Effect of chest mobilization on intercostal muscle stiffness

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ABSTRACT 

This study examined the effect of chest mobilization on intercostal (IC) muscle stiffness using the IC muscle shear modulus. Sixteen healthy young men participated on two days with a minimum of 24 h between the stretching and control conditions (SC and CC). The tasks were resting breathing and deep breathing. The IC muscle shear modulus and muscle activity and rib cage circumference were measured before and after each condition. In the SC, IC stretching was performed for 1 min x 5 sets. In the CC, resting breathing, in a sitting position, was performed for 5 min. In the SC, the IC muscle shear modulus decreased significantly (p < 0.05) at maximum inspiration compared to the CC pre- and post-intervention. The results suggest that IC muscle stretching decreases IC muscle stiffness and improves muscle flexibility and that the IC muscle shear modulus may measure the effectiveness of chest mobilization.

1. Introduction

The thorax is composed of the thoracic vertebrae, ribs, and sternum and has the mobility to expand its antero-posterior and lateral diameters with inspiration during respiration (Moll and Wright, 1972). Thoracic mobility has been reported to be reduced in respiratory diseases such as chronic obstructive pulmonary disease (Reddy et al., 2019), ankylosing spondylitis (AS) (Hsieh et al., 2016), and scoliosis (Romberg et al., 2020). Hsieh et al. (2016) showed that AS patients with reduced thoracic mobility had reduced lung capacity compared with healthy participants. Yeh et al. (2020) also reported that in postoperative funnel chest patients who underwent a Nuss procedure to widen the depressed thorax, the 6-min walking distance increased, with improvement in rib cage circumference during maximal inspiration. Thus, thoracic mobility is thought to be related to physical functions such as respiratory function and exercise tolerance.

Factors that contribute to decreased thoracic mobility include stiffness of the lung parenchyma (DiMarco et al., 1983), decreased mobility of the costovertebral joints (Hsieh et al., 2016), and decreased flexibility of the respiratory muscles (Rehman et al., 2020). Among the respiratory muscles, the intercostal (IC) muscles are attached between the upper and lower ribs (De Troyer et al., 2005) and are elongated in the caudal ventral region during deep inspiration (Wilson et al., 2001). It is also known that the thoracic spine range of motion is increased in a model of the thorax with the intercostal muscles removed (Liebsch et al., 2017), suggesting that intercostal muscles may contribute to reduced thoracic mobility.

Chest mobilization is one of the physical therapies used for decreased thoracic mobility. Examples of chest mobilization include active exercises by the patient, such as respiratory muscle stretch gymnastics (Yamada et al., 1996) and manual stretching by the therapist (Rehman et al., 2020). Chest mobilization is performed to improve respiratory function, thoracic mobility, and the flexibility of the respiratory muscles. Previous studies have reported an increase in ventilation (Leelarungrayub et al., 2009) and an increase in chest wall expansion (Rehman et al., 2020) after chest mobilization. However, one of the objectives, the improvement of respiratory muscle flexibility, is estimated from chest expansion, and it is unclear whether the flexibility of the muscle itself has changed.

Chest expansion measurement is a method of measuring the difference in rib cage circumference between maximal inspiration and maximal expiration and is widely used in research and clinical practice as it is simple, inexpensive, and highly reliable (Debouche et al., 2016). However, chest expansion is an index that reflects the overall movement...
of the thorax and cannot evaluate the flexibility of a single muscle. Thus, it is difficult to verify the effect of thoracic chest mobilization on the flexibility of the IC muscles by measuring chest expansion.

Muscle stiffness is one of the indices of muscle flexibility. Recently, it has been suggested that the shear modulus, which can be measured by ultrasound shear wave elastography (SWE), is useful for assessing muscle stiffness (Shinohara et al., 2010). SWE is a method of generating shear waves in biological tissue and calculating the elastic modulus based on their propagation velocity, which can help evaluate the stiffness of a single muscle (Shinohara et al., 2010). Higher values obtained using this method indicate faster shear wave propagation and stiffer tissue, signifying greater muscle stiffness (Eby et al., 2013). Recently, high intra- and inter-examiner reproducibility has been reported for the elasticity measurements of skeletal muscles using this method (Lacour-paille et al., 2012). In addition, a strong correlation between the validity of this method has also been verified by the strong correlation between the Young’s modulus determined using conventional mechanical tests and the shear modulus obtained using this method (Eby et al., 2013). Therefore, this method has also been used to determine the effectiveness of stretching (Nakamura et al., 2020; Nakao et al., 2018; Taniguchi et al., 2015). High measurement reproducibility has also been reported in the IC muscles (Pietton et al., 2021). In conclusion, measuring the shear modulus of the IC muscle can evaluate the flexibility of these muscles and verify the effect of stretching on them. However, there have been no reports of quantitative evaluation of the acute effects of chest mobilization on muscle stiffness using SWE.

