

Mechanical characteristic of supraspinatus muscle changes independent of its size and intramuscular fat in patient with rotator cuff repair

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Abstract (197/200 words)

Purpose: This study aimed i) to investigate the mechanical, morphological, and compositional characteristics of the supraspinatus muscle after rotator cuff repair by using ultrasound shear wave elastography (SWE) and B-mode imaging, and ii) to determine whether the morphological or compositional characteristics are associated with the mechanical characteristic of the supraspinatus during contraction.

Methods: Using SWE and B-mode imaging, active and passive shear moduli, muscle thickness, and echo intensity of the supraspinatus were measured from the repaired and contralateral control shoulders of 22 patients with rotator cuff repair. The shear modulus, muscle thickness, and echo intensity were compared between the repaired and control shoulders. The association between the active shear modulus and the other variables was determined.

Results: While the active and passive shear moduli were lower in the repaired shoulder compared to the control, the muscle thickness and echo intensity did not vary between them. Interestingly, the passive shear modulus was positively correlated with the active shear modulus only in the control shoulder.

Conclusion: The mechanical characteristic of supraspinatus remains impaired, even without degenerative changes in the morphological and compositional characteristics after rotator cuff repair. Furthermore, the association between contractile and elastic characteristics in the supraspinatus was deteriorated in control shoulder.

Introduction

Rotator cuff tear is a common shoulder condition, which causes disability and pain in the shoulder joint. The prevalence of rotator cuff tear increases with aging (Yamaguchi et al. , 2001) and was found in more than 40% of the population above 60 years (Milgrom et al. , 1995, Yamamoto et al. , 2010). The supraspinatus muscle, which is part of the rotator cuff, is most susceptible to tendon tear (Mehta et al. , 2003, Wolff et al. , 2006). The treatment of rotator cuff tear mainly involves surgical repair of the affected tendon (Hurley et al. , 2019); however, healing rate after rotator cuff repair is a significant problem in clinical settings (e.g., the retear rate ranges from 20% to 90% (Galatz et al. , 2004, Iannotti et al. , 2013, Kluger et al. , 2011)), although the number of rotator cuff repairs is on the increase from the 1990s (Colvin et al. , 2012, Ensor et al. , 2013). Repair failure and poor clinical outcome are not only determined by the affected tendon itself (Killian et al. , 2015), but also the contractile element attached to the tendon i.e., the muscle (Laron et al. , 2012). As such, assessment of the supraspinatus muscle characteristics itself is crucial for management and rehabilitation after rotator cuff repair.

Magnetic resonance imaging (MRI) is used for assessing the muscles after rotator cuff repair (Khoury et al. , 2008). More recently, ultrasound B-mode imaging is being employed for assessing the rotator cuff, with certain advantages such as user-friendliness, low cost, lower time consumption, and sufficient utility (Bailey et al. , 2015). Prior research using these modalities have found atrophy and fatty infiltration after rotator cuff repair, which influenced the clinical outcome (Deniz et al. , 2014, Gladstone

et al. , 2007, Kim et al. , 2018). Although these conventional technologies can comprehend these morphological (i.e., muscle size) and compositional (i.e., intramuscular fat) features of the supraspinatus muscle, they cannot identify its mechanical characteristic that may be a determinant of the muscle function.

To date, ultrasound shear wave elastography (SWE) is a promising technology capable of quantifying individual muscle mechanics (Hug et al. , 2015). Based upon certain assumptions regarding the shear wave velocity and muscle mechanical characteristic, the individual muscle stiffness and force can be indirectly estimated in several conditions such as rest (Lacourpaille et al. , 2012), passive lengthening (Eby et al. , 2013), and isometric contraction (Bouillard et al. , 2011). However, few studies have used SWE for observation of the supraspinatus muscle mechanics after rotator cuff repair.

A previous study used SWE for prospectively investigating the shear modulus of supraspinatus muscle after surgical repair and has provided useful information for understanding the healing process of the mechanical properties (Itoigawa et al. , 2020). However, they examined the muscle shear modulus only while the muscle did not activate (i.e., only in passive condition). Although recent prospective study investigated the shear modulus of the supraspinatus muscle during contraction in patients with rotator cuff repair (Sakaki et al. , 2022), vice versa, this study did not measure the shear modulus in passive condition. Additionally, the muscle size and intramuscular fat are still crucial indices to predict muscle function. But these previous studies did not consider them. Therefore, overarching investigation in

terms of the shear modulus, muscle size, and intramuscular fat is needed to understand the effect of rotator cuff repair on the supraspinatus muscle function.

