# Assessments of Fatty Infiltration and Muscle Atrophy From a Single Magnetic Resonance Image Slice Are Not Predictive of 3-Dimensional Measurements

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**Purpose:** To (1) determine whether standard clinical muscle fatty infiltration and atrophy assessment techniques using a single image slice for patients with a rotator cuff tear (RCT) are correlated with 3-dimensional measures in older individuals (60+ years) and (2) to determine whether age-associated changes to muscle morphology and strength are compounded by an RCT. **Methods:** Twenty older individuals were studied: 10 with an RCT of the supraspinatus (5 men and 5 women) and 10 matched controls. Clinical imaging assessments (Goutallier and Fuchs scores and cross-sectional area ratio) were performed for participants with RCTs. Three-dimensional measurements of rotator cuff muscle and fat tissues were obtained for all participants using magnetic resonance imaging (MRI). Isometric joint moment was measured at the shoulder. **Results:** There were no significant associations between single-image assessments and 3-dimensional measurements of fatty infiltration for the supraspinatus and infraspinatus muscles. Compared with controls, participants with RCTs had significantly increased percentages of fatty infiltration for each rotator cuff muscle (all $P \leq .023$); reduced whole muscle volume for the supraspinatus, infraspinatus, and subscapularis muscles (all $P \leq .038$); and reduced fat-free muscle volume for the supraspinatus, infraspinatus, and subscapularis muscles (all $P \leq .027$). Only the teres minor ($P = .017$) fatty infiltration volume was significantly greater for participants with RCTs. Adduction, flexion, and external rotation strength (all $P \leq .021$) were significantly reduced for participants with RCTs, and muscle volume was a significant predictor of strength for all comparisons. **Conclusions:** Clinical scores using a single image slice do not represent 3-dimensional muscle measurements. Efficient methods are needed to more effectively capture 3-dimensional information for clinical applications. Participants with RCTs had increased fatty infiltration percentages that were likely driven by muscle atrophy rather than increased fat volume. The significant association of muscle volume with strength production suggests that treatments to preserve muscle volume should be pursued for older patients with RCTs. **Level of Evidence:** Level II, diagnostic study, with development of diagnostic criteria on the basis of consecutive patients with universally applied reference gold standard.

*See commentary on page 140*

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Rotator cuff tears (RCTs) are a common musculoskeletal injury in older individuals. It is estimated that 20% to 50% of those 60+ years of age have a known RCT and up to 65% of those older than 70 years have an asymptomatic RCT, and prevalence increases with age.[1-4] RCTs are associated with muscle atrophy and fatty infiltration,[5-8] and fatty infiltration may affect muscle tissue recovery after a tear in older individuals.[9] Clinicians evaluate atrophy and fatty infiltration when developing treatment plans for patients with RCTs. High levels of fatty infiltration are a contraindication for rotator cuff tendon repair because of the high likelihood of a poor surgical outcome, increased likelihood of a retear, and no reversal of the fatty infiltration after surgery.[5,10,11] Traditionally, computed tomography and magnetic resonance imaging (MRI) have been used to evaluate the muscle to fat ratio of rotator cuff muscles, as described by Goutallier et al.[5] and Fuchs et al.,[12] respectively. Atrophy is also frequently assessed from a single image slice, using muscle cross-sectional area as a surrogate.[13] However, these clinical methods consider only a single image slice to view the rotator cuff muscle bellies, selected for consistency of anatomic landmarks. One image cannot fully capture morphologic changes in other areas of the muscle,[14] but little work has focused on the acquisition of 3-dimensional measurements of muscle morphology to evaluate whether a single image is indicative of 3-dimensional muscle information. Further, the Goutallier score does not have high reliability,[15-18] suggesting that more objective methods should be used.[15,16]

Physiologic and morphologic changes accompanying rotator cuff injury are also observed during healthy aging,[19] which may cloud the presentation of injury in older patients. Older adults exhibit muscle atrophy, fatty infiltration, and strength deficits even in the absence of musculoskeletal injury.[19,20] Thus when working with older adults with RCTs, it is difficult to determine whether measured deficits result from injury or age alone. Such an understanding is critical to creating an effective care plan and maintenance of function in older adults. For example, muscle atrophy may be an important contributor to strength deficits seen in patients with RCTs.[10,11] Muscle volume is a significant predictor of upper limb strength,[21-23] and maintenance of a minimal strength threshold is necessary to perform functional upper limb tasks.[20] Strength is critical to older adults' ability to maintain independence,[1] although the mechanisms relating muscle morphology to function in older adults with RCTs are not clear.

The purposes of this study were (1) to determine whether standard clinical muscle fatty infiltration and atrophy assessment techniques using a single image slice for patients with RCTs would be correlated with 3-dimensional measures in older individuals (60+ years) and (2) to determine whether age-associated changes to muscle morphology and strength would be compounded by an RCT. It was hypothesized that (1) single-image assessments would be correlated with muscle morphology and (2) patients with RCTs would have less muscle volume, greater fat volume, and reduced strength compared with controls and that muscle volume would be correlated with strength.

## Methods

This study was approved by the Wake Forest University Health Sciences Institutional Review Board, and written informed consent was provided by all participants. A sample of 20 participants (mean age, 63.6 ± 1.6 years)—10 with degenerative supraspinatus tears and 10 age- and sex-matched controls (Table 1)—was recruited to prospectively evaluate the applicability of measuring 3-dimensional muscle morphology to identify the association between single-image assessments and 3-dimensional measurements in an older adult group. Participants with RCTs were recruited from the outpatient clinics of C.J.T., G.G.P., and M.T.F. from October 2011 to September 2013; one patient (M05) approached the study team regarding participation. The presence of supraspinatus tearing was independently confirmed by all 3 orthopaedic surgeon authors. After physician assessment, the medical records of potential participants were reviewed to ensure that eligibility criteria was met (Fig 1) before recruitment. Control participants were recruited from the community through a newsletter advertisement (Fig 1). Potential control participants were screened with a telephone questionnaire and a modified Jobe's test.[24] The injured side was evaluated for participants with RCTs, and the dominant side was evaluated for controls.

