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This study was approved by the Henry Ford Health System’s Institutional Review Board (study no. 12162).
ABSTRACT

Background: Although rotator cuff repair provides pain relief for many patients, retears are relatively common and affect approximately 20-70% of patients after repair. Although MRI offers the ability to assess tissue characteristics such as tear size, retraction, and fatty infiltration, it provides little insight into the quality of the musculotendinous tissues the surgeon will encounter during surgery. However, shear wave elastography (SWE) could provide an indirect assessment of quality (i.e., stiffness) by measuring the speed of shear waves propagating through tissue. The objective of this study was to determine the extent to which estimated shear modulus predicts repair integrity and functional outcomes 1-year after rotator cuff repair.

Methods: Thirty-three individuals scheduled to undergo arthroscopic rotator cuff repair were enrolled in this study. Prior to surgery, shear modulus of the supraspinatus tendon and muscle was estimated using ultrasound SWE. MRIs were obtained before and 1-year after surgery to assess tear characteristics and repair integrity, respectively. Shoulder strength, range of motion, and patient-reported pain and function were assessed pre- and post-surgery. Functional outcomes were compared between groups and across time using a two-factor mixed model ANOVA. Stepwise regression with model comparison was used to investigate the extent to which MRI and shear modulus predicted repair integrity and function at 1-year post-surgery.

Results: At 1-year post surgery, 56.5% of patients had an intact repair. No significant differences were found in any demographic variable, pre-surgical tear characteristic, or shear modulus between patients with an intact repair and those with a recurrent tear. Compared to pre-surgical measures, patients in both groups demonstrated significant improvements at 1-year post-surgery in pain (p<0.01), self-reported function (p<0.01), range of motion (p<0.01), and shoulder
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strength (p<0.01). Additionally, neither pre-surgical MRI variables (p>0.16) nor shear modulus (p>0.52) were significantly different between groups at 1-year post-surgery. Finally, pre-surgical shear modulus generally did not improve the prediction of functional outcomes above and beyond that provided by MRI variables alone (p>0.22).

Conclusion: While SWE remains a promising modality for many clinical applications, this study found that SWE-estimated shear modulus did not predict repair integrity or functional outcomes at 1-year post-surgery, nor did it add to the prediction of outcomes above and beyond that provided by traditional pre-surgical MRI measures of tear characteristics. Therefore, it appears that further research is needed to fully understand the clinical utility of SWE for musculoskeletal tissue and its potential use for predicting outcomes after surgical rotator cuff repair.

Level of Evidence: Level I; Prospective Cohort Design; Prognosis Study

Keywords: Shear wave elastography, shear modulus, rotator cuff, tear chronicity, repair integrity, tissue quality

Rotator cuff tears affect at least 40% of individuals over age 60, resulting in approximately 250,000 surgical repairs performed annually in the United States. This procedure provides pain relief for many patients, but post-surgical healing is a major clinical problem as 20-70% of rotator cuff repairs fail (i.e., retear) and post-surgical shoulder function is often unpredictable. Previous clinical studies have suggested that age, tear size, and tear retraction may be risk factors for recurrent tearing and poor clinical outcomes. Unfortunately, these imaging and clinical descriptors provide little insight into the quality of the
musculotendinous tissues the surgeon will encounter during surgery. This limitation is clinically important because without a reliable measure of tear quality, it is difficult for surgeons to assess the potential for repair healing prior to surgery and how best to counsel patients on post-surgical activities and expected outcomes.

Shear wave elastography (SWE) is an ultrasound-based technology that provides an indirect assessment of quality (i.e., stiffness) by measuring the speed of shear waves propagating through tissue. Although clinical applications of this technology initially focused on diagnosing breast and liver pathology,\(^4,17,25,36\) the technology has been used increasingly to assess musculoskeletal tissues including the rotator cuff.\(^3,22,26-28,32-34,53,64\) Although recent evidence suggests that SWE is not associated with individual rotator cuff tear characteristics,\(^41\) it may provide a more global assessment of tissue quality. Furthermore, it is possible that SWE, either alone or in conjunction with existing MRI-based measures, could be a stronger predictor of healing and functional outcomes than conventional parameters such as patient age, rotator cuff tear size, and muscle fatty degeneration or atrophy.

