Ultrasound elastography–based assessment of the elasticity of the supraspinatus muscle and tendon during muscle contraction

Takayuki Muraki, PhD, PT\^a,\* a, Hiroaki Ishikawa, MS, PT\^a, Shuhei Morise, MS, PT\^a, Nobuyuki Yamamoto, MD, PhD\^b, Hirotaka Sano, MD, PhD\^b, Eiji Itoi, MD, PhD\^b, Shin-ichi Izumi, MD, PhD\^a

\^aDepartment of Physical Medicine and Rehabilitation, Tohoku University Graduate School of Medicine, Sendai, Japan
\^bDepartment of Orthopedic Surgery, Tohoku University School of Medicine, Sendai, Japan

**Background:** Although elasticity of the supraspinatus muscle and tendon is a useful parameter to represent the conditions of the supraspinatus muscle and tendon, assessment of the elasticity in clinical settings has not been established. The purpose of this study was to determine the elasticity of the supraspinatus muscle belly and tendon under different muscle contraction conditions using ultrasound real-time tissue elastography (RTE).

**Methods:** Twenty-three healthy individuals participated in this study. Ultrasound RTE was used for elasticity measurements of the muscle belly and tendon of the supraspinatus muscle. The elasticity was defined as the ratio of strain in the tissues to that in an acoustic coupler (reference). A greater ratio indicated that the tissue was softer. Measurements were performed with study subjects in the lateral decubitus position at 10° of shoulder abduction under conditions of (1) no contraction, (2) isometric contraction without a weight, and (3) isometric contraction with a 1-kg weight.

**Results:** The intraclass correlation coefficient (ICC\textsubscript{1,3}) of 3 measurements under each condition ranged from 0.931 to 0.998, showing high intraobserver reliability. Strain ratios for both the supraspinatus muscle belly and tendon significantly decreased with increases in muscle contraction (\(P < .001\)).

**Conclusions:** Ultrasound RTE with the acoustic coupler has the potential to noninvasively detect changes in the elasticity of the supraspinatus muscle belly and tendon that accompany varying levels of muscle contraction in clinical practice.

**Level of evidence:** Basic Science Study, Biomechanics, Imaging.

© 2015 Journal of Shoulder and Elbow Surgery Board of Trustees.

**Keywords:** Rotator cuff; ultrasound elastography; supraspinatus muscle; elasticity; shoulder; muscle contraction; strain

The elasticity of human tissue is a parameter that indicates tissue quality or condition. In cadaveric shoulders or animal models, the elasticity of the supraspinatus tendon has been investigated under normal and pathologic conditions. Although elasticity could be an important parameter in assessing the condition of the tendon and determining the...
Measurement of elasticity could also be useful in assessing the activity of skeletal muscle. Although electromyography remains the gold standard for the assessment of muscle activation, fine-needle electromyography to measure the activation of deep muscle layers has a disadvantage of being invasive. Instead, noninvasive measurements of elasticity using magnetic resonance imaging and ultrasound have the potential to detect muscle activity. A previous study showed that elasticity of muscle obtained from magnetic resonance elastography (MRE) linearly correlated with the activity of the muscle.\(^7\) Theoretically, MRE is capable of measuring elasticity of various tissues that conventional magnetic resonance imaging can depict. However, MRE is affected by the measurement environment, such as place, space, and subject positioning.

Ultrasound elastography appears to be more suitable for measuring muscle activity than MRE in clinical settings because it offers real-time measurement with patients in less restricted postures and joint positions. Ultrasound real-time tissue elastography (RTE) is one of the elastography techniques and uses light tissue compression with an ultrasound transducer. The compression is applied to generate strain in living tissues, and then, RTE shows mapping of strain distribution within the tissues in real time. Elasticity in a target tissue can be calculated by comparing the strain in the tissue with that in another tissue. Previous studies reported using RTE to measure the elasticity of the Achilles tendon\(^2,3\) and the biceps brachii muscle.\(^12,17\) However, similar measurements of elasticity for the supraspinatus muscle and tendon have not been established.