Therefore, the purpose of this study was to examine the effects of chest mobilization on thoracic mobility and IC muscle stiffness using chest expansion measurements and the IC muscle shear modulus. We hypothesized that chest mobilization would decrease IC muscle stiffness, especially during deep inspiration when the muscles are stretched.

2. Materials and methods

2.1. Participants

Sixteen healthy young men (age: 24.29 ± 3.04 years, height: 1.74 ± 0.06 m, weight: 67.84 ± 10.09 kg, body mass index [BMI]: 22.44 ± 2.68) participated in the study. The exclusion criteria were respiratory or cardiovascular disease, motor dysfunction in the limbs or trunk, history of chest surgery, history of smoking, and BMI less than 18.5 or greater than 30. Before the experiment, the participants were fully briefed on the outline, purpose, and risks associated with the study in writing and gave their consent. In addition, this study was approved by the Ethics Committee of Sapporo Medical University (Approval No. 2-1-16) and was conducted according to the provisions of the Declaration of Helsinki.

2.2. Experimental procedures

A crossover design was used in this experiment. The participants were divided into two groups, the first group performed stretching (stretching condition [SC]) the first time, and the other performed resting breathing (control condition [CC]) as a control. Both groups then crossed over to perform the other condition on different days with an interval of at least 24 h. The interventions included five sets of IC muscle stretching for 1 min per set (total of 5 min) in the SC and 5 min of resting breathing in a seated position in the CC to match the intervention time in the stretching condition. In each condition, the exercise tasks were performed in sequence with pre-and post-intervention measurements. The IC muscle shear modulus, IC electromyography (EMG), and rib cage circumference were also measured before and after the intervention.

2.3. Exercise tasks

A 45° reclined chair sitting position was used for measurement, and the right upper limb was placed on a table with 45° shoulder joint flexion abduction to secure the measurement position of the shear modulus (Fig. 1). First, the resting breathing task was performed for 30 s at a respiratory rate of 16 breaths per minute. The resting breathing task was performed similarly to a previous study (Pietton et al., 2020), where 10 s of images were used for analysis, and 10 s were added before and after to obtain more stable breathing, resulting in a 30-s task. A deep breathing task was performed after the resting breathing task. For deep breathing, inspiration was performed slowly for 2–3 s to the maximum and then paused for 5 s at the maximum inspiration position. Thereafter, the participant exhaled comfortably and paused for 5 s at the fully exhaled position (maximal expiratory position). This 5-s period was chosen as it was the time at which all participants were able to stall stably in the pilot experiment. To minimize the changes in breathing patterns and the influence of the internal intercostal muscles and scapular external oblique abdominal muscles, the participant was taught to "expand the rib cage to the maximum" during deep inhalation and "breathe out easily, not effortfully" during deep exhalation. Therefore, in this study, the maximal expiratory position was defined as the resting expiratory position, not the deep expiratory position.

2.4. Chest mobilization

Chest mobilization was performed using IC muscle stretching. Since the effect of stretching on the shear modulus decreases in a time-dependent manner (Taniguchi et al., 2015), the only site of the stretching was the sixth IC muscle on the right side between the anterior axillary line and a vertical line passing through the nipple, the position where the shear modulus is measured. The examiner’s index, middle, ring, and little fingers were placed on the upper margin of the seventh rib, and the ribs were pressed down to dilate the IC space with maximum expiration. During the procedure, we checked whether the participant was in pain and took care to avoid any pain. Based on previous studies on stretching of the skeletal muscles of the extremities (Taniguchi et al., 2015; Umehara et al., 2021), one set was performed 10 times in 1 min for a total of 5 sets, with rest of approximately 10 s between sets. Stretching techniques were performed by one physical therapist (licensed certified therapist of respiration in Japan) with four years of respiratory physiotherapy experience.

