JSES International 7 (2023) 2373–2378

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

Muscle belly ratio is the most suitable estimate of the activity of the torn supraspinatus muscle

Kyosuke Hoshikawa, PT, MS[a,b,c,*], Takuma Yuri, OT, PhD[a], Ryuta Oishi, MD[c,d], Tomohiro Uno, MD, PhD[c,d], Jun Nagai, MD[c,d], Hugo Giambini, PhD[b], Nariyuki Mura, MD, PhD[a,c]

[a]Graduate School of Health Sciences, Yamagata Prefectural University of Health Sciences, Yamagata, Japan
[b]Department of Biomedical Engineering and Chemical Engineering, The University of Texas at San Antonio, San Antonio, TX, USA
[c]Department of Orthopedic Surgery, Yoshioka Hospital, Yamagata, Japan
[d]Department of Orthopaedic Surgery, Yamagata University Faculty of Medicine, Yamagata, Japan

A R T I C L E I N F O

Keywords:
Rotator cuff tears
Supraspinatus muscle
Muscle atrophy
Muscle belly ratio
Magnetic resonance imaging
Muscle activity
Real-time tissue elastography

Level of evidence: Basic Science Study; Imaging

Background: A torn rotator cuff muscle deteriorates over time leading with an increase in muscle atrophy and fatty infiltration. There are several clinical assessments for evaluating the atrophy of the torn supraspinatus muscle. However, it is unclear which approach can more accurately estimate the activity of the torn supraspinatus muscle. The purpose of this study was to determine which magnetic resonance imaging–based muscle atrophy imaging assessment currently implemented in the clinical setting accurately estimates the activity of the torn supraspinatus muscle.
Methods: Forty patients who were diagnosed with a rotator cuff tear and were candidates for repairs were selected for this study. Cross-sectional area, occupation ratio, and tangent sign were analyzed on T1-weighted oblique sagittal plane magnetic resonance images in which the scapular spine leads to the Y-section. Muscle belly ratio of the supraspinatus muscle was analyzed by calculating the ratio of the width of the muscle belly to the distance from the greater tubercle to the proximal end of the muscle on T1-weighted coronal plane magnetic resonance imaging images. Fatty infiltration was evaluated using the Goutallier classification system. Tear size was obtained intraoperatively by measuring the width and length of the tear and classified based on the Cofield's classification. To assess activity of the torn supraspinatus muscle, participants were first instructed to sit on a chair with the affected arm resting on a table and the shoulder abducted to 60° in the scapular plane with neutral rotation. Elasticity of the supraspinatus muscle belly was then obtained at rest and during isometric contraction using with real-time tissue elastography. Muscle activity, a surrogate for contractility, was defined as the difference between the elasticities measured at rest and during isometric contraction. A stepwise multiple regression analysis was used to investigate independent factors, such as sex, tear width, cross-sectional area, occupation ratio, tangent sign, and muscle belly ratio, related to muscle activity.
Results: Stepwise multiple regression analysis ($R^2 = 0.522$, $P < .001$) revealed that supraspinatus muscle activity was significantly correlated with muscle belly ratio ($\beta = 0.306$, $P = .044$) and Goutallier stage ($\beta = -0.490$, $P = .002$).
Conclusion: Estimations of muscle belly ratio are most suitable for assessing the activity of a torn supraspinatus muscle compared to other clinical measurements.