The objective of this study was to determine the extent to which estimated shear modulus predicts repair integrity and functional outcomes 1-year after rotator cuff repair. We hypothesized that pre-surgical shear modulus of the rotator cuff would be associated with repair tissue healing, shoulder function, and pain after rotator cuff repair. Furthermore, we hypothesized that pre-surgical shear modulus would provide a significant improvement when added to the prediction of these outcomes provided by MRI-based measures alone.

**MATERIALS AND METHODS**
Participants

Following institutional review board approval and informed consent, 33 participants enrolled in this study. Participants were eligible to participate in the study if they were 50–80 years old and were scheduled for surgical repair of a small- or medium-sized full-thickness tear of the supraspinatus tendon, as confirmed via pre-surgical MR imaging. Exclusion criteria included a traumatic tear, prior shoulder surgery, more than one steroid injection, BMI greater than 30 kg/m², current smoker, uncontrolled diabetes, or an outstanding worker’s compensation claim.

Pre-surgical Shear Wave Elastography

Approximately 1–2 weeks prior to surgery, ultrasound SWE images of each participant’s supraspinatus muscle and intramuscular tendon were acquired by one operator using a Siemens ACUSON S3000 with a 9L4 linear transducer (Siemens; Erlangen, German). Images were acquired with the participant’s shoulder supported in 30° of scapular-plane abduction in neutral rotation. The intramuscular tendon was imaged by placing the transducer in the supraspinatus fossa, in the long-axis relative to the intramuscular tendon, and visually aligning with the tendon fibers (Figures 1A–B). The muscle was imaged by placing the transducer in the supraspinatus fossa, in the long-axis relative to the supraspinatus muscle belly, and visually aligning with the muscle fibers. Five trials were acquired for each tissue region of interest (i.e., intramuscular tendon, muscle) using the system’s built-in elastography module and a transmit frequency of 8 MHz. Each trial acquired a B-mode image and a corresponding SWE image (Figures 1B–C). Reliability of this protocol was established previously by Baumer and colleagues (ICCs: intra-rater >0.87, inter-rater >0.72).
For each trial, the region of interest (i.e., muscle or intramuscular tendon) was isolated from surrounding tissues on the B-mode image using ImageJ interfaced with custom software (MATLAB, The MathWorks, Inc.; Natick, MA, USA). Per manufacturer recommendations, data within the region of interest in the corresponding SWE image were retained for pixels whose proprietary quality metric was greater than 0.87 (Figure 1D). For each pixel the shear wave speed data were then converted to an estimate of shear modulus as previously described, and then a single estimated shear modulus was determined as the median value of all retained pixels. Lastly, the mean shear modulus was calculated across all five trials for each tissue region.

Pre-Surgical Functional Assessment

Patient-reported measures of pain and function were assessed using the visual analog scale (VAS) for pain and the Western Ontario Rotator Cuff (WORC) index. Active range of motion (AROM) was manually measured with a goniometer for sagittal-plane flexion and frontal-plane abduction. Isometric shoulder strength was measured during coronal-plane abduction at 30° of abduction, sagittal-plane elevation at 30° elevation, internal-rotation at 15° of frontal plane elevation and 0° of humeral rotation, external rotation at 15° of frontal-plane elevation and 0° of humeral rotation with an isokinetic dynamometer (Biodex System 2, Biodex Medical Systems, Shirley, NY, USA). The order of strength testing was randomized, and three trials were performed at each testing position. Average strength was calculated across the three trials and normalized based on the research of Hughes and colleagues.

Pre-Surgical MRI Assessment
Pre-surgical MRI scans were obtained for each participant. These exams were typically acquired on a 1.5T scanner, with the scan protocol including axial and sagittal-oblique fat-suppressed proton density sequences, coronal-oblique and sagittal-oblique T1-weighted sequences, and a coronal-oblique fat-suppressed T2-weighted sequence. A fellowship-trained, board-certified musculoskeletal radiologist (SBS) with 12 years clinical experience, evaluated each pre-surgical MRI examination in terms of the full-thickness rotator cuff anteroposterior tear size, amount of tendon retraction, supraspinatus occupation ratio, supraspinatus atrophy using the “tangent sign,” and amount of fatty degeneration according to the Goutallier classification system.

