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Regional differential stretching of the pectoralis major muscle: An ultrasound elastography study

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Abstract

Pectoralis major (PMa) muscle injuries are becoming more prevalent, and their incidence differs among the PMa regions, i.e., the clavicular, sternal, and abdominal regions. Therefore, identifying the position for effectively lengthening each PMa region is critical in preventing PMa injuries. The purpose of this study was to determine the effective stretching position for each PMa region through shear wave elastography, which can indirectly assess individual muscle lengthening. Fifteen men participated in this study. Twelve stretching positions were compounded with shoulder abductions (45°, 90°, and 135°), pelvic rotation (with or without), shoulder external rotation (with or without), and shoulder horizontal abductions. The shear modulus of each PMa region was measured through shear wave elastography in the stretching positions mentioned above. At the clavicular region, the shear modulus was higher for three stretching positions: shoulder horizontal abduction at 45° abduction during pelvic rotation and shoulder external rotation, shoulder horizontal abduction at 90° abduction, and shoulder horizontal abduction at 90° abduction while considering shoulder external rotation. For the sternal region, the shear modulus was higher in two stretching positions: shoulder horizontal abduction at 90° abduction while adding external rotation, and combination of pelvic rotation and external rotation. For the abdominal region, the shear modulus was higher in the shoulder horizontal abduction at 135° abduction with pelvic and external rotation. These results indicated that the effective stretching position was different for each PMa region.

Keywords

Elastography; Shear modulus; Stretching; Pectoralis major

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1. Introduction

Pectoralis major (PMa) muscle injuries are relatively rare and occur mainly in males that perform high-intensity activities, such as athletes (Bak et al., 2000). With the increasing number of people living more active lives (e.g., during sports competitions and strength training), PMa injuries are becoming more common in both athletic and general populations (ElMaraghy and Devereaux, 2012, Haley and Zacchilli, 2014). The PMa is divided into three regions: the clavicular, sternal, and abdominal (Wolfe et al., 1992) regions and the incidences of PMa injuries can be ranked in the following order: abdominal, sternal, and clavicular (Schachter et al., 2006). For instance, the abdominal region is susceptible to rupture in a bench press (a representative of strength training) when the shoulder joint abducts and extends, owing to the extreme mechanical stress from eccentric contraction (Provencher et al., 2010). Similarly, in football, a blocking position with the shoulder abducted, externally rotated, and extended puts the PMa under maximum tension with eccentric contraction, and muscle strain occurs in the clavicula and sternal regions (Kakwani et al., 2007, Sahota et al., 2020).

One of the risk factors for the muscle strain is a reduction in muscle flexibility (Bradley and Portas, 2007, Witvrouw et al., 2003). The muscle strain injuries occur when the PMa muscle with insufficient flexibility eccentrically contracts because tension within the muscle increases significantly. Static stretching improves muscle flexibility (Hirata et al., 2016, Kay et al., 2015, Konrad et al., 2019, Nakamura et al., 2014, Umegaki et al., 2015a) and could reduce the risk of muscle strain (McHugh and Cosgrave, 2010). As the incidence of PMa injuries differs among its regions, therefore, the optimal stretching of each region is necessary to prevent PMa injuries and for conditioning.

Given the tendon excursion method, where the moment arm is defined as the partial derivative of the muscle length with respect to the joint angle (An et al., 1984), the muscle length is related to the moment arm of the muscle itself. The moment arms of the clavicular, sternal, and abdominal regions are different from one another and change with the shoulder abduction angle (Ackland et al., 2008, Ackland and Pandy, 2011), suggesting that each PMa region lengthens independently. However, shoulder horizontal abductions, abductions, or external rotations are generally performed to stretch the PMa without considering inter-regional differences (Manske and Prohaska, 2007, Putt et al., 2008). Moreover, few studies have investigated the effective stretching positions for each region. A musculoskeletal simulation study showed that the clavicular and sternal fibers of the PMa lengthen differently, depending on the stretching position (Stegink-Jansen et al., 2011). The study scaled the model to cadaveric properties but ignored muscle collisions with other objects (e.g., muscles, aponeurosis, and bones); such collisions could change muscle paths and attachments. Hence, it is unclear whether the results of the previous study can be completely generalized to humans. Thus, there is a need to conduct a study exploring a corresponding effective stretching position for each PMa region in vivo.

Ultrasound shear wave elastography (SWE) is a reliable and valid method used for assessing the regional shear modulus of a muscle (Hug et al., 2015, Lacourpaille et al., 2012), and has recently been applied to research in muscle stretching. The SWE can be used to identify the effective stretching positions of individual muscles (Nishishita et al., 2018, Umegaki et al., 2015b, Umehara et al., 2017) based on the interpretation of a higher shear modulus as indicating more extended muscle lengthening (Koo et al., 2013).