The purpose of this study was to measure the elasticity of the supraspinatus muscle belly and tendon using ultrasound real-time elastography and determine the changes in elasticity that occur with muscle contraction.

**Methods**

**Subjects**

Twenty-three healthy individuals (13 male and 10 female subjects) participated in this study. The mean age, height, and weight were 26 years (SD, 3 years), 168.1 cm (SD, 7.9 cm), and 61.5 kg (SD, 9.6 kg), respectively. The right arm was the dominant arm in all participants. The subjects had no history of orthopaedic disease or trauma around the shoulder joint, including rotator cuff tear, and no participant was involved in any physical training programs during the study. All participants provided written informed consent before RTE measurement.

**Measurement of elasticity**

To measure elasticity, all participants were kept in the left lateral decubitus position. The knee and hip on both sides were flexed so that participants felt comfortable in maintaining the required body position. The right shoulder was abducted 10° by placing a rolled towel under the forearm.

A diagnostic ultrasound system (HI VISION Avius; Hitachi Aloka Medical Japan, Tokyo, Japan) with a linear array transducer (14-/6-MHz EUP-L65; Hitachi Aloka Medical Japan) was used in this study. As reference material, an acoustic coupler (EZU-TECPL1; Hitachi Aloka Medical Japan) was placed onto the transducer with a plastic attachment (EZU-TEATC1; Hitachi Aloka Medical Japan) (Fig. 1). The elasticity of the acoustic coupler was 22.6 ± 2.2 kPa according to material testing performed by the manufacturer.

First, the shoulder was scanned to display longitudinal images of the supraspinatus muscle belly and tendon in B-mode imaging. The transducer was placed on the center of the supraspinous fossa for imaging of the supraspinatus muscle belly. For imaging of the supraspinatus tendon, the transducer was placed so that the anterior edge of the superior facet of the greater tuberosity appeared. To realize constant measurement, the locations of the transducer were marked with oil-based ink on the skin (Fig. 2). While keeping images of the supraspinatus muscle tissue, we turned on the RTE mode, and another B-mode image appeared next to the original B-mode image. After selection of the rectangular region of interest (ROI), an elastogram was superimposed on the second B-mode image by repeating manual compression with the transducer. With each compression, an elastogram appeared and was recorded. The mean strain in the ROI was monitored in a strain graph to adjust and maintain the force and frequency of the compression. The frequency was adjusted from 2 Hz to 4 Hz depending on each individual and condition so that the elastogram was sufficiently superimposed on the ROI. On the elastogram, areas of low and high strain were displayed in blue and red, respectively. Repetitive compression continued until more than 3 RTE images were obtained. The ultrasound system is capable of saving the RTE images automatically with a frame rate of 15 frames per second during measurement. Thus, we could review the images after the measurement and could choose the last 3 images in which the elastogram was completely superimposed.

After the RTE image was obtained, the elasticity was calculated using the ratio of the strain in the supraspinatus muscle tissue to that in the acoustic coupler, which was used as the reference. On the basis of the principle that tissues with low elasticity deform more than those with high elasticity,\(^13\) a higher strain ratio indicates lower elasticity. By using the acoustic coupler, the supraspinatus tendon and muscle tissues could be compared with the material in which a constant elasticity was obtained. This method allowed a more
accurate measurement of the strain ratio. Local ROIs for a measurement of strain were newly set on the acoustic coupler and supraspinatus muscle belly or tendon. For the supraspinatus muscle belly, a local ROI was set on approximately the middle two-thirds of the supraspinatus muscle belly to avoid effects of the boundary condition. For the supraspinatus tendon, strain was detected in the segment 1 cm proximal to the distal edge of the tendon insertion.