![Fig. 1. Measurement posture and position for intercostal muscle shear modulus, rib cage circumference, and intercostal electromyogram.](image-url)
2.5. Measurements

2.5.1. IC muscle shear modulus

The shear modulus was measured using ultrasound SWE (Aixplorer Ver. 12, Supersonic Imagine, France) and a linear probe (50 mm, 2–10 MHz, Supersonic Imagine, France). The shear modulus was measured in the sixth IC muscle between the anterior axillary line and a vertical line passing through the nipple (Fig. 1). The ultrasound probe was placed along the direction of the muscle fibers of the external intercostal muscles and oriented to obtain a clear longitudinal image of the IC muscles and transverse images of the upper and lower ribs. The elastic color map was placed on the IC muscle area, excluding the ribs (Fig. 2). Longitudinal muscle images and elastic color images during measurement were recorded as moving images in the ultrasound system. The movies were synchronized with other digital data using a capture board (Epiphian video DV12USB 3.0, Argo Corp, Osaka, Japan) and the Video Capture module (Lab Chart Pro 7.2, AD Instruments), and recorded on a personal computer at 2 Hz. In Aixplorer, which was used in this study, the elastic color image changes at 2-Hz intervals; therefore, the video movies were synchronized with other digital data using a capture board (Epiphian video DV12USB 3.0, Argo Corp, Osaka, Japan) and the Video Capture module (Lab Chart Pro 7.2, AD Instruments), and recorded on a personal computer at 2 Hz. In Aixplorer, which was used in this study, the elastic color image changes at 2-Hz intervals; therefore, the video recorded was also at 2 Hz. All shear modulus measurements were performed by one examiner.

SWE is a technique for calculating the Young's modulus (E), a type of elastic modulus, by capturing the velocity (c) of shear wave propagation caused by a focused ultrasonic pressure beam (acoustic radiation force) on a region of interest (ROI). The Young’s modulus is calculated based on the wave equation, \( E = 3\rho c^2 \), where the tissue density \( \rho \) is assumed to be constant at 1000 kg/m\(^3\). This equation is calculated assuming that the tissue density is isotropic. However, the muscle tissue has anisotropic elastic properties that vary with the direction of force applied to the fibers. Therefore, it is reasonable to use the shear modulus, which is calculated as the Young’s modulus divided by 3, as a measure of the elasticity of the muscle tissue (Royer et al., 2011).

2.5.2. Rib cage circumference

Rib cage circumference was measured using a thoracic excursion measuring device (T.K.K. 3345, Takai Scientific Instrument Co., Ltd., Niigata, Japan) (Fig. 1). Details of the device are as follows: sensor method, wire linear encoder method; measuring range, 60–110 cm; and sampling frequency, 50 Hz. The measurement site was at the height of the xiphoid process and the spinous process of the tenth thoracic vertebra (Debouche et al., 2016). The rib cage circumference was recorded on a personal computer using dedicated software (Lab Chart 7.2, AD Instruments) via an AD converter (Power Lab ML800, AD Instruments, Bella Vista, NSW, Australia). The sampling frequency was 1 kHz.

2.5.3. IC muscle electromyography

Surface EMG was measured using active electrodes. Details of the recording device for surface EMG are as follows: amplifier type, differential amplification; distance between the electrodes, 1 cm; sensor part, 0.1 × 1 cm silver; amplification factor in the electrode, 10 times; input impedance, 1015 Ω/0.2 pF; and common-mode rejection ratio, 92 dB. The main amplifier unit featured a gain of 1000-fold and a frequency response of 20 ± 5 to 450 ± 50 Hz (electrode, DE-2.1; amplifier, Bagnoli-8, Delsys, Boston, MA, USA). The electrode position was the sixth IC space on the anterior axillary line (Chino et al., 2018) (Fig. 1), and skin treatment (shaving, mild polishing with compound paste, and cleaning with alcohol) was performed before electrode application to reduce skin resistance. The electrodes were affixed with double-sided tape parallel to the running of the muscle fibers and fixed using surgical tape. The lead wires were fixed with surgical tape to reduce the effects of motion artifacts. The grounding electrode was placed on the radial styloid process of the left upper limb. The rib cage circumference and surface EMG were recorded in time synchronized with the elastic color images on a personal computer using dedicated software (Lab Chart Pro 7.2, AD Instruments) via an analog/digital converter (Power Lab ML800, AD Instruments, Bella Vista, NSW, Australia) for the electrical signals. The sampling frequency was set to 1 kHz. A 30 Hz high pass filter was also adapted to the IC muscle EMG to remove artifacts from the electrocardiogram (ECG) (Ando et al., 2020).