### Single-Image Assessments

Three orthopaedic surgeons (C.J.T., G.G.P., M.T.F.) independently evaluated each participant with an RCT to assign a Goutallier score. Evaluations were performed by each surgeon twice, with reviews separated by 1 week. Surgeons were blinded to patient identity, and the order in which patients were reviewed was randomized. Assessment was made using a standard T1-weighted MRI scan available from each patient's medical record. For one participant, a T1-weighted scan was not available, so that participant was excluded from these analyses. A Goutallier score was assigned to each rotator cuff muscle according to the methods of Goutallier,[5] as modified by Fuchs,[12] in which the image slice immediately lateral to the scapular spine's attachment to the body of the scapula was evaluated. Assessment of the Goutallier score, which ranges from 0 (no fat visible in the muscle) to 4 (more fat than muscle tissue is visible), was made for the supraspinatus, infraspinatus,

**Table 1.** Participant Demographics for Rotator Cuff Tear and Control Participants

| Participant | Age, yr | Height, cm | Body Mass, kg | Dominant Arm | Injured Arm | Supraspinatus | Infraspinatus | Subscapularis | Teres Minor | SF-36 Pain Score |
|---|---|---|---|---|---|---|---|---|---|---|
| RF01 | 64 | 162.6 | 58.5 | Right | Right | Partial-thickness tear | No tear | No tear | No tear | 20 |
| RF02 | 65 | 165.1 | 83.9 | Right | Right | Full-thickness tear | No tear | No tear | No tear | 40 |
| RF03 | 65 | 149.9 | 53.5 | Right | Left | Full-thickness tear | Tear | Tear | No tear | 40 |
| RF04 | 63 | 160 | 73.5 | Right | Right | Full-thickness tear | Tear | No tear | No tear | 40 |
| RF05 | 65 | 162.6 | 65.8 | Right | Left | Partial-thickness tear | No tear | Tear | No tear | 40 |
| RM01 | 64 | 175.3 | 73 | Right | Left | Partial-thickness tear | No tear | Possible tear | No tear | 40 |
| RM02 | 61 | 167.6 | 83.9 | Right | Left | Full-thickness tear | Tear | No tear | No tear | 40 |
| RM03 | 64 | 177.8 | 108 | Left | Left | Full-thickness tear | Tear | No tear | No tear | 40 |
| RM04 | 64 | 182.9 | 88.5 | Right | Left | Full-thickness tear | Tear | Tear | No tear | 40 |
| RM05 | 62 | 177.8 | 95.3 | Left | Left | Partial-thickness tear | Possible tear | Possible tear | No tear | 40 |
| CF01 | 64 | 152.4 | 74.8 | Left | – | – | – | – | – | 40 |
| CF02 | 63 | 172.7 | 54.4 | Right | – | – | – | – | – | 80 |
| CF03 | 67 | 172.7 | 70.8 | Right | – | – | – | – | – | 80 |
| CF04 | 65 | 162.6 | 65.8 | Right | – | – | – | – | – | 100 |
| CF05 | 64 | 160 | 60.3 | Right | – | – | – | – | – | 100 |
| CM01 | 64 | 172.7 | 70.3 | Right | – | – | – | – | – | 20* |
| CM02 | 61 | 177.8 | 99.8 | Right | – | – | – | – | – | 60 |
| CM03 | 64 | 182.9 | 86.2 | Right | – | – | – | – | – | 100 |
| CM04 | 62 | 172.7 | 73.5 | Right | – | – | – | – | – | 100 |
| CM05 | 61 | 175.3 | 70.3 | Right | – | – | – | – | – | 60 |
| Rotator Cuff Tear, Mean ± SD | 63.7 ± 1.3 | 168.1 ± 10.1 | 78.4 ± 16.8 | | | | | | | 38.0 ± 6.3 |
| Control, Mean ± SD | 63.5 ± 1.8 | 170.2 ± 9.1 | 72.6 ± 12.8 | | | | | | | 74.0 ± 28.4 |
| Difference between groups | 0.2 ($P = .66$) | 2.1 ($P = .32$) | 5.8 ($P = .18$) | | | | | | | 36.0 ($P < .01$) |

The tear characteristics corresponding to the magnetic resonance image in each rotator cuff tear (RCT) participant's medical record are also reported. Supraspinatus tears are described as either full- or partial-thickness tears, whereas the remaining tendons are denoted as to whether or not tearing was observed. In cases in which the radiologist's report could not make a definitive determination regarding the tear status, in correspondence with the report, a possible tear is reported. Pain assessments from the pain category of the RAND 36-Item Short Form Health Survey (Medical Outcomes Study: 36-Item Short Form Survey Instrument, RAND Health, Santa Monica, CA) are reported; scores can range from 0-100, where a score of 100 is the best possible score, indicating no pain. Differences between groups were assessed with a *t* test, with significance considered to be $P \leq .05$.

CF, control group, female; CM, control group, male; RF, rotator cuff tear group, female; RM, rotator cuff tear group, male; SD, standard deviation; SF-36, 36-Item Short Form.

*Participant reported unrelated lower back pain.

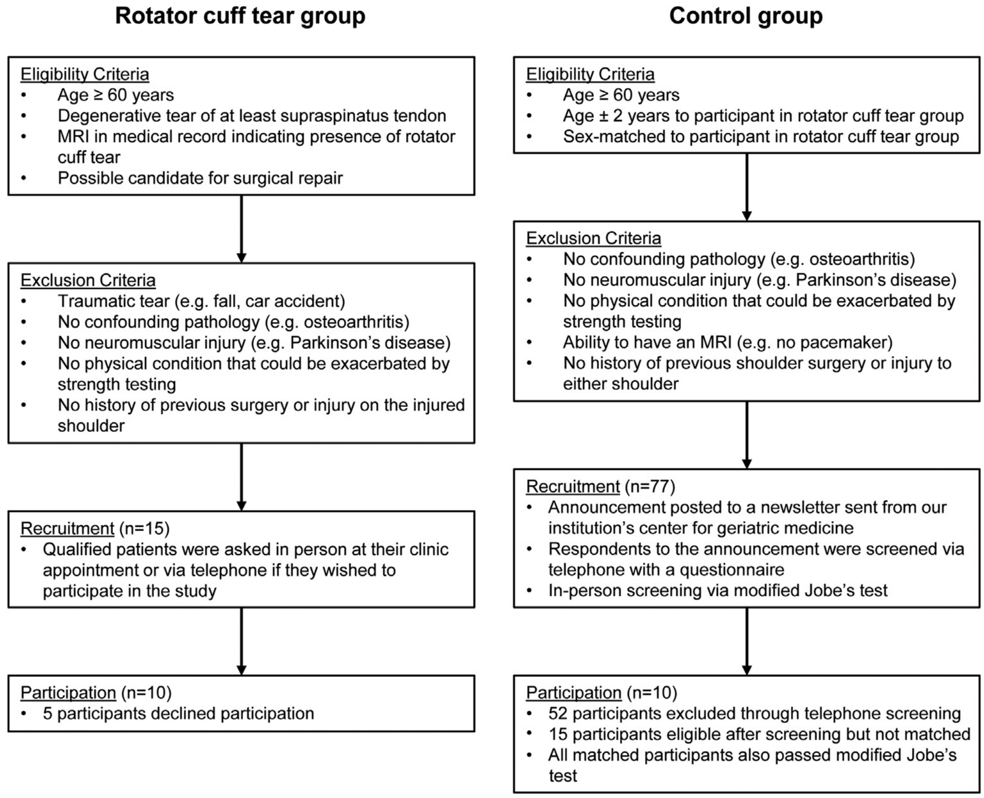


**Fig 1.** Study participant recruitment flow chart. The left side of the chart shows the recruitment criteria and process for participants with a rotator cuff tear (RCT), and the right side of the chart shows the recruitment criteria and process for participants in the control group. (MRI, magnetic resonance imaging.)

subscapularis, and teres minor muscles. Because it is thought to improve interobserver reliability,[12] Goutallier scores were translated into the corresponding Fuchs score, which includes 3 stages (Fuchs stage 0 = Goutallier scores 0 and 1; Fuchs stage 1 = Goutallier score 2; Fuchs stage 2 = Goutallier scores 3 and 4). Each physician's score from both reviews was used to calculate a mean Goutallier score and a mean Fuchs score, which were used in subsequent analyses. The range of assigned scores is shown in Table 2.

