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Comparison of Passive Stiffness Changes in the Supraspinatus Muscle after Double-row and Knotless Transosseous-equivalent Rotator Cuff Repair Techniques: A Cadaveric Study

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Abstract

Purpose—To investigate the alteration of passive stiffness in the supraspinatus muscle after double-row (DR) and knotless transosseous-equivalent (KL-TOE) repair techniques, using the shear wave elastography (SWE) in cadavers with rotator cuff tears. We also aimed to compare altered muscular stiffness after these repairs to that obtained from shoulders with intact rotator cuff tendon.

Methods—Twelve fresh-frozen cadaveric shoulders with rotator cuff tear (tear size; small [6], medium-large [6]) were used. Passive stiffness of four anatomical regions in the supraspinatus muscle was measured based on an established SWE method. Each specimen underwent DR and KL-TOE footprint repairs at 30° glenohumeral abduction. SWE values, obtained at 0°, 10°, 20°, 30°, 60°, and 90° abduction, were assessed in 3 different conditions: preoperative (torn) and postoperative conditions with the 2 techniques. The increase ratio of SWE values after repair was compared among the four regions to assess stiffness distribution. In addition, SWE values were obtained on 12 shoulders with intact rotator cuff tendons as control.

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Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. **Hatta T, Giambini H, Hooke AW, Zhao C, Sperling JW, Steinmann SP, Yamamoto N, Itoi E, An KN**

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Results—In shoulders with medium-large size tears, supraspinatus muscles showed an increased passive stiffness after rotator cuff repairs, and this was significantly observed at adducted positions. KL-TOE repair showed uniform stiffness changes among the four regions of the supraspinatus muscle (mean, 189-218% increase after repair), whereas, DR repair caused a significantly heterogeneous stiffness distribution within the muscle (mean, 187-319% after repair, $P = 0.002$). Although a repair-induced increase in muscle stiffness was observed also in small size tear, there were no significant differences in repaired stiffness changes between DR and KL-TOE (mean, 127-138% and 127-130% after repairs, respectively). Shoulders with intact rotator cuff tendon showed uniform SWE values among the four regions of the supraspinatus muscle (mean, 38.2-43.0 kPa).

Conclusion—Passive stiffness of the supraspinatus muscle increases after rotator cuff repairs for medium-large size tears. KL-TOE technique for the medium-large size tear provided a more uniform stiffness distribution across the repaired supraspinatus muscles compared to the DR technique.

Clinical Relevance—Based on this insight investigating rotator cuff muscle stiffness changes, further studies using SWE may determine the optimal repair technique for various sizes of rotator cuff tears.

Keywords

Shear wave elastography; Rotator cuff tear; Supraspinatus muscle; Passive muscle stiffness; Double row repair; Transosseous-equivalent repair

Introduction

Rotator cuff tear is a common cause of shoulder pain and dysfunction, especially in the middle-aged and elderly population ^{1, 2}. Arthroscopic rotator cuff repair has been an established treatment option for symptomatic rotator cuff repair. Although repair techniques and tools have been improved, the prevalence of re-tear after surgery remains relatively high ^{3, 4}. Clinical evidence suggests that proper healing onto the original footprint may contribute to a positive postoperative recovery of shoulder function ^{5, 6}. Therefore, improvement in repair techniques is still a great topic to provide optimal healing environment and satisfactory outcomes ⁷⁻⁹.

Biomechanical studies investigating repair techniques have mainly focused on the tendon-bone interface properties, including initial fixation strength, gap formation, and/or mechanical stability ¹⁰⁻¹³. To date, double-row (DR) and transosseous-equivalent repair techniques has been known to provide better biomechanical properties than the traditional single-row repair technique ^{10, 11, 13}. However, there still exists a debate on the biomechanical, biological and clinical advantages between the former two repairs ^{12, 14-16}. Despite such a vigorous topic, to our knowledge, no studies have addressed the effect of repair techniques on rotator cuff muscle after repair. It is clear that rotator cuff tear is an age related chronic injury, in which rotator cuff muscles are subjected to hypotrophy or degeneration ^{17, 18}. In addition, the musculotendinous junction has been shown to have inferior mechanical properties after placement of medial row sutures; thus, being susceptible

to re-tears due to the excessive mechanical environment^{9, 19}. Accordingly, biomechanical assessment of rotator cuff muscle should also be considered essential for determining the optimal technique with an improved rotator cuff muscle condition, in addition to repaired tendon-bone interface properties.

