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Three-dimensional sectional measurement approach for serial volume changes in shoulder muscles after arthroscopic rotator cuff repair

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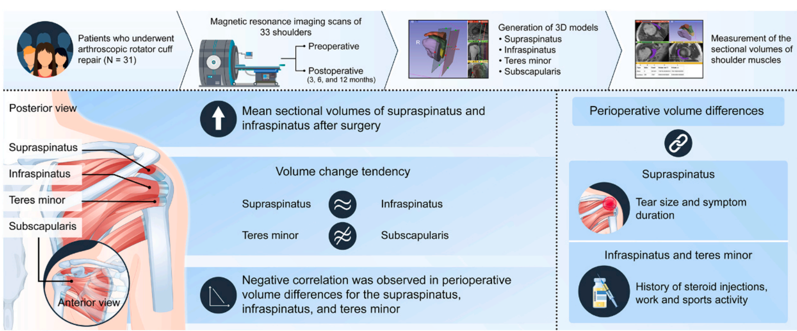
GRAPHICAL ABSTRACT



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ABSTRACT

Purpose: This study assessed the serial volume changes in multiple shoulder muscles simultaneously following arthroscopic rotator cuff repair (ARCR) by a three-dimensional (3D) modeling-based sectional measurement. These volume changes were correlated with background preoperative factors.

Methods: Four consecutive magnetic resonance imaging scans (preoperatively and postoperatively at 3, 6, and 12 months) of 33 shoulders from 31 patients who underwent arthroscopic rotator cuff repair were examined. We focused on the sectional volume differences of the supraspinatus, infraspinatus, teres minor, and subscapularis between preoperatively and 3 months postoperatively (Dif.pre.3mo) and between 3 and 12 months postoperatively (Dif.3.12mo). The correlation between volume differences and clinical/demographic parameters was determined by a multivariate analysis.

Results: No statistically significant differences were observed for most serial changes in the shoulder muscle volumes. The tear-site muscles (supraspinatus and infraspinatus) showed similar tendencies for volume changes, whereas the non-tear-site muscles (teres minor and subscapularis) differed. A negative correlation was observed between Dif.pre.3mo and Dif.3.12mo for the supraspinatus, infraspinatus, and teres minor. These perioperative

Abbreviations: 2D, Two-dimensional; 3D, Three-dimensional; ARCR, arthroscopic rotator cuff repair; DICOM, Digital Imaging and Communications in Medicine; Dif.pre.3mo, difference between preoperatively and 3 months postoperatively; Dif.3.12mo, difference between 3 and 12 months postoperatively; Dif.pre.12mo, difference between preoperatively and 12 months postoperatively; GL, glenoid labrum; ICC, intraclass correlation coefficient; MRI, magnetic resonance imaging.

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volume differences might correlate with tear size and symptom duration in the supraspinatus, as well as with a history of steroid injections and work and sports activity levels in the infraspinatus and teres minor.
Conclusion: The serial volume changes in multiple shoulder muscles after ARCR measured using our 3D sectional approach exhibited different tendencies and clinical implications depending on the primary and non-primary site of tears. Our method may serve as a potential indicator to facilitate muscle recovery and prevent the progression of postoperative muscle atrophy.

1. Introduction

Rotator cuff tears are the most common type of shoulder injuries. Arthroscopic rotator cuff repair (ARCR) results in good mid-to long-term outcomes, and has become a widely accepted treatment for rotator cuff tears. However, re-tear remains the most prominent complication that leads to poor outcomes [1,2].

Several factors can predict the surgical and clinical outcomes of ARCR. Muscle atrophy and fatty infiltration are well-known prognostic factors that determine the postoperative structural and functional outcomes [3,4]. Chronic rotator cuff tears can lead to muscle atrophy and fatty infiltration, which can reduce the ability to generate force. Improvements in muscle atrophy and fatty infiltration have been reported following ARCR [5,6]. However, some studies have indicated that these effects are irreversible [7,8].

Most previous studies on postoperative changes in the rotator cuff muscle have compared preoperative shoulder scans with a series of postoperative magnetic resonance imaging (MRI) scans. Qualitative and quantitative approaches for evaluating muscle atrophy and fatty infiltration have been actively studied. Quantitative measurements of muscle atrophy involve 2-dimensional (2D) muscle cross-sectional areas and occupation ratio [6,9,10]. The tangent sign is a qualitative indicator of muscle atrophy [6,9,10]. Regarding fatty muscle infiltration, the Goutallier classification is the most well-known qualitative score [11]. Quantitative approaches such as the fatty infiltration ratio and degenerative fat area have also been used [12,13]. Although the use of these methods has been demonstrated, they are mainly performed on single-image slices of oblique sagittal MRI sequences in the conventional Y-view plane. A comparison with a series of single-slice MRIs may inevitably result in interpretation errors because lateralization of the myotendinous portion caused by tear repair alters the specific slice used for assessments [14–18]. This variability has mainly confounded the evaluation of postoperative recovery in muscle atrophy as 2D slices cannot represent the three-dimensional (3D) volume [16,18,19].

Recent technological advancements have made the 3D evaluation of medical images possible. In the shoulder joint area, the 3D muscle volume measurements have been applied to the supraspinatus after the tear repair [18,20,21]. However, current studies remain controversial concerning the recovery of muscle atrophy after ARCR: an increase in muscle volume postoperatively compared with that preoperatively was reported in one study [17,22], while no longitudinal statistical changes were observed in another [23]. Importantly, routine MRI scans reveal that the shoulder muscles are often imaged partially, sparing the medial end, as the main focus is on the joint rather than the muscle in the usual clinical settings. In this context, it is worthy to note that Chung et al. (2017) presented 3D modeling-based sectional measurement approach; they dissected and obtained the volumes of the supraspinatus at a position along the Y-view plane and 1 and 2 cm medial to the Y-view plane [22]. However, because this method was introduced as an in-house tool, its feasibility and validity in clinical settings have not been thoroughly studied.

The anatomy and structure of the shoulder muscles are more complex than those of a simple model consisting only of the supraspinatus. However, current research on rotator cuff tears has mainly assessed the supraspinatus muscles at the primary tear site. In addition to the supraspinatus, the infraspinatus, teres minor, and subscapularis muscles, which arise from the scapula and are inserted into the humerus, making up the rotator cuff with these four muscles. Notably, the tendons of the rotator cuff muscles blend at the joint level to form a united musculotendinous collar, generating coordinated function and movement of the shoulder muscles [24,25]. In the context of muscle recovery after rotator cuff repair, the impact of muscles not only at the tear site but also at the non-tear site may be substantiated.