The purpose of this study was to determine the effective stretching position for each PMa region (the clavicular, sternal, and abdominal). To this end, we investigated whether shoulder abductions, external

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rotation, and pelvic rotation influence the PMa muscle lengthening by measuring the shear modulus of the clavicular, sternal, and abdominal regions using the SWE system. The main functions of the PMa were considered as shoulder internal rotation, adduction, and horizontal adduction (Ackland et al., 2008, Ackland and Pandy, 2011, Kuechle et al., 1997). Given the anatomy and function of the PMa and the findings of previous studies (Stegink-Jansen et al., 2011), we hypothesized that the clavicular and sternal regions were adequately stretched by shoulder horizontal abductions with external rotation at<90° abduction and 90° abduction, respectively. Additionally, in vivo, pelvic rotation may change the shape of rib cage due to the relative spinal rotation and generate a force to stretch the abdominal region along with the aponeurosis of the external oblique muscle; therefore, we hypothesized that the abdominal region was effectively stretched by shoulder horizontal abduction with pelvic rotation and external rotation at more than 90° abduction.

2. Materials and methods

2.1. Participants

Fifteen men (age: 24.3 ± 1.5 years; height: 172.2 ± 6.2 cm; weight: 65.4 ± 5.7 kg) participated in this study. The exclusion criteria were as follows: (i) athletes who belonged to college teams, and (ii) persons with orthopedic injuries/disabilities or neurological diseases. Using G*power (version 3.1; Heinrich Heine University, Düsseldorf, Germany), we calculated the sample size for multiple comparisons following a three-way analysis of variance (ANOVA) (effect size = 0.8; α error = 0.05; power = 0.8) and 15 participants were needed. This effect size d of 0.8 was used because the differences in the shear modulus among positions showed a large effect (at least d = 0.8; e.g., shear moduli were 13.4 ± 5.2 kPa and 24.6 ± 8.0 kPa in the resting position and neutral position of hip rotation and knee flexion, respectively) in the previous study examining the effect of hip and knee angles on the shear modulus of the tensor fasciae latae for the effective stretching position (Umehara et al., 2015). All the procedures were approved by the Ethics Committee of Kyoto University Graduate School and the Faculty of Medicine (R0233-4) and conformed to the principles of the Declaration of Helsinki. We explained the aim and procedures of this study to all the participants and obtained informed consent.

2.2. Experimental setup

A cross-sectional laboratory design was carried out in this study. The participants visited the laboratory. They laid on a therapeutic bed and moved to the edge of the bed to avoid interfering with the shoulder motions during stretching, as shown in Fig. 1. We then secured their trunk using a nonelastic band. Ultrasound images of three PMa regions (clavicular, sternal, and abdominal) in the nondominant upper limb were captured before performing the stretching maneuvers while the participants remained relaxed (i.e., in a resting position). Ultrasound images of each of the three regions were subsequently captured during 12 stretching positions. The dominant upper limb was defined as the limb that was used to throw a ball. The effects of side dominance on the PMa muscle properties remain unknown. Given a use-dependent adaptation of the muscle properties in the dominant limb, we used the non-dominant limb for the measurement.

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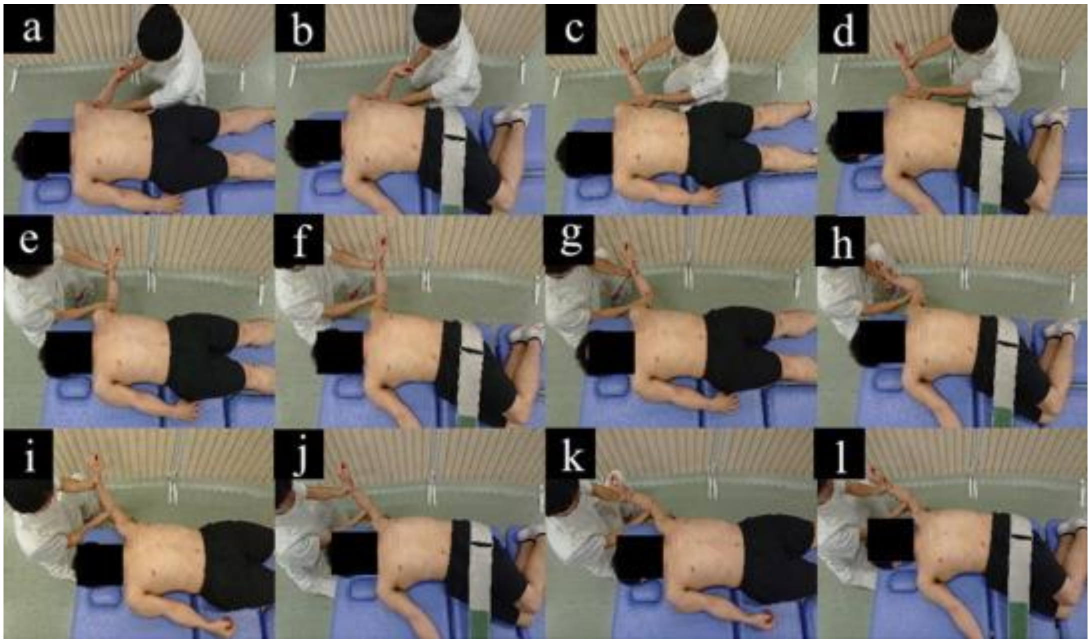

Fig. 1. Twelve stretching positions: (a) abduction 45°, (b) abduction 45° with pelvic rotation, (c) abduction 45° with external rotation, (d) abduction 45° with pelvic rotation and external rotation, (e) abduction 90°, (f) abduction 90° with pelvic rotation, (g) abduction 90° with external rotation, (h) abduction 90° with pelvic rotation and external rotation, (i) abduction 135°, (j) abduction 135° with pelvic rotation, (k) abduction 135° with external rotation, (l) abduction 135° with pelvic rotation and external rotation. Shoulder horizontal abduction was performed in all stretching positions.