Ultrasound elastography has been recently used for quantitative assessment of the mechanical properties in various tissues. In particular, shear wave elastography (SWE) evaluates the propagation velocity distribution of the shear waves generated by a focused acoustic push pulse to reconstruct quantitative data of tissue shear modulus²⁰. This has been successfully used clinically for breast cancers diagnosis²¹ and liver fibrosis staging²². In addition, passive stiffness of skeletal muscles, including the supraspinatus muscle, has been assessed using SWE by *in vivo* and *ex vivo* studies²³⁻²⁶. Therefore, the purpose of this study was to investigate the alteration of passive stiffness in the supraspinatus muscle after DR and knotless transosseous-equivalent (KL-TOE) repair techniques, using SWE in cadavers with rotator cuff tears. In addition, we aimed to compare altered muscular stiffness after these repairs to that measured in shoulders with intact rotator cuff tendon. We hypothesized that 1) these two repairs might provide an increased stiffness in the supraspinatus muscle compared to the preoperative torn condition and/or shoulders with intact rotator cuff tendon, and 2) each repair might show a characteristic pattern of stiffness distribution according to the fixation mechanism.

Material and Methods

Specimen Preparation

Twelve fresh-frozen shoulders from 12 human cadavers with rotator cuff tear were obtained from the anatomy department from our institute after approval by the bio-specimens committee at our institute. The presence of the rotator cuff tear was identified using ultrasound B-mode imaging before specimen dissection from an evaluation of 40 shoulders. The size of the tear was measured macroscopically using a digital caliper after removing all soft tissues and acromion above the rotator cuff tendinous regions with a scalpel, except those overlying the supraspinatus muscle belly. Tears were classified according to the classification by Post et al²⁷. Briefly, measured in its longest diameter, each tear was defined as a small (less than 1 cm), medium (less than 3 cm), large (less than 5 cm), or massive tear (more than 5 cm). Inclusion criterion for this study was a tear involving the supraspinatus tendon; thus, shoulders with massive tear (> 5 cm) and isolated subscapularis tear were excluded. Specimens were separated into two groups: small tear (n = 6) and medium-large tear (n = 6; medium [2] and large [4]), and each group was analyzed independently. In addition, 12 shoulders with intact rotator cuff tendons we obtained as control.

Before the experimental and imaging procedures, the scapulae were dissociated from the thorax, and the humerus was cut at the level of the midshaft. The scapula and a fiberglass rod inserted into the humeral medullary canal were attached to a custom-designed experimental fixture. According to the International Society of Biomechanics recommendation, the scapula was secured at 0° of upward/downward rotation, considered as a neutral position^{28, 29}. The fixture, designed to provide 6 degrees-of-freedom motion of the

glenohumeral joint in consistent motion paths, was used to abduct the humerus parallel to the scapular plane.

Surgical techniques

Before repair of the rotator cuff tears, specimens were visualized and examined to confirm that the edge of torn supraspinatus tendon could be pulled out to the footprint. All repairs were carried out by a single surgeon (T.H.). Each specimen underwent two types of footprint repair techniques (DR and KL-TOE) in a randomized order. After concluding the experimental process of one repair technique, all sutures and anchors were carefully removed, and a similar procedure was undertaken with the second repair technique. Shoulders were positioned at 30° of glenohumeral abduction using a built-in custom fixture device and tears were repaired onto their original footprint. Repair of small tears were performed with 2 suture anchors (1-medial and 1-lateral), with medium-large tears requiring 4 suture anchors (2-medial and 2-lateral). The positions of the placement of the medial-row anchors and the passage of sutures through the supraspinatus tendon were consistent for both repair techniques (DR or KL-TOE), in order to avoid any effect on outcome measurements. For a single specimen with a large U-shaped tear, two stitches for tendon-to-tendon suture were added as the margin convergence (side-to-side) technique in advance of the footprint repairs. After each repair, attachment of the proximal origin of the supraspinatus to the supraspinous fossa was confirmed using ultrasound imaging.

Double-row repair

DR repair was performed with 5.5 mm Corkscrew FT II suture anchors (Arthrex, Naples, FL) loaded with No. 2 Fiberwire sutures (Arthrex). Medial-row anchors were placed along the articular margin. Lateral-row anchors were placed 10 mm apart, lateral from medial-row anchors. Sutures were passed through the reduced supraspinatus tendon and then tied either in a simple fassion (for lateral-row) or in a horizontal mattress configuration (for medial-row, Figure 1A).