**Table 2.** Range of Goutallier Score and Fuchs Score, and Mean CSA Ratios for Each Participant With a Rotator Cuff Tear

| | RF01 | RF02 | RF03 | RF04 | RF05 | RM01 | RM02 | RM03 | RM04 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Goutallier score | | | | |
| Supraspinatus score range | 1-3 | 2 | 1-4 | 0-2 | 1-2 | 1-2 | 1-4 | 1-3 | 1-2 |
| Infraspinatus score range | 0-1 | 2 | 2-4 | 0-1 | 0-2 | 0-1 | 0-2 | 0-2 | 0-1 |
| Teres minor score range | 0 | 2-4 | 0-3 | 0-3 | 0-1 | 0 | 0-2 | 0-3 | 0-1 |
| Subscapularis score range | 0-1 | 1 | 2-4 | 0-1 | 0-2 | 0-1 | 0-1 | 0-2 | 0-1 |
| | | | | | Fuchs score | | | | |
| Supraspinatus score range | 0-2 | 1 | 0-2 | 0-1 | 0-1 | 0-1 | 0-2 | 0-2 | 0-1 |
| Infraspinatus score range | 0 | 1 | 1-2 | 0 | 0-1 | 0 | 0-1 | 0-1 | 0 |
| Teres minor score range | 0 | 1-2 | 0-2 | 0-2 | 0 | 0 | 0-1 | 0-2 | 0 |
| Subscapularis score range | 0 | 0 | 1-2 | 0 | 0-1 | 0 | 0 | 0-1 | 0 |
| | | | | | CSA ratio | | | | |
| Supraspinous fossa area | 5.1 | 5.8 | 5.2 | 4.2 | 4.8 | 5.7 | 3.8 | 8.6 | 6.4 |
| Supraspinatus CSA ratio | 0.5 | 0.5 | 0.5 | 1.2 | 0.6 | 0.7 | 1.0 | 0.6 | 1.1 |
| Infraspinatus CSA ratio | 1.2 | 1.4 | 0.6 | 1.7 | 1.1 | 1.0 | 2.7 | 1.6 | 1.2 |
| Teres minor CSA ratio | 0.9 | 0.4 | 0.4 | 0.1 | 0.3 | 1.0 | 1.5 | 0.8 | 0.5 |
| Subscapularis CSA ratio | 3.0 | 1.5 | 0.5 | 1.5 | 2.0 | 2.2 | 3.4 | 1.4 | 1.9 |

Goutallier scores were assigned individually by 3 orthopaedic surgeons at 2 reviews separated by at least 1 wk. Goutallier scores were converted into their corresponding Fuchs score. Cross-sectional area ratios were calculated by taking the mean measurements from 2 reviewers.

CSA, cross-sectional area; RF, rotator cuff tear group, female; RM, rotator cuff tear group, male.

Cross-sectional area ratio, which is a clinical measure used to describe muscle atrophy, was calculated for patients with RCTs using the segmentation methods of Zanetti et al.[13] Briefly, these methods entail calculation of cross-sectional areas of the supraspinatus, total infraspinatus, total subscapularis, teres minor, and supraspinatus fossa by tracing their boundaries using the measurement tool included with the MR viewing software (iSite PACS; Philips Healthcare Informatics, Foster City, CA). Two reviewers (M.E.V., A.C.S.) calculated cross-sectional areas, and the mean value between reviewers was used. Cross-sectional area ratio was calculated separately for each muscle by dividing the mean muscle cross-sectional area by the supraspinatus fossa area. Muscle cross-sectional areas were assessed from the same T1-weighted image slice used to assess the Goutallier score.

### Three-Dimensional Assessments

Three-dimensional measurements of rotator cuff muscle volume and fatty infiltration were acquired using MRI. Participants were imaged in a supine position with either a 1.5T (GE Healthcare, Milwaukee, WI) or 3T (Siemens Medical Solutions USA, Malvern, PA) scanner because of an institutional system upgrade. Images of the muscles crossing the glenohumeral joint were acquired with a flexed-array long bone coil (1.5T; Invivo, Orlando, FL) or an 18-channel body matrix coil (3T; Siemens Medical Solutions USA, Malvern, PA). Scanning was performed using the clinically available pulse sequence for each machine and the Three Point Dixon (1.5T) or the Two Point Dixon (3T) method,[25,26] which enables quantification of water (muscle) and fat within the region of interest. Images were acquired in 3-mm (1.5T) or 1-mm (3T) slices. Scan parameters were configured on each machine to allow for collection of analogous images across machines (1.5T scanner: TE = 4.200, 6.581, 8.962 ms; TR = 13.5 ms; flip angle = 18°; matrix size = 320 × 256; bandwidth = ± 62.5 kHz; field of view = 320 mm; slice thickness = 3 mm; 3T scanner: TE = 2.46, 3.69 ms; TR = 7.0 ms; flip angle = 9°; matrix size = 256 × 256; bandwidth = ± 248.3 kHz; field of view = 224 mm (read), 120.5% (phase); slice thickness = 1 mm). Total scan time was approximately 13 minutes (1.5T) or approximately 15 minutes (3T). Postscan processing to produce the fat and water images associated with the Dixon method was conducted using the software supplied by each scanner manufacturer. Accuracy of the Dixon method was assessed with a fat-water phantom of known composition. Findings were consistent between 1.5T and 3T scanners, with a mean difference in calculated fat volume percentage of 0.54%.

Three-dimensional measurements of whole muscle volume of the supraspinatus, infraspinatus, subscapularis, and teres minor muscles were calculated using manual segmentation, as previously described.[22,23] Briefly, muscle boundaries were traced on each image slice (3D Doctor; Able Software Corp., Lexington, MA), and a 3-dimensional polygonal surface was created from the boundaries. Individual muscle volumes were calculated from the polygonal surfaces. Supraspinatus muscle volume was calculated using 1-mm slices, when available. All other muscle volumes were calculated using a 3-mm slice thickness. For scans acquired with 1-mm slices, every third image was used to achieve a 3-mm slice thickness.

