred in the fatigued limb after the fatigue task.

293 Theoretically, muscle flexion strength of the serratus anterior muscle at the flexed
294 shoulder position decreases after the fatigue because the serratus anterior muscle contributes to
295 the upward rotation of the scapula during arm elevation²⁸ and is maximally activated at shoulder
296 flexion of 90–130°,¹ which is similar to the position used to measure the muscle strength of
297 shoulder flexion in this study. However, muscle strength did not change after the fatigue task in
298 this study. The serratus anterior does not flex the glenohumeral joint; rather, it stabilizes the
299 scapula in the scapulothoracic joint due to its origin and insertion from the first to eighth or
300 ninth ribs to the medial border of the scapula. Since the upper and lower trapezius muscles also
301 stabilize the scapula, they may have compensated for the serratus anterior muscle's inability to
302 stabilize the scapula; resulting no change in muscle strength was seen.

303 The present study showed that endurance decreased after serratus anterior muscle
304 fatigue and that the upper trapezius, serratus anterior, and infraspinatus muscles were activated
305 at the flexed shoulder position, which is inconsistent with our hypothesis. For the upper
306 trapezius muscle, Ludewig and Cook²⁷ reported an increase in the muscle activity of the upper
307 trapezius and a decrease in that of the serratus anterior muscle in the patient with shoulder
308 impingement syndrome. Considering this report, it is possible that the upper trapezius muscles
309 were activated to compensate for the functional impairment of the serratus anterior. For the
310 serratus anterior muscle, greater muscle activity after the fatigue task is characteristic of muscle

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fatigue, the regulation of motor unit recruitment and rate coding patterns.³⁴ The increased activity of the serratus anterior muscle after the fatigue task in this study is in accordance with this phenomenon. It is unknown how the mechanism to activate the infraspinatus muscle occurs after serratus anterior fatigue. Further research to investigate the interaction between muscles after fatigue is needed.

The external rotation of the scapula during the muscle endurance test significantly increased after the fatigue task due to the change in the activities of the upper trapezius, serratus anterior, and infraspinatus muscles. In addition, the amount of change in the upper trapezius muscle activity was significantly greater than those of the other muscles. Moreover, the MDPF of the upper trapezius muscle increased significantly after the fatigue task. The upper trapezius retracts and upwardly rotates the scapula¹³, and the retraction corresponds to external rotation of the scapula in this study. Given the contribution of the upper trapezius muscle to the scapular movement, the increase in scapular external rotation that occurred in this study was a result of compensation of the upper trapezius for the functional impairment of the serratus anterior, causing so-called scapular winging.⁴² Scapular winging, in which the scapula rotates downward at rest and its inferior border becomes more prominent, corresponds to the scapular internal rotation in this study. Contrary to our hypothesis, no significant difference in upward scapular rotation angle was seen before versus after the fatigue task, which may be a result of compensation by the upper trapezius to avoid downward scapular rotation.

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330 The muscle activities of the trapezius and the serratus anterior muscle are important
331 factors in shoulder management. The excessive activation of the upper trapezius combined with
332 the decreased activation of the lower trapezius and the serratus anterior has been proposed to
333 be a contributor to abnormal scapular movement.^{10,11,27} Subjects with shoulder impingement
334 syndrome or shoulder pain typically present with excessive upper trapezius activity, attenuation
335 of the lower trapezius and serratus anterior activity^{17,26} and the scapular dysfunction at the same
336 time.¹⁷ In the current study, however, sole increase in upper trapezius muscle activation to
337 compensate for the fatigue of the serratus anterior without the decrease in the lower trapezius
338 muscle activation induced external rotation of the scapula which is similar to the impingement-
339 sparing change. These findings suggest that single muscle dysfunction could induce alteration
340 in scapular muscle balance. Therefore, therapists need to examine scapular muscular imbalance
341 and identify not only the secondarily occurring compensation but also the primary muscle
342 dysfunction.

343 The present study investigated the acute effect of selective serratus anterior fatigue on
344 shoulder muscle activity and scapular movement to increase our knowledge of shoulder
345 biomechanics. However, it has some limitations. First, scapular kinematics up to 120° were
346 analyzed in this study because the previous study ensured adequate reliability and validity of
347 scapular measurement up to 120° and suggested that measurement errors increased past 120°. ²⁰
348 Therefore, the changes in the scapular kinematics at >120° remain unclear. Second, the subjects

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349 were all healthy men. Therefore, it is unclear whether our findings can be generalized to
350 selective cases of shoulder disease. Third, the degree of fatigue might not have been equal
351 among subjects, although the same duration of electrical muscle stimulation (i.e., 20 minutes)
352 was used. This may affect the results to some extent. Fourth, the fatigue induced by electrical
353 muscle stimulation would differ from the fatigue in a clinical situations to some extent. Fatigue
354 is classified into central fatigue, which occurs at central nervous system and involves central
355 activation failure,^{3,31} and peripheral fatigue, which occurs at the intramuscular contractile
356 machinery and involves metabolic inhibition of the contractile process and excitation-
357 contraction coupling failure.^{2,16,21} The fatigue in the current study is mainly accounted for with
358 peripheral fatigue. In other words, the current results could precisely show compensation
359 strategies in the shoulder joint in terms of biomechanics.