A torn rotator cuff muscle deteriorates over time leading to an increase in muscle atrophy and fatty infiltration.[4,8,13,18,27,35] Rotator cuff muscle atrophy negatively influences clinical outcomes.[1,13,20,23,29] Therefore, accurate assessments of atrophy from these muscles may play a crucial role in predicting the reparability of torn rotator cuff tendons and outcomes of conservative management and surgical treatment. There are several assessments for evaluating the atrophy of the torn supraspinatus muscle using magnetic resonance imaging (MRI).[15,18,21,22,27,35] Cross-sectional area and occupation ratio first described by Thomazeau et al,[27] and tangent sign, first introduced by Zanetti et al,[35] became the most commonly used approaches to estimate muscle atrophy using

The Yoshioka Hospital Ethics Committee approved this study; study no. YHTIB-2020-011

*Corresponding author: Kyosuke Hoshikawa, PT, MS, Graduate School of Health Sciences, Yamagata Prefectural University of Health Sciences, 260 Kamiyanagi, Yamagata 990-2212, Japan.
E-mail address: d.kyosuke.hoshikawa@yachts.ac.jp (K. Hoshikawa).

https://doi.org/10.1016/j.jseint.2023.07.004
2666-6383/

T1-weighted oblique sagittal-plane MRI images in the Y-view. On the other hand, muscle belly ratio, first defined by Nakagaki et al,[21,22] describes the ratio of the width of the muscle belly and the distance from the greater tuberosity to the proximal end of the muscle on T1-weighted coronal plane MRI images. However, it is unclear which atrophy assessment approach is the most suitable for estimating the activity of a torn supraspinatus muscle.

Real-time tissue elastography (RTE) has been widely used to assess muscle contractile activity.[11,12,17,19,31-34] This technique allows for noninvasive estimations of tissue elasticity during muscle contraction, as a surrogate for activity, by measuring strain wave propagation within the tissue. Previous studies have implemented RTE presurgical and postsurgical repair of torn supraspinatus tendons to evaluate muscle contractility showing excellent reliability and determining the feasibility of contractility as a predictor for muscle quality and function.[11,32,33] Therefore, the purpose of this study was to determine which muscle atrophy imaging assessment using MRI accurately estimates the activity of the supraspinatus muscle with a torn tendon measured by RTE.

Materials and methods

Participants

Between September 2021 and March 2022, 40 patients (mean age 64.3 ± 8.8 years; 33 males and 7 females) who underwent arthroscopic rotator cuff repair were included in this study after approval from our Ethics Committee (Yoshioka Hospital, study no. YHTIB-2020-011). A written informed consent to participate in this study was obtained from all patients. The inclusion criteria consisted of patients with known full-thickness rotator cuff tears who underwent arthroscopic rotator cuff repair. Patients with a history of previous shoulder surgery and supraspinatus muscle with fatty infiltration classified as Goutallier stage 4 were excluded due to substantial muscle fatty infiltration and not being able to acquire reliable data from RTE measurements in these types of tissues. Width and length of the tears were intraoperatively measured, and tear size was classified based on the Cofield's classification system.[2]

Muscle atrophy and fatty infiltration assessments

MRI was performed the day before surgery to assess muscle atrophy and fatty infiltration using a 1.5-T scanner (Vantage M-Power [Ver.3.0], Canon Medical Systems, Tochigi, Japan). Evaluations were performed using T1-weighted images (repetition time: 450 ms, echo time: 12 ms, field of view: 16 × 16 cm, slice thickness: 5 mm in the oblique coronal plane and 6 mm in oblique sagittal plane). Cross-sectional area, occupation ratio, and tangent sign were analyzed on T1-weighted oblique sagittal plane images in which the scapular spine leads to the Y-section (the most lateral image on which the scapular spine is still in contact with the rest of the scapula).[18,27,35] Cross-sectional area was measured by outlining the supraspinatus muscle belly by hand using ImageJ (ImageJ; National Institutes of Health, Bethesda, MD, USA) (Fig. 1*A*).[26] Occupation ratio was measured by calculating the ratio of the cross-sectional area of the supraspinatus muscle belly to the scapula fossa (Fig. 1*B*). Tangent sign was analyzed by drawing a cross line through the superior borders of the scapular spine and the superior margin of the coracoid. A positive tangent sign indicating muscle atrophy was considered if the supraspinatus muscle belly did not intersect the line connecting the tip of the coracoid to the superior aspect of the scapular spine. Muscle belly ratio of the supraspinatus muscle was analyzed by calculating the ratio of the width of the muscle belly to the distance from the greater tubercle to the proximal end of the muscle on the T1-weighted oblique coronal plane (Fig. 1*C*).[21,22] Fatty infiltration of the supraspinatus muscle was evaluated on the sagittal Y-section of the magnetic resonance images and classified using the Goutallier stage.[4,7,8]