The purpose of this study was to investigate the mechanical, morphological, and compositional characteristics of the supraspinatus muscle after rotator cuff repair by using shear wave elastography and ultrasound B-mode imaging. To this end, we compared the shear modulus, muscle thickness, and echo intensity of the supraspinatus between the repaired and contralateral control shoulders. Furthermore, we determined which characteristics are associated with the mechanical characteristics of supraspinatus muscle during contraction. We hypothesized that the shear moduli in passive and active conditions decrease, the muscle thickness is thinner, and the echo intensity is higher in the repaired shoulder compared to that in the control. Additionally, we hypothesized that the passive shear modulus, muscle thickness, and echo intensity are associated with the active shear modulus only in control shoulder but not repaired shoulder.

Methods

1. Participants

Twenty-nine patients after rotator cuff repair were recruited from an orthopedic hospital. All the rotator cuff repairs were performed using the McLaughlin procedure with an open approach (Nobuhara, 2003). We defined the shoulder in which surgical repair was performed and the contralateral healthy shoulder

as the repaired and control shoulder, respectively. The inclusion criteria for the repaired shoulder were as follows: (i) eight weeks post-operative or more but less than a year, (ii) tear involving the supraspinatus tendon, (iii) no large tear (<3 cm) prior to operation, (iv) no retear of the repaired tendon, and (v) more than 90° abduction of the repaired shoulder. The inclusion criteria for the control shoulder were as follows: (i) no pain and (ii) no history of any orthopedic disease and surgical operation (Liem et al. , 2014). In the criteria, the relatively long postoperative period and mixture of tear size were explicitly prepared for a subgroup analysis (see Online Resource). We did not priorly recruit patients with rheumatoid arthritis, cervical spondylosis, neuropathy, cardiovascular diseases, and phycological disorders. Based on these criteria, we excluded seven patients, consequently 22 patients (age: 66 ± 10 years; height: 161 ± 10 cm; body mass: 65 ± 13 kg; 12 male) were used in this study. The patients' characteristics and Western Ontario rotator cuff index (WORC), that is an disease-specific questionnaire (Kawabata et al. , 2013), are listed in Table 1. The study protocol was approved by the ethics committee of Kyoto University Graduate School and the Faculty of Medicine (R1277) and the institutional review board in Nobuhara Hospital and Institute of Biomechanics (no. 188). We provided the aim and procedure of the study to all the participants and obtained written informed consent.

2. Protocol

This study was designed as a cross-sectional case-control study. The supraspinatus muscle of repaired and control shoulder was assessed by ultrasound elastography and B-mode imaging. Elastography images of the supraspinatus muscle were obtained in following two conditions: one was passive condition in which the participants' shoulder joint was passively abducted at 30° by a physiotherapist (S.N.) (Fig.1a), and another was active condition where the participants actively abducted their shoulder at 30° while sitting on a stool and maintaining a posture with full elbow extension, neutral wrist position, and their thumb pointing upward (Fig.1b). We set these conditions for elastographic assessment based on a previous study (Baumer et al. , 2018). The shear moduli during these passive and active condition (i.e., passive and active shear moduli) were used for the muscle mechanical characteristics. The B-mode image of the supraspinatus muscle was captured in the natural shoulder configuration, i.e., with a shoulder abduction-adduction angle of 0°, approximately (Fig.1c). The shoulder joint angle was secured using a goniometer. The muscle thickness and echo intensity obtained from the B-mode image were used for the muscle morphological and compositional characteristics. We instructed the participants to remain relaxed as much as possible during the measurements of passive condition in elastography and B-mode imaging. Two experienced investigators performed the elastography (J.U.) and B-mode assessments (M.Y.), respectively.

3. Shear wave elastography

An ultrasound scanner (Aixplorer v12.2, Supersonic Imagine, Aix-en-Provence, France) coupled with a linear transducer (2–10 MHz, SuperLiner SL10-2) was used in the SWE mode (custom musculoskeletal preset, penetration mode, frequency: 1.7 Hz, smoothing level: five, persistence off, opacity: 100%, gain; 90%) to measure the shear modulus of the supraspinatus muscle. SWE generates shear waves into individual tissue (s) by applying a focused push pulse to cause the acoustic radiation force and then calculates the propagation velocity of the shear wave using an ultrafast imaging technique. Further, it provides a two-dimensional color map of the shear wave velocity on the B-mode image of the target tissue (Lacourpaille, Hug, 2012). The muscle shear modulus can be an index of muscle stiffness (Bernabei et al. , 2020) and force (Ates et al. , 2015, Bouillard, Nordez, 2011).