Postoperative recovery of muscle volume after rotator cuff repair is essential for positive patient outcomes. However, the extent of muscle volume recovery should vary depending on the individual tear and the clinical background. According to a recent systematic review, several preoperative factors such as sex, workload, chronicity, and tear size may affect the rate and duration of return to daily activity levels after rotator cuff repair [26]. Therefore, the contribution of these clinical factors to muscle volume recovery should be examined to investigate prognostic factors for good postoperative outcomes. However, the research on this topic is limited.

In this study, we hypothesized that our 3D sectional measurement of multiple shoulder muscles after ARCR has the potential to discern consecutive site-specific and interrelated volume changes and that these changes may be linked to clinical implications. Our objectives were to (1) evaluate postoperative serial volume changes using 3D modeling-based sectional measurements, (2) assess muscle volume changes not only at the tear site but also at the non-tear site by examining multiple muscle volumes simultaneously, and (3) identify the background preoperative factors associated with these volume changes.

2. Materials and methods

2.1. Participants

This study was approved by the Research Ethics Committee of Saitama Medical University Hospital (approval number 2023–073). All experiments were performed in accordance with the relevant guidelines and regulations. Given the retrospective nature of the study, the requirement for informed consent was waived.

After receiving approval from the institutional review board, we identified a consecutive series of patients with rotator cuff tears who underwent shoulder MRI before ARCR in the Department of Orthopedics at our institution between January 2012 and December 2021. Fig. 1 shows the inclusion and exclusion criteria for patient selection. The study population was selected primarily based on adequate postoperative follow-ups, including regular MRI scans.

The inclusion criteria were as follows: (1) age $\geq$15 years and (2) four consecutive shoulder MRI scans with full Y-views performed preoperatively (within 3 months before surgery) and postoperatively at 3, 6, and 12 months (range, 2–4, 5–7, and 11–13 months). Postoperative MRI scans were obtained as part of the routine follow-up without any special indications for these scans. These follow-up timings were based on our hospital routine and in accordance with existing reports [22,23].

The exclusion criteria were as follows: inadequate MRI data for proper evaluation and comparison, including the absence of any of the four consecutive MRI scans ($n = 21$), preoperative MRI scans at other institutions ($n = 31$), and presence of artifacts on MRI images ($n = 19$). Furthermore, patients with a medical history of prior shoulder surgery ($n = 3$) were also excluded, being inappropriate for evaluation. To focus on the primary rotator cuff tear site, we excluded patients with subscapularis tendon tears ($n = 13$). Finally, data from 33 shoulder MRI scans of 31 patients were analyzed.

2.2. Demographic data

Sports activity levels were defined as high (rugby, basketball, football), medium (golf, swimming, running), or low. Work level was defined as high (heavy manual labor), medium (manual labor with less activity), and low (sedentary work). The tear size was measured arthroscopically at the time of surgery and classified according to the rating system of Cofield [27]. The fatty infiltration of each rotator cuff muscle (supraspinatus, infraspinatus, and subscapularis) was evaluated using preoperative scans according to the criteria established by Goutallier and Fuchs [11,28]. Repair integrity was evaluated on postoperative MRI performed at 12 months postoperatively and classified using the Sugaya classification [29] as follows: type I, sufficient thickness with homogeneously low intensity; type II, sufficient thickness with partial high-intensity areas; type III, less than half of the thickness without discontinuity; type IV, minor discontinuity; and type V, major discontinuity. Two raters evaluated the fatty infiltration of each rotator cuff muscle and integrity of the repaired tendon.

2.3. MRI acquisition and 3D visualization of the shoulder muscles

MRI scans were obtained using a 3.0 Tesla superconducting unit (Skyra; Siemens Healthcare, Erlangen, Germany) equipped with a dedicated shoulder coil. The standard dedicated MRI protocol consists of the following sequences: fat-saturated T2-weighted images in the sagittal and coronal planes, proton density-weighted images in the sagittal and coronal planes, and T2*-weighted images in the transverse plane. For the 3D segmentation of the muscles, proton density-weighted images were chosen to clearly define the fat and muscle boundaries. Fat-saturated T2-weighted images were used to define synovial fluid and muscle boundaries on the articular side. T2*-weighted images were used to confirm the boundaries in transverse sections.

Representative MRI scanning sequences and parameters are summarized in Table 1.

To generate a 3D model of the shoulder muscles, segmentation was performed using an open-source software (ITK-SNAP version 3.8.0). A summary of the 3D model creation is shown in Fig. 2. After the MRI scans were loaded into ITK-SNAP using the Digital Imaging and Communications in Medicine (DICOM) format, the areas of the supraspinatus, infraspinatus, teres minor, and subscapularis in every sagittal image were delineated using semi-automatic segmentation tools (Fig. 2A). From the delineated contours, a 3D model of each shoulder muscle was reconstructed and saved as a standard 3D model in the NIFTI file format (*. nii.gz).

Table 1
Representative MRI scanning sequences and parameters.

Parameters	FST2WI		PDWI		T2*WI
	(cor.)	(sag.)	(sag.)	(cor.)	(tra.)
TR (ms)	2800	2800	1800	1800	550
TE (ms)	64	66	22	20	10
FA (°)	90	90	90	90	25
FOV (cm)	14 × 14 × 8	14 × 14 × 8	14 × 14 × 8	14 × 14 × 8	14 × 14 × 8
Voxel size (mm)	0.36 × 0.36 × 3.3	0.36 × 0.36 × 3.3	0.31 × 0.31 × 3.3	0.31 × 0.31 × 3.3	0.31 × 0.31 × 3.3
Slice thickness (mm)	3	3.5	3.5	3	3

FA, flip angle; FOV, field of view; FST2WI, fat-saturated T2-weighted imaging; IP, in-phase; OP, opposed-phase; PDWI, proton density-weighted imaging; T2*WI, T2*-weighted imaging; TE, echo time; TR, repetition time; WO, water-only. cor. = coronal, sag. = sagittal, tra. = transverse.