Muscle contractility measurements

RTE measurements were performed on the day before surgery to assess muscle contractility of the torn supraspinatus muscle by one examiner (K.H.) who is trained in musculoskeletal ultrasonography. A diagnostic ultrasound system (Noblus; Hitachi-Aloka Medical Japan, Tokyo, Japan) with a linear array probe (L-64; Hitachi-Aloka Medical Japan) combined with an acoustic coupler (EZU- TECPL1; Hitachi-Aloka Medical Japan: 22.6 ± 2.2 kPa) was used to obtain the measurements. Briefly, the patient was first instructed to sit on a chair with the affected arm resting on a table and then the shoulder was abducted to 60° in the scapula plane (scaption) in a neutral rotation (Fig. 2). The anterior-middle subregion of the supraspinatus, as determined by Kim,[14] was scanned to obtain the longitudinal axial B-mode images, and elastography images were obtained by performing cyclic manual compression with the probe (Fig. 3). RTE evaluations were performed with the muscle at rest and during contraction consisting on the patient holding the affected arm against gravity for 5 seconds. After continuous scanning, 3 random images at rest and contraction were selected to calculate mean ± standard deviation (SD). Elasticity from the anterior-middle subregion of the supraspinatus muscle was calculated as the strain ratio (SR), which describes the relative value in reference to the stiffness of the acoustic coupler. Two SR values were defined: SR value at rest and SR value at contraction. Because the former is an indicator of the muscle elasticity at rest, while the latter represents the sum of muscle elasticity at rest and the elasticity produced by contraction, we defined the difference between SR value at rest and SR value at contraction as the muscle activity reflecting muscle contractility.[17,31-34]

Statistical analysis

IBM SPSS Statistics, version 24.0 (IBM Corp., Armonk, NY, USA) was used for all statistical analyses. Intraclass correlation coefficient ($ICC_{1,3}$; one-way random-effects, absolute agreement, multiple measurements) was implemented to evaluate intrarater reliability of the 3 RTE images obtained from the torn supraspinatus muscle at 60° scaption during muscle rest and contraction on all participants.[16] Reliability was classified as poor (<0.50), moderate (0.50-0.75), good (0.75-0.90), and excellent (>0.90). A stepwise multiple regression analysis was used to investigate independent factors such as age, sex, tear width, cross-sectional area, occupation ratio, tangent sign, muscle belly ratio, and Goutallier stage related to muscle activity. Additionally, Pearson correlation analysis was performed to demonstrate the relationship between muscle activity and muscle belly ratio, cross-sectional area, occupation ratio, tangent sign, and Goutallier stage of the torn supraspinatus muscle. Significance was set at $P < .05$. G*Power 3.1 software (Heinrich Heine Universität, Düsseldorf, Germany) was used to conduct posthoc power analysis from the results of stepwise multiple regression analysis of independent predictors (muscle belly ratio and Goutallier stage) of muscle activity with an α of 0.05. The power for a stepwise multiple regression analysis was >0.90.[3]

Results

The characteristics of the patients are presented in Table I. Mean ± SD tear width and length were 17.7 ± 8.4 (median: 15.0, range: 8.0-45.0) and 21.2 ± 9.6 (20.0, 8.0-45.0) mm, respectively. The distribution of tear size in our patient cohort was as follows: 1