Image acquisition was performed with a probe positioned by the investigator perpendicular to the skin on the middle of the scapular spine in the mediolateral direction and between the clavicle and the scapular spine in the antero-posterior direction; the transverse image of the supraspinatus muscle belly was identified (Itoigawa et al. , 2015). The probe was then rotated parallel to the fascicle of the supraspinatus muscle (Fig.1d). The region of interest (1.0 cm × 1.0 cm) was set at approximately 1.5 – 2.0 cm below the skin and the posterior deep region of the supraspinatus was measured owing to mechanical and functional significance (Itoigawa et al. , 2018). Three consecutive images of the supraspinatus muscle were obtained in both passive (Fig.1a) and active (Fig.1b) conditions. We carefully captured these images during a relatively steady state of the color map.

4. Ultrasound B-mode imaging

An ultrasonography system (Noblus, Hitachi Aloka Medical Systems, Tokyo, Japan) with a linear transducer (L64, 5–18 MHz) was used to capture the B-mode images of the supraspinatus muscle. The sonographic parameters were set as a gain of 25 dB, dynamic range of 70, depth of 4.0 cm, and the shallowest focus. These settings were maintained constant for all the participants. The B-mode image of the supraspinatus was consecutively acquired twice at the same site as well as the SWE measurement while we recognized the fossa, aponeurosis, and muscle fascicle of the supraspinatus on the B-mode image (Fig.1c).

5. Image processing

The SWE images were processed using Aixplorer software. The shear modulus (G) is estimated from the shear wave velocity (V_s) and muscle density (ρ) as following equation: $G = \rho V_s^2$, where the muscle density is assumed to be 1,000kg/m³ (Nordez et al. , 2008). The Q-box of 10 mm diameter was set in the center of the region of interest. The shear modulus within the Q-box was calculated in each image. As this Q-box included tissues other than the supraspinatus muscle for two participants, a modified Q-box of 9 mm diameter was used in these cases. The mean values of the three images in each passive and active conditions were used for statistics. Additionally, the amount of change was calculated by subtracting the passive shear modulus from the active one. We excluded three images because of certain

noise and blanks on the color maps, and consequently utilized 19 control shoulders for the data of passive shear modulus and change in shear modulus.

The B-mode images were exported from sonographic system to a personal computer as tagged image format files and processed using ImageJ software (National Institutes of Health, Bethesda, Maryland, USA). The thickness and echo intensity of the supraspinatus muscle were derived from the B-mode images. The muscle thickness was calculated as the distance between the muscle aponeurosis and supraspinatus fossa in middle of the image (Juul-Kristensen et al. , 2000). The echo intensity was determined as the average of the grayscale value within the region of interest in each B-mode image, represented from 0 (white) – 255 (black), which fairly reflects the intramuscular fat (Watanabe et al. , 2018, Young et al. , 2015) and is associated with the fatty infiltration (Bailey, Beattie, 2015). The region of interest was created using the freehand selection tool in ImageJ software and included as much of the muscle as possible, while avoiding the fascicle and bone (Nielsen et al. , 2006). Moreover, the echo intensity of subcutaneous fat was measured, and the echo intensity ratio of the supraspinatus muscle to subcutaneous fat was computed to correct the effect of probe orientation on the echo intensity (Wu et al. , 2010). The intraobserver reliabilities of SWE and B-mode imaging are presented in Table 2 as the intraclass correlation coefficients.

6. Statistics

All the statistical analyses were performed using Matlab R2019b (MathWorks, Natick, MA, USA). The normality of the data was assessed using the Shapiro-Wilk test. The echo intensity ratio in both shoulders did not show normal distributions. Consequently, parametric and nonparametric tests were used depending on each data distribution.

For comparing the mechanical, morphological, and compositional properties between the repaired and control shoulders, the paired *t*-test was used for the passive and active shear moduli, its amount of change, muscle thickness, and echo intensity. Wilcoxon signed rank test was used for the echo intensity ratio. In addition, the effect size (ES *d* or ES *r*) was determined for all the comparisons.

In the repaired and control shoulders, Pearson's correlation coefficient (*r*) was applied to determine what variables associate with the active shear modulus, among the passive force, muscle thickness, and echo intensity.

Additionally, we conducted subgroup analysis to investigate whether the tear size (small vs. medium) and post-operative day (< 3 months vs. ≥3 months) affected the variables of the supraspinatus muscle (see Online Resource, which provides the subgroup analysis details). An alpha level of 0.05 was used for all the statistical tests.