2.6. Data analysis

2.6.1. IC muscle shear modulus

The analysis interval was defined as the interval during which the color change in the elastic color image was stable. In the resting breathing task, the analysis interval was 10 s based on previous studies. In the deep breathing task, the images were extracted for 2 s each during maximal inspiration and expiration, as the elastic color images, thoracic circumference, and electromyogram with different temporal resolutions from the pilot experiment were consistent and the color map was stable at the time of maximal inspiration and expiration (Fig. 2). Using the analysis software on the ultrasound system (Iida et al., 2021), circular ROIs, 2–4 mm in diameter, were set at the center and on either side along the IC muscle in the extracted elastic color images, and the shear modulus (kPa) was calculated from the average Young’s modulus of the three circles. For the deep breathing task, the values of the two elastic color images extracted during maximum inspiration and expiration were averaged, and the average of the two performed values was representative of maximal inspiration and expiration, respectively. For the resting breathing task, the average of the 10 extracted elastic color images was calculated and used for statistical analysis.
2.6.2. Rib cage circumference and IC muscle electromyography

Rib cage circumference and surface EMG were calculated using analysis software (Lab Chart Pro 7.2, AD Instruments). Rib cage circumference was calculated for the same analysis interval as the shear modulus, and the mean value and the difference between maximum inspiration and expiration (chest wall expansion) were calculated and used for statistical analysis. The EMG values were calculated as the root mean square (RMS) values at 100 ms intervals. The mean values for the analysis interval, excluding ECG artifacts, were normalized by the value at the first deep inspiration pre-intervention for each condition and used for the statistical analysis of each condition.

2.7. Statistical analysis

All values were calculated as means ± standard deviation. Before the analysis of variance, Mauchly’s sphericity test was used to test for uniformity of variance and covariance. If this test was rejected, the degrees of freedom were corrected using Greenhouse-Geisser’s method. To investigate the measurement reproducibility of the shear modulus, the standard error of measurement (SEM), intraclass correlation coefficient (ICC (1, 1)), and coefficient of variation (CV) were calculated using the shear modulus at maximal inspiration and expiration, two times each, measured in the deep breathing task for each condition, Pre and Post. To compare the shear modulus, rib cage circumference, chest wall expansion, and EMG before and after IC muscle stretching in each task, repeated measures of two-way ANOVA (condition [stretching, control] × time [Pre, Post]) was performed and the Bonferroni method was used as a post hoc test. Statistical analyses were performed using statistical software (SPSS Statics Ver. 25.0; IBM, Armonk, USA). The significance level was set at 5%.

3. Results

3.1. Reproducibility of shear modulus measurements

The ICC, SEM, and CV of the shear modulus for the two deep breathing tasks are shown in Table 1.

3.2. Effect of IC muscle stretching

3.2.1. IC muscle shear modulus

Fig. 3 shows the shear modulus before and after intervention in the deep breathing (Fig. 3A and B) and resting breathing tasks (Fig. 3C). The shear modulus at maximal inspiration showed significant main effects of condition (F (1, 15) = 5.88, p < 0.05) and time (F (1, 15) = 11.86, p < 0.05), and a significant interaction between condition and time (F (1, 15) = 44.69, p < 0.05) in the analysis of variance. Multiple comparisons revealed a significant decrease in the shear modulus after IC muscle stretching only in the SC (p < 0.05). In contrast, for the maximal expiration and resting breathing tasks in the SC, analysis of variance showed no significant main effects of condition (maximal expiration: F (1, 15) = 0.78, p = 0.39; resting breathing: F (1, 15) = 0.40, p = 0.54) or time (maximal expiration: F (1, 15) = 3.16, p = 0.10; resting breathing: F (1, 15) = 3.21, p = 0.09), and no significant interaction between the condition and time (maximal expiration: F (1, 15) = 0.48, p = 0.50; resting breathing: F (1, 15) = 0.03, p = 0.86).