Surgical Repair and Post-Surgical Rehabilitation

Within two weeks of acquiring the SWE images, each patient underwent arthroscopic rotator cuff repair by one of three orthopedic surgeons fellowship-trained in sports medicine or orthopedic surgery (median post-fellowship experience: 9 years). The repair technique (i.e., number of rows and anchors) was determined based on surgeon discretion. A double-row repair technique was used in 71% of cases with a median of 2 anchors (min=1, max=5). Following surgery, patients were discharged with a shoulder abduction sling and standard postoperative medications and precautions. A continuous passive motion device was used by 90% of patients during the first month after surgery. Although post-surgical rehabilitation was not standardized, general guidelines were as follows: 1) postop weeks 0-5: passive range of motion only; 2) postop week 6: progression to active-assisted range of motion; 3) postop week 8: progression to active range of motion; 4) postop weeks 6-8: isometric strengthening; and 5) postop weeks 10-12:
progression to resisted exercises. All rehabilitation progressions were guided by patient tolerance and the avoidance of compensatory movement patterns (e.g., shoulder shrugging).

Post-Surgical Assessments

At 1-year post-surgery, participants were contacted in regard to returning for reevaluation. Of the 33 participants who completed pre-surgical testing, 23 completed the post-surgical testing. Demographic data of these participants are presented in Table I. The suboptimal follow-up rate was predominantly due to the COVID-19 public health crisis and the associated health system restrictions which precluded human subjects’ data collection for several months.

Patient-reported measures of pain and function were reassessed as previously described. Lastly, a post-surgical MRI was obtained for each participant and evaluated by the same radiologist (SBS) in terms of rotator cuff repair integrity (i.e., intact repair or recurrent tear and muscle quality).

Statistical Analysis

Demographics, pre-surgical tear characteristics, and post-surgical function were described using summary statistics and compared between groups using two-sample t-tests and Fisher’s exact tests, as appropriate. Functional outcomes were compared between groups and across time (i.e., preop and postop) using a two-factor mixed model ANOVA. Main effects were only interpreted in the absence of a significant group-by-time interaction. Stepwise regression with model comparison was used to investigate the extent to which MRI and shear modulus predicted repair integrity and function at 1-year post-surgery as follows. First, variable distribution was assessed using skewness and kurtosis. Second, a logistic regression model was calculated with the MRI variable (tear size, retraction, occupation ratio) that was the strongest
predictor of repair integrity at 1-year post surgery (MRI model). Third, the mean shear modulus was added to the logistic regression (MRI+SWE model). Finally, the two models (MRI and MRI+SWE) were compared via ANOVA model comparison to determine whether the addition of the shear modulus significantly improved the prediction of repair integrity above and beyond the MRI variable alone. Separate models were fit using the estimated shear moduli of the supraspinatus muscle and intramuscular tendon. A similar approach was used with linear regression to investigate the extent to which MRI and SWE variables predicted shoulder function at 1-year post surgery. All statistical analyses were performed using R (R Core Team, 2018). Statistical significance was defined as p<0.05.

RESULTS

As a result of disruptions in human subjects’ data collection due to the COVID-19 pandemic, only 23 patients completed the study with an average 1-year follow-up time of 1.2 ± 0.2 years (range: 1.0-1.6 years). Of the patients who completed the study, the average age was 60±7 years old, 8 (34.8%) were female, 12 (52.2%) had the surgical repair on their dominant shoulder, and 13 (56.5%) had an intact repair at 1-year post-surgery. No significant differences were found in any demographic variable, MRI-based pre-surgical tear characteristic, or shear modulus measure between individuals with an intact repair and those with a recurrent tear (Table I). Compared to pre-surgical measures, patients in both groups demonstrated significant improvements at 1-year post-surgery in pain (i.e., VAS) (p<0.01), self-reported function (i.e., WORC) (p<0.01), abduction and flexion AROM (p<0.01), and all measures of shoulder strength (p<0.01) (Figure 2). Abduction strength improved in both groups, but patients with an intact
repair experienced significantly greater improvement in abduction strength than those with a recurrent tear (p=0.047, Figure 2).