Results

The shear modulus, muscle thickness, and echo intensity of the supraspinatus muscle in the repaired and control shoulders are depicted in Fig.2. Comparison between the repaired and control shoulders indicated that the passive ($P = 0.022$, ES $d = 0.82$) and active shear moduli ($P < 0.001$, ES $d = 0.87$) and the amount of change in the shear modulus ($P = 0.018$, ES $d = 0.56$) were significantly lower in the repaired shoulder than in the control one. Nonetheless, there were no differences between the repaired and control shoulders with respect to the muscle thickness ($P = 0.207$, ES $d = 0.40$), echo intensity ($P = 0.190$, ES $d = 0.21$), and echo intensity ratio ($P = 0.445$, ES $r = 0.16$).

The correlation coefficients between the active shear modulus and muscle thickness and echo intensity are depicted in Fig.3. Although no variables influenced the active shear modulus in the repaired shoulder, not muscle thickness ($P = 0.220$, $r = 0.29$) and echo intensity ($P = 0.315$, $r = 0.24$) but only the passive shear modulus ($P = 0.021$, $r = 0.51$) was significantly positively correlated with the active shear modulus in the control shoulder.

The subgroup analysis results are listed in the appendices (Online Resource). They present the comparisons of shear moduli, muscle thickness, and echo intensity between the small- ($n = 13$) and medium- ($n = 9$) tear groups, and between the < 3 months- ($n = 9$) and ≥ 3 months- ($n = 13$) groups, respectively. Briefly, there were no differences for all variables in both subgroup comparisons regarding tear size and post-operative day.

Discussion

This study aimed to investigate the mechanical, morphological, and compositional characteristics of the supraspinatus muscle after rotator cuff repair. Moreover, which characteristics are associated with the mechanical characteristics of supraspinatus muscle during contraction was determined. This study discovered that the mechanical characteristic of the supraspinatus muscle remains impaired, even without degenerative changes in the morphological and compositional characteristics after rotator cuff repair. Furthermore, the association between contractile and elastic characteristics was preserved only in the control shoulder. To the best of our knowledge, this is the first study to comprehensively determine the supraspinatus muscle characteristics after rotator cuff repair using SWE and B-mode imaging.

We hypothesized that the shear moduli of the supraspinatus muscle during passive and active conditions were decreased in the repaired shoulder compared to those in the control shoulder; the obtained results supported our hypothesis. In the repaired shoulder, the decreased shear modulus is probably attributed to the healing process, after rotator cuff repair. A previous study utilizing an animal model for rotator cuff repair had reported that while the musculotendinous stiffness of the supraspinatus increased with the post-operative duration, the repaired supraspinatus stiffness still remained lesser than the healthy one (Gimbel et al. , 2007). An experimental study had histologically examined the muscle structure in sheep after rotator cuff repair and had demonstrated that atrophy of the muscle fiber and myofibril

developed acutely after tear and irreversible change in the muscular microstructure occurred, despite recovery of the muscle volume (Gerber et al. , 2004). In addition, a prospective cohort study monitored the supraspinatus stiffness in vivo from preoperation to six post-operative months using SWE and found U-shaped recovery, indicating that the stiffness decreased during first few months after surgery and then almost improved to that prior to operation, four months after surgery (Itoigawa, Wada, 2020). Based on these reports and our findings, the decrease in the passive shear modulus of the repaired shoulder suggests that the supraspinatus muscle stiffness did not improve completely in the repaired shoulder compared to that in the control one.

The active shear modulus of the repaired shoulder was lesser than that of the control. This result is consistent with previous studies indicating that the shear wave velocity of the supraspinatus muscle decreases in patients with rotator cuff tear during isometric shoulder abduction (Baumer, Dischler, 2018) and after its repair (Sakaki, Taniguchi, 2022). The decreases in both active and change in shear moduli of the repaired shoulder may be attributed to both neural and structural aspects. Regarding the neural aspect, motor command from the central nervous system to the supraspinatus muscle would change due to pain (Hodges and Tucker, 2011), although the muscle activity of the supraspinatus has not been measured after rotator cuff repair because electromyography with fine-wire electrodes after rotator cuff repair is invasive to record the muscle activity of the supraspinatus. Besides this, the results of previous studies on patients with rotator cuff tears are contradictory, whether they had reported a

266 decrease (Rathi et al. , 2018), increase (Kelly et al. , 2005), or no change (Hawkes et al. , 2015) in the
267 supraspinatus muscle activity after rotator cuff tear, may be due to unique individual motor command
268 features. Regarding the structural aspect, the supraspinatus muscle itself could be damaged as we
269 mentioned above. Therefore, these deteriorations of neural and structural aspects themselves and their
270 interaction would cause a decrease in the active shear modulus.