3.2.2. Rib cage circumference and chest wall expansion

Rib cage circumference showed no significant main effects of condition (maximal inspiration: F (1, 15) = 0.72, p = 0.41; maximal expiration: F (1, 15) = 0.01, p = 0.94; resting breathing: F (1, 15) = 0.00, p = 0.98), time (maximal inspiration: F (1, 15) = 0.27, p = 0.61; maximal expiration: F (1, 15) = 1.03, p = 0.33; resting breathing: F (1, 15) = 2.58, p = 0.13), or significant interaction between condition and time (maximal inspiration: F (1, 15) = 0.20, p = 0.66; maximal expiration: F (1, 15) = 0.76, p = 0.40; resting breathing: F (1, 15) = 3.84, p = 0.07) for each task. Chest expansion showed no main effects of condition (F (1, 15) = 2.53, p = 0.13) or time (F (1, 15) = 1.08, p = 0.32), and no significant interaction between condition and time (F (1, 15) = 1.16, p = 0.30).

3.2.3. IC EMG

IC EMG showed no significant main effects of condition (maximal inspiration: F (1, 15) = 0.06, p = 0.81; maximal expiration: F (1, 15) = 0.11, p = 0.75; resting breathing: F (1, 15) = 0.41, p = 0.53) or time (maximal inspiration: F (1, 15) = 0.08, p = 0.78; maximal expiration: F (1, 15) = 0.73, p = 0.41; resting breathing: F (1, 15) = 0.90, p = 0.36), and no significant interactions between condition and time (maximal inspiration: F (1, 15) = 2.39, p = 0.14; maximal expiration: F (1, 15) = 0.31, p = 0.86; resting breathing: F (1, 15) = 0.68, p = 0.42) for either task.

4. Discussion

This study examined the effects of IC muscle stretching on the IC muscle shear modulus in healthy young men. The results showed that only the shear modulus of the IC muscles during maximal inspiration was significantly reduced after stretching. This indicated that IC muscle stretching may decrease IC muscle stiffness during maximal inspiration. To the best of our knowledge, this is the first study to examine the effects of IC muscle stretching on the mechanical properties of IC muscles.

4.1. Reproducibility of shear modulus measurements

The ICC, which indicates measurement reproducibility, was in the "almost perfect" range and showed good reproducibility during maximal inspiration. During maximal expiration, it was in the substantial range and showed moderate reproducibility (Landis and Koch, 1977). In a

| Table 1A | Respiratory phase | SC pre | SC post |
|-----------|-------------------|--------|--------|
|           | ICG(1, 1) (95%CI) | CV (%) | SEM (kPa) |
| Shear modulus | Inspiration | 0.94 (0.83-0.98) | 8.8 | 1.2 |
|             | Expiration     | 0.75 (0.43-0.91) | 23.3 | 0.4 |

| Table 1B | Respiratory phase | CC pre | CC post |
|-----------|-------------------|--------|--------|
|           | ICG(1, 1) (95%CI) | CV (%) | SEM (kPa) |
| Shear modulus | Inspiration | 0.93 (0.81-0.97) | 11.6 | 1.1 |
|             | Expiration     | 0.75 (0.43-0.91) | 12.9 | 0.3 |
been reported that the shear modulus of skeletal muscle varies with the
unreliable values of shear modulus on maximal expiration. It has
lower reproducibility. The effect of probe manipulation was a factor in
the study. However, the shear modulus on expiration showed somewhat
comparable with the reproducibility during maximal inspiration in our
study. Previous study (Pietton et al., 2021) that measured the IC muscle elastic
modulus during the maximal expiration and resting breathing tasks may
have resulted from a decrease in passive muscle stiffness.

4.2. Effect of IC muscle stretching on IC stiffness

In this study, a total of five sets of stretching were performed for
approximately 5 min, with one set of 10 breaths. The results showed a
15.9% decrease in the shear modulus during maximal inspiration. In
contrast, the CC showed a slight change, an increase of 0.9%, and no
difference was observed. Intercostal muscles have similar mechanical properties as other skeletal muscles of the extremities (Kelly
et al., 1993). Previous studies (Taniguchi et al., 2015; Umehara et al.,
2021) that utilized 5-min stretching on skeletal muscles of the extremities
similar to the present study reported a significant decrease in the
elastic modulus, with a change rate of 14–17%, which was similar to the
present study. Therefore, we believe that the stretching effect in this
study was reasonable.