Three-dimensional measurements of fatty infiltration were calculated for each muscle using a custom Matlab (Rev. 2012b; The MathWorks, Natick, MA) program and equation 1, where $SI_{fat}$ and $SI_{water}$ are the signal intensities for fat and water images of the Dixon method, respectively. This calculation was performed on a voxel-by-voxel basis and then averaged across all voxels in the volume to determine the percentage of fatty infiltration (%fat) within each muscle. T1 corrections were applied using the scaling coefficients described by Gold et al.,[27] which accounted for signal-to-noise bias across scanners; noise correction was performed using magnitude discrimination, described by Liu et al.,[28] which was implemented using equation 1.

$$\%\text{fat} = \frac{SI_{fat}}{SI_{fat} + SI_{water}}, \text{ when } SI_{fat} > SI_{water};$$

$$\%\text{fat} = 1 - \frac{SI_{water}}{SI_{fat} + SI_{water}}, \text{ when } SI_{water} > SI_{fat}$$

Percentage of fatty infiltration was converted to fatty infiltration volume by multiplying %fat × whole muscle volume. Fat-free muscle volume was calculated by subtracting fatty infiltration volume from whole muscle volume measurements.

## Strength Assessment

Strength was evaluated by measuring the maximal isometric joint moment with a Biodex dynamometer (Biodex Medical Systems, Shirley, NY). Three 5-second trials were recorded for abduction/adduction (shoulder abducted to 30°, elbow braced in full extension, forearm in neutral posture, and wrist braced), flexion/extension (shoulder flexed to 30°, elbow braced in full extension, forearm pronated to 90°, and wrist braced), and internal/external rotation (shoulder abducted to 30°, elbow flexed to 90°, forearm in neutral posture, and wrist braced). Sixty seconds of rest was given between trials, and 2 minutes of rest was given between tests to reconfigure the dynamometer. Participants were instructed to stop a trial if they felt any pain. During each trial, participants were given verbal encouragement to elicit maximum performance. A custom Matlab program was used to determine the maximum joint moment for each trial. The program consisted of a search window that identified the maximum joint moment that was maintained for at least 0.5 seconds.[21] The maximum value across the 3 trials was considered the participant's maximum isometric strength.

### Statistical Analysis

Descriptive statistics were used to describe the demographic characteristics of the participants in the RCT and control groups. Linear regression was used to evaluate the relationships between single-image assessments and 3-dimensional measurements. Specifically, the associations between mean Goutallier and Fuchs scores relative to percentage of fatty infiltration and muscle cross-sectional area ratio relative to whole muscle volume measurements were examined. Kappa statistics were calculated for inter- and intrarater repeatability measures for Goutallier scores and Fuchs scores. Kappas are reported for each pairwise comparison for each combination of reviewers to assess interrater repeatability; intrarater reliability was evaluated by calculating a kappa statistic for each reviewer across the 2 reviews. A higher positive kappa indicates better agreement, a kappa equal to zero is agreement resulting from chance, and a negative kappa indicates worse agreement than chance. Exact tests were used to calculate statistical significance of the kappa statistics.

Analysis of covariance with adjustments for age and sex was used to separately evaluate mean differences between the RCT and control groups for 3-dimensional measurements of muscle volume, fatty infiltration volume, percentage of fatty infiltration, fat-free muscle volume, and isometric joint moment. The 4 failed joint moment trials, which were stopped because of pain, were excluded from statistical analyses. Linear regression analyses were used to evaluate the relationship between 3-dimensional measurements of muscle volume and the isometric joint moment of each muscle's primary movement; parallel lines analysis of covariance showed that there were no differences between the RCT and control groups, so participants were considered as a single cohort for these analyses, with adjustments for group and sex. Significance was set to $P < .05$. Because of the exploratory nature of the analyses, type I error was not accounted for by adjusting for multiple measurements. Analyses were performed with SAS software, version 9.3 (SAS Institute, Cary, NC).

## Results

Six participants with RCTs had full-thickness tears, whereas 4 participants had marked partial-thickness (> 50% tendon thickness) tears. All recruited patients volunteered to participate and no participants withdrew from the study. Each participant completed all study evaluations within 2 weeks.

### Single-Image Assessments

The linear relationship between 3-dimensional measurements of percentage of fatty infiltration and mean Goutallier score (Fig 2A) and mean Fuchs score (Fig 2B) was not significant for the supraspinatus or infraspinatus muscle but was significant for the subscapularis and teres minor muscles. There was no significant linear relationship between cross-sectional area ratio for any of the rotator cuff muscles and 3-dimensional measures of whole muscle volume (Fig 3). Few of the inter- and intrarater agreements for Goutallier score or Fuchs score reached statistical significance (Table 3), indicating that there was not statistical agreement across raters or reviews.

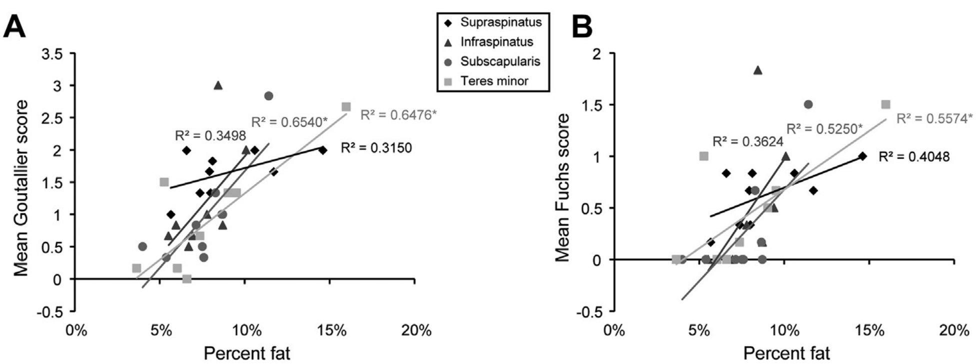


**Fig 2.** (A) Mean Goutallier score and (B) mean Fuchs score versus percentage of fatty infiltration for rotator cuff muscles. The injured arm (3 right/6 left) was assessed for participants with rotator cuff tears (RCTs), and the dominant arm (9 right/1 left) was assessed for controls. * denotes a significant linear relationship, whereby significance indicates that the Goutallier score or Fuchs score captures 3-dimensional measures of fatty infiltration. The relationship between (A) mean Goutallier score and percentage of fatty infiltration was significant for the subscapularis and teres minor muscles (supraspinatus, $P = .116$; infraspinatus, $P = .094$; subscapularis, $P = .008$; teres minor, $P = .009$). The relationship between (B) Fuchs score and percentage of fatty infiltration was significant for the subscapularis and teres minor muscles (supraspinatus, $P = .065$; infraspinatus, $P = .086$; subscapularis, $P = .027$; teres minor, $P = .021$).

