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The Effect of Dynamic External Rotation Comparing 2 Footprint-Restoring Rotator Cuff Repair Techniques

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Background: Allowing for humeral external rotation while loading rotator cuff repairs has been shown to affect tendon biomechanics when compared with testing with the humerus fixed. Adding dynamic external rotation to a tendon-loading model using footprint-restoring repairs may improve our understanding of rotator cuff repair response to a common postoperative motion.

Hypothesis: A tendon suture-bridging repair will demonstrate better load sharing compared to a double-row repair, and there will be a differential gap formation between the anterior and posterior tendon regions.

Study Design: Controlled laboratory study.

Methods: In 6 fresh-frozen human cadaveric shoulders, a tendon suture-bridging rotator cuff repair was performed; a suture limb from each of 2 medial anchors was bridged over the tendon and fixed laterally with an interference screw. In 6 contralateral match-paired specimens, a double-row repair was performed. For all specimens, a custom jig was employed that allowed dynamic external rotation (0° to 30°) with loading. A materials testing machine was used to cyclically load each repair from 0 N to 90 N for 30 cycles; each repair was then loaded to failure. A deformation rate of 1 mm/s was employed for all tests. Gap formation between tendon edge and insertion was measured using video digitizing software.

Results: The yield load for the suture-bridging technique (161.88 ± 35.09 N) was significantly larger than the double-row technique (135.17 ± 24.03 N) ($P = .026$). The yield gap between tendon and lateral footprint was significantly greater anteriorly than posteriorly (1.62 ± 0.82 mm and 0.68 ± 0.47 mm, respectively) for the suture-bridging technique ($P = .024$) but not for the double-row technique (1.35 ± 0.52 mm and 1.05 ± 0.50 mm, respectively) ($P = .34$). There were no differences for gap formation, stiffness, ultimate load to failure, and energy absorbed to failure between the 2 repairs ($P > .05$). The anterior regions of the repair were the first to fail in all constructs. The suture-bridging repair remained interconnected for 5 of 6 repairs.

Conclusions: The tendon suture-bridging rotator cuff repair has a yield load that is higher than the double-row repair when allowing for external rotation during load testing. External rotation can accentuate gap formation anteriorly at a repaired rotator cuff footprint.

Clinical Relevance: Based on the tension of repair, there may be a role for reinforcing the repair anteriorly and limiting external rotation postoperatively.

Keywords: rotator cuff; double-row; transosseous-equivalent; rotation; biomechanics

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Numerous studies have shown that the persistent tear rate after open and arthroscopic rotator cuff repair remains remarkably high.[2,10,11,13] To improve the healing environment between tendon and bone, new rotator cuff repair techniques have been developed to better restore the supraspinatus footprint.[17,20,23] On the basis of a previous study,[22] a suture anchor technique has been developed that mimics a traditional transosseous tunnel technique. It has been called a "transosseous-equivalent" rotator cuff repair with respect to what the tendon experiences with

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tendon-bridging sutures.[23] Park et al[24] have shown that a suture-bridging rotator cuff repair technique can improve contact characteristics at a repaired rotator cuff footprint when compared with a double-row technique. They also showed, in a model that keeps the humerus fixed, that a tendon suture-bridging rotator cuff repair technique can provide significantly more ultimate failure load and energy absorbed to failure than a double-row repair.[26]

Loading rotator cuff repair constructs with the humerus fixed (not allowing rotation) has been a common method for comparing biomechanical properties of various repair constructs.[5,16,18,26] However, this method does not allow for testing the effect of external rotation, which is a common postoperative motion, on rotator cuff repairs. With in vivo supraspinatus loading, humeral rotation is generated internally or externally depending on the starting position,[15] which can influence the biomechanics of different repairs. Park et al[25] have shown that dynamic external rotation, even while using relatively low loads, as may be seen postoperatively,[8,27] can create significant differences in gap formation and tendon strain at the anterior footprint when compared with a model that fixes the humerus during loading.

Relatively low loads were employed based on electromyographic studies in a rehabilitation setting[8,27]; this may better simulate what actually occurs at a newly repaired rotator cuff footprint, which is most relevant in a cadaver model where no healing can occur. Given the complexities of modeling in vivo shoulder motion, which has innumerable variables, the current study attempts to isolate the effects of a single motion (external rotation) on supraspinatus repair. On the basis of the observation that a tendon suture-spanning rotator cuff repair can remain interconnected between fixation points, mimicking a single implant,[26] we hypothesize that the suture-bridging repair will withstand significantly more load (yield and ultimate) then a double-row repair when using a testing model that allows for external rotation with muscle loading. Because the double-row repair has lateral tendon fixation points, we further hypothesize that the double-row repair will protect lateral tendon gap formation better than the suture-bridging technique with external rotation. The objective of the current study is to elucidate the effects of external rotation on both footprint-restoring double-row and tendon suture-bridging repairs.