Predicting Post-Surgical Repair Integrity

Although not significantly different between patient groups, occupation ratio was the pre-surgical MRI measure with the highest potential to distinguish between groups (i.e., lowest p-value in Table I) and therefore was used as the MRI predictor in the regression models. On its own, occupation ratio was not a significant predictor of repair integrity at 1-year post-surgery (p=0.22, $r^2=0.06$). Furthermore, the prediction of repair integrity at 1-year post-surgery was not significantly improved by the addition of shear modulus of the supraspinatus muscle (p=0.22, change in $r^2=0.05$) or intramuscular tendon (p=0.35, change in $r^2=0.03$)

Predicting Post-Surgical Functional Outcomes

Across all pre-surgical variables, only tear size and tear retraction were significantly correlated with post-surgical functional outcomes (Table II). Specifically, smaller pre-surgical tear size and tear retraction were found to be moderately but significantly associated with higher post-surgical abduction, flexion, and internal rotation strength (Table II). Pre-surgical shear modulus of the supraspinatus muscle and intramuscular tendon were not found to be significantly associated with any post-surgical functional outcome measure (p$\geq0.12$, $r^2\leq0.12$, Table II).

In general, pre-surgical shear modulus did not improve the prediction of post-surgical functional outcomes (Table III). The only exception was that the combination of tear size and shear modulus for the supraspinatus intramuscular tendon significantly improved the prediction
of post-surgical flexion AROM above and beyond tear size alone (p=0.01, change in $r^2=0.22$, Table III).

DISCUSSION

The objective of this study was to determine the extent to which pre-surgical shear modulus predicts repair tissue healing and functional outcomes at one year after surgical rotator cuff repair. We hypothesized that pre-surgical shear modulus would be associated with repair tissue healing, shoulder function, and pain after rotator cuff repair. However, pre-surgical shear modulus was not found to be associated with repair tissue healing or any post-surgical functional outcome measure. Furthermore, with only one exception, the addition of pre-surgical shear modulus to pre-surgical MRI-based tear characteristics was not found to improve the prediction of post-surgical repair integrity or functional outcomes.

Predicting structural outcomes – i.e., whether a rotator cuff repair is likely to remain intact after surgery – remains a challenging endeavor. It is therefore not surprising this study failed to identify any pre-surgical factors that were significantly different between the intact repair and recurrent tear patient groups. However, this outcome is consistent with previous research as there are conflicting reports regarding the ability of conventional clinical data to predict post-surgical repair integrity. For example, some previous studies have reported that tear size is associated with repair integrity after surgical repair,\(^1,11,31,49\) while other studies have reported no such association exists.\(^19,39,43,50\) These conflicting findings likely reflect the implicit heterogeneity of patient populations and large number of factors including genetics, biological factors, and post-surgical activity levels that are difficult to control in clinical studies. Thus,
identifying factors that discriminate between intact repair and recurrent tear patient groups requires substantial differences between groups and/or large sample sizes. For example, Le and colleagues measured 18 pre-surgical and surgical variables in 1000 patients following rotator cuff repair and reported that only pre-surgical tear dimensions (specifically, anteroposterior tear size, mediolateral tear length, tear size area, and tear thickness), patient age, and surgical time were independent predictors of repair integrity.\textsuperscript{42} In a follow-up study with an even larger patient cohort (n=1962), this same research team determined that patient age, tear size, hospital type (private vs. public), and case number (i.e., surgeon experience) were the only significant predictors of repair integrity.\textsuperscript{15} Taken together, these comprehensive studies suggest that patient age and tear size may be the most reliable pre-surgical predictors of post-surgical repair integrity.

Similar to the challenges in predicting post-surgical repair integrity, predicting post-surgical functional outcomes (i.e., strength, ROM, pain) after rotator cuff repair is equally difficult. In the current study, pre-surgical tear size and tear retraction were significantly associated with measures of post-surgical abduction strength, flexion strength, and external rotation strength. These findings are consistent with previous research indicating that pre-surgical tear dimensions significantly impact post-surgical shoulder strength.\textsuperscript{52,56} In contrast, neither muscle nor tendon pre-surgical shear modulus values were significantly associated with any post-surgical functional outcomes. Furthermore, the addition of shear modulus to MRI-based outcomes did not result in widespread improvements in the prediction of any post-surgical functional outcomes over MRI-based outcomes alone (Table III). The notable exception was that the addition of tendon shear modulus to occupation ratio improved the prediction of flexion ROM over occupation ratio alone (p=0.01, Table III). However, this outcome should be interpreted with caution since it is difficult to understand mechanistically as to how the
combination of tendon material properties (i.e., shear modulus) and muscle volume (i.e.,
occupation ratio) would significantly influence ROM but not shoulder strength.