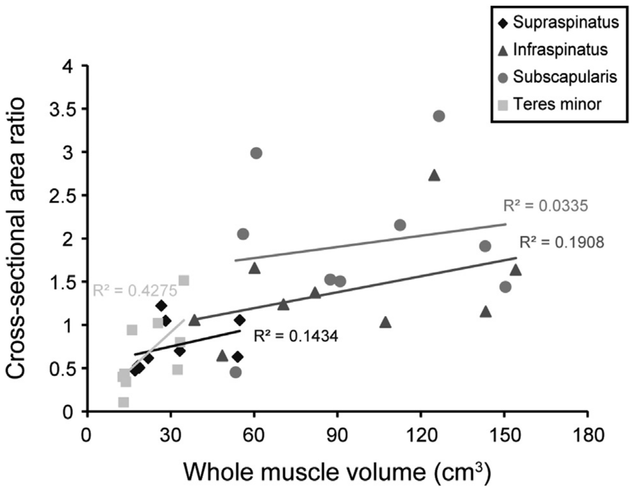


**Fig 3.** Three-dimensional muscle volume measurements versus cross-sectional area ratio (muscle cross-sectional area/ supraspinatus fossa area) for supraspinatus ($P = .315$), infraspinatus ($P = .240$), subscapularis ($P = .637$), and teres minor ($P = .056$) muscles. The injured arm (3 right/6 left) was assessed for participants with a rotator cuff tear (RCT), and the dominant arm was assessed for controls. The presence of a significant correlation would have indicated that the cross-sectional area ratio effectively estimates 3-dimensional muscle volume.

### Three-Dimensional Assessments

The mean difference between 3-dimensional muscle volumes calculated using segmented images of 1-mm versus 3-mm slice thickness was 0.28%. Based on 3-dimensional assessments of muscle morphology (Table 4), patients with RCTs had increased percentages of fatty infiltration compared with controls, which was driven by muscle atrophy. The RCT group had a significantly larger *percentage* of fatty infiltration compared with controls for the supraspinatus, infraspinatus, subscapularis, and teres minor muscles (Fig 4A). However, except for the teres minor muscle, the RCT group did not have larger *volumes* of fatty infiltration (Fig 4B). The RCT group had smaller whole muscle volumes for the supraspinatus, infraspinatus, and subscapularis muscles (Fig 4C). Fat-free muscle volume was significantly less for the RCT group than for the control group for the supraspinatus, infraspinatus, and subscapularis muscles (Fig 4D).

### Strength Versus Volume

One participant with an RCT could not perform the abduction trials, and 3 participants with RCTs could not perform the flexion trials because of pain (Table 4). Isometric joint moment was less for the RCT group in adduction, flexion, and external rotation, but the other joint moments were similar between groups (Fig 5). There were significant associations between whole muscle volume and the joint moment of a muscle's primary action for the supraspinatus, infraspinatus, subscapularis, and teres minor muscles (Fig 6A). Similarly, the relationship between strength and fat-free muscle volume was significant for all comparisons (Fig 6B).

## Discussion

The results from this study show that single-image assessments did not capture 3-dimensional measures of fatty infiltration or muscle volume. These 3-dimensional assessments of muscle morphology indicate that muscle atrophy, not increased fatty infiltration volume, drives the increased fat percentage in these patients with RCTs. Muscle volume measurements are significant predictors of strength in older adults with and without RCTs, highlighting the need for clinicians to consider the amount of muscle tissue in older patients with RCTs, because strength capacity is known to have important functional implications.[20]

This study presents evidence that assessments from a single image are insufficient for estimating the amount of muscle tissue or fatty infiltration in the entire muscle.

**Table 3.** Kappa Statistics of Goutallier Score and Fuchs Score for Each of the 3 Reviewers at 2 Separate Reviews

| | Supraspinatus | Total Infraspinatus | Total Subscapularis | Teres Minor |
|---|---|---|---|---|
| Goutallier score | | | | |
| Inter-rater kappa (κ) | | | | |
| Review 1 | 0.05, −0.03, 0.06 | 0.44, 0.10, 0.06 | 0.36, 0.26, 0.13 | 0.20, 0.37, 0.12 |
| Review 2 | 0.11, 0.05, 0.61 | 0.45, 0.18, 0.16 | 0.02, 0.17, 0.35 | −0.03, 0.13, 0.27 |
| Intra-rater kappa (κ) | | | | |
| Reviews 1 and 2 | 0.49*, 0.37, 0.63 | 0.75*, 0.45, 0.40* | 0.80*, 0.65*, 0.34 | 0.31, 0.68*, 0.42 |
| Fuchs score | | | | |
| Inter-rater kappa (κ) | | | | |
| Review 1 | 0.05, 0.09, 0.18 | 0.44, 1.0*, 0.44 | 0.70*, 0.61, 0.25 | 0.14, 0.25, 0.10 |
| Review 2 | 0.11, 0.05, 0.61 | 0.58*, 0.75*, 0.36 | 0.50, 0.18, 0.63 | 0.12, 0.63, 0.36 |
| Intra-rater kappa (κ) | | | | |
| Reviews 1 and 2 | 0.80*, 0.37, 1.0 | 0.75*, 0.60, 1.0* | 0.73, 1.0*, 0.47 | 0.25, 0.80*, 0.63 |

Kappas are shown for each pairwise comparison of all combinations of reviewers. Exact tests were used to determine the statistical significance of each kappa statistic.

*Indicates statistical significance.

**Table 4.** Three-Dimensional Muscle Morphology Measurements for Each Participant for Rotator Cuff Muscles and Maximum Isometric Joint Moment Measurements