MATERIAL AND METHODS

Specimen Preparation

Six matched pairs of fresh-frozen human cadaveric shoulders (mean age, 59.3 ± 7.3 years; range, 46-67) without gross evidence of rotator cuff injury or greater tuberosity asymmetries such as footprint size, cysts, and bone quality were used for this study. The specimens were from 3 female and 3 male donors. Specimens were stored at –20°C and thawed for 24 hours at room temperature before dissection. All soft tissues were carefully dissected from the scapula and proximal humerus; the supraspinatus muscle and tendon was sharply dissected free from its scapular origin and its insertion on the greater tuberosity, respectively. The bony footprint was treated with a fine rasp, as might be performed during open or arthroscopic repairs. After the supraspinatus tendon was sharply removed from the greater tuberosity, the distal 10 mm of the supraspinatus tendon was sharply resected from straight anterior to posterior to standardize rotator cuff tear simulation.[16] The humerus was cut transversely in the midshaft region approximately 10 cm from the medial surgical neck. Normal saline solution kept specimens moist during all phases of dissection, preparation, and testing.

Repair Technique

In 6 randomly chosen shoulder specimens, in 1 limb from each specimen (right or left), a rotator cuff repair employing tendon-bridging sutures was performed using 4 suture limbs and 2 Bio-Tenodesis screws (Arthrex, Inc, Naples, Fla).[24,26] In the 6 contralateral matched pairs, a double-row repair was performed.[26] All measurements were carefully performed using digital calipers to standardize the technique for each specimen. All knots were tied with a sliding double half-hitch knot first, followed by alternating simple half-hitches for a total of 5 throws.

Double-Row Suture Anchor Repair. After each specimen was mounted, 2 medial row holes were punched and tapped at the far medial edge of the greater tuberosity footprint along the sulcus just lateral to the articular cartilage; the anterior-medial suture anchor was always placed 5 mm posterior to the bicipital groove. Two lateral holes were punched and tapped as far lateral as possible while still remaining on top of the footprint,[17] thus maximizing the potential tendon contact area on the actual bony insertion. All holes were placed at a 45° angle relative to the footprint surface.[4] For the medial and lateral rows, the distance between each suture anchor in the same row was approximately 12.5 mm anterior to posterior. We used four 6.5-mm suture anchors (Arthrex) that were single-loaded with No. 2 FiberWire (Arthrex) sutures. We used horizontal mattress suture configurations for the medial row and simple suture configurations for the lateral row, as previously described.[9,17] For the medial row, in the anterior-posterior plane, the suture passes were approximately 7 mm apart, centered over each corresponding suture anchor. The suture passes through the tendon were approximately 12.5 mm medial to the lateral edge to allow complete coverage of the lateral footprint insertion. For the lateral row, suture passes 7 mm medial to the tendon edge were performed (Figure 1).

Repair Using 4 Tendon-Bridging Sutures and 2 Interference Screws.[24,26] The medial row for this construct is exactly as described above. The suture limbs are not cut after tying. The medial and lateral fixation points are placed at points where drill holes would be placed for a traditional open transosseous technique. Two 4.5-mm holes were drilled 1 cm distal to the lateral edge of the footprint,[7] each in-line with the medial suture anchors distanced 12.5 mm apart in the anterior-posterior direction. The suture passes through the tendon were approximately 12.5 mm medial to the lateral edge to allow complete coverage of the footprint insertion. A No. 2 FiberWire suture loop was placed through a cannulated Bio-Tenodesis screwdriver

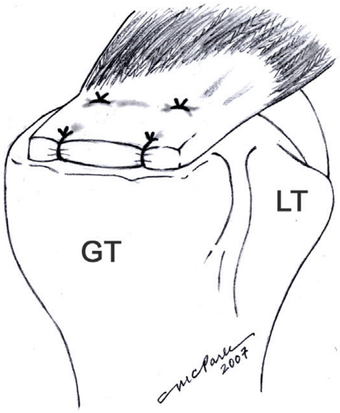

Figure 1. Schematic for the double-row repair. GT, greater tuberosity; LT, lesser tuberosity.