2.4. Measurement of the Sectional Volumes of Shoulder Muscles

To assess the morphological changes and the degree of medial retraction of the rotator cuff tendons and muscles, we adopted the technique proposed by Chung et al. (2017) [22]. We performed sectional volume measurements of the shoulder muscles from the most lateral end of the tendons to the plane of the glenoid labrum (GL) and the Y-view plane (referred to as the GL and Y sections, respectively). 3D modeling-based measurements typically rely on high-end hardware and specialized MATLAB software. The technique introduced by Chung et al. (2017) also necessitated in-house software [22]. Instead, we propose a cutting-edge open-source software for 3D modeling-based analysis: the 3D Slicer platform (3D Slicer 5.0.3) [30]. This application contains a set

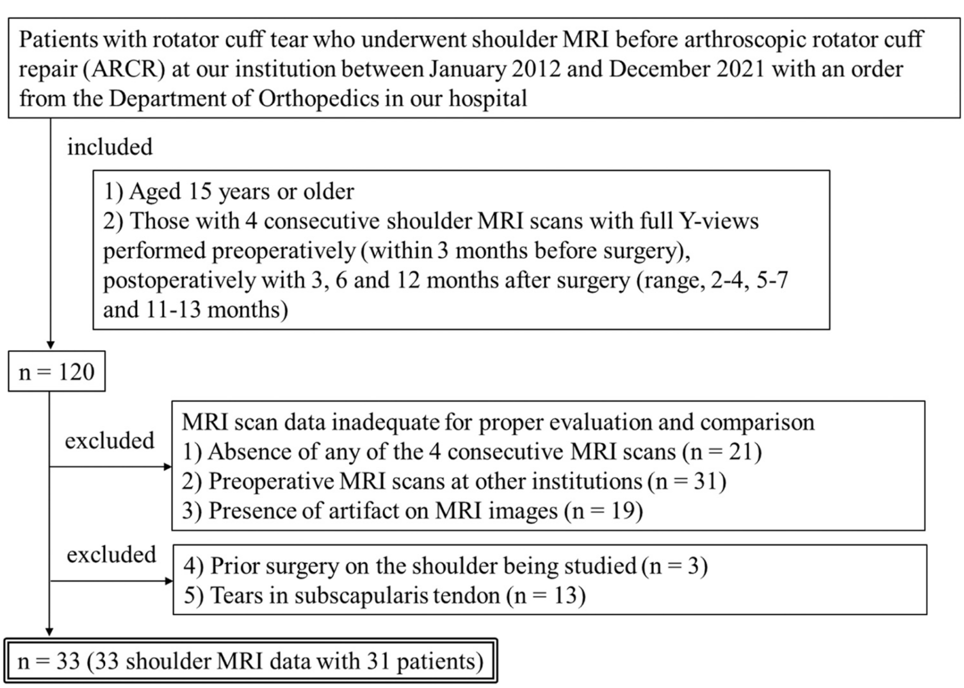


Fig. 1. Flow chart of the patient selection process for the study. ARCR, arthroscopic rotator cuff repair; MRI, magnetic resonance imaging.

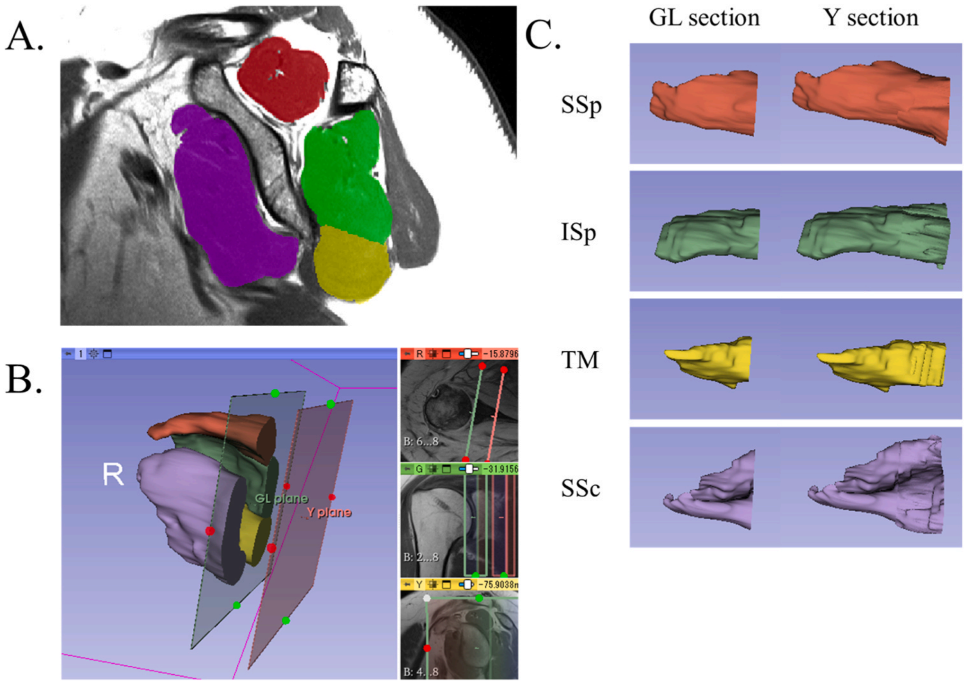


Fig. 2. (A) The area of supraspinatus (red), infraspinatus (green), teres minor (yellow), and subscapularis (purple) in every sagittal image was delineated by applying semi-automatic segmentation tools. (B) The 3D models of supraspinatus, infraspinatus, teres minor, and subscapularis were separated by the glenoid labrum (GL)-plane (green) and Y-view plane (red) using the Dynamic Modeler module. (C) For each model of the four shoulder muscles, two sections of 3D models were newly created (hence we obtained 8 models in total). GL section, from the most lateral end of the muscles to the GL-plane; Y section, from the most lateral end of the muscles to the Y-view plane.

of modules and toolkits for processing 3D models, and shoulder muscle volumes were measured using this software in the present study. After the 3D reconstructed model of each muscle and the original MRI scans were loaded onto a 3D slicer, the GL-plane and Y-view planes were defined using the Markup module, and the muscle model was segregated into GL and Y sections using the Dynamic Modeler tool (Figs. 2B and 2 C). Muscle volumes were measured using the corresponding statistical modules. The specific implementation schemes are described in the Supplemental File.

To assess interobserver reproducibility in the segmentation and measurement process, two radiologists with seven and six years of experience performed these steps independently. Both radiologists were blinded to the clinical information. The intraclass correlation coefficient (ICC) was measured to evaluate interobserver reproducibility.

2.5. Evaluation and statistical analysis

Serial changes in shoulder muscle volume before and after arthroscopic rotator cuff repair at four different time points were examined. A paired t-test was used to compare the changes in volume, area, and fatty infiltration preoperatively and postoperatively at 3, 6, and 12 months.

We examined the differences in muscle volumes between the two time points, particularly preoperatively and 3 months postoperatively (Dif.pre.3mo), 3 and 12 months postoperatively (Dif.3.12mo), and preoperatively and 12 months postoperatively (Dif.pre.12mo). We also evaluated the correlations between them.

We further evaluated the correlation between the perioperative volume differences (i.e., Dif.pre.3mo, Dif.3.12mo, and Dif.pre.12mo) for the supraspinatus, infraspinatus, teres minor, and subscapularis, and clinical and demographic parameters (i.e., age, sex, symptom duration, trauma onset, work and sports activity level, and tear size and location) using multivariate analysis.