| | RF01 | RF02 | RF03 | RF04 | RF05 | RM01 | RM02 | RM03 | RM04 | RM05 | CF01 | CF02 | CF03 | CF04 | CF05 | CM01 | CM02 | CM03 | CM04 | CM05 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Muscle morphology measurements | | | | | | | | | | | | | | | | | | | | |
| Supraspinatus | | | | | | | | | | | | | | | | | | | | |
| Whole volume, $cm^3$ | 18.7 | 18.1 | 17.2 | 26.6 | 21.8 | 33.3 | 28.1 | 54.1 | 54.8 | 66.2 | 31.2 | 39.4 | 44.5 | 29.8 | 37.5 | 77.7 | 44.8 | 61.3 | 65.3 | 64.2 |
| Fatty infiltration volume, $cm^3$ | 2.2 | 2.7 | 1.1 | 1.5 | 1.7 | 2.7 | 3.0 | 4.4 | 4.0 | 3.6 | 1.6 | 1.6 | 1.6 | 2.1 | 2.0 | 2.1 | 2.2 | 3.2 | 3.1 | 4.1 |
| Fat-free volume, $cm^3$ | 16.5 | 15.5 | 16.1 | 25.1 | 20.1 | 30.6 | 25.2 | 49.7 | 50.8 | 62.6 | 29.6 | 37.9 | 42.9 | 27.8 | 35.5 | 75.6 | 42.6 | 58.2 | 62.2 | 60.1 |
| %Fat | 11.7 | 14.6 | 6.6 | 5.7 | 7.9 | 8.0 | 10.6 | 8.1 | 7.4 | 5.5 | 5.1 | 4.0 | 3.7 | 7.0 | 5.2 | 2.7 | 5.0 | 5.2 | 4.8 | 6.4 |
| Infraspinatus | | | | | | | | | | | | | | | | | | | | |
| Whole volume, $cm^3$ | 70.5 | 81.9 | 48.6 | 60.2 | 38.5 | 107.3 | 124.9 | 154.2 | 143.4 | 157.6 | 89.1 | 84.2 | 96.9 | 67.5 | 77.6 | 172.8 | 133.4 | 146.3 | 153.8 | 129.3 |
| Fatty infiltration volume, $cm^3$ | 4.9 | 8.3 | 4.1 | 3.3 | 3.4 | 7.2 | 9.7 | 14.5 | 8.6 | 6.1 | 3.9 | 4.1 | 5.0 | 4.7 | 4.9 | 4.7 | 11.1 | 6.3 | 7.4 | 7.3 |
| Fat-free volume, $cm^3$ | 65.6 | 73.7 | 44.5 | 56.8 | 35.2 | 100.1 | 115.1 | 139.7 | 134.8 | 151.4 | 85.2 | 80.1 | 92.0 | 62.8 | 72.7 | 168.2 | 122.4 | 140.0 | 146.4 | 122.1 |
| %Fat | 7.0 | 10.1 | 8.5 | 5.5 | 8.7 | 6.7 | 7.8 | 9.4 | 6.0 | 3.9 | 4.4 | 4.8 | 5.1 | 7.0 | 6.3 | 2.7 | 8.3 | 4.3 | 4.8 | 5.6 |
| Teres Minor | | | | | | | | | | | | | | | | | | | | |
| Whole volume, $cm^3$ | 16.1 | 13.3 | 12.7 | 13.0 | 13.9 | 25.4 | 34.7 | 33.4 | 32.4 | 36.6 | 16.7 | 13.2 | 29.9 | 11.7 | 22.0 | 28.0 | 38.5 | 25.1 | 34.1 | 21.6 |
| Fatty infiltration volume, $cm^3$ | 1.1 | 2.1 | 1.1 | 0.7 | 0.8 | 1.7 | 2.6 | 3.2 | 1.2 | 1.9 | 0.7 | 0.4 | 0.8 | 0.5 | 0.7 | 0.7 | 1.4 | 1.7 | 1.4 | 1.6 |
| Fat-free volume, $cm^3$ | 15.0 | 11.2 | 11.6 | 12.3 | 13.0 | 23.7 | 32.2 | 30.2 | 31.3 | 34.8 | 15.9 | 12.8 | 29.0 | 11.2 | 21.4 | 27.4 | 37.1 | 23.4 | 32.8 | 19.9 |
| %Fat | 6.6 | 16.0 | 9.0 | 5.3 | 6.0 | 6.6 | 7.4 | 9.5 | 3.6 | 5.1 | 4.4 | 3.3 | 2.8 | 4.4 | 3.0 | 2.4 | 3.6 | 6.8 | 4.0 | 7.6 |
| Subscapularis | | | | | | | | | | | | | | | | | | | | |
| Whole volume, $cm^3$ | 60.8 | 91.0 | 53.4 | 87.4 | 56.0 | 112.6 | 126.5 | 150.5 | 143.2 | 172.4 | 100.2 | 80.6 | 106.1 | 84.0 | 96.4 | 168.2 | 161.3 | 155.7 | 158.6 | 141.4 |
| Fatty infiltration volume, $cm^3$ | 4.6 | 7.9 | 6.1 | 4.7 | 4.9 | 8.0 | 9.5 | 12.5 | 5.7 | 7.6 | 5.5 | 3.2 | 4.1 | 7.0 | 4.7 | 5.5 | 10.9 | 7.6 | 6.0 | 7.3 |
| Fat-free volume, $cm^3$ | 56.2 | 83.1 | 47.3 | 82.7 | 51.2 | 104.5 | 117.0 | 138.0 | 137.5 | 164.8 | 94.7 | 77.3 | 102.0 | 77.0 | 91.7 | 162.7 | 150.4 | 148.1 | 152.6 | 134.1 |
| %Fat | 7.6 | 8.7 | 11.4 | 5.4 | 8.7 | 7.1 | 7.5 | 8.3 | 4.0 | 4.4 | 5.5 | 4.0 | 3.8 | 8.3 | 4.9 | 3.3 | 6.8 | 4.9 | 3.8 | 5.2 |
| Isometric joint moment | | | | | | | | | | | | | | | | | | | | |
| Abduction, Nm | 3.8 | 16.4 | 2.2 | 12.0 | — | 4.7 | 38.7 | 58.9 | 21.5 | 35.1 | 29.6 | 16.3 | 19.0 | 15.0 | 16.5 | 54.4 | 27.1 | 28.4 | 42.4 | 34.1 |
| Adduction, Nm | 18.5 | 24.7 | 38.5 | 34.6 | 36.3 | 65.9 | 34.1 | 66.8 | 84.6 | 48.6 | 33.7 | 41.0 | 51.1 | 42.0 | 46.6 | 97.7 | 48.5 | 61.7 | 86.6 | 75.0 |
| Flexion, Nm | 1.2 | 4.0 | — | 11.1 | — | — | 32.9 | 28.6 | 21.8 | 26.6 | 14.8 | 16.8 | 20.2 | 9.0 | 16.5 | 38.8 | 24.8 | 24.2 | 38.9 | 41.5 |
| Extension, Nm | 31.0 | 42.4 | 41.3 | 41.4 | 37.5 | 83.7 | 64.6 | 77.5 | 88.4 | 26.6 | 45.3 | 48.5 | 59.6 | 43.1 | 48.3 | 64.1 | 69.0 | 72.0 | 84.0 | 64.3 |
| Internal rotation, Nm | 16.8 | 33.4 | 15.1 | 28.5 | 12.7 | 42.0 | 37.0 | 44.9 | 57.8 | 28.8 | 25.3 | 21.0 | 24.5 | 22.9 | 29.7 | 57.7 | 36.3 | 35.9 | 54.6 | 38.4 |
| External rotation, Nm | 0.5 | 7.4 | 3.8 | 5.5 | 0.8 | 6.9 | 18.2 | 14.3 | 12.3 | 14.7 | 5.6 | 12.6 | 16.8 | 12.6 | 13.0 | 35.2 | 11.0 | 16.4 | 24.7 | 20.7 |

%Fat, percentage of fatty infiltration; CF, control group, female; CM, control group, male; RF, rotator cuff tear group, female; RM, rotator cuff tear group, male.