2.3. Stretching position

The 12 stretching positions were compounded with shoulder abductions at three different angles (45°, 90°, and 135°), pelvic rotation (with or without), and shoulder external rotation (with or without), in addition to shoulder horizontal abduction (Fig. 1). In the stretching positions, the maneuvers were performed in the following order: pelvic rotation, shoulder abductions, horizontal abduction, and then external rotation when combining with these motions. These maneuvers, except for the shoulder abduction, were performed for as much of the angle as the participants could tolerate the stretching without pain. When the maneuvers were performed as mentioned above, the maximal horizontal abduction angle was different by whether the pelvic rotation was added or not. Thus, the same maximal horizontal abduction angles within participants were used in stretching positions with or without pelvic rotation. An experienced physiotherapist passively moved the participants' upper limbs and pelvises while they remained relaxed as much as possible and tried not to contract any muscle. The scapular movement was not restricted during all stretching maneuvers. The maximal range of motions for the shoulder horizontal abduction and external rotation were measured in all stretching maneuvers at which the participants could tolerate the stretching without pain. The stretching positions were set in a random order using a computerized random function in Microsoft Excel (Microsoft Corp., Redmond, WA, USA). Care was taken not to maintain the same posture for more than 1 min when the PMa was stretched because of the possibility that the muscle stiffness would decrease and to provide rest between each

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stretching position for minimizing carry-over effects from stretching (which would influence the ultrasound measurement value). The participants were placed in supine position (e.g., natural joint configurations) while resting in between successive stretching maneuvers.

2.4. Ultrasound measurement

An ultrasound scanner (Aixplorer v12.2, Supersonic Imagine, Aix-en-Provence, France) coupled with a linear transducer (4–15 MHz, SuperLinear SL15-4) was used in SWE mode (musculoskeletal preset, penetration mode, smoothing level five, and persistence medium) to measure the shear modulus of the PMa. The SWE technology generates shear waves into the individual tissue(s) using the acoustic radiation force from a push pulse. Next, the propagation velocity of the shear wave was determined using ultrafast-imaging technique. SWE provides a two-dimensional map of the shear modulus on the B-mode image of the target tissue with a spatial resolution of 1 mm × 1 mm (Lacourpaille et al., 2012).

Imaging acquisition was performed using a probe held by an experienced examiner. Fig. 2A shows the typical images of the three PMa regions in all stretching positions. We defined the measurement sites of the clavicular, sternal, and abdominal regions as the midpoint between the greater tubercle of the humerus and sternoclavicular joint, the midpoint between the greater tubercle of the humerus and fourth costosternal joint, and a site 3 cm lateral to the midpoint between the greater tubercle of the humerus and xiphoid process, respectively. The probe was transversely placed on the muscle belly of the PMa region at first and then rotated parallel to the fascicles to obtain the region of interest in the B-mode image. Three consecutive images of each PMa region were captured in each stretching position. The participants were instructed not to take a deep breath during the measurement to prevent the involuntary stretching of the PMa from rib cage motion.

2.5. Data analysis

The images were processed using Aixplorer software. The mean values of the shear modulus in each image were calculated from the propagation velocity of the shear wave within one Q-box of 6 mm diameter. The Q-box was placed at the center of the region of interest (i.e., color map), and the epimysium and deep fascia were visually detected and not included (Fig. 2B). As the Aixplorer scanner displayed Young's modulus, Young's modulus was divided by three to obtain the shear modulus of the muscles (i.e., $E = 3G = 3\rho Vs2$, where E is the Young's modulus, G is the shear modulus, Vs is the propagation velocity of the shear wave, and ρ is the muscle density assumed to be equal to 1,000 kg/m3 (Nordez et al., 2008)) (Creze et al., 2018). The mean values of the three images were used for further analysis. Additionally, the ratio of the shear modulus at each stretching position to that of the resting position was calculated and the stretching positions were exhibited based on the rank order of the ratio.

2.6. Statistics

All statistical analyses were performed using IBM SPSS statistics software (version 22; IBM, Armonk, NY, USA). The intra-observer reliability of the shear wave measurements was verified using intraclass correlation coefficients (1,3) (ICC1,3) at 95% confidence interval with < 0.4, 0.40–0.75, and greater than

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0.75 representing poor, moderate to good, and excellent reliability, respectively (Leong et al., 2013). The ICCs were calculated in each stretching position from the three images for all the participants.