271 How the patients achieved the shoulder abduction task with a decline in the active shear modulus may
272 be related to a compensation by the shoulder synergist muscles. A recent study found that the
273 compensation strategy was different among patients after rotator cuff repair (Umehara et al. , 2023).
274 The compensation strategy is derived from the force-sharing among synergistic muscles (Herzog, 2000).
275 Sophisticated studies had emphasized the causal effect of the muscle force distribution on the
276 development of musculoskeletal disorders (Hug and Tucker, 2017), and have discovered unique force-
277 sharing strategies in patients with Achilles tendinopathy (Crouzier et al. , 2020) and hamstrings injury
278 (Avrillon et al. , 2020). For the rehabilitation of musculoskeletal disorders, modulation of the
279 compensation and force-sharing strategies are required for normal motor control and pain relief.

280 Our hypothesis for the association with active shear modulus was partly supported. The positive
281 correlation of the passive shear modulus with the active one in the control shoulder, but not in the
282 repaired shoulder can reflect the consequences of mechanical adaptation. It is possible that the more the
283 participants activated the supraspinatus during shoulder movements, the more the supraspinatus muscle

284 adapted to repetitive stimulus, resulting in mechanical changes. A previous study had indicated changes
285 in the soft tissue due to repetitive stimulus, wherein college baseball players had stiffer posterior
286 shoulder capsules (Takenaga et al. , 2015). As the risk of rotator cuff tendinopathy possibly increases
287 with repetitive stimulus to the supraspinatus musculotendon (Soslowky et al. , 2000), a prospective
288 cohort study that noninvasively monitors the supraspinatus mechanics using SWE is warranted, and
289 maybe useful for the preventing rotator cuff tear.

290 There were no differences between the repaired and control shoulders with respect to the muscle
291 thickness, echo intensity, and echo intensity ratio. These results were inconsistent with previous findings.
292 It was reported that the muscle atrophy and fatty infiltration persist even after rotator cuff repair (Deniz,
293 Kose, 2014, Gladstone, Bishop, 2007). There are some reasons to explain this discrepancy. First, since
294 the tear size of our patients were limited in small and medium tears, the extent of atrophy and fatty
295 infiltration was not naturally so large. Previous study reported that the patients with partial-thickness
296 tear did not demonstrate the atrophy of SSP muscle (Maman et al. , 2009). Second, the ultrasound
297 assessment could not detect the muscle changes because the accuracy of US is slightly inferior to that
298 of MRI (Strobel et al. , 2005, Wall et al. , 2012).

299 For the subgroup analysis, there were no differences in shear modulus, muscle thickness, and echo
300 intensity, and its ratio between < 3 months- and ≥ 3 months-groups (Online Resource). This result is
301 inconsistent with previous studies in terms of mechanical characteristics. Previous studies reported that

the mechanical characteristic changes along with the time course, and that there was a difference between the earlier and later stages after rotator cuff repair (Gimbel, Van Kleunen, 2007, Gimbel et al. , 2004, Itoigawa, Wada, 2020). This discrepancy may have been caused by the comparison method. While these previous studies used an intra-subject comparison between early and late stages, this study used an inter-subject comparison which did not take a bias in the baseline data among participants into account. Further study is needed to prospectively investigate the mechanical characteristics of supraspinatus after rotator cuff repair.

This study includes certain limitations. First, the arm weight may not be equal between the repaired and control shoulders and may vary among the participants. This factor likely causes a bias in muscle activity levels. Because the shear modulus increases with the exerted torque and muscle activity during isometric contraction (Bouillard, Nordez, 2011), generally, it is assumed that the heavier the arm weight, the higher the shear modulus. However, we performed an intraparticipant comparison to confirm that the influence of the arm weight on our results can be considered small. Next, our subgroup analysis could not find intergroup differences in the supraspinatus muscle variables. These results may be attributed to the small sample size and its heterogenicity. Further study using a larger sample size is needed to investigate the effect of the tear size and post-operative day on the supraspinatus muscle force. Finally, we defined the contralateral control shoulder as the control shoulder of the same person and did not adopt a control group whose characteristics matched with the rotator cuff repair group. However,

our findings are practical for rehabilitation because the therapist sets a goal for improving the impaired shoulder to the level of the contralateral control shoulder.

Conclusions

This study investigated the mechanical, morphological, and compositional characteristics of the supraspinatus muscle in patients with rotator cuff repair using SWE and B-mode imaging. Although there were no differences in the thickness and echo intensity of the supraspinatus muscle, the passive and active shear moduli and its amount of change were decreased in the repaired shoulder compared to the control one. Moreover, the association between contractile and elastic characteristics was preserved only in the control shoulder. These results indicated that the mechanical characteristic of the supraspinatus muscle remains impaired, even without degenerative changes in the morphological and compositional characteristics after rotator cuff repair.