Statistical analyses were performed using the open-source software package (Python scikit-learn 0.22.1). Statistical significance was set at $P < 0.05$.

3. Results

This study included 33 shoulder MRI scans (including both sides of the shoulders in two patients) from 31 patients. The demographic and

Table 2
Demographic and clinical characteristics of the study population.

Variable	Value
Age, years, mean ± SD	62.0 ± 11.0
Sex, male	16 (48)
Side, right	22 (67)
Symptom duration, month, mean ± SD	13.6 ± 12.6
Trauma onset	12 (36)
Sports activity level, high/medium/low	2/3/28
Work level, high/medium/low	9/14/10
History of steroid injections	8 (24)
Diabetes	9 (27)
Tear size, n (%)	
Small	15 (45)
Medium	13 (39)
Large	5 (15)
Tear location, n (%)	
SSp	19 (58)
SSp and Isp	14 (42)
Preoperative fatty infiltration (Goutallier and Fuchs criteria), mean ± SD	
SSp	1.2 ± 0.6
Isp	1.2 ± 0.6
TM	0.4 ± 0.7
SSc	0.7 ± 0.8
Preoperative range of motion, deg, mean ± SD	
Forward flexion	145.3 ± 32.5
Abduction	131.8 ± 43.0
Repair integrity (Sugaya classification) at 12 months postoperatively, n (%)	
Type I	4 (12)
Type II	21 (64)
Type III	7 (21)
Type IV	1 (3)

Data are presented as number (%) of patients unless otherwise indicated. ISp, infraspinatus; SSc, subscapular; SSp, supraspinatus; TM, teres minor.

clinical data are summarized in Table 2. The postoperative MRI was evaluated at 3 months (92.5 ± 15.9 days), 6 months (186.8 ± 26.1 days), and 12 months (364.6 ± 44.9 days) postoperatively. Interobserver reproducibility was good to excellent for all 3D volumes of the shoulder muscles, with mean ICC values of 0.802, 0.835, and 0.810 at 3, 6, and 12 months postoperatively, respectively.

Table 3 summarizes the serial changes in the 3D volumes of the shoulder muscles. Overall, no statistically significant differences were observed for most serial changes in muscle volume. Statistically significant differences were observed between the preoperative and 3 months postoperative values for the supraspinatus and infraspinatus muscle volumes in the GL section and between 3 and 12 months postoperatively for the subscapularis in the GL section. Fig. 3 shows an example of serial changes in the 3D volumes of shoulder muscles.

Table 4 summarizes the perioperative muscle volume differences (i.e., Dif.pre.3mo, Dif.3.12mo, and Dif.pre.12mo) and the correlations between the two variables. For the supraspinatus, infraspinatus, and teres minor, a statistically significant negative correlation was observed between Dif.pre.3mo and Dif.3.12mo. The postoperative changes in the supraspinatus and infraspinatus muscle volumes showed a different trend from those of the teres minor and subscapularis.

Finally, Tables 5–8 summarize the comparison between the perioperative volume differences in each shoulder muscle and the clinical and demographic parameters using multivariate analysis.

Regarding the supraspinatus (Table 5), significant correlations with tear size were observed for Dif.pre.3mo in the GL and Y sections and Dif.pre.12mo in the Y section. Additionally, a significant correlation was observed between symptom duration and Dif.pre.3mo and Dif.3.12mo in the GL section.

Multivariate analysis was performed to assess the correlation between the difference in supraspinatus volume during the perioperative period (i.e., between preoperatively and 3 months postoperatively (Dif.pre.3mo), between 3 and 12 months postoperatively (Dif.3.12mo), and between preoperatively and 12 months postoperatively (Dif.pre.12mo)) and the clinical and demographic parameters. Sectional volume measurements of each shoulder muscle were performed as follows: GL section, from the most lateral end of the tendons to the plane of the glenoid labrum (GL plane); Y section, from the most lateral end of the tendons to the Y-view plane. RC, regression coefficient. Significant correlations with tear size were observed for Dif.pre.3mo in the GL and Y sections and Dif.pre.12mo in the Y section. Additionally, a significant correlation was observed between symptom duration and Dif.pre.3mo and Dif.3.12mo in the GL section.

Regarding the infraspinatus (Table 6), a significant correlation was observed between symptom duration and Dif.pre.3mo and Dif.3.12mo in the GL section. We also observed a significant correlation between history of steroid injections and diabetes in Dif.3.12mo.

Multivariate analysis was performed to assess the correlation between the volume difference of the infraspinatus during the perioperative period (i.e., between preoperatively and 3 months postoperatively (Dif.pre.3mo), between 3 and 12 months postoperatively (Dif.3.12mo), and between preoperatively and 12 months postoperatively (Dif.pre.12mo)) and the clinical and demographic parameters. Sectional volume measurements of each shoulder muscle were performed as follows: the GL section, from the most lateral end of the tendons to the plane of the glenoid labrum (GL plane), and the Y section, from the most lateral end of the tendons to the Y-view plane. RC, regression coefficient. A significant correlation was observed between symptom duration for Dif.pre.3mo and Dif.3.12mo in the GL section. We also observed a significant correlation between history of steroid injections and diabetes in Dif.3.12mo.

Regarding the teres minor (Table 7), a significant correlation was observed with trauma onset, sports activity level, work level, and history of steroid injections for Dif.3.12mo.

Multivariate analysis was performed to assess the correlation between the volume difference of the teres minor during the perioperative period (i.e., between preoperatively and 3 months postoperatively (Dif.pre.3mo), between 3 and 12 months postoperatively (Dif.3.12mo), and between preoperatively and 12 months postoperatively (Dif.pre.12mo)) and clinical and demographic parameters. Sectional volume measurements of each shoulder muscle were performed as follows: GL section, from the most lateral end of the tendons to the plane of the glenoid labrum (GL plane); Y section, from the most lateral end of the tendons to the Y-view plane. RC, regression coefficient. A significant correlation was observed between trauma onset, sports activity level, work level, and history of steroid injections for Dif.3.12mo.

No significant correlations were observed between any of the variables in the subscapularis (Table 8).

Multivariate analysis was performed to assess the correlation between the volume difference of the subscapularis during the perioperative period (i.e., between preoperatively and three months postoperatively (Dif.pre.3mo), between three and 12 months postoperatively (Dif.3.12mo), and between preoperatively and 12 months postoperatively (Dif.pre.12mo)) and the clinical and demographic parameters. Sectional volume measurements of each shoulder muscle were performed as follows: GL section, from the most lateral end of the tendons to the plane of the glenoid labrum (GL plane); Y section, from the most lateral end of the tendons to the Y-view plane. RC, regression

Table 3
Serial changes in the 3D volumes of the shoulder muscles during the perioperative period.