A three-way ANOVA with repeated measures — (within-factor: abduction (45°, 90°, and 135°), pelvic rotation (with and without), and external rotation (with and without)) — was used as a single model with all main effects and interactions to test the effects of these stretching maneuvers on the shear modulus of each PMa region. When the sphericity assumption in the ANOVA with repeated measures as Mauchly's test was violated, a Geisser–Greenhous correlation was applied. When a two-way interaction was found instead of a three-way interaction, simple main effect tests were performed. When a two-way interaction was not observed, the main effect tests were performed for each factor. Post hoc tests were conducted through multiple comparisons with a Bonferroni correlation or paired t-test. An alpha level of 0.05 was used for all the statistical tests.

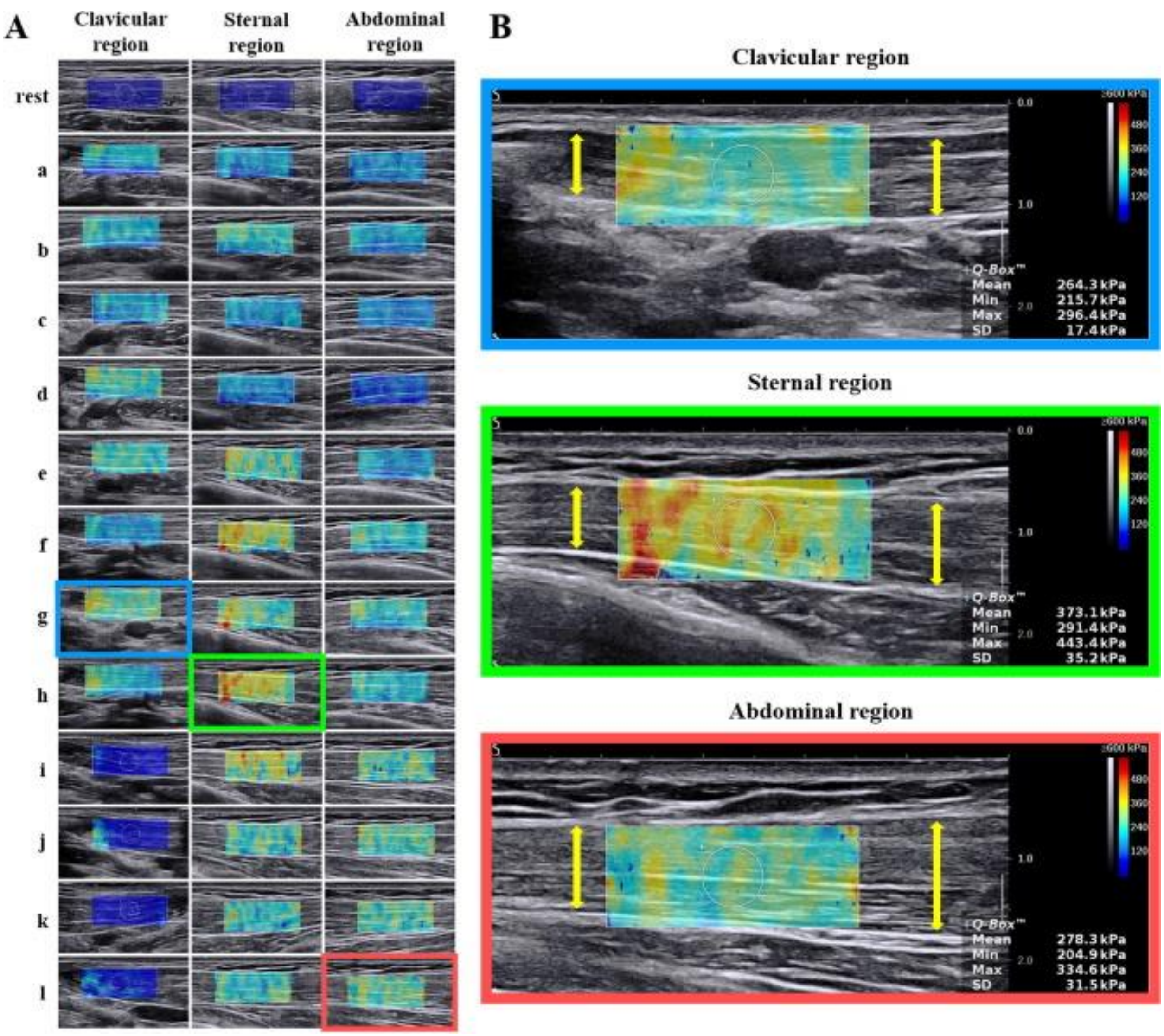

Fig. 2. Shear wave elastographic images of each region of the pectoralis major muscle at all stretching positions (A). Images in each column correspond to elastoraphic images of the clavicular, sternal, and

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abdominal regions, respectively. Images in each row correspond to elastographic images in the resting position and each stretching position. The letters from a to l correspond with each stretching position in Fig. 1. Representative images showing the greatest value of the shear modulus for the clavicular, sternal, and abdominal regions, respectively (B). The yellow arrows within each image represent the muscle thickness of each region of the pectoralis major muscle. One Q-box of 6 mm diameter was placed on the center of the color map within each image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

The intra-observer reliabilities for the shear wave measurements at each stretching position are listed in Table 1. The ICCs ranged from 0.91 to 0.99, and the reliability could be considered sufficient. The data of the shear modulus are represented as the mean ± standard deviation. The shear moduli in the resting positions were 6.3 ± 1.5, 5.6 ± 1.0, and 5.5 ± 1.5 kPa for the clavicular, sternal, and abdominal regions, respectively. The maximal range of motions for the shoulder horizontal abduction and external rotation in all stretching positions were described in Table 2. The statistical results obtained from the ANOVA, simple-main effect test, and the main effect test for each factor are presented in Table 3.