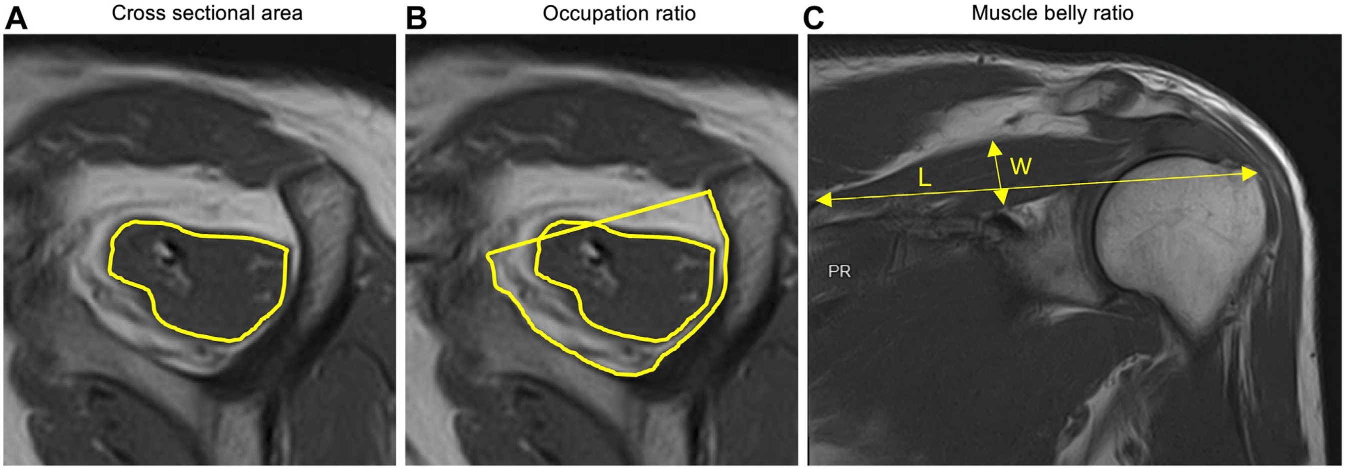

Figure 1 Muscle atrophy measurements. (**A**) Cross-sectional area was measured by calculating the area of the muscle belly tracked manually. (**B**) Occupation ratio was measured by calculating the ratio of the area of the muscle belly to the muscle fossa tracked manually. (**C**) Muscle belly ratio was measured by calculating the ratio of the width (W) of the muscle belly to the length (L) from the greater tubercle to the proximal end of the muscle on the T1-weighted coronal-plane MRI images. *MRI*, magnetic resonance imaging.