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460

Table 1. Physical characteristics of the repaired and control shoulders

	Repaired shoulder	Control shoulder	<i>P</i> -value
Dominance side (%)	54.5	45.5	—
Shoulder range of motion (°)			
Flexion	140.0±16.6	157.0±16.2	< 0.001
Abduction	141.4±21.4	164.3±9.7	< 0.001
External rotation	46.1±19.8	64.3±14.0	< 0.001
WORC (points)	975.0±507.1	—	—
Pain (mm)	25.0±24.3	—	—
Postoperative day (days)	114.2±56.0	—	—

Data is shown as mean and standard deviation. The shoulder flexion and abduction were compared using Wilcoxon signed-rank test. The shoulder external rotation was compared using paired t-test. The shoulder pain was evaluated on a visual analog scale using the first item in the WORC physical symptom (i.e., extent of sharp pain experienced in operative shoulder). WORC: Western Ontario Rotator Cuff Index.

Table 2. Reliability of ultrasound shear wave elastography and B-mode imaging

	ICC (95% CI)	
	Repaired shoulder	Control shoulder
Passive shear modulus	0.94 (0.89–0.97)	0.96 (0.92–0.98)
Active shear modulus	0.95 (0.91–0.98)	0.97 (0.94–0.99)
Muscle thickness	0.99 (0.98–0.99)	0.99 (0.98–0.99)
SSP echo intensity	0.99 (0.98–0.99)	0.99 (0.99–0.99)
SF echo intensity	0.96 (0.91–0.98)	0.98 (0.97–0.99)

The intraobserver reliability of shear wave elastography and B-mode imaging are described as ICC_{1,3} and ICC_{1,2}, respectively. ICC: intraclass correlation coefficient; CI: confidence interval; SSP: supraspinatus muscle; SF: subcutaneous fat.

Figure Captions

Fig.1 Ultrasound shear wave elastography and B-mode images of the supraspinatus muscle. Ultrasound images and measurements for the (a) passive shear modulus, (b) active shear modulus, and (c) muscle thickness, echo intensity, and echo intensity ratio in the repaired and control shoulders. (d) Illustration of the supraspinatus and scapula in the right shoulder. Top-view of the ultrasound measurement site (left upper panel), measurement planes denoted by black rectangles with marks of 1 (cross-sectional plane) and 2 (longitudinal plane) (right upper panel), and cross-sectional view for the B-mode (left bottom panel) and the longitudinal view for elastography (right bottom panel). In the left upper panel, the black dots and gray cross represent the positions of the skin markers and the measurement site, respectively. AA: acromial angle; TS: trigonum spinae; MS: middle of the scapular spine; MC: middle of the clavícula; ST: subcutaneous fat; UT: upper trapezius muscle; SSP: supraspinatus muscle.

Fig.2 Scatter plots for comparison of the mechanical, morphological, and compositional properties of the supraspinatus muscle between the repaired and control shoulders: The dots indicate each data in the repaired (orange) and control (blue) shoulders, respectively. The mean value and standard deviation are represented by the gray bar with error bar. The asterisk denotes statistical significance (n.s.: not significant). (a) Passive shear modulus, (b) Active shear modulus, (c) Change in shear modulus, (d) Muscle thickness, (e) Echo intensity, and (f) Echo intensity ratio.

Fig.3 Correlation of the active shear modulus and the passive shear modulus, the muscle thickness and echo intensity between repaired and control shoulders: The orange and blue dots represent individual data of repaired and control shoulders, respectively. In the repaired shoulder (upper panels), there were no correlations between the active shear modulus and the passive shear modulus (a: $r = 0.14$, $p = 0.548$), the muscle thickness (b: $r = -0.10$, $p = 0.652$), and echo intensity (c: $r = 0.14$, $p = 0.556$). In the control shoulder (lower panels), while significant correlation between the active and passive shear moduli was found (d: $r = 0.51$, $p = 0.021$), there were no correlations between the active shear modulus and the muscle thickness (e: $r = 0.29$, $p = 0.220$) and the echo intensity (f: $r = 0.24$, $p = 0.315$).