Table 1. The intra-observer reliability for the shear wave measurement in each stretching position

Stretching Position	Clavicular region		Sternal region		Abdominal region	
	$ICC_{1,3}$	95%CI	$ICC_{1,3}$	95%CI	$ICC_{1,3}$	95%CI
abduction 45°	0.92	0.81-0.97	0.97	0.94-0.99	0.98	0.96-0.99
abduction 45°, pelvic rotation	0.97	0.93-0.99	0.98	0.94-0.99	0.97	0.93-0.99
abduction 45°, external rotation	0.97	0.92-0.99	0.97	0.93-0.99	0.97	0.93-0.99
abduction 45°, pelvic rotation, external rotation	0.94	0.85-0.98	0.96	0.90-0.99	0.97	0.93-0.99
abduction 90°	0.94	0.87-0.98	0.95	0.89-0.98	0.95	0.89-0.98
abduction 90°, pelvic rotation	0.95	0.89-0.98	0.97	0.93-0.99	0.92	0.81-0.97
abduction 90°, external rotation	0.93	0.83-0.97	0.92	0.81-0.97	0.92	0.81-0.97
abduction 90°, pelvic rotation, external rotation	0.98	0.96-0.99	0.96	0.91-0.99	0.95	0.87-0.98
abduction 135°	0.97	0.93-0.99	0.99	0.97-1.00	0.91	0.78-0.97
abduction 135°, pelvic rotation	0.97	0.94-0.99	0.95	0.90-0.98	0.99	0.97-1.00
abduction 135°, external rotation	0.97	0.92-0.99	0.97	0.93-0.99	0.96	0.90-0.99
abduction 135°, pelvic rotation, external rotation	0.99	0.97-1.00	0.98	0.95-0.99	0.94	0.85-0.98

ICC, intraclass correlation coefficient; 95%CI, 95% confidence interval

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Table 2. Maximal range of motions for shoulder joint during stretching positions

Stretching position	Horizontal abduction (°)	External rotation (°)
abduction 45°	79.3 ± 9.8 †	–
abduction 45°, pelvic rotation	68.7 ± 12.6 *	–
abduction 45°, external rotation	79.3 ± 9.8 †	55.7 ± 19.6
abduction 45°, pelvic rotation, external rotation	68.7 ± 12.6 *	53.3 ± 17.3
abduction 90°	68.0 ± 14.7 †	–
abduction 90°, pelvic rotation	62.0 ± 15.5 *	–
abduction 90°, external rotation	68.0 ± 14.7 †	38.0 ± 12.5
abduction 90°, pelvic rotation, external rotation	62.0 ± 15.5 *	35.0 ± 8.6
abduction 135°	47.0 ± 13.8 †	–
abduction 135°, pelvic rotation	40.3 ± 13.6 *	–
abduction 135°, external rotation	47.0 ± 13.8 †	36.7 ± 15.3
abduction 135°, pelvic rotation, external rotation	40.3 ± 13.6 *	33.7 ± 17.3

The values represent the mean and standard deviation of the maximal shoulder range of motions. The same maximal horizontal abduction angles within participants were used in stretching positions with (marked with asterisks) or without (marked with dagger) pelvic rotation.

Table 3. The statistical results of main effect for each factor and its interaction from three-way analysis of variance

Factors	Interaction and main effect [F value (P value)]						
	abduction	pelvic rotation	external rotation	abduction×pelvic rotation	abduction×external rotation	pelvic rotation×external rotation	abduction×pelvic rotation×external rotation
Clavicular region	95.13 (<.001)*	2.46 (.139)	14.92 (.002)*	7.69 (.002)*	10.34 (<.001)*	0.30 (.587)	0.725 (.493)
Sternal region	8.06 (.007)*	3.03 (.103)	21.36 (< .001)*	2.88 (.072)	13.16 (< .001)*	0.03 (.851)	0.21 (.806)
Abdominal region	56.08 (< .001)*	36.42 (< .001)*	116.96 (< .001)*	1.84 (.177)	1.89 (.169)	0.20 (.660)	0.46 (.632)

Asterisk marks represent statistical significance ($P < .05$).