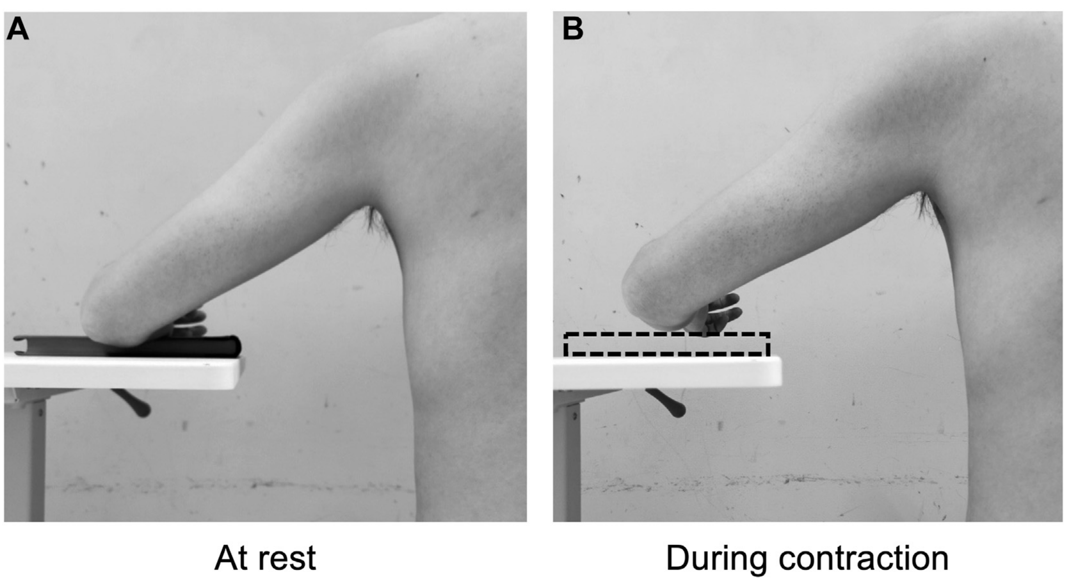

Figure 2 Contractility measurement procedures. (**A**) Patient position during "at rest" measurements. The patient was instructed to sit on a chair with the affected arm resting on a table with 60° abduction in the scapula plane in a neutral rotation. (**B**) Patient position during "contraction" measurements. The patient was instructed to hold the affected arm against gravity for 5 seconds at 60° in the scapula plane in a neutral rotation.

small, 31 medium, and 8 large. Mean ± SD cross-sectional area and occupation ratio were 421 ± 193 (428, 79-865) mm^2 and 0.71 ± 0.25 (0.71, 0.12-1.17), respectively. A positive tangent sign was determined in 6 patients. Mean ± SD muscle belly ratio measurements were 0.15 ± 0.02 (0.15, 0.10-0.20). Goutallier stage classifications for fatty infiltration resulted in 11 stage 0, 17 stage 1, 10 stage 2, and 2 stage 3. Intraclass correlation coefficient ($_{1,3}$) analyses for RTE outcomes of the supraspinatus muscle were 0.97 and 0.96 for SR at rest and during contraction, respectively. Mean ± SD SR at rest and during isometric contraction and mean ± SD muscle activity outcomes were 0.91 ± 0.29 (0.96, 0.29-1.62), 0.27 ± 0.19 (0.20, 0.02-0.96), and 0.65 ± 0.28 (0.64, 0.10-1.47), respectively.

The correlation between supraspinatus muscle activity and each muscle atrophy and fatty infiltration assessment is shown in Fig. 4. Stepwise multiple regression analysis ($R^2 = 0.522$, $P < .001$) revealed that the supraspinatus muscle activity was significantly correlated with muscle belly ratio ($\beta = 0.306$, $P = .044$) and Goutallier stage ($\beta = -0.490$, $P = .02$) (Table II).

Discussion

Previous studies have established various methodologies for assessing supraspinatus muscle atrophy using MRI.[15,18,21,22,27,35] However, it is unclear which atrophy assessment can more accurately estimate the activity of the torn supraspinatus muscle. In this study, we aimed to determine which MRI-based muscle atrophy imaging assessment currently implemented in the clinical setting accurately estimates the activity of the torn supraspinatus muscle. Our study found that muscle belly ratio assessments, compared to other routine approaches such as cross-sectional area, occupation ratio, or tangent sign, are the most suitable in predicting the activity of the torn supraspinatus muscle.