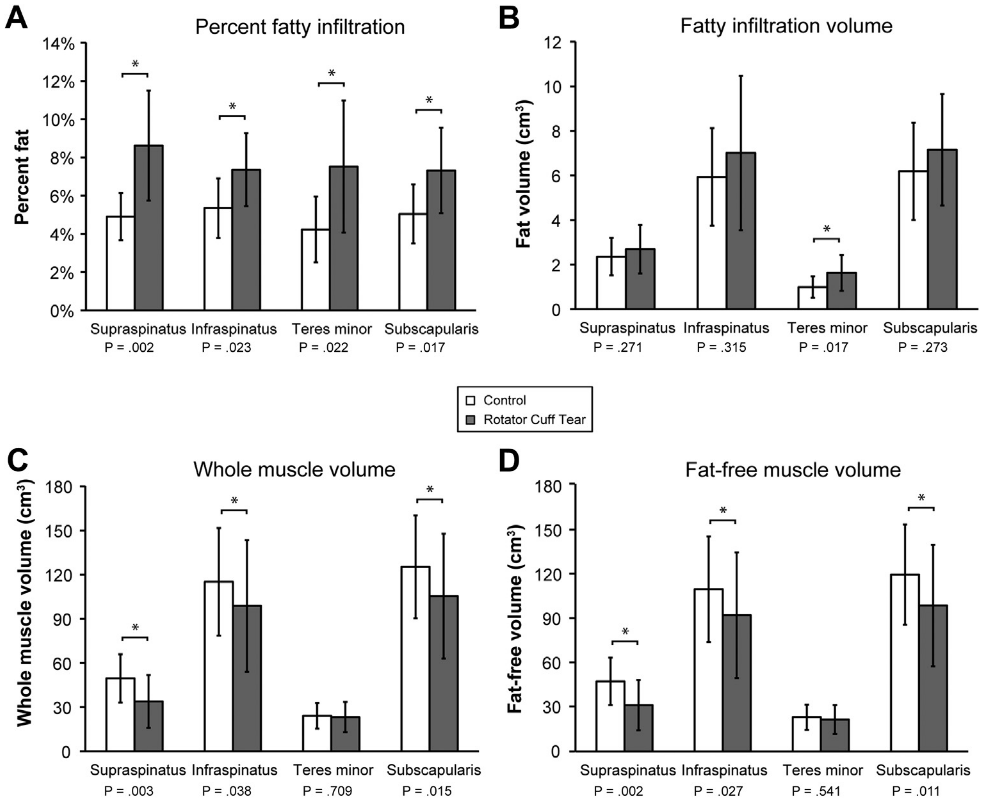


**Fig 4.** Mean ± standard deviation for quantitative measurements of muscle and fatty infiltration volume for rotator cuff muscles for older adults with a rotator cuff tear (RCT) and healthy controls. For participants with an RCT, the injured arm (3 right/7 left) was assessed, and for controls, the dominant arm (9 right/1 left) was assessed. (A) There was a significantly greater percentage of fatty infiltration for all muscles (supraspinatus, $P = .002$; infraspinatus, $P = .023$; teres minor, $P = .022$; subscapularis, $P = .017$) for the RCT group. (B) Only the teres minor ($P = .017$) had a significantly greater volume of fatty infiltration for the participants with an RCT. (C) The RCT group had significantly reduced whole volume measurements for the supraspinatus ($P = .003$), infraspinatus ($P = .038$), and subscapularis ($P = .015$) muscles. (D) Fat-free muscle volume was significantly reduced for the RCT group for the supraspinatus ($P = .002$), infraspinatus ($P = .027$), and subscapularis ($P = .011$) muscles.

The Goutallier and Fuchs scores were originally developed to estimate the proportion of fatty infiltration using a single image slice. Although this single image has a reliable bony landmark, it does not capture morphological changes at other locations, particularly the musculotendinous junction. Fatty infiltration has been shown to be distributed nonuniformly throughout the muscle belly,[8,29] challenging the rationale of using a single image to evaluate fatty infiltration.[14] Jo and Shin[30] showed that new baseline images are needed after surgical repair because surgery moves the muscle and changes its appearance in the MR image. Additionally, the large image slices (e.g., 5-mm slices with 1.5-mm interslice gap[12]) of clinical scans average signal intensity across the slice thickness, potentially masking valuable morphological information.

The 3-dimensional measurements acquired in this study represent a quantitative technique applied to the entire muscle. Recently, Nardo et al.[31] quantified fatty infiltration for rotator cuff muscles using MRI, but only 4 image slices of the muscle belly that were within 8 mm of the traditional slice were used in their evaluation; 3-dimensional muscle volumes were not assessed and important morphologic information was likely missed. The 3-dimensional measurements of percentage of fatty infiltration calculated here were less than those traditionally associated with Goutallier scores (e.g., Goutallier score of 3 is defined as 50% fatty infiltration), which is consistent with the findings of Nardo et al. This discrepancy may result from the tendency of individuals to visually identify image voxels as either muscle or fat.[31] Nardo et al. reported a significant linear relationship between percentage of fatty infiltration and Goutallier scores when all rotator cuff muscles were considered together, including muscles graded 3 to 4. However, they did not identify significant differences between grades 0 and 1 or between grades 1 and 2, which are the grades typically considered for surgical repair.[32,33] This suggests that quantitative measurements of fat percentage are not as well correlated among lower Goutallier scores, which

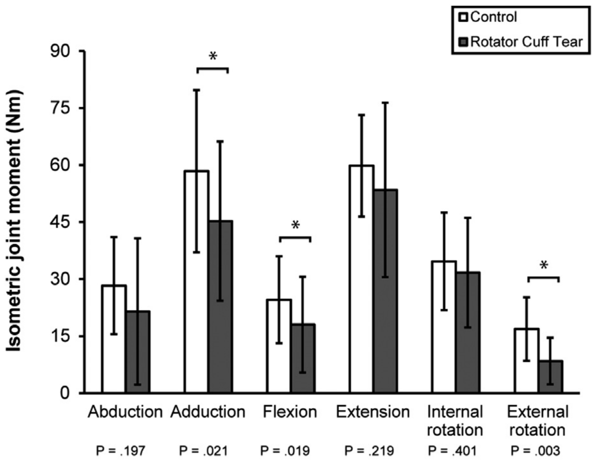


**Fig 5.** Mean ± standard deviation isometric joint moment for the rotator cuff tear group and healthy controls. The injured arm (3 right/7 left) was evaluated for participants with a rotator cuff tear (RCT), and the dominant arm (9 right/1 left) was assessed for controls. One participant could not perform abduction, and 3 participants could not perform flexion because of pain; these trials were not included in the statistical analyses. Isometric joint moment was significantly reduced for adduction ($P = .021$), flexion ($P = .019$), and external rotation ($P = .003$).

is consistent with the results of the current study, in which mean Goutallier scores were primarily low scores, but ranged from 0 to 3. The 3-dimensional assessments reported here suggest that important information about the amount of muscle and fat tissue is missed with single-image assessment techniques, especially for lower Goutallier stages. These results encourage future work to develop efficient methods to calculate 3-dimensional measurements of muscle morphology and to characterize the spatial localization of fatty infiltration within the whole muscle, which is possible using the technique described here.