It was somewhat surprising that pre-surgical shear modulus values had negligible value
for predicting post-surgical repair integrity given that SWE has been shown to be correlated with
tissue mechanical properties,\textsuperscript{16} which are generally believed to affect post-surgical outcomes.
Evidence supporting this premise comes from previous studies that have focused on the role of
fatty degeneration (an issue shown to affect mechanical properties\textsuperscript{45}) as an important factor in a
patient’s potential outcome from rotator cuff repair,\textsuperscript{44} as well as studies with small animal
models demonstrating that muscle/tendon degeneration negatively affects rotator cuff repair
tissue healing.\textsuperscript{24,35,38,40,55} One potential explanation for this discrepancy is that tissue changes
associated with a rotator cuff tear likely have opposing influences on SWE measurements.\textsuperscript{41} For
example, fatty degeneration is expected to reduce the estimated shear modulus since fat
presumably reduces a tissue’s stiffness. Conversely, other tissue changes found in degenerative
rotator cuff tears (e.g., tendon retraction and fibrosis) have been shown to increase tissue
stiffness\textsuperscript{21,23,29,54,55} and are therefore expected to increase SWE measurements. Given that these
tissue changes occur to various degrees simultaneously within an individual patient, the global
nature of the SWE measure may have hindered the predictive value of SWE-estimated shear
modulus for estimating the clinical construct of “tissue quality” in this patient population.

In addition to differences between patients in pre-surgical muscle/tendon properties, it is
highly likely that many other factors played important roles in the patient’s post-surgical
functional and structural outcomes. For example, factors such as the patient’s post-surgical
activity levels, adherence to post-surgical management prescription, the tendon’s microvascular
supply, and intrinsic healing capacity are difficult to assess and/or control in a clinical study.
Therefore, it is possible that these and other more rudimentary factors (e.g., patient age, tear size) may have overwhelmed the effect of pre-surgical tissue quality. Furthermore, repair “failure” may occur due to distinct mechanisms that were not assessed in the current study. For example, the ability of the repaired tendon to resist suture pull-out and its biological capacity for healing may define distinct clinical subgroups. More research is needed to better understand these mechanisms of structural repair failure and to develop assessment tools to predict their occurrence and inform pre-surgical clinical decision making.

Despite the associations detected in the current study between tear dimensions and shoulder strength, a perplexing issue that continues to confound the prediction of functional outcomes is the disconnect between functional and structural outcomes after rotator cuff repair. Specifically, patients can have acceptable strength despite a recurrent tear or limited strength with an intact repair. For example, some studies have reported differences in shoulder strength between intact and failed repairs, whereas other studies have reported no difference. Similarly, some studies have reported a difference in patient-reported outcome scores between intact and failed repairs, whereas other studies have failed to detect a difference in these outcomes. McElvany and colleagues reviewed 77 studies that compared the clinical results for intact and failed repairs, and concluded that patient-reported outcomes generally improve regardless of whether or not the repair remains intact. Furthermore, they concluded that there was no consistent relationship between the integrity of the repair and the clinical outcome.

While the results of this study suggest that SWE provides little additional predictive value compared to MRI alone, it is important to remember that MRI and SWE provide very different, but potentially complementary, information as recently described. Clinical MRIs
typically provide information regarding rotator cuff structure (e.g., tear dimensions, tear thickness, muscle atrophy), integrity, and tissue composition or degeneration, whereas SWE provides an estimate of tissue mechanical properties. This discrepancy may help explain the poor relationship between pre-surgical shear modulus and post-surgical tear integrity observed in the current study, and the lack of strong associations between SWE measures and rotator cuff tear characteristics previously reported.\(^{41,53}\) Although the clinical utility of SWE may still hold promise, it appears that more research is needed to fully understand its clinical utility for musculoskeletal tissues and, in particular, its potential for predicting outcomes after surgical rotator cuff repair.

This study has several limitations to consider when interpreting the results. First, only 23 of 33 participants returned for the post-surgical follow-up visit due to the ongoing COVID-19 public health crisis. Second, the small sample size likely affected the study’s statistical power. An a priori power analysis suggested a sample size of 40 patients was required to detect an increase in \(r^2\) of 0.18 with 80% power. However, the generally weak associations between predictors and outcomes suggest that meaningful predictions were not likely ignored despite the small sample size. Third, only patients scheduled to undergo arthroscopic repair of a small- or medium-sized rotator cuff tear were included in the study. As a result, the between-subject variability in measures of tear chronicity was limited, which may have impacted our ability to identify potentially meaningful relationships. Fourth, patients with acute tears were excluded from the study to increase the likelihood that chronic changes would be seen within the muscle-tendon unit. However, doing so may have increased the observed rate of recurrent tear. Fifth, although the reliability of the methods used in this paper has been established,\(^2\) SWE measurements are often challenging to standardize both within and across individuals.
Consequently, the current study used a standardized patient position, the same SWE operator for all subjects, and custom software run by a single operator in an attempt to improve reliability and to quantitatively calculate SWE measures.