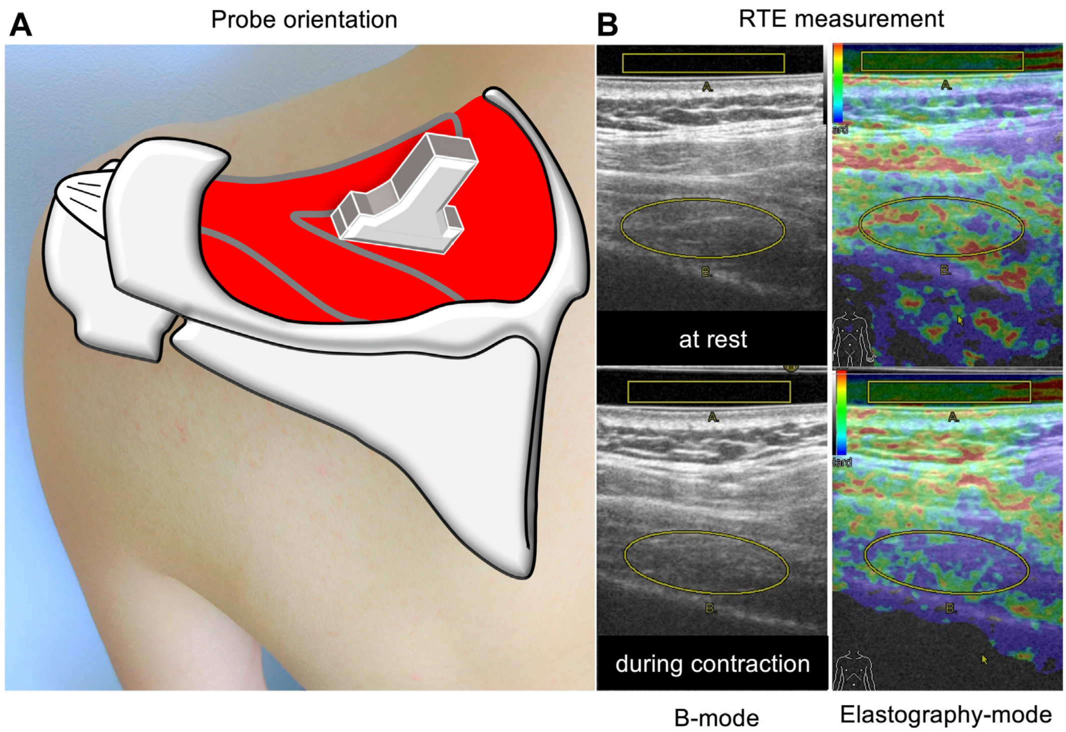

Figure 3 (**A**) Probe orientations for the anterior-middle subregion of the supraspinatus muscle. (**B**) RTE measurement of the anterior-middle subregion of the supraspinatus muscle at rest and during contraction. Two regions of interest were set on the acoustic coupler and the muscular region of the anterior-middle subregion of each image to calculate the strain ratio which describes the relative value in reference to the stiffness of the acoustic coupler. *RTE*, real-time tissue elastography.

Table I
Demographic characteristics.

	n or mean ± SD	% or median, range
Age (y)	64.3 ± 8.8	64, 39-80
Sex		
Male	33	82.5%
Female	7	17.5%
Affected side		
Dominant	27	67.5%
Nondominant	13	32.5%
Tear width (mm)	17.7 ± 8.5	15.0, 8.0-45.0
Tear length (mm)	21.1 ± 9.6	20.0, 8.0-45.0
Cofield classification		
Small	1	2.5%
Medium	31	77.5%
Large	8	20.0%

SD, standard deviation.

Several methods currently implemented to evaluate muscle atrophy of the torn supraspinatus muscle include cross-sectional area, occupations ratio, and tangent sign assessments using the oblique-sagittal plane on MRI images.[15,18,27,35] However, the suitability of these methods in assessing the atrophy of the supraspinatus muscle can be questioned as these approaches can be influenced by the medial retraction of the muscular-tendon unit from a rotator cuff tear and/or by the lateral traction from surgery.[5,25] Sasaki et al showed that the changes observed in occupation ratio measurements using 2-dimensional and 3-dimensional imaging techniques can be related to the lateral retraction of the supraspinatus muscle.[25] Recently, other approaches obtaining 3-dimensional assessments of the torn supraspinatus muscle have been attempted; however, these methods are time intensive.[1,29] On the other hand, muscle belly ratio evaluations assessed in the longitudinal plane are convenient, easy, and may account for the effect of medial and lateral retraction of the muscular-tendon unit before and after surgery.[21,22] Importantly, Nakagaki et al reported that the contractility of the torn supraspinatus muscle measured by electromyography was positively correlated with muscle belly ratio.[22] The outcomes of our study align well with these previous findings, suggesting that the activity of the torn supraspinatus muscle measured by RTE can be correlated with the muscle belly ratio. Thus, it is logical to consider the muscle belly ratio as a suitable preoperative and postoperative assessment method for muscle atrophy in patients with a torn supraspinatus muscle.