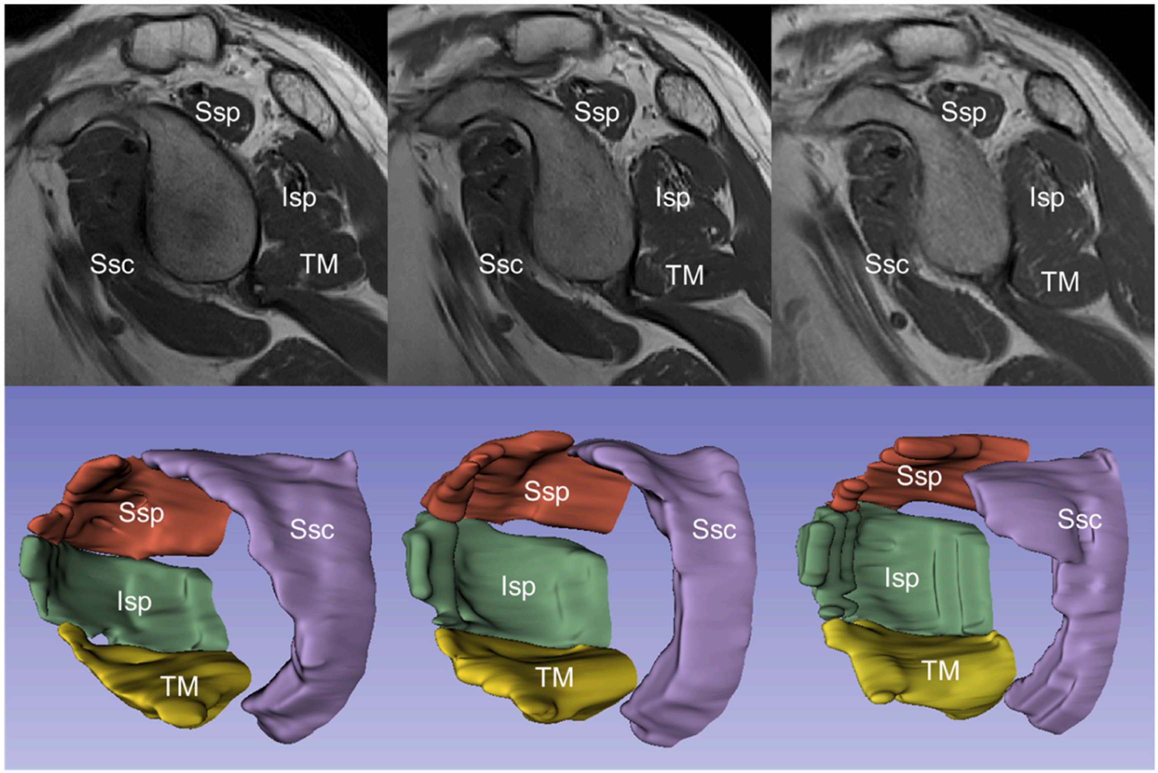
		Preoperatively	Postoperatively					
			3 months postoperatively		6 months postoperatively		12 months postoperatively	
Muscle	Section	Volume (ml)	Volume (ml)	P-value*	Volume (ml)	P-value**	Volume (ml)	P-value***
Supraspinatus	GL section	5.42 ± 1.94	6.06 ± 1.92	**0.031**	6.24 ± 1.78	0.219	5.89 ± 1.96	0.372
	Y section	11.09 ± 3.64	11.26 ± 3.33	0.696	11.77 ± 3.18	0.096	11.54 ± 3.65	0.360
Infraspinatus	GL section	7.76 ± 2.72	8.52 ± 3.04	**0.045**	8.52 ± 2.67	0.979	8.24 ± 2.51	0.387
	Y section	16.05 ± 4.76	16.11 ± 5.26	0.932	16.59 ± 4.70	0.306	16.42 ± 4.75	0.585
Teres minor	GL section	7.75 ± 2.95	7.45 ± 2.20	0.428	7.91 ± 2.57	0.063	7.41 ± 2.86	0.874
	Y section	12.95 ± 3.93	12.48 ± 3.52	0.213	12.85 ± 3.85	0.322	12.78 ± 4.08	0.323
Subscapularis	GL section	9.59 ± 3.68	9.11 ± 3.78	0.349	9.10 ± 3.63	0.988	10.24 ± 4.59	**0.031**
	Y section	24.78 ± 7.16	23.90 ± 7.75	0.466	24.32 ± 7.81	0.653	26.17 ± 8.98	0.069

Data are presented as means ± standard deviation. Sectional volume measurements of each shoulder muscle were performed as follows: the GL section, from the most lateral end of the tendons to the plane of the glenoid labrum (GL plane); and the Y section, from the most lateral end of the tendons to the Y-view plane. No statistically significant differences were observed for most of the serial changes in muscle volumes. Statistically significant differences were observed between the preoperative and 3 months postoperative values for the supraspinatus and infraspinatus muscle volumes in the GL section, and between 3 and 12 months postoperatively for the subscapularis in the GL section.

* Comparison between the values obtained preoperatively and at 3 months postoperatively.

** Comparison between the values obtained at 3 and 6 months postoperatively.

*** Comparison between the values obtained at 3 and 12 months postoperatively.



Volume (ml)	Preoperatively	Three months postoperatively	Twelve months postoperatively
Supraspinatus (Ssp)	4.09	4.26	3.47
Infraspinatus (Isp)	6.89	7.87	7.39
Teres minor (TM)	6.14	5.96	6.79
Subscapularis (Ssc)	14.52	8.38	7.87

Fig. 3. An example (57-year-old female with a middle size tear) of the serial volume changes in four shoulder muscles after arthroscopic rotator cuff repair measured by our 3D sectional approach. Proton density-weighted images in the sagittal planes passing through the glenoid labrum (GL) (at the top row) and the 3D models dissected by the GL planes (at the middle row) were shown. The tear-site muscles (supraspinatus and infraspinatus) showed similar tendencies for volume changes, whereas those for the non-tear site muscles (teres minor and subscapularis) differed.

coefficient. No significant correlations were observed between any of the variables in the subscapularis.

4. Discussion

In this investigation, we focused on serial volume changes in each shoulder muscle after ARCR by a novel 3D modeling-based sectional measurement. The findings revealed that the perioperative muscle volume changes in the supraspinatus and infraspinatus were different from those in the teres minor and subscapularis. Volume changes between 3 and 12 months postoperatively were negatively correlated with those preoperatively and 3 months postoperatively for the supraspinatus, infraspinatus, and teres minor. Moreover, postoperative volume differences might correlate with tear size and symptom duration in the supraspinatus as well as with a history of steroid injections and work and sports activity levels for the infraspinatus and teres minor.