Knotless transosseous-equivalent repair

For the KL-TOE technique, 5.5 mm Corkscrew FT II anchors (Arthrex) with No. 2 Fiberwire (Arthrex) and 4.75 mm SwiveLock anchors (Arthrex) were used. Medial-row anchors were placed along the articular margin. For the lateral-row bridging, one or two holes were punched 10 mm apart from the lateral edge of the footprint. Medial sutures passed through the tendon were threaded through the SwiveLock anchors, and the anchors were inserted into the holes (Figure 1B).

Shear wave elastography

Ultrasound B-mode and SWE imaging were performed using a commercial ultrasound system (Aixplorer; Supersonic Imagine, Aix-en-provence, France) and a linear array probe (10-2 MHz; Supersonic Imagine). Images for SWE measurements were acquired based on an established methodology²⁵. Briefly, the supraspinatus muscle was divided into 4 regions according to the muscle fiber orientation (anterior deep [AD], anterior superficial [AS], posterior deep [PD], and posterior superficial [PS], Figure 2). The ultrasound probe was

placed on the plane parallel to the muscle fiber orientation for each region, and SWE measurements were recorded independently. Quantitative values of SWE modulus, corresponding to the elastic modulus (kPa) of each region, were obtained using a built-in software. For all experimental conditions, SWE values were measured repeatedly (3 times) in each region, and the mean values were then calculated, as previously described²⁵.

SWE measurements for the supraspinatus muscle were performed at 0°, 10°, 20°, 30°, 60°, and 90° glenohumeral abduction. For each shoulder position, the SWE values were compared in 3 different conditions: preoperative (torn) and postoperative conditions with the two repair techniques. The ratio of increased muscle elasticity for each repair was calculated as follows:

$$\frac{\text{SWE values after repair}}{\text{SWE values before repair}} \times 100(\%)$$

The values for the four regions (AD, AS, PD, or PS) were compared to assess regional stiffness variability within the supraspinatus muscles.

To assess the stiffness distribution patterns in the intact rotator cuff condition, moreover, SWE measurements for the four muscular regions were obtained from twelve intact specimens. Based on the previous literature³⁰ describing the highest SWE values at adducted shoulder position due to a stretched supraspinatus muscle, SWE values were obtained at 0° abduction.

Statistical Analyses

Wilcoxon signed rank test was used to compare SWE values between preoperative (torn) and postoperative (repaired) conditions. For each condition, Friedman with Dunn's post hoc test was used to compare SWE values among the four regions (AD, AS, PD, and PS). These non-parametric tests were adopted as an initial analysis showed the data to not present a normal distribution. However, the specimen number used in this study is similar to other biomechanical studies investigating repair techniques³¹⁻³³. Statistical analyses were performed using the software GraphPad Prism (version 5.0, GraphPad Prism Software, San Diego, CA). The level of significance was set at a 0.05.

Results

Specimens with small size tear showed a repair-induced increase of muscle stiffness, with significant increase only at 0° abducted shoulders after both repairs when compared to the tear (unrepaired) condition (Figure 3). This increase in stiffness was observed in all four regions of the supraspinatus muscle; mean SWE values were 52.7-62.6 kPa on the torn condition, 70.0-77.1 kPa after DR repair, and 68.1-83.0 kPa after KL-TOE repair at 0° abduction. On the contrary, shoulders with medium-large size tears, presented an increased passive stiffness in the supraspinatus muscle after rotator cuff repairs, and these changes were significantly observed at 0°, 10°, 20° and 30° adduction positions (Figure 4). These differences were observed in all four regions of the muscle. Mean values for the medium-

large tear group were 46.7-49.3 kPa on the torn condition, 100.0-141.7 kPa after DR repair, and 92.0-114.7 kPa after KL-TOE repair at 0° abduction. There were no significant differences in stiffness measurements between the KL-TOE and DR repair techniques in the small size tear group in all four regions (mean, 127-138% and 127-130% increase after DR and KL-TOE, respectively) (Figure 5A). In the group with medium-large size tears, the KL-TOE repair showed a uniform stiffness distribution among the four regions of the supraspinatus muscle (mean, 189-218%), whereas, the DR repair caused a significantly heterogeneous stiffness distribution within the muscle (mean, 187-312%, $P = 0.002$) (Figure 5B). In contrast, the twelve shoulders with intact rotator cuff tendon showed uniform SWE values among the four regions of the supraspinatus muscle at 0° abduction (mean, 41.3 kPa for AD, 43.0 kPa for AS, 38.2 kPa for PD, and 42.4 kPa for PS).