CONCLUSION

While SWE remains a promising modality for many clinical applications, this study found that SWE-estimated shear modulus did not predict repair integrity or functional outcomes at 1-year post-surgery, nor did it add to the prediction of outcomes above and beyond that provided by traditional pre-surgical MRI measures of tear characteristics. Therefore, it appears that further studies are necessary to fully understand the clinical utility of SWE for musculoskeletal tissue and, in particular, its potential use for predicting outcomes after surgical rotator cuff repair.

BIBLIOGRAPHY


36. Kim HJ, Lee HK, Cho JH, Yang HJ. Quantitative comparison of transient elastography (TE), shear wave elastography (SWE) and liver biopsy results of patients with chronic liver disease. J Phys Ther Sci 2015;27:2465-2468. 10.1589/jpts.27.2465


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10.2106/jbjs.f.00749


10.2106/JBJS.I.00506


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Figure and Table Legends

Table I: Comparison of demographics, MRI-based measures of pre-surgical tear characteristics, and shear wave elastography between individuals with an intact repair and a recurrent tear at 1-year post-surgery. Continuous outcome measures are reported as mean ± standard deviation.

Table II: Correlations between pre-surgical tear/tissue characteristics and functional outcome measures at approximately 1-year post-surgery. Data listed as r (p-value). Statistically significant associations (i.e., p<0.05) are indicated in bold. ABD=abduction, ER=external rotation, FLX=flexion, IR=internal rotation, VAS=visual analog scale, WORC=Western Ontario Rotator Cuff score.

Table III: Comparison of predictive utility of two linear regression models: 1) a model predicting the functional outcome at 1-year post-surgery using a single MRI predictor, and 2) a model predicting the combined effect of the MRI predictor and shear modulus. Results are presented as p-values testing whether the two linear regression models are significantly different (i.e., p<0.05 suggests that SWE adds to the prediction of the functional outcome above and beyond that provided by the MRI measure alone). Statistically significant differences (i.e., p<0.05) are indicated in bold.

Figure 1: Ultrasound shear wave image acquisition of the supraspinatus intramuscular tendon with the transducer placed just anterior to the scapular spine (A), the resulting B-mode (B) and shear wave elastography (C) images, and extraction of the relevant shear wave values for analysis using image segmentation (D).

Figure 2: Changes in functional outcomes between pre-surgery and approximately 1-year post-surgery. Strength data are normalized relative to each patient’s theoretical maximum strength using the regression equation by Hughes et al.30 AROM=active range of motion, VAS=visual analog scale, WORC=Western Ontario Rotator Cuff score.
<table>
<thead>
<tr>
<th>TABLE I: Demographics</th>
<th>Intact Repair (n=13)</th>
<th>Recurrent Tear (n=10)</th>
<th>p-value</th>
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<tr>
<td><strong>Patient Demographics</strong></td>
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<tr>
<td>Age (years)</td>
<td>60 ± 7</td>
<td>63 ± 8</td>
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<tr>
<td>Sex (% female)</td>
<td>38.5%</td>
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<td>Laterality (% dominant)</td>
<td>46.2%</td>
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<td>BMI (kg/m$^2$)</td>
<td>25.8 ± 3.5</td>
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<tr>
<td><strong>Pre-surgical Tear Characteristics (MRI)</strong></td>
<td></td>
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<tr>
<td>Tear size (cm)</td>
<td>1.9 ± 1.1</td>
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<td>Tear retraction (cm)</td>
<td>1.9 ± 1.0</td>
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<td>0.18</td>
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<td>Stage 2</td>
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<td><strong>Shear Modulus (SWE)</strong></td>
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<td>Muscle (kPa)</td>
<td>11.9 ± 9.5</td>
<td>9.7 ± 6.4</td>
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<tr>
<td>Intramuscular tendon (kPa)</td>
<td>19.7 ± 8.3</td>
<td>22.2 ± 13.3</td>
<td>0.61</td>
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**TABLE II:** Correlations between pre-surgical tear/tissue characteristics and functional outcome measures at approximately 1-year post-surgery.