It has been reported that the shear modulus reflects muscle activity
associated with muscle contraction (Yoshitake et al., 2014). Muscle
activity did not change significantly before and after stretching in this
study, suggesting that muscle activity did not affect the shear modulus
reduction caused by stretching. It has also been reported that the shear
modulus reflects passive stiffness associated with muscle elongation
(Eby et al., 2013). Stiffness is a measure of the relationship between
muscle length change and applied stress, and its value decreases as the
muscle length increases or stress decreases. Although the muscle length
was not measured in this study, previous studies have reported that
during maximal inspiration, the rib cage circumference is expanded
(Moll and Wright, 1972) and the muscle length of the ventral sixth IC
muscle, the measurement position, is elongated (Wilson et al., 2001). In
this study, the rib cage circumference was measured, and there was no
difference before and after stretching. This suggests that stiffness
decreased due to a decrease in stress, not a change in muscle length.
Thus, the results indicate that the decrease in the shear muscle
modulus during maximal inspiration caused by IC muscle stretching
may have resulted from a decrease in passive muscle stiffness.

In contrast, the shear modulus during maximal expiration was 0.37
kPa in the SC and 0.17 kPa in the CC, and the shear modulus during the
resting breathing task was 0.36 kPa in the SC and 0.29 kPa in the CC,
showing a slight decrease and no significant difference before and after
stretching. As a factor for the lack of stretching effect, previous studies
have reported that the stretching effect is not observed when the muscles
are slacked (Hirata et al., 2017). During maximal expiration, the IC
muscles that were stretched during maximal inspiration were consid-
ered to be slacked. The resting breathing task also includes values during
resting inspiration and expiration. Resting inspiration results in only a
2% increase in muscle length during expiration and the stretched muscle
is slacked during expiration (Decramer et al., 1986). Therefore, the shear
modulus during the maximal expiration and resting breathing tasks may
not have shown a stretching effect because the IC muscle length was in
the slacked position.

4.3. Effect of IC muscle stretching on thoracic mobility

In this study, thoracic mobility was assessed using chest wall
expansion, which showed an increasing trend, with an increase of 0.12
cm after stretching, but this was not significantly different compared
with that at pre-intervention. This result differed from a previous study

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Fig. 3. Changes in intercostal muscle shear modulus before (Pre) and after
( Post) stretching (SC) and control (CC) conditions during maximal inspiration
(A) and expiration (B) and a resting breathing task (C). The values represent
means ± standard deviations (SD). *Significant difference between Pre and
Post (P < 0.05).
that reported a significant increase in chest wall expansion after chest mobilization. In previous studies (Leelarungrayub et al., 2009; Rehman et al., 2020), the manual intervention involving the entire thorax, including trunk rotation and extension, was performed for 10 min, and stretching of the sternocleidomastoid and trapezius muscles and other respiratory support muscles, in addition to the IC muscles, was performed for 60 min a day, for a total of 5 days, which is a higher frequency and longer duration of intervention than that of the present study. These results indicate that the localized and brief IC muscle stretching used in this study may not affect thoracic mobility.

4.4. Study limitations

There are several limitations to this study. The first is that muscle shear modulus measurement using ultrasound imaging is affected by superficial tissues (Yoshitake et al., 2016). The external oblique abdominis and serratus anterior (SA) muscles are in the shallow portion of the sixth IC muscle measured in this study, and its superficial layer contains subcutaneous fat tissue and skin. The influence of superficial tissue on IC muscle stiffness cannot be completely removed; therefore, the measurement was performed by teaching the participant to avoid forceful exhalation to minimize the influence of muscle activity of the external abdominal oblique muscles, which are superficial to the intercostal muscles, on the shear modulus measurement. In addition, the intercostal muscles are composed of overlapping internal and external intercostal muscles with opposing myofiber running directions and activity characteristics (Wilson et al., 2001), making it difficult to delineate them separately in humans in vivo. Therefore, it is necessary to consider that the values within the region of interest include the influence of both intercostal muscles. The second is that measurement of the IC muscles was only partly positioned. It is known that IC muscles differ in function, and their length changes with respiration, between ventral and dorsal or cranial and caudal muscles (Wilson et al., 2001). Hence, it is possible that the stretching effect on the sixth IC muscle measured in this study may not be common to all other IC muscles. Fourth, it is not possible to completely separate whether the shear modulus during inspiration reflects a passive component or muscle activity. The ventral sixth intercostal muscle measured in this study is known to elongate with inspiration (Wilson et al., 2001). In contrast, muscle activity is also known to occur (Chino et al., 2018). Therefore, the shear modulus during inspiration may include both elements. Lastly, crosstalk from other accessory respiratory muscles may have occurred in the IC muscle EMG measured in this study. In the sixth IC space of the ventral thoracic region, which is the measurement position in this study, the external oblique or SA muscle is present on the surface of the IC muscles. The external abdominal oblique muscles are accessory respiratory muscles during effort expiration (Ninane et al., 1988) and are thought to have little effect on the IC muscle EMG during inspiration. However, it has been shown that the muscular activity of the SA muscle is present at about 60% of maximal inspiration (Reid et al., 1976), and it is possible that the SA muscle activity affected IC muscle activity during maximal inspiration.