The 3D modeling-based volume measurements have recently attracted significant attention in the field of medical imaging. In musculoskeletal imaging, the quantitative evaluation of sequential imaging has mainly been performed on a single 2D slice. The development of 3D modeling tools has made volume measurements more accurate and easier. Notably, in the area of shoulder joint, Chung et al. (2017) evaluated serial changes in supraspinatus muscle volume after ARCR [22]. They measured the sectional volume of the supraspinatus dissected in the vertical plane and reported an increase in the supraspinatus muscle volume postoperatively compared to that preoperatively. The present study applied the same 3D modeling-based sectional approach to multiple shoulder muscles to discern the interrelationship between them. Intriguingly, our research revealed a distinction between tear- and non-tear site-specific perioperative muscle volume changes. This observation could stem from the notion that the rotator cuff tendons blend and form a united collar and that coordinative and complementary behavior could be expected in these muscles [24,25].

Preoperative muscle changes at the tear site include atrophy, retraction, and fatty infiltration induced by tendon tears. Tears occur primarily in the posterosuperior rotator cuff, which corresponds to the muscle-tendon unit of the supraspinatus and infraspinatus. Larger tendon tears are associated with severe atrophy and retraction of the supraspinatus and infraspinatus muscles [31]. Furthermore, large rotator cuff tears have been shown to cause traction of the suprascapular nerve, potentially contributing to the progression of atrophy and fatty infiltration of both the supraspinatus and infraspinatus [32,33]. Tear

Table 4
Volume differences between the two perioperative periods and their correlations.

Muscle	Section	Volume difference between the values obtained preoperatively and at 3 months postoperatively (ml) (Dif.pre.3mo)	Volume difference between the values obtained at 3 and 12 months postoperatively (ml) (Dif.3.12mo)	Correlation* Value	Correlation* P-value	Volume difference between the values obtained preoperatively and at 12 months postoperatively (ml) (Dif.pre.12mo)	Correlation** Value	Correlation** P-value
Supraspinatus	GL section	0.64 ± 1.60	0.47 ± 1.53	-0.400	0.021	-0.17 ± 1.07	0.767	<0.001
	Y section	0.17 ± 2.50	0.46 ± 2.44	-0.379	0.030	0.28 ± 1.72	0.756	<0.001
Infraspinatus	GL section	0.76 ± 2.06	0.48 ± 1.81	-0.574	<0.001	-0.29 ± 1.84	0.555	0.001
	Y section	0.06 ± 3.89	0.37 ± 3.11	-0.631	<0.001	0.31 ± 3.20	0.601	<0.001
Teres minor	GL section	-0.30 ± 2.09	-0.34 ± 1.77	-0.552	0.001	-0.04 ± 1.47	0.720	<0.001
	Y section	-0.47 ± 2.10	-0.17 ± 1.85	-0.539	0.001	0.30 ± 1.68	0.645	<0.001
Subscapularis	GL section	-0.48 ± 2.87	0.64 ± 4.34	0.165	0.359	1.13 ± 2.82	0.768	<0.001
	Y section	-0.89 ± 6.81	1.39 ± 8.10	-0.298	0.092	2.28 ± 6.86	0.588	<0.001

Data are presented as means ± standard deviation. Differences in muscle volume preoperatively and 3 months postoperatively (Dif.pre.3mo), between 3 and 12 months postoperatively (Dif.3.12mo), and between preoperatively and 12 months postoperatively (Dif.pre.12mo) were evaluated. Sectional volume measurement of each shoulder muscle was performed as follows: GL section, from the most lateral end of the tendons to the plane of the glenoid labrum (GL plane), and the Y section, from the most lateral end of the tendons to the Y-view plane. For the supraspinatus, infraspinatus, and teres minor, a statistically significant negative correlation was observed between Dif.pre.3mo and Dif.3.12mo. The postoperative changes in the supraspinatus and infraspinatus muscle volumes showed a different trend from those of the teres minor and subscapularis.

* Correlation between Dif.pre.3mo and Dif.3.12mo.

** Correlation between Dif.pre.3mo and Dif.pre.12mo.

Table 5
Comparison between perioperative volume differences of the supraspinatus and clinical and demographic parameters using multivariate analysis.

	Dif.pre.3mo				Dif.3.12mo				Dif.pre.12mo			
	GL section		Y section		GL section		Y section		GL section		Y section	
	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value
Age, years	18.95	0.639	-1.1149	0.988	-18.55	0.540	-27.24	0.626	4.20	0.801	-28.36	0.684
Sex	11.15	0.988	-274.91	0.829	-414.62	0.465	-227.49	0.810	-487.71	0.927	-502.39	0.671
Side	157.65	0.804	1343.88	0.246	-161.21	0.734	-67.85	0.936	104.62	0.534	1276.03	0.234
Symptom duration	-54.70	**0.028**	-40.71	0.332	37.77	**0.041**	51.24	0.108	-4.09	0.880	10.53	0.783
Trauma onset	157.80	0.788	290.44	0.783	284.94	0.519	-263.22	0.736	151.26	0.872	27.22	0.978
Sports activity level	289.49	0.614	497.36	0.628	-343.91	0.426	101.49	0.894	89.93	0.815	598.85	0.529
Work level	-237.78	0.605	-197.25	0.831	256.31	0.458	482.21	0.485	88.60	0.886	284.95	0.739
History of steroid injections	143.60	0.824	438.71	0.708	-956.37	0.059	-572.80	0.511	-534.66	0.876	-134.09	0.901
Diabetes	1244.07	0.083	1840.84	0.134	-363.26	0.485	57.97	0.947	952.50	0.458	1898.81	0.097
Tear size	1478.77	**0.011**	3040.75	**0.015**	-296.21	0.466	-547.56	0.519	1131.65	0.201	2493.19	**0.028**
Tear location	-528.39	0.465	-1146.55	0.373	-101.44	0.850	-63.63	0.946	-574.00	0.118	-1210.17	0.311
Preoperative range of motion												
Forward flexion	-19.79	0.416	-36.84	0.359	15.13	0.418	16.90	0.567	-4.65	0.848	-19.94	0.589
Abduction	8.85	0.590	12.35	0.648	-13.79	0.281	-19.37	0.339	-4.93	0.765	-7.02	0.778

repair can alleviate tension on the nerve and ultimately allow recovery of the two muscles. Therefore, the recovery of muscle volume is expected in these muscles after successful repair.