Discussion

Our study showed an increased passive stiffness in the supraspinatus muscle after rotator cuff repair after DR and KL-TOE repairs, especially in shoulders with medium-large size tear. This muscle property changes are due to reattaching teared tendon back to greater tuberosity that generates tensile force to the muscle. This phenomenon has not been studied before as neither normal human cadavers nor animal models can mimic the real clinical rotator cuff tear conditions. We have also confirmed characteristic patterns of stiffness distribution after DR and KL-TOE repairs by measuring SWE values from four anatomical regions in the supraspinatus muscle.

SWE has been reliably used to obtain stiffness measurements in the crural and the brachial muscles^{23, 26, 34}. Contrast to these muscles that demonstrate a relatively consistent muscle fiber orientation composition, SWE for the supraspinatus muscle requires segmental assessment due to its complicated fiber architectures^{25, 35}. SWE has been previously shown to be a reliable and feasible technique for measuring quadrisectioned regions of the supraspinatus muscle independently^{25, 30}. Furthermore, it has been shown to have the capability to detect changes in mechanical properties based on varied passive tensions due to shoulder abduction-adduction in cadaveric shoulders³⁰. Using this technique with various shoulder positions, therefore, we attempted to reveal an insight into preferable repair techniques from the perspective of the effects on mechanical properties in the muscle after rotator cuff repair.

In this study, quasi-static SWE assessment during shoulder abduction/adduction could elucidate stiffness differences caused by passive changes in tension in the supraspinatus muscle. Passive stiffness in the SSP muscle with the arm in 0° abduction mildly increased after repair of small size tear. On the other hand, same shoulder positions in repaired medium-large tears showed the supraspinatus muscle to have an approximate two-to-three-fold increase in stiffness after repairs, when compared to those with torn, unrepaired, conditions. Specimens repaired with the KL-TOE technique showed no significant differences in measured stiffness in all four regions of the muscle. On the other hand, the DR repair technique caused a significant heterogeneous stiffness distribution within the muscle. Despite presenting a same orientation for medial-row anchors and suturing process between both techniques, imbalanced stiffness changes in the supraspinatus muscle existed only with

the DR technique. These different stiffness patterns may be due to their fixation mechanisms. The KL-TOE technique provides stabilization without any tying on suture anchors; instead, using lateral-row bridging anchors, all sutures can compress the cuff tendon onto the footprint with similar stresses. In contrast, the DR technique stabilizes the tendon by tying each suture above the anchors. This independent fixation mechanism on the DR technique might cause nonuniform pull-out stresses in the rotator cuff structures.

This study showed a notable increase in stiffness in the posterior superficial region of the supraspinatus muscle. Previous studies on the supraspinatus tendon have demonstrated variable mechanical properties between anterior, medial and posterior sub-regions^{36, 37}. Tendon and muscle properties play a key role in balancing the stresses in an intact shoulder. However, once a significant cuff tear occurs, there might be a deteriorated force transmission from the muscles to the humerus³⁸. Hence, a repaired rotator cuff tendon might cause balanced/imbalanced muscle stiffness based on the repair technique. To generate regular muscular function, mechanical properties within a muscle should remain unchanged upon surgical intervention. If an irregular or abnormal passive stiffness presents in the muscle after surgery, as shown in the supraspinatus muscle after DR repair, subsequent pathologies including pain or muscular cramp, rotator cuff dysfunction, or consequent re-tear might be present. Especially, after placement of medial row sutures, the musculotendinous junction has been shown to have inferior mechanical properties; therefore, being susceptible to re-tears due to the excessive mechanical environment^{9, 19}. To date, there have been a number of biomechanical studies relating rotator cuff repair techniques^{10-13, 16}. Repair techniques have been investigated to improve repair site properties including maximal initial failure strength, minimal gap formation, or mechanical stability^{13, 39-41}. In addition to these approaches, the effect of repair techniques on the alteration of mechanical properties in the muscular regions should be also evaluated. Our findings indicate that the KL-TOE technique provides a uniform stiffness distribution when compared to the DR repair, and could be a more suitable surgical approach when performing rotator cuff repairs in patients with medium-large size tears.