360

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361 **Conclusion**

362 The present study showed no changes in muscle strength but decreased muscle endurance after
363 selective fatigue of the serratus anterior. Increased muscle activities of the upper trapezius,
364 infraspinatus, and serratus anterior and external rotation of scapula were noted after the fatigue
365 task at the flexed shoulder position. These findings suggest that the compensatory motion to
366 avoid the internal scapular rotation occurred due to the increased shoulder muscle activity after
367 the fatigue task.

368

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502 **Figure and Table Legends**

503 Figure 1. Measurement posture of the muscle endurance test. Participants sat and flexed the
504 shoulder 90°, fully extended the elbow, and kept the trunk upright while holding a dumbbell
505 corresponding to 40% of the muscle strength as long as possible.

506

507 Figure 2. Locations of EMG electrodes for each muscle. AD, anterior deltoid muscle; MD,
508 middle deltoid muscle; UT, upper trapezius muscle; LT, lower trapezius muscle, ISP,
509 infraspinatus muscle; SA, serratus anterior muscle.

510

511 Figure 3. Definition of the coordinate system and motions relative to the thorax for the scapula
512 and humerus. In the local coordinate system of the scapula, the Sx axis was perpendicular to
513 the plane defined by the TS, AA, and AI; Sy-axis was defined as the cross product of the Sx-
514 axis and Sz-axis; and Sz-axis was directed from the TS to the AA. In the local coordinate system
515 of the humerus, the Hx-axis was perpendicular to the plane defined by the GH, LH, and MH.
516 TS, trigoum spina scapula; AA, acromial angle; AI, inferior angle; GH, glenohumeral rotation
517 center; EL, lateral epicondyle; EM, medial epicondyle; ER, external rotation, IR, internal
518 rotation; UR, upward rotation; DR, downward rotation; AT anterior tilt; PT, posterior tilt.

519

520 Figure 4. Muscle activity and amount of change of muscle activity at the flexed shoulder

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521 position. AD, anterior deltoid (A); MD, middle deltoid (B); UT, upper trapezius (C); LT, lower
522 trapezius (D); ISP, infraspinatus (E); SA, serratus anterior (F); Change in muscle activities (G);
523 Pre, the value of pre-fatigue task; Post, the value of post fatigue task. The asterisk represents
524 the significant main effect and indicated that the value of Post is significantly greater than that
525 of Pre. The dagger represents the significant main effect and indicates that the changes in UT
526 was significantly greater than that of other muscles.

527

528 Figure 5. Scapular kinematics at the flexed shoulder position. Left, internal/external rotation of
529 the scapula; middle, downward/upward rotation of the scapula; right, posterior/anterior tilt. The
530 solid line and the dotted line represent the values of the scapula in pre- and post-fatigue,
531 respectively. The asterisk indicates the significant main effect of the period and that the external
532 rotation after the fatigue task was significantly greater than that before it.

533

534 Table 1. Muscle strength and endurance and MDPF of the serratus anterior before versus after
535 the fatigue task.

536

537 Table 2. MDPF of all muscles but the serratus anterior before versus after the fatigue task.

538

Scapular kinematics and serratus anterior fatigue

539 Figure 1

540

541

Scapular kinematics and serratus anterior fatigue

Figure 2

Scapular kinematics and serratus anterior fatigue

Figure 3

Scapular kinematics and serratus anterior fatigue

548 Figure 4

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Scapular kinematics and serratus anterior fatigue

551 Figure 5

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553

Scapular kinematics and serratus anterior fatigue

554 Table 1

	Muscle strength (Nm)		Muscle endurance (sec)		MDPF of serratus anterior	
	Fatigue	Control	Fatigue	Control	Fatigue	Control
Pre	57.5±13.5	58.3±10.8	80.7±13.0	77.0±17.1	59.8±7.2	59.0±10.8
Post	58.2±12.2	57.6±11.6	66.5±15.3*	76.7±16.7	51.2±6.0*	59.1±11.0
Interaction	F = 1.08, P = .32		F = 16.91, P < .001		F = 41.92, P < .001	
Main effect	Period: F < 0.01, P = .97		Period: F = 15.53, P < .001		Period: F = 73.72, P < .001	
	Limb: F < 0.01, P = .98		Limb: F = 0.78, P = .42		Limb: F = 2.92, P = .11	

555 Fatigue, fatigue limb; Control, control limb; Pre, the value of pre fatigue task; Post, the value
556 of post fatigue task. The asterisk indicates that the value of Post is significantly lower than that
557 of Pre.

558

559

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560 Table 2

MDPF (Hz)	AD	MD	UT	LT	ISP
Pre	78.9±12.7	68.5±10.5	68.6±10.6	52.1±9.9	101.4±23.7
Post	80.3±12.8	68.0±11.7	71.3±11.6	52.1±9.6	101.7±21.6
P value	P = .30	P = .69	P = .02	P = .99	P = .93

561 AD, anterior deltoid; MD, middle deltoid; UT, upper trapezius; LT, lower trapezius; ISP,
562 infraspinatus; Pre, the value of pre fatigue task; Post, the value of post fatigue task.

563

564