However, previous studies have remained controversial regarding the reversibility of muscle atrophy after surgical repair; changes in muscle volume after surgery vary from increasing to decreasing [14,15]. Some studies have indicated that atrophy is irreversible regardless of successful healing or failure, whereas others have shown that it is reversible [5–8]. These studies were performed as 2D cross-sectional evaluations of muscles on a single image slice in the conventional Y-view plane. Lateralization of the myotendinous unit after repair is considered to alter the assessment plane, and thereby resulting in an immediate increase in the muscle occupation ratio. The 3D volumetric measurements are ideal, considering that 2D data fail to represent the actual 3D volume. Recently, Xu et al. reported that the entire 3D volume and fatty infiltration of the supraspinatus showed no statistical changes preoperatively and 12 months postoperatively [23]. Notably, in our study, no significant differences were found in most of the serial changes in muscle volume. Compared with 2D evaluation, 3D muscle volume measurement may be less affected by surgical modification and is less likely to show statistical differences. Furthermore, the present study found a negative correlation between muscle volume changes at the early and late postoperative time points. Xu et al. also suggested that the 3D muscle volume of the supraspinatus decreased transiently during the first 3months but recovered to baseline at 12 months postoperatively [23]. Through direct reinsertion of the tendon, the repaired tendon and muscle would stretch longer than that before the tear [34]. According to our hypothesis, the tension or loosening of the muscle-tendon units caused by repair surgery might lead to a temporary increase or decrease in volume, which is then gradually reversed by mechanical reloading of the repaired tendon.

Our study revealed that the behavior of the teres minor and subscapularis differed from that of the supraspinatus and infraspinatus. In theory, torn muscle-tendon units, particularly the supraspinatus and

Table 6
Comparison between perioperative volume differences of the infraspinatus and clinical and demographic parameters using multivariate analysis.

	Dif.pre.3mo				Dif.3.12mo				Dif.pre.12mo			
	GL section		Y section		GL section		Y section		GL section		Y section	
	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value
Age, years	41.69	0.445	18.14	0.876	42.92	0.299	96.60	0.192	82.55	0.233	114.73	0.315
Sex	850.07	0.359	-135.01	0.945	499.56	0.515	1727.80	0.169	1267.72	0.278	1592.79	0.408
Side	-503.83	0.539	-711.94	0.684	466.67	0.470	1006.57	0.361	44.90	0.965	294.62	0.862
Symptom duration	-76.45	**0.018**	-80.40	0.218	51.09	**0.041**	65.49	0.112	-19.36	0.605	-14.91	0.810
Traumatic onset	40.48	0.957	-87.27	0.957	961.15	0.117	1294.39	0.210	772.30	0.420	1207.12	0.447
Sports activity level	433.04	0.558	-92.16	0.953	-1070.09	0.076	-387.31	0.693	-615.69	0.507	-479.47	0.754
Work level	-1189.40	0.087	-1437.61	0.320	932.51	0.055	1475.50	0.109	-52.82	0.949	37.89	0.978
History of steroid injections	1192.42	0.168	2514.89	0.174	-2552.07	**0.001**	-3524.39	**0.005**	-1079.94	0.312	-1009.50	0.565
Diabetes	1645.81	0.067	2901.45	0.125	-1477.20	**0.045**	-1722.67	0.142	245.60	0.818	1178.77	0.509
Tear size	380.22	0.644	301.06	0.864	-875.14	0.120	-175.89	0.872	-412.76	0.688	125.17	0.941
Tear location	257.02	0.779	1135.00	0.564	158.66	0.827	-1268.22	0.306	478.14	0.677	-133.23	0.944
Preoperative range of motion												
Forward flexion	11.29	0.693	18.45	0.763	5.17	0.835	-3.20	0.933	16.46	0.646	15.24	0.797
Abduction	-3.35	0.863	-22.23	0.594	-13.93	0.414	-18.20	0.484	-17.28	0.480	-40.43	0.323

Table 7
Comparison between perioperative volume differences of the teres minor and clinical and demographic parameters using multivariate analysis.

	Dif.pre.3mo				Dif.3.12mo				Dif.pre.12mo			
	GL section		Y section		GL section		Y section		GL section		Y section	
	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value
Age, years	4.33	0.938	-28.62	0.586	43.39	0.166	61.21	0.144	36.93	0.547	24.10	0.699
Sex	138.44	0.882	-462.86	0.603	-102.68	0.858	-80.06	0.916	-9.39	0.993	-632.29	0.550
Side	59.07	0.944	-173.93	0.826	-326.50	0.501	-459.73	0.476	-276.23	0.764	-592.16	0.530
Symptom duration	8.91	0.770	25.70	0.378	21.12	0.244	9.72	0.682	36.03	0.290	47.50	0.176
Traumatic onset	-909.33	0.249	-635.20	0.391	1187.81	**0.014**	798.88	0.188	234.54	0.783	-41.45	0.962
Sports activity level	77.12	0.918	12.37	0.986	-1223.05	**0.010**	-1361.68	**0.027**	-921.64	0.274	-1076.65	0.213
Work level	-424.63	0.535	-756.75	0.249	860.95	**0.021**	1022.93	**0.037**	262.10	0.727	160.05	0.834
History of steroid injections	1033.39	0.238	1510.30	0.076	-1893.49	**0.001**	-1847.85	**0.009**	-730.45	0.444	-71.40	0.941
Diabetes	-309.94	0.722	-369.24	0.655	-379.49	0.473	-27.78	0.968	-560.39	0.561	-245.14	0.802
Tear size	-970.42	0.256	-869.27	0.281	-568.87	0.175	-290.88	0.596	-1390.07	0.145	-1067.77	0.265
Tear location	354.18	0.705	558.14	0.530	343.42	0.531	-138.40	0.849	556.84	0.590	335.47	0.750
Preoperative range of motion												
Forward flexion	24.44	0.407	18.59	0.503	-10.32	0.578	-9.88	0.679	14.13	0.661	8.71	0.790
Abduction	-21.61	0.283	-22.87	0.232	3.66	0.770	-0.88	0.956	-17.95	0.415	-23.75	0.294

Table 8
Comparison between perioperative volume differences of the subscapularis and clinical and demographic parameters using multivariate analysis.