It is widely accepted that a fatty infiltrated supraspinatus muscle presents with decreased muscle contractility.[8,34] Our data indicated that muscle activity was significantly related with muscle atrophy and fatty infiltration. Yuri et al reported that the activity of repaired supraspinatus muscles classified with Goutallier stages lower than 2 can improve 1 year postsurgery, while those muscles classified with Goutallier stages 2 or greater do not show improvement.[34] Wieser et al showed that atrophy of a repaired supraspinatus muscle can be minimally reversed after surgery, while the amount of fat within the muscle remains unchanged.[30] Trevino et al demonstrated that the superficial part of the supraspinatus muscle primarily shows atrophy, while the deep part mainly shows fatty infiltration in a torn supraspinatus muscle.[28] From these studies, we can infer that the progression of muscle atrophy and fatty infiltration have different etiologies and characteristics, and further studies are needed to better examine the relationship between muscle activity, fatty infiltration, and muscle atrophy.

There are several limitations in this study that should be noted. First, we had an unbalanced cohort of male and female patients within the study population due to finding a smaller number of eligible female patients during the recruitment period. This could

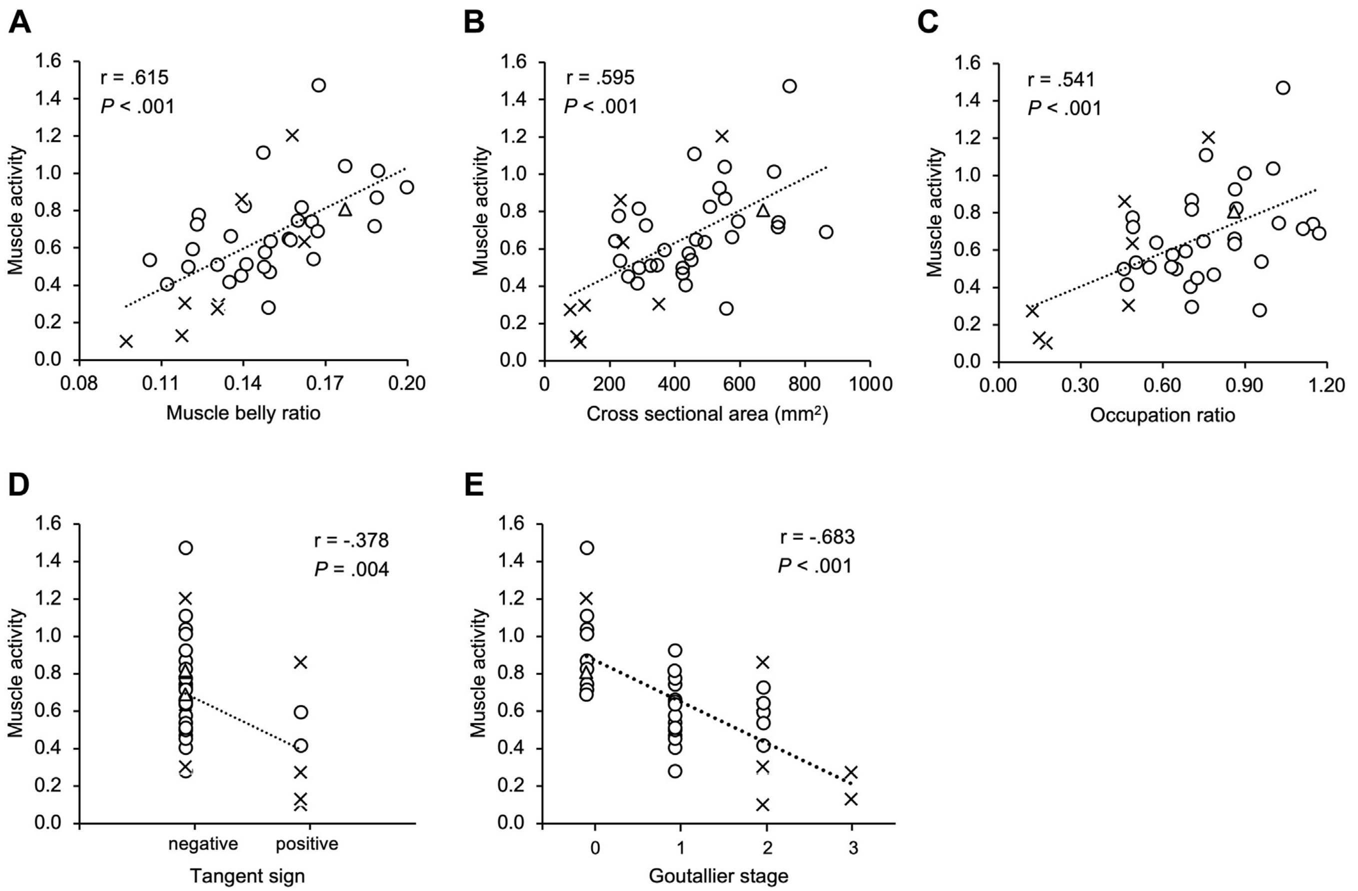

Figure 4 Correlation between the activity of the torn supraspinatus muscle and each imaging assessment for the evaluation of supraspinatus muscle atrophy (**A**: muscle belly ratio, **B**: cross sectional area, **C**: occupation ratio, **D**: tangent sign, **E**: Goutallier stage). Tear classification is △: small, ○: medium, ×: large.

Table II
Stepwise multiple regression analysis for the activity of the supraspinatus muscle.

	B	β	P
Age		−0.062	.647
Sex		0.136	.250
Tear width		0.056	.687
Cross-sectional area		−0.061	.783
Occupation ratio		−0.159	.431
Tangent sign		0.089	.548
Muscle belly ratio	3.586	0.306	**.044**
Goutallier stage	−0.163	−0.490	**.002**

$R^2 = 0.522$, $P < .001$.