4.5. Prospects

Future prospects include, first, studies on different participant groups. In this study, the participants were healthy young men only. It is known that there are sex differences in the size of the rib cage at thoracic extension (Mendes et al., 2020; Vogiatzis et al., 2005) and thoracic shape (García-Martínez et al., 2019). Furthermore, no consistent results have been presented on the effects of sex (Chino and Takahashi, 2018) or menstrual cycle (Miyamoto et al., 2018) on the shear modulus. For this reason, this study was limited to male participants. In addition, healthy young participants were included because reduced thoracic mobility is influenced by disease and aging (Moll and Wright, 1972; Rehman et al., 2020; Romberg et al., 2020), and skeletal muscle stiffness varies with age (Hirata et al., 2020; Kelly et al., 1993). Therefore, the results may differ in women, patients, and the elderly.

The second prospect is to measure respiratory function before and after stretching. This study did not measure respiratory function, and the detailed respiratory function of the participants and the effects of intercostal muscle stretching on respiratory function are unknown. Chest mobilization, including intercostal muscle stretching, has been reported to affect respiratory function, and respiratory function, such as lung capacity, is an indicator of the effectiveness of chest mobilization training (Leelarungrayub et al., 2009; Mohan et al., 2012; Rehman et al., 2020). Therefore, it is necessary to evaluate the respiratory function and verify the effectiveness of chest mobilization in the future.

5. Conclusion

Five minutes of localized IC muscle stretching reduced the muscle shear modulus during maximal inspiration, but resting breathing alone in the sitting position did not show intervention effects. In contrast, thoracic mobility did not change significantly in both conditions. Furthermore, IC muscle shear modulus measurements during maximal inspiration showed good reproducibility. Thus, the results of this study suggest that IC muscle stretching decreases IC muscle stiffness and improves muscle flexibility, and the IC muscle shear modulus may be a new measure of the effectiveness of chest mobilization.

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CRediT authorship contribution statement

Yu Yokoyama: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Project administration. Taiki Kodesho: Methodology, Writing – original draft, Writing – review & editing, Visualization. Takuya Kato: Methodology, Visualization. Gakuto Nakao: Methodology, Visualization. Yuhei Saito: Methodology, Visualization. Keigo Taniguchi: Methodology, Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

Data will be made available on request.

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References

Ando, R., Ohya, T., Kusanagi, K., Koizumi, J., Ohnuma, H., Katayama, K., Suzuki, Y., 2020. Effect of inspiratory resistive training on diaphragm shear modulus and accessory inspiratory muscle activation. Appl. Physiol. Nutr. Metabol. 45, 851–856. https://doi.org/10.1139/apnm-2019-0096.
Chino, K., Ohya, T., Katayama, K., Suzuki, Y., 2018. Diaphragmatic shear modulus at various submaximal inspiratory mouth pressure levels. Respir. Physiol. Neurobiol. 252, 253–267. https://doi.org/10.1016/j.resp.2018.03.009.
Chino, K., Takahashi, H., 2018. Association of gastrocnemius muscle stiffness with passive ankle joint stiffness and sex-related difference in the joint stiffness. J. Appl. Biomech. 34, 169–174. https://doi.org/10.1123/jab.2017-0121.
De Troyer, A., Kirkwood, P.A., Wilson, T.A., 2005. Respiratory action of the intercostal muscles. Physiol. Rev. 85, 717–756. https://doi.org/10.1152/physrev.00007.2004.