	Dif.pre.3mo				Dif.3.12mo				Dif.pre.12mo			
	GL section		Y section		GL section		Y section		GL section		Y section	
	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value	RC	P-value
Age, years	-43.25	0.613	21.08	0.924	-56.97	0.501	-83.11	0.693	-100.23	0.452	-62.03	0.800
Sex	-2385.97	0.111	-6260.67	0.106	-54.67	0.969	3258.87	0.365	-2440.65	0.284	-3001.81	0.473
Side	1145.98	0.378	3373.64	0.317	-346.64	0.785	-243.59	0.939	799.33	0.689	3130.05	0.402
Symptom duration	53.55	0.262	127.89	0.299	10.83	0.815	-73.74	0.526	64.38	0.381	54.15	0.689
Traumatic onset	-1224.56	0.311	-1391.73	0.652	-1318.23	0.272	-2453.48	0.408	-2542.79	0.181	-3845.21	0.271
Sports activity level	391.59	0.736	-2723.43	0.369	741.11	0.520	2806.07	0.332	1132.70	0.531	82.64	0.980
Work level	307.47	0.769	3439.65	0.214	706.97	0.497	-94.13	0.971	1014.44	0.535	3345.52	0.275
History of steroid injections	-882.42	0.507	1145.24	0.738	1643.51	0.219	3331.50	0.314	761.30	0.711	4476.73	0.249
Diabetes	-2063.74	0.137	-3854.68	0.275	1670.51	0.218	5335.00	0.120	-393.23	0.850	1480.31	0.702
Tear size	916.43	0.481	2505.40	0.456	-873.41	0.496	-890.35	0.780	43.02	0.983	1615.05	0.664
Tear location	-3.20	0.998	385.60	0.917	-535.38	0.707	-1620.83	0.649	-538.56	0.810	-1235.23	0.766
Preoperative range of motion												
Forward flexion	-41.13	0.366	-108.93	0.354	43.85	0.330	137.64	0.224	2.72	0.969	28.71	0.824
Abduction	12.59	0.680	8.49	0.914	-21.32	0.483	-86.42	0.259	-8.73	0.854	-77.93	0.380

infraspinatus, cannot participate in load sharing, thereby increasing the load on the remaining rotator cuff tendons. We hypothesized that this might cause relative hypertrophy of the remaining muscles, such as the teres minor, and that postoperatively, the remaining muscles could return to their original volume as the repaired muscle tendon volume increases. In addition, the subscapularis, which primarily acts as the anterior part of the axial force couple of the shoulder muscles, may provide a posterior driving force for the posterior counterpart tears [35]. In our opinion, this driving force would cause a relative volume increase in the subscapularis muscle-tendon unit, which would return to its original balance postoperatively. However, this situation might be more complicated than previously thought because the force couple of the shoulder muscles is considered to be based on multidirectional balance [36].

The clinical implications of postoperative volume changes may differ between primary and nonprimary tear sites. Regarding the primary tear site, tear size and symptom duration correlated with postoperative muscle volume changes in our study. Naturally, a temporary volume change occurs at the primary tear location and depends on tear size. For symptom duration, recovery from muscle volume loss is more difficult and takes longer in chronic rotator cuff tears than in acute tears because chronic tears can cause irreversible changes in structure (e.g., fibrosis) and increased muscle stiffness and tension reduce repair and healing potential [37]. In contrast, for the non-primary site of the tear, recovery from perioperative wasting and atrophy is thought to occur primarily rather than changes directly related to tears. Therefore, preoperative history and life activity levels correlated with postoperative muscle volume differences in our results. Diabetes is the well-known cause of impaired tissue repair, and it has been shown to be associated with worse postoperative clinical outcomes [38]. Additionally, corticosteroid treatment has been suggested to reduce inflammation, thereby considerably suppressing tissue repair process [39]. However, whether a history of transient steroid injection influences the late postoperative stages remains unclear. Continued force application during daily activities is also important in the process of muscle volume recovery [40]. A previous study suggested that 10 %–20 % of patients who underwent ARCR could not return to their preoperative activity levels [41]. Preoperative factors such as sex, workload, chronicity, and tear size may contribute to the rate and duration of return to daily activity levels [26].

Muscle volume recovery is necessary for an early return to daily life, and there are two types of recovery processes depending on the site; focal tear healing for the primary site of the tear, whereas recovery of perioperative wasting and atrophy for the non-primary tear site. Clinically, these postoperative site-specific changes in muscle volume are particularly important in rehabilitation therapy. We can support the recovery of non-tear site muscles to allow a faster postoperative return to daily life, while adequate curation of tears is expected at the focal tear site. Therefore, in the future, our method will be utilized to select the optimal treatment for muscle recovery and prevent the progression of postoperative muscle atrophy.

Our study had several limitations. First, the major limitation of this study was its small sample size. Not all patients with rotator cuff tears were included in this study because we limited our study to those who underwent all four consecutive MRI scans and did not subscapularis tendon tears. As our study adopted a retrospective analysis, the exclusion of a large number of patients was inevitable and would have caused a selection bias. Additionally, because this was a single-center study, there are problems with its generalizability. Therefore, in the future, we will endeavor to prospectively obtain and analyze consecutive postoperative MRI scans for all patients with rotator cuff tears and at multiple centers, if possible. Second, this study lacked statistically significant results for many comparisons. There are several possible explanations for these results. A small sample size can reduce the accuracy of statistical analysis. The sectional measurement we adopted could have led to an underestimation of the relative volume changes. In addition, differences in MRI positioning may have influenced the results of the sectional approach. The ideal method for precisely evaluating muscle volume recovery is to measure whole muscle volume. Therefore, in the future, we must assess the reproducibility and reliability of the sectional approach by comparing it with whole-muscle measurements.

5. Conclusions

In summary, our sectional volume measurements have the capacity to assess continuous volume changes in multiple shoulder muscles after ARCR. Postoperative changes in muscle volume are considered to differ depending on the primary and non-primary tear sites, and the associated clinical implications may also be different for each site. Our method may serve as a potential indicator to facilitate optimal treatment for muscle recovery and prevent the progression of postoperative muscle atrophy. However, this study lacked statistically significant results for several comparisons. Further studies are needed to evaluate the efficacy of our method, and various background factors should be carefully considered when correlating changes in muscle volume.

Ethics approval and consent to participate

This study was approved by the Research Ethics Committee of the Saitama Medical University Hospital (approval number 2022–073). All experiments were performed in accordance with relevant guidelines and regulations. The requirement for informed consent was waived by the Research Ethics Committee of Saitama Medical University Hospital.

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Consent for publication

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CRediT authorship contribution statement

Kaiji Inoue: Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Conceptualization. **Koichiro Matsuura:** Formal analysis, Data curation. **Hirokazu Shimizu:** Formal analysis, Data curation. **Yuki Hara:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Mamoru Niitsu:** Writing – review & editing, Conceptualization. **Katsunobu Sakaguchi:** Writing – review & editing, Resources, Project administration. **Eito Kozawa:** Writing – review & editing. **Keita Nagawa:** Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no competing interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejro.2024.100577.

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