For the clavicular region, there was no significant three-way interaction, but two-way interactions of abduction × pelvic rotation and abduction × external rotation were observed. A post hoc test of the abduction × pelvic rotation interaction indicated that for the comparisons between the abduction angles, the shear moduli of abductions at 45° and 90° were higher than that at 135°, with and without pelvic rotation (P < .001 for both comparisons). However, there was no difference between the abductions at 45° and 90°. When comparing the pelvic rotations, the shear modulus of the abduction at 90° without pelvic rotation was higher than that with pelvic rotation (P = .003). A post hoc test of the abduction × external rotation interaction showed that for the comparisons between abduction angles, the shear moduli of abductions at 45° and 90° with external rotation were higher than that at 135° (P < .001 for both comparisons), but there was no difference between the abductions at 45° and 90°. The shear modulus of

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the abduction at 90° without external rotation was the highest (45° vs. 90° P = .020, 45° vs. 135° P < .001, and 90° vs. 135° P < .001). By comparing the external rotations, the external rotation affected the shear modulus of the abduction at 45°, and the shear modulus with external rotation was higher than that without external rotation (P < .001) (Fig. 3A).

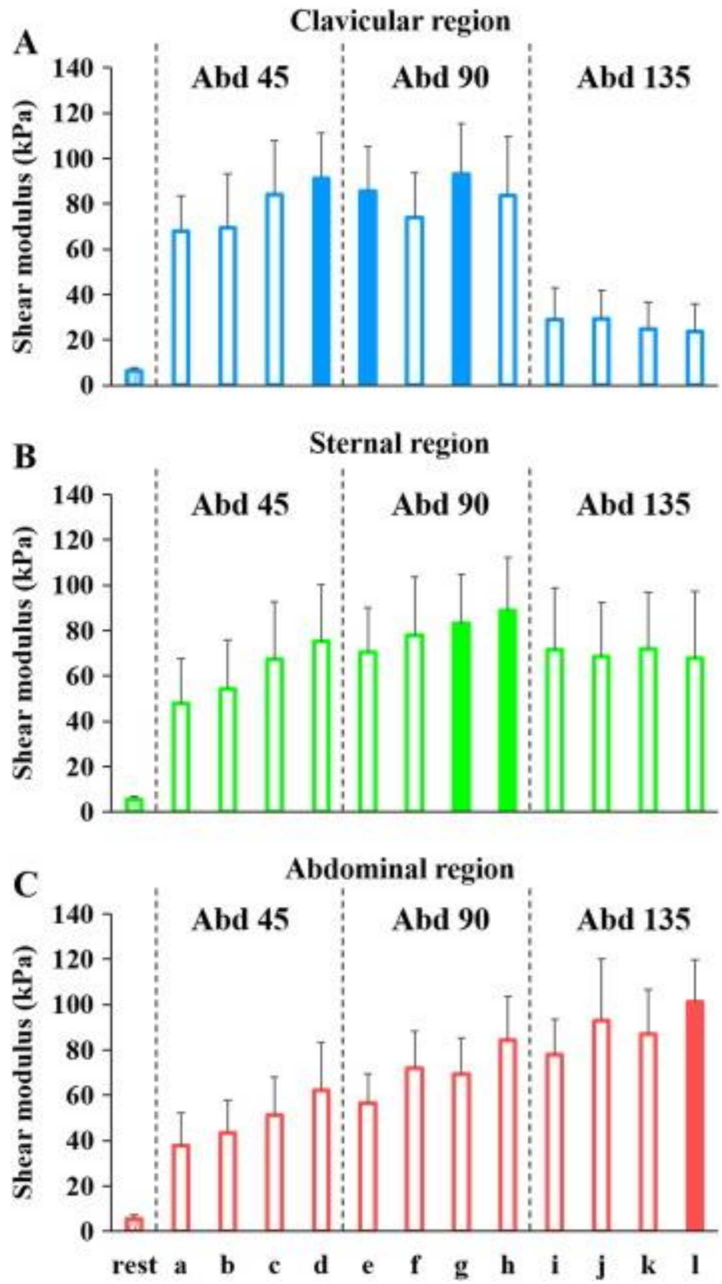

Fig. 3. The shear modulus of the clavicular (A), sternal (B), abdominal (C) of the pectoralis major muscle. Filled color bars show effective stretching positions with consideration of statistical significance and rank order of ration of shear modulus. Labels from a to l correspond with the stretching positions in Fig. 1. Abd, abduction.

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For the sternal region, there was no significant three-way interaction, but an abduction × external rotation interaction was observed. Post hoc tests revealed that the shear modulus of the abduction at 90° with external rotation was the highest when comparing the abduction angles (45° vs. 90° P = .013; 90° vs. 135° P = .012). Additionally, the shear moduli of the abductions at 90° and 135° without external rotations were higher than those at 45° (P < .001 and P = .017, respectively), but the shear modulus at 90° abduction did not differ from that at 135°. The shear moduli of the abductions at 45° and 90° with external rotation were higher than those without external rotation (P < .001 for both comparisons), but there was no difference in the shear modulus of the abduction at 135° with and without external rotation (Fig. 3B).

For the abdominal region, neither three-way nor two-way interactions were found. However, the main effects were observed for each factor. Comparing the abduction angles, the shear modulus for the abduction at 135° was the highest (P < .001 for all comparisons). For pelvic rotations, the shear modulus with pelvic rotation was higher than that without pelvic rotation (P < .001). Concerning the external rotation, the shear modulus with external rotation was higher than that without external rotation (P < .001) (Fig. 3C).