There are notable strengths in our study. All specimens presented genuine and real rotator cuff tears. Unlike artificial tear models mostly used in biomechanical studies, the supraspinatus muscles with rotator cuff tears may have a specific mechanical response to surgical interventions. Therefore, we strongly believe that our results of passive stiffness measurements could correlate with those observed in patients with rotator cuff tears. In addition, SWE, as a noninvasive and fast technique, allowed for a completely-matched comparison between repair techniques, completely eliminating inter-specimen differences.

Limitations

On the other hand, there are several limitations. All data were obtained from cadaveric shoulders. Although this study appropriately assessed passive stiffness changes following two repair techniques, we believe further studies using *in vivo* subjects would complement our results. Moreover, *in vivo* SWE measurements might present variability due to the time when measurements are obtained (from repair to examination). However, intra-operative measurements could be performed to understand acute changes in stiffness based on the

repair technique. Second, we utilized shoulders with rotator cuff tears involving the supraspinatus tendon, and divided these into two groups based on the tear size (small and medium-large); thus, we did not perform any sample size calculation. Accordingly, this study might be underpowered due to small number of specimens per group. Although representative stiffness patterns after cuff repairs could be obtained for both groups, further studies including more specimens with various sizes of tear will provide a more detailed analysis regarding stiffness changes related to an increased tear size as well as tear location. In addition, stiffness changes in other rotator cuff muscles (infraspinatus, teres minor, and subscapularis) would also be required to identify the overall effect of repair techniques. Third, we have adopted two types of repairs among current techniques. The transosseous-equivalent technique includes various suture configurations and it can be divided into two types for medial row sutures; tied and knotless^{31, 42, 43}. Although controversial, several biomechanical studies have indicated a superior initial strength or sealing capacity using the tied configuration^{13, 44, 45}. Therefore, tied and knotless medial row sutures within the transosseous-equivalent techniques may provide technique-specific changes in muscular stiffness which should be further evaluated in future studies. Fourth, we did not assess muscular pathologies including hypotrophy and specific fatty infiltration. The presence or absence of such pathologies might have affected our results, especially in larger tears. Fifth, we performed both repair techniques in each specimen. Although this process allowed for a match comparison, there exists potential altered anchor-bone or suture-tendon interface properties between initial and secondary repairs. However, we believe this process to have negligible effects on our results as no interfaces broke during shoulder abduction-adduction.

Conclusion

Passive stiffness of the supraspinatus muscle increases after rotator cuff repairs for medium-large size tears. KL-TOE technique for the medium-large size tear provided a more uniform stiffness distribution across the repaired supraspinatus muscles compared to the DR technique.

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A Double-row (DR) **B Knotless Transosseous Equivalent (KL-TOE)**

Figure 1. Rotator cuff repair techniques

Double-row (DR; **A**) and knotless transosseous-equivalent (KL-TOE; **B**) techniques were used.

Figure 2. Quadrisected regions of the supraspinatus muscle for shear wave elastography (SWE) The SSP muscles were divided into 4 regions: anterior deep (AD), anterior superficial (AS), posterior deep (PD), and posterior superficial (PS) based on the muscular fiber orientation. SWE measurements were performed on each region by placing the ultrasound probe on the plane parallel to the muscle fiber orientation, as shown in the blue and white planes depicting the anterior and posterior regions, respectively.

Figure 3. Passive stiffness of the supraspinatus muscles obtained from the shear wave elastography (SWE) measurements in specimens with small rotator cuff tear; preoperative (Tear) and after repairs (KL-TOE, DR)

Mean values and their standard deviations were obtained from 4 muscular regions (anterior deep, anterior superficial, posterior deep, and posterior superficial regions) with the arm in 0°, 10°, 20°, 30°, 60° and 90° abduction. For the 12 control shoulder specimens, SWE measurements at 0° abduction were also plotted. *: significant difference between Tear and KL-TOE. †: significant difference between Tear and DR.

Figure 4. Passive stiffness of the supraspinatus muscles in specimens with medium-large rotator cuff tear

*: significant difference between Tear and KL-TOE. †: significant difference between Tear and DR.

Figure 5. Increased supraspinatus muscle stiffness after repairs of small tear (A) and medium-large tear (B)

Red and blue bars represent the mean ratios of increased stiffness with the shoulder position at 0° abduction after repairs, and error bars show their standard deviations. Preoperative values of the SSP muscle stiffness were set as 100% (dotted line).