Measurement conditions

Measurements were performed under 3 conditions of muscle contraction: (1) no contraction (NC), (2) isometric contraction without a weight (IC 0 kg), and (3) isometric contraction with a 1-kg weight (IC 1 kg). The participants were instructed to keep their shoulders relaxed in the NC condition, whereas in the isometric contraction conditions, they were instructed to hold the abducted shoulder position after removing the towel. For the IC 1 kg condition, participants grasped a 1-kg dumbbell with the right hand. Before the measurement, the participants practiced the isometric contraction several times to eliminate the effect of exercise. The measurements were divided into 2 sessions, namely, measurement sessions for the muscle belly and tendon. The order of the measurement condition was randomized in each session.

Statistical analyses

The intraclass correlation coefficient (ICC1,3) was used to assess intraobserver reliability. The ICC1,3 was calculated for the 3 measurements in each condition. Two-way repeated-measures analysis of variance (ANOVA) was performed to test the effects of tissue structure (muscle belly or tendon) and muscle contraction condition on the strain ratio. A paired t test with Bonferroni correction was used as a post hoc test. In addition, 2-way repeated-measures ANOVA was conducted to test the effects of sex and muscle contraction condition on the strain ratio. A post hoc test for the sex difference of the strain ratio in each condition was performed with an unpaired t test. Furthermore, a Pearson product-moment correlation coefficient was used to examine the correlation between strain ratios of the supraspinatus muscle belly and tendon. All statistical analyses were performed with SPSS statistical software, version 15 (SPSS, Chicago, IL, USA). The statistical significance level was set at .05.

Results

The ICC1,3 values of the strain ratio under each condition of muscle contraction in the supraspinatus muscle belly and tendon are shown in Table 1. Overall, intraobserver reliability of the strain ratio measurement was excellent. For the supraspinatus tendon, the lowest and highest ICC1,3 values were observed with the IC 1 kg condition (0.923) and IC 0 kg condition (0.991), respectively. For the muscle belly, although the ICC1,3 was lowest with the NC condition (0.915), the value was still excellent.

Two-way repeated-measures ANOVA showed that the strain ratios of the supraspinatus tendon were significantly lower than those of the supraspinatus muscle belly (P < .001).
In addition, a significant difference was observed among the 3 muscle contraction conditions \((P < .001)\). There was significant interaction between the tissue structure and muscle contraction condition \((P < .001)\).

As shown in Figure 3, the strain ratio in the muscle belly significantly decreased from 4.521 (SD, 5.023) in the NC condition to 0.995 (SD, 1.072) in the IC 0 kg condition \((P = .002)\) and further decreased to 0.277 (SD, 0.233) in the IC 1 kg condition \((P = .003)\) according to the post hoc test. The typical changes in strain in the muscle belly are presented in Figure 4. As shown in Figure 5, in the supraspinatus tendon, the strain ratio significantly decreased from 0.138 (SD, 0.137) in the NC condition to 0.050 (SD, 0.796) in the IC 0 kg condition \((P < .001)\) and further decreased to 0.011 (SD, 0.012) in the IC 1 kg condition \((P = .020)\). The typical changes in strain in the muscle belly are presented in Figure 6.

For the sex difference, 2-way repeated-measures ANOVA showed that the strain ratio of the supraspinatus muscle belly in the male subjects was significantly higher than that in the female subjects \((P = .004)\). There was also significant interaction between the sexes \((P = .001)\). The results of the post hoc test showed that the strain ratio of the muscle belly in the male subjects was significantly higher than that in the female subjects in the NC condition \((P = .006)\). No significant differences in the strain ratio of the muscle belly were observed in the IC 0 kg and IC 1 kg conditions. For the supraspinatus tendon, there was no significant difference in the strain ratio between the sexes \((P = .289)\).

A low correlation of strain ratios between the supraspinatus tendon and muscle belly was observed throughout all measurements \((r = 0.241, P = .046)\).

### Table I

<table>
<thead>
<tr>
<th></th>
<th>NC</th>
<th>IC 0 kg</th>
<th>IC 1 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle belly</td>
<td>0.915</td>
<td>0.978</td>
<td>0.984</td>
</tr>
<tr>
<td>Tendon</td>
<td>0.953</td>
<td>0.991</td>
<td>0.923</td>
</tr>
</tbody>
</table>

**Figure 3**  
Histogram of strain ratio in supraspinatus muscle belly under each condition of contraction. The bars and error bars represent the mean strain ratio and standard deviation, respectively.