<table>
<thead>
<tr>
<th>Post-Surgical Functional Outcome</th>
<th>Pre-surgical Tear/Tissue Characteristics (Predictor Variables)</th>
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</thead>
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<td></td>
<td>Tear Size (MRI)</td>
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<tr>
<td>Pain (VAS)</td>
<td>-0.13 (0.57)</td>
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<tr>
<td>Function (WORC)</td>
<td>-0.14 (0.57)</td>
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<tr>
<td>AROM: ABD</td>
<td>-0.16 (0.51)</td>
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<tr>
<td>AROM: FLX</td>
<td>-0.22 (0.35)</td>
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<tr>
<td>Strength: ABD</td>
<td><strong>-0.53 (0.02)</strong></td>
</tr>
<tr>
<td>Strength: FLX</td>
<td><strong>-0.52 (0.02)</strong></td>
</tr>
<tr>
<td>Strength: ER</td>
<td><strong>-0.56 (0.01)</strong></td>
</tr>
<tr>
<td>Strength: IR</td>
<td>-0.12 (0.61)</td>
</tr>
<tr>
<td></td>
<td>Tear Retraction (MRI)</td>
</tr>
<tr>
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<td>-0.07 (0.78)</td>
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<tr>
<td></td>
<td>-0.26 (0.27)</td>
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<tr>
<td></td>
<td>-0.03 (0.90)</td>
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<tr>
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<td>-0.08 (0.73)</td>
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<tr>
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<td><strong>-0.52 (0.02)</strong></td>
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<tr>
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<td><strong>-0.55 (0.01)</strong></td>
</tr>
<tr>
<td></td>
<td>-0.03 (0.92)</td>
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<tr>
<td></td>
<td>Occupation Ratio (MRI)</td>
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<tr>
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<td>0.08 (0.74)</td>
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<tr>
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<td>-0.08 (0.73)</td>
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<tr>
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<td><strong>0.23 (0.31)</strong></td>
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<tr>
<td></td>
<td>0.00 (0.99)</td>
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<tr>
<td></td>
<td><strong>0.56 (0.01)</strong></td>
</tr>
<tr>
<td></td>
<td>0.01 (0.96)</td>
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<tr>
<td></td>
<td>Muscle Shear Modulus (SWE)</td>
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<td>-0.18 (0.44)</td>
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<tr>
<td></td>
<td>0.10 (0.67)</td>
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<tr>
<td></td>
<td>0.17 (0.47)</td>
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<tr>
<td></td>
<td>0.05 (0.84)</td>
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<td></td>
<td>-0.21 (0.35)</td>
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<tr>
<td></td>
<td>Tendon Shear Modulus (SWE)</td>
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<td>-0.20 (0.40)</td>
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<td>0.20 (0.38)</td>
</tr>
<tr>
<td></td>
<td>-0.35 (0.12)</td>
</tr>
<tr>
<td></td>
<td>0.21 (0.35)</td>
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</table>
**TABLE III:** Comparison of predictive utility of two linear regression models.

<table>
<thead>
<tr>
<th>Post-Surgical Functional Outcome</th>
<th>Best MRI Predictor</th>
<th>MRI + Muscle Shear Modulus</th>
<th>MRI + Tendon Shear Modulus</th>
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<tbody>
<tr>
<td>Pain (VAS)</td>
<td>Occupation ratio</td>
<td>0.56</td>
<td>0.73</td>
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<tr>
<td>Function (WORC)</td>
<td>Tear retraction</td>
<td>0.15</td>
<td>0.67</td>
</tr>
<tr>
<td>AROM: ABD</td>
<td>Tear size</td>
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<td>0.19</td>
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<tr>
<td>AROM: FLX</td>
<td>Occupation ratio</td>
<td>0.20</td>
<td><strong>0.01</strong></td>
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<td>Strength: ABD</td>
<td>Tear size</td>
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<td>0.80</td>
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<td>Strength: FLX</td>
<td>Tear size</td>
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<td>0.93</td>
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<td>Strength: ER</td>
<td>Tear size</td>
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<td>Strength: IR</td>
<td>Tear size</td>
<td>0.06</td>
<td>0.76</td>
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