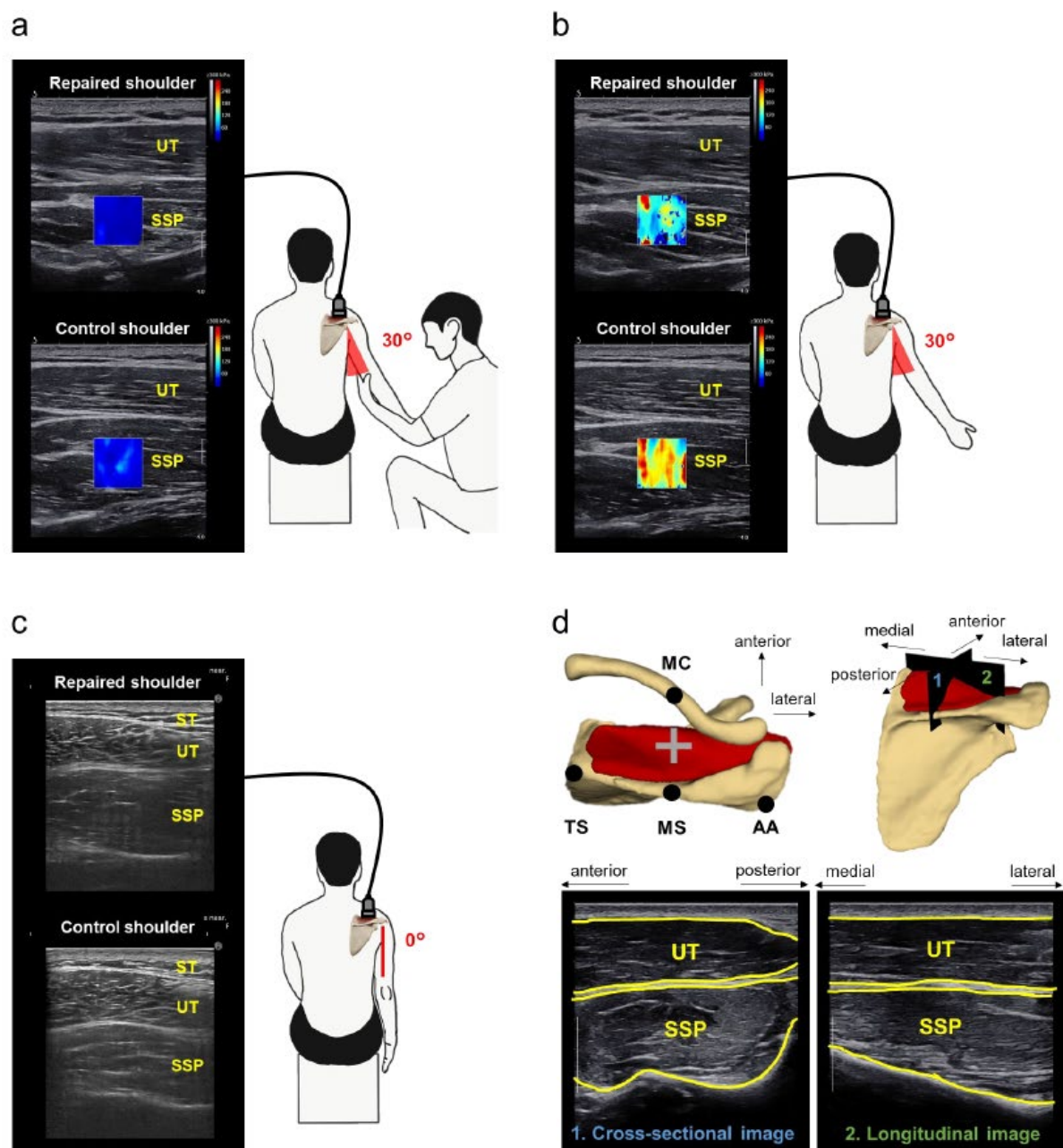


Figure 1

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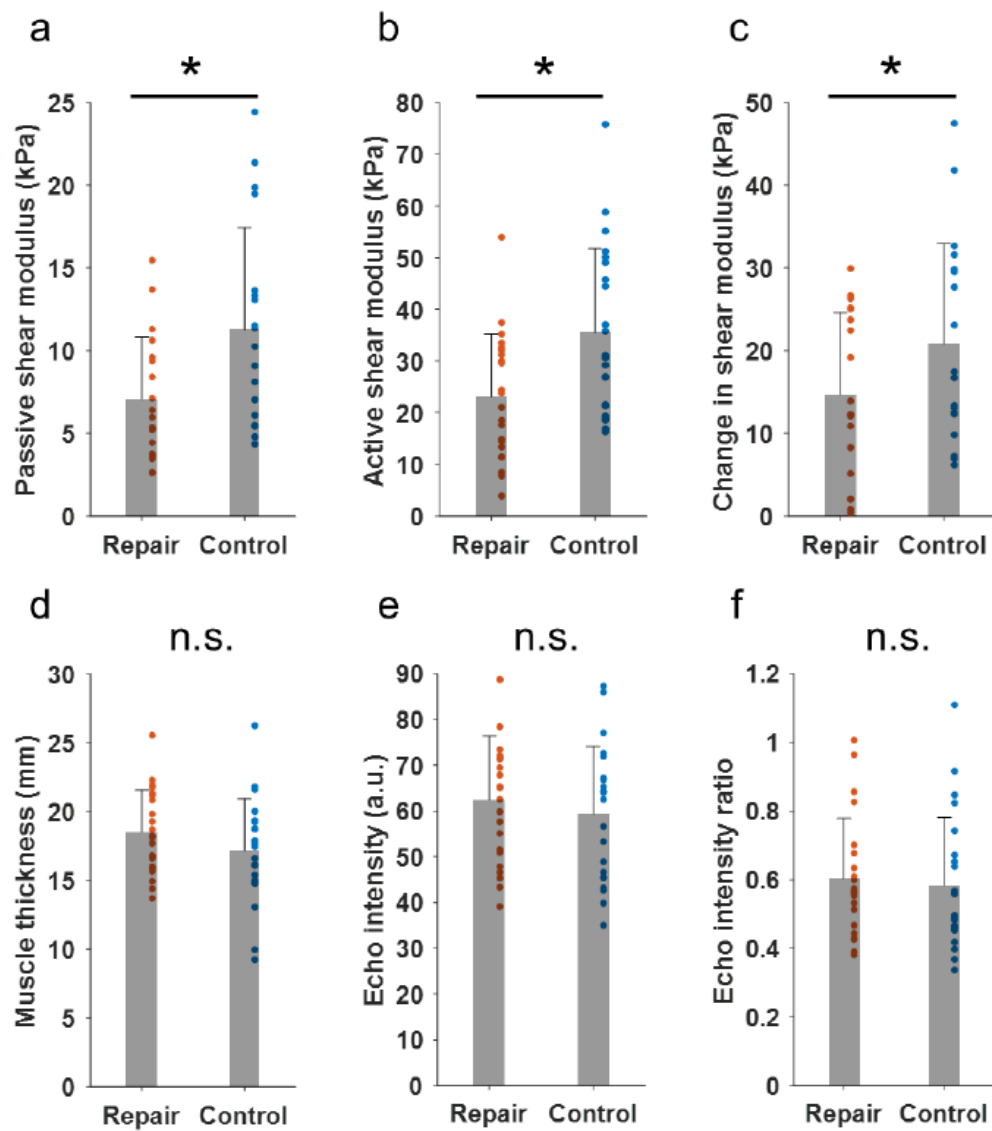