**Figure 4**  
Typical changes on ultrasound RTE images in supraspinatus muscle belly with increase in muscle contraction. (A) NC condition. (B) IC 1 kg condition. The right and left images are B-mode and RTE images, respectively. The yellow rectangles indicate local ROIs on the supraspinatus muscle belly and acoustic coupler. The color of the muscle belly changed from red to blue in almost all parts of the muscle, which meant that strain produced by compression with the transducer became lower in the muscle belly.

**Figure 5**  
Histogram of strain ratio in supraspinatus tendon under each contraction condition. The bars and error bars represent the mean strain ratio and standard deviation, respectively.

**Discussion**

The evaluation of elasticity in RTE is limited because the elasticity of a target tissue is calculated in comparison with other tissues whose elasticity is unclear and variable. However, this study showed that RTE could precisely detect...
Our finding regarding ultrasonography reported the Achilles tendon to have higher elasticity of the tendon was higher than that of the muscle belly. A previous study using ultrasound shear-wave elasticity of the tendon was higher than that of the muscle belly. This finding indicated that the measurement of the strain ratio in the tendon to some extent when the tendon could be used to noninvasively determine muscle activity when the measurement is performed in the muscle belly.

In addition, decreases in the strain ratio of the supraspinatus tendon with increases in muscle contraction were significant. It is known that the mechanical behavior of tendon tissue is nonlinear and is characterized by low elasticity in the region of the stress-strain relationship and high elasticity in the linear region. Lake et al. reported that the elastic moduli of the supraspinatus tendon in the linear region were approximately 10 times higher than those in the toe region. In our study, the strain ratio in the supraspinatus tendon decreased by less than one-tenth from the NC condition to the IC 1 kg condition. On the basis of these findings, we considered that the strain ratios in the NC and IC 1 kg conditions (representing muscle relaxation and contraction, respectively) corresponded to those in the toe and linear regions, respectively. Therefore, the measurement of the strain ratio using RTE might be useful not only to measure the elasticity in a certain condition but also to detect change in stress or strain of the supraspinatus tendon.

The changes in the strain ratio observed with the different types of muscle contraction showed different trends between the muscle belly and tendon because the interaction between tissue structure and muscle contraction condition was significant in this study. Structural differences between the tendon and muscle (ie, the difference between noncontractile and contractile tissues) most likely caused the difference. Nevertheless, this study showed a low correlation between the strain ratios of the muscle belly and tendon. This finding indicated that the measurement of the strain ratio in the supraspinatus muscle belly might also be able to estimate the strain ratio in the tendon to some extent when the tendon cannot be observed directly with ultrasonography (eg, in shoulder flexion or abduction positions). However, the current technique for RTE is required to be further refined so that the elasticity of the supraspinatus tendon can be estimated more precisely in various shoulder positions and muscle contraction conditions by measuring the strain ratio in the muscle belly with RTE.

This study had several limitations. First, in the measurement using RTE, manual compression was used to produce strain in the supraspinatus muscle and tendon. There was a concern that the reliability of this measurement might be limited. However, at a minimum, this study showed excellent intraobserver reliability (ICC1,3 of 0.915-0.991) for the measurement of the strain ratio. Yanagisawa et al. reported that RTE of the biceps brachii muscle using another reference material provided excellent reliability in the ICC1,3 of the strain ratio, which ranged from 0.939 to 0.971. These findings suggested that the measurement of the strain ratio for the supraspinatus muscle belly decreased with an increase in muscle contraction. Previous studies validated measurement of elasticity or stiffness for contractions and activities of skeletal muscles. Shinohara et al. showed that the Young moduli for the gastrocnemius and soleus muscles, measured by ultrasound shear-wave imaging, increased during plantar flexion of the ankle joint. Heers et al. reported that the wavelength indicating shear stiffness in the ankle plantar flexors measured by MRE increased with an increase in electromyographic activity. The measurement of strain ratio using RTE could be used to noninvasively determine muscle activity when the measurement is performed in the muscle belly.