B, beta coefficients; β, standardized beta coefficients.
Bold P values indicates $P < .05$.

have biased the outcomes. Second, we included a limited number of patients with small and large cuff tears and no patients with massive tendon tears. Additionally, a small number of patients were classified as Goutallier stage 3 and we excluded patients classified as stage 4. Further studies with a larger population are needed to more comprehensively evaluate the effect of tear size and fatty infiltration on the outcomes from this study. Third, we only measured a single subregion of the supraspinatus muscle, namely the anterior-middle.[14] Although there are several studies further compartmentalizing the supraspinatus muscle into additional subregions,[6,9] the selection of the region was based on the anterior subregion being responsible for the majority of force production, while the posterior subregion mainly plays a role in the adjustment of tension on the tendon.[14,24] Furthermore, we have previously shown that the anterior-middle subregion has a significant and substantial role as an initiator of shoulder scaption motion.[10] Therefore, the evaluation of the anterior-middle subregion of the supraspinatus muscle is well justified.

Conclusion

Muscle belly ratio is the most suitable assessment in predicting the activity of a torn supraspinatus muscle compared to other clinical measurements currently being used to estimate muscle atrophy. Muscle belly ratio evaluations can be easily implemented to obtain estimates of muscle activity and contribute to selecting appropriate rehabilitation and surgical approaches.

Acknowledgments

The authors would like to thank the head of the Yoshioka Hospital, Dr. Shinya Yoshioka, and all of the staff department of orthopedic surgery at Yoshioka hospital, whose support made this project possible.

Disclaimers:

Funding: This study was supported by a Grant-in-Aid for JSPS fellows (Grant number 22J22344).
Conflicts of interest: The authors, their immediate families, and any research foundation 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.

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