Figure 2

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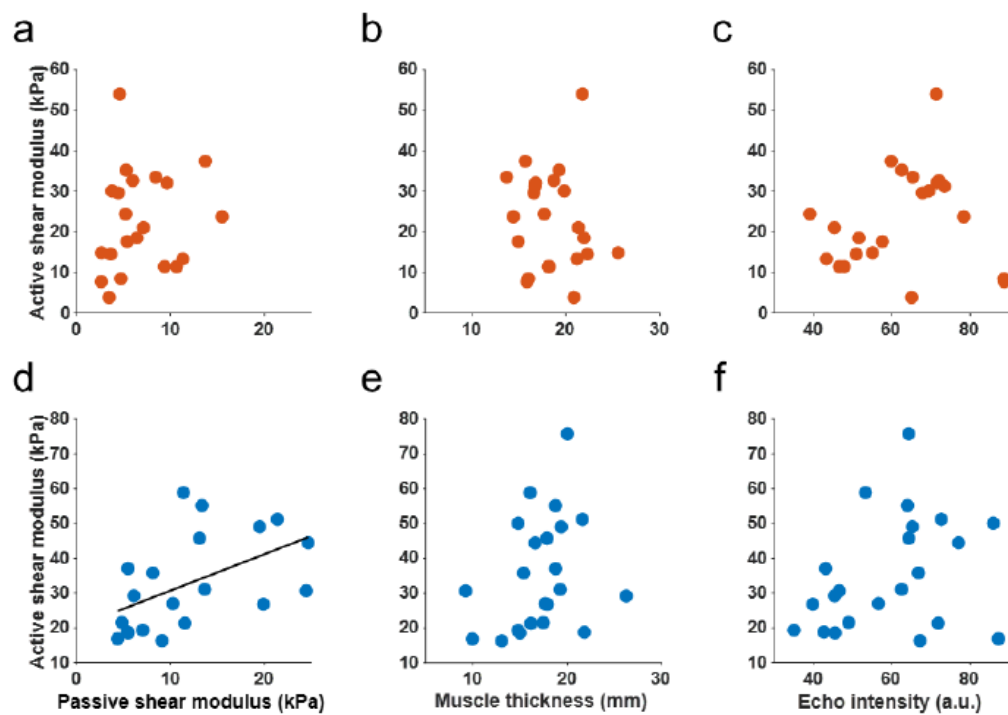


Figure 3