Generally, tendons have a higher elastic modulus, which means that tendons are harder than the muscle belly. In this study, the strain ratio of the supraspinatus tendon was lower than that of the muscle belly. This finding indicated that the elasticity of the tendon was higher than that of the muscle belly. A previous study using ultrasound shear-wave elastography reported the Achilles tendon to have higher elasticity than the gastrocnemius muscle. Our finding regarding the difference in elasticity between the supraspinatus tendon and muscle belly was consistent with the finding in this previous study. Our study showed that RTE could quantitatively compare the elasticity of different structures by using the acoustic coupler.

This study also attempted to detect changes in the elasticity of the supraspinatus muscle belly and tendon among the different muscle contraction conditions. The strain ratio of the supraspinatus muscle belly decreased with an increase in muscle contraction. Previous studies validated measurement of elasticity or stiffness for contractions and activities of skeletal muscles. Shinohara et al. showed that the Young differences in strain ratios between tissues by using an acoustic coupler as a reference.

Figure 6 Typical changes on ultrasound RTE images in supraspinatus tendon with increase in muscle contraction. (A) NC condition. (B) IC 1 kg condition. The right and left images are B-mode and RTE images, respectively. The yellow circles indicate the local ROI on the supraspinatus tendon. The yellow rectangles indicate the local ROI on the acoustic coupler. The color of the tendon changed from blue and green in A to almost completely blue, which meant that strain produced by compression with the transducer became lower in the tendon.
supraspinatus tendon and muscle using RTE in our study was comparable with the measurement of different tissues in the previous study.\textsuperscript{17}

Second, the ROI in our study did not analyze all areas of each tendon and muscle belly and might not appropriately represent the state of the tissue. In this study, the anterior portion of the supraspinatus tendon was chosen because a previous study suggested that the anterior portion of the supraspinatus tendon seemed to perform its main functional role.\textsuperscript{7} However, other portions of this tendon should also be investigated in future studies. Because the supraspinatus muscle is a circumpennate muscle, the center of the supraspinous fossa might not represent the main part. Hence, we attempted to measure the area of the muscle belly as much as possible.

Third, our findings in this study were not compared with parameters of the reference standards such as histologic and electromyographic findings. However, because the subjects in this study were healthy and relatively young, it is assumed that the influences of swelling and degeneration in the supraspinatus tendon were small. Klauser et al\textsuperscript{10} reported excellent agreement between histologic findings and sonoelastographic findings. RTE findings of the supraspinatus tendon with various pathologic conditions need to be validated in a future study. For the supraspinatus muscle, although an increase in electromyographic activity of the supraspinatus muscle during shoulder abduction was shown in a previous study,\textsuperscript{5} it was not clear how the measurement of the strain ratio reflects muscle activity.

Fourth, the elastic moduli of the supraspinatus muscle belly and tendon might not be entirely the same as the actual elastic moduli. Compression force from the transducer might be attenuated somewhat because of the compression from the outside of the skin. In addition, the relationship between elasticity and strain produced by compression tends to be nonlinear when the tissue is deformed to a larger extent.\textsuperscript{18} Although light compression was applied in this study, the supraspinatus muscle belly and tendon might have been deformed too much, particularly in the NC condition. In further studies, the RTE findings of the supraspinatus muscle and tendon need to be compared with those obtained from another technique without the use of compression, which has been proved to adequately show the stress-strain state of a tissue, such as acoustoelasticity measurement.\textsuperscript{4}

Conclusions

RTE has a potential to detect changes in the elasticity of the supraspinatus muscle and tendon under various muscle contraction conditions. This technique might be useful in the noninvasive assessment of supraspinatus tendon stress/strain and supraspinatus muscle activity in clinical practice.

Acknowledgment

The authors thank Hitachi Aloka Medical Japan (Tokyo, Japan), which provided the acoustic coupler (EZU-TECPL1) and the attachment (EZU-TEATC1).

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References