The ratio of each shear modulus and its rank orders are listed in Table 4. For the clavicular region, shoulder horizontal abduction at 90° abduction with external rotation was first in the rank order. The shear modulus was approximately 15 times greater in this stretching position than in the resting position. For the sternal region, shoulder horizontal abduction at 90° abduction with pelvic rotation and external rotation was first in the rank order in which the shear modulus was approximately 16 times larger than the resting position. For the abdominal region, the shear modulus in the shoulder horizontal abduction with pelvic rotation and external rotation was approximately 19 times larger against the resting position, the order of which was first.

Table 4. Ratio of shear modulus and its rank order of each stretching position

Stretching Position	Clavicular region		Sternal region		Abdominal region	
	Ratio of change	Rank order	Ratio of change	Rank order	Ratio of change	Rank order
abduction 45°	11.1 ± 2.9	8	8.8 ± 3.7	12	7.2 ± 3.2	12
abduction 45°, pelvic rotation	11.3 ± 4.3	7	10.0 ± 4.6	11	8.2 ± 3.0	11
abduction 45°, external rotation	13.5 ± 3.8	5	12.3 ± 5.3	10	9.8 ± 4.3	10
abduction 45°, pelvic rotation, external rotation	15.1 ± 4.6	2	13.7 ± 5.4	4	11.6 ± 4.4	8
abduction 90°	14.3 ± 5.0	3	12.9 ± 4.3	7	10.7 ± 3.3	9
abduction 90°, pelvic rotation	12.0 ± 3.5	6	14.5 ± 6.2	3	13.7 ± 4.7	6
abduction 90°, external rotation	15.5 ± 5.3	1	15.1 ± 4.7	2	13.2 ± 4.8	7
abduction 90°, pelvic rotation, external rotation	13.7 ± 5.0	4	16.5 ± 6.5	1	15.8 ± 5.0	4
abduction 135°	4.7 ± 2.1	10	13.4 ± 6.2	5	14.9 ± 5.4	5
abduction 135°, pelvic rotation	4.8 ± 2.1	9	12.6 ± 5.2	8	17.7 ± 7.4	2

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abduction 135°, external rotation	4.0 ± 1.9	11	13.2 ± 5.4	6	16.6 ± 6.0	3
abduction 135°, pelvic rotation, external rotation	3.9 ± 2.3	12	12.4 ± 5.4	9	19.1 ± 5.8	1

The rank order is from the largest to the smallest of the mean of shear modulus values. The ratio was calculated from the shear modulus in each stretching position divided by that of resting position.

4. Discussion

The current study measured the shear moduli of three PMa regions, i.e., the clavicular, sternal, and abdominal regions using SWE, and determined the effective stretching position for each PMa region by investigating the effect of shoulder abductions, external rotation, and pelvic rotation on the PMa muscle lengthening. Our results revealed that different stretching positions could effectively stretch each PMa region. To the best of our knowledge, this is the first study to show an effective stretching position for each PMa region using SWE in vivo.

Only two studies investigated the effect of shoulder joint angles on the PMa muscle properties using the shear wave elastography. Chodock et al. (2020) observed whether shoulder abduction influences on the shear modulus of the clavicular and sternocostal regions of the PMa. The shear modulus of the sternocostal region increased with shoulder abduction up to 105°, while shoulder abduction did not influence the shear modulus of the clavicular region. This result was consistent with our findings, that there was no difference between the abductions at 45° and 90° in the clavicular region, while the shear modulus at 90° abduction was higher than that at 45° abduction in the sternal region. Furthermore, Leonardis et al. (2017) investigated the material properties of each fiber in different postures comprising shoulder abduction and external rotation. They showed that in both the clavicular and sternocostal regions, the shear modulus at 90° abduction was higher than that at 60° abduction, and the shear modulus in external rotation was greater than that without external rotation. Our result did not completely support this previous study because for the clavicular region the shear modulus at 45° abduction did not differ from that at 90° abduction and the external rotation did not increase the shear modulus at 90° abduction in the current study.

For the clavicular region, the interactions of abduction × pelvic rotation and abduction × external rotation were found, which means the combined motions of the shoulder abduction and the pelvic rotation as well as the shoulder abduction and the external rotation influenced on the shear modulus of the clavicular region. Given these interactions and the rank order of the ratio, the effective stretching positions were obtained as follows: shoulder horizontal abduction at 45° abduction with pelvic rotation and shoulder external rotation, shoulder horizontal abduction at 90° abduction, and shoulder horizontal abduction at 90° abduction with shoulder external rotation (Fig. 3A). These results partly supported our hypothesis, i.e., that the clavicular region is passively stretched by a shoulder horizontal abduction at<90° abduction with shoulder external rotation. As the noninvasive measurement of whole individual muscle lengthening in vivo is challenging, studies on the lengthening of each PMa region have not been investigated in detail. A simulation study using a musculoskeletal model proposed that the combined motion of a shoulder extension with an external rotation increased the clavicular portion strain of the PMa (Stegink-Jansen et al., 2011). Our results for the clavicular region, as mentioned above, could be in line with the findings

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reported in this previous study. These positions effectively stretch the clavicular region owing to tendon excursion method, where the moment arm is defined as the partial derivative of the muscle length with respect to the joint angle (An et al., 1984). The muscle lengthening is, therefore, assumed as the summation of the moment arm given the change in the joint angle. The clavicular region of the PMa exhibits a shoulder adduction moment arm at the lower abduction angle, but the moment arm changes to that of shoulder abduction with the abduction angle (Ackland et al., 2008). The clavicular region, additionally, has moment arms for the shoulder internal rotation, which are higher in the order of the shoulder at 30°, 60°, and 90° (Ackland and Pandy, 2011). Therefore, the clavicular region seemed to be effectively stretched at<90° of shoulder abduction with external rotation.