As in previous reports,[12,15-18] inconsistency in assignment of Goutallier scores was observed. It has been suggested that condensing the 5 Goutallier score categories to the 3 Fuchs score categories improves reliability,[16] but results from this study do not support that conclusion. The Goutallier score has appeal because it can be assessed quickly in a busy clinical setting, although consistent reports describing a lack of agreement between raters is problematic. Nevertheless, these assessment techniques are applied to identify surgical candidates.[5,7,11,14] Single-image assessments may mislead clinicians because they do not account for variation in 3-dimensional muscle morphology. Both atrophy and fatty infiltration occur with aging but are separate processes,[6] and the results of increased muscle atrophy without marked increases in fatty infiltration volume after an RCT support that report. Muscle atrophy without increased fatty infiltration volume may cause fat proportions to appear larger. Development of an efficient and objective method to quantify 3-dimensional fat and muscle tissue would improve reliability, supply clinicians with a more comprehensive muscle morphology assessment for older patients, and provide a better foundation to determine treatment.

Similar to previous work,[8,12] muscle atrophy was identified in older adults with RCTs. Older adults have reduced upper limb muscle volume compared with healthy young adults,[23] and the current study suggests that an RCT may be associated with muscle atrophy

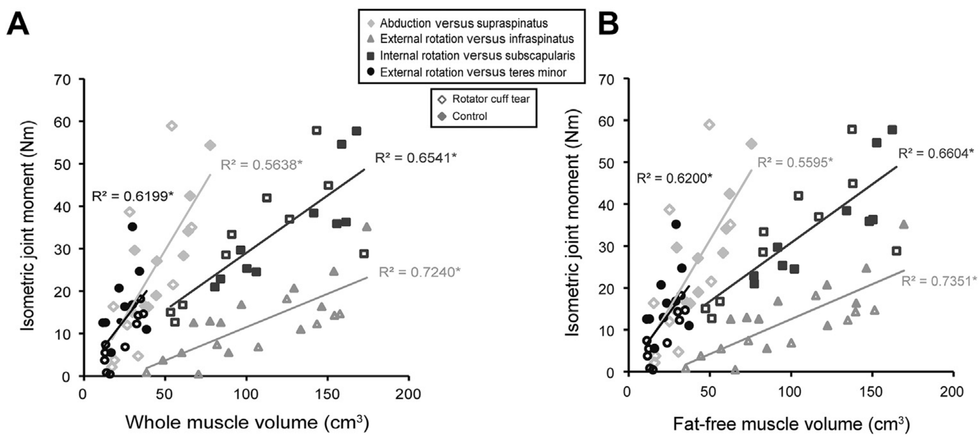


**Fig 6.** Isometric joint moment versus (A) whole muscle volume and (B) fat-free muscle volume for participants with rotator cuff tears (RCTs) and healthy controls. The injured arm (3 right/7 left) was assessed for participants with RCTs and the dominant arm (9 right/1 left) was evaluated for controls. Asterisks denote a significant linear relationship, which indicates that strength production is dependent on 3-dimensional muscle volume measures. There are significant relationships for (A) whole muscle volume and the joint moment of each muscle's primary action (supraspinatus, $P = .005$; infraspinatus, $P < .001$; subscapularis, $P = .006$; teres minor, $P = .001$) and for (B) fat-free muscle volume and isometric joint moment (supraspinatus, $P = .005$; infraspinatus, $P < .001$; subscapularis, $P = .001$; teres minor, $P = .001$).

exceeding age-associated atrophy. This work showed that 3-dimensional muscle volume is an important predictor of strength after an RCT, which is consistent with previous studies in healthy adults.[21,23] Strength is a factor in functional ability, and marked strength decreases after an RCT may affect the ability of older individuals to successfully perform the daily activities necessary to maintain independence[1] because of strength losses below the minimum threshold necessary to complete the tasks.[20] Conservative treatment for older patients with RCTs may further compound the muscle atrophy shown here, and arthroscopic repair, which has been shown to be successful in older patients,[32-34] should be proactively considered to avoid further atrophy and strength loss.

The RCT group had reduced strength for adduction, flexion, and external rotation. The large interparticipant variability in strength measurements (Fig 5) likely reflects the natural variability inherent to the population. The lack of difference between the RCT and control groups for some strength measures may be due to the large variability or may be the result of age-associated strength decreases[20] in the absence of a musculoskeletal injury in the control group. Importantly, there were patients with RCTs who could not perform flexion and abduction strength trials because of pain. Repeating the analysis to include failed trials (0 Nm) resulted in larger mean differences between groups but did not change the outcome of the analysis. Although 3 participants with RCTs failed flexion strength assessments because of pain, these measurements were not included in regression analyses because flexion was not the primary movement direction of any rotator cuff muscles.

### Limitations

This study had a small sample size of 20 participants, which may be underpowered, and we did not adjust for type I error. Although manual segmentation methods are impractical for a busy clinical setting, these results encourage further work to develop efficient techniques to effectively capture 3-dimensional muscle information. Although other studies have evaluated changes in muscle atrophy and fatty infiltration after successful and failed surgical repairs,[10,11] the objectives of this study were to obtain baseline assessments of muscle morphology and strength in the context of aging. MR images were acquired with one of 2 scanners. A control group was used rather than the contralateral shoulder because of the increased incidence of an asymptomatic tear on the contralateral side when a symptomatic tear presents.[35]

## Conclusions

Clinical scores using a single image slice do not represent 3-dimensional muscle measurements. Efficient methods are needed to more effectively capture 3-dimensional information for clinical applications. Participants with RCTs had increased fatty infiltration percentages that were likely driven by muscle atrophy rather than increased fat volume. The significant association of muscle volume with strength production suggests that treatments to preserve muscle volume should be pursued for older patients with RCTs.

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