For the sternal region, the abduction × external rotation interaction was observed, which expresses the combined motion of the shoulder abduction and the external rotation impacted on the shear modulus of the sternal region. Taking the rank order into account of this interaction, the effective stretching positions for the sternal region were shoulder horizontal abduction at 90° abduction with external rotation, and with pelvic rotation and external rotation (Fig. 3B). We hypothesized that the sternal region was adequately stretched by the shoulder horizontal abduction at 90° abduction with external rotation, and this hypothesis was partly supported by our results. The shoulder adduction moment arm of the sternal region is maximum at an approximate abduction of 45° and then decreases with the abduction angle (Ackland et al., 2008). Data for a shoulder abduction/adduction moment arm above 120° is unavailable, but considering the given abduction angle-moment arm curve, the adduction moment arm could reach zero (i.e., no abduction/adduction moment arm exists) above 120°. Moreover, the moment arm of the shoulder internal rotation is constant at all abduction angles (Ackland and Pandy, 2011). Hence, the sternal region was effectively stretched in the positions described above, as the summation of the moment arm of the abduction and external rotation could be higher at an approximately 90° abduction with external rotation. However, it remains unclear why the shear modulus of the sternal region at 90° abduction with external rotation exceeds that at 135° with external rotation.

For the abdominal region, there were three main effects of each factor but not its interactions, indicating that each shoulder and pelvic motion was influential to the shear modulus, and these combined motions had insignificant effect on muscle lengthening. Based upon this main effect and the rank order, the abdominal region of the PMa was effectively stretched by the shoulder horizontal abduction at 135° with pelvic rotation and external rotation (Fig. 3C). Our hypothesis, i.e., that a shoulder horizontal abduction at more than 90° abduction with pelvic rotation and external rotation lengthens the abdominal region was supported by this result. The abdominal region has a moment arm of shoulder adduction and internal rotation at all abduction angles (Ackland et al., 2008, Ackland and Pandy, 2011). Furthermore, the abdominal region originates from the superior fifth-sixth costal cartilages and aponeurosis of the external oblique muscle and inserts into the bicipital groove and the greater tuberosity of the humerus (Haley and Zacchilli, 2014, Sanchez et al., 2014). A recent study examining the ribcage kinematics showed that the spinal axial rotation causes a relative ipsilateral rotation of the ribs (Liebsch et al., 2019). Consequently, a stretching position with shoulder abduction at 135° with external rotation arranges the muscle fibers in a straight line of the origin and insertion, and the pelvic rotation stabilizes the aponeurosis of the external oblique according to the insertion and contralaterally rotated the distal ribs relative via the spinal rotation. Therefore, the abdominal was effectively stretched by the shoulder horizontal abduction at 135° abduction with pelvic rotation and external rotation.

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Our findings regarding the effective stretching positions for the three PMa regions are useful for the conditioning, rehabilitation, and prevention of PMa injuries in both clinical settings and athletics. However, this study has some limitations. First, the participants were limited to healthy men with no limits in the shoulder range of motion. Whether our findings could be generalized to individuals with limitations in the shoulder range of motion is unclear. Second, effective stretching positions were found, but the intervention effects were not revealed. Further studies are needed on the intervention and prevention effects in individuals with limited ranges of motion using the effective stretching positions. Third, we did not include women in this study because the accumulation of subcutaneous adipose tissue would be a potential bias for measuring the shear modulus. Fourth, there is a possibility of measuring the different muscle fiber within each region of PMa across the stretching positions because the muscle could slide beneath the skin marked as the measurement point. However, we took particular care to measure the same muscle site by screening the muscle structure on the ultrasound image.

In conclusion, the shear moduli of three PMa regions (the clavicular, sternal, and abdominal regions) were determined in this study using SWE. We found that the effective stretching position was different for each PMa. The effective stretching positions of the clavicular and sternal regions were sensitive to the combination of shoulder abduction, pelvic rotation, and external rotation, whereas the stretching position of the abdominal region was determined from each maneuver. Our findings are practical and useful for the conditioning, rehabilitation, and prevention of PMa injuries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions

J.U., T.I., Y.S., M.Y., and N.I. conceived and designed the research; Y.S., S.N., and K.Y. performed the experiment; J.U. and S.N. analyzed the data; J.U., M.Y., S.N., T.H., and N.I. interpreted the results; J.U. and T.I. wrote the manuscript; J.U. and N.I. edited and revised the manuscript; All the authors approved the final version of the manuscript.

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