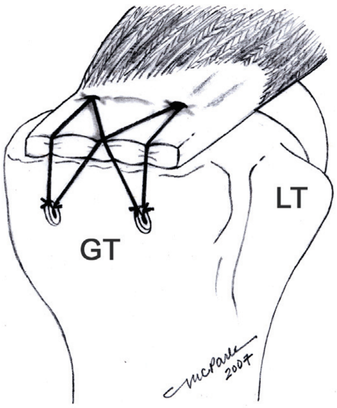

Figure 2. Schematic for the suture tendon-bridging repair. GT, greater tuberosity; LT, lesser tuberosity.

(Arthrex) with a 5.5-mm screw already loaded. A suture limb from each medial suture anchor is then placed through the suture loop at the end of the screwdriver. With use of a tensiometer (Arthrex), a minimum 4 kg of tension was gauged for these suture limbs passing through the suture loop in the screwdriver. With constant tension applied, a Bio-Tenodesis screw was placed at a 45° angle relative to the proximal lateral humerus.[4] After the screw was countersunk 1 mm, each suture limb was tied to a limb from the loop previously passed through the cannulation of the screwdriver; therefore, 2 knots were tied over each Bio-Tenodesis screw in the same manner described above. The remaining 2 suture limbs, one from each medial anchor, were then fixed with a Bio-Tenodesis screw[24,26] (Figure 2).

Biomechanical Testing

The rotator cuff repair constructs were tested using an Instron materials testing machine with load-cell capacity of 5 kN (Instron Corp, Model #4411, Canton, Mass), and a video digitizing system (VDS) (WINAnalyze, Micromak, Berlin, Germany). The accuracy, precision, and repeatability of the VDS for the tested field were determined to be within 0.15 mm, 0.075 mm, and 0.071 mm, respectively.

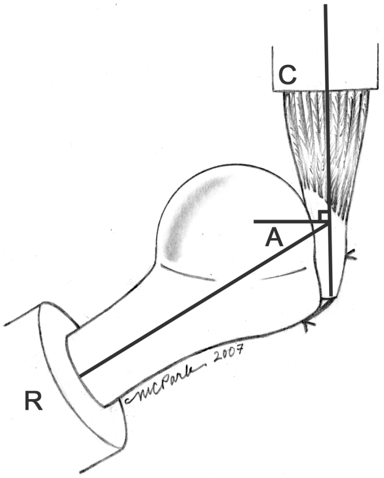

Figure 3. Side view of testing set-up demonstrating abduction angle. R, rotating clamp (secures humerus); A, abduction angle; C, clamp (secures supraspinatus muscle and tendon).

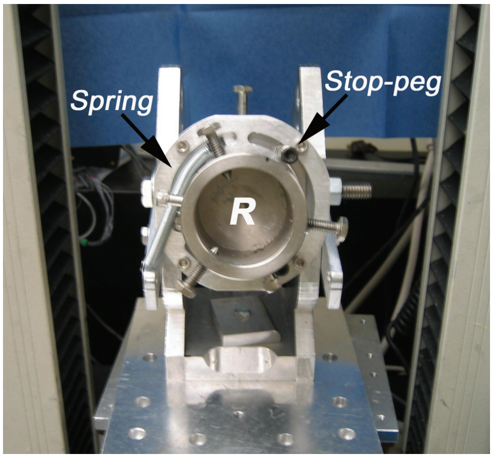

Figure 4. Customized apparatus allowing external rotation with tendon loading. R, rotating clamp (secures humerus).

The proximal humerus was potted with plaster of Paris in 1.5-in diameter polyvinyl chloride (PVC) piping. The potted specimen was then secured within a custom clamp to a custom-designed testing apparatus that was oriented in 30° of glenohumeral abduction to simulate a common postoperative abduction angle[27] (Figure 3).

The apparatus allows for humeral rotation with tendon loading by the materials testing machine and returns the humerus to the designated starting position with a spring as the return cycle occurs (Figure 4). The spring constant for the apparatus was measured at 0.0793 N/mm. The specimens were clamped with the humerus in neutral rotation.[25] Neutral rotation was defined as the point where loading of the humerus via traction on the supraspinatus initiated external rotation[15]; during preloading, the humerus was manually rotated until external rotation was initiated, then secured into the testing apparatus. Because the supraspinatus has been shown to lie just posterior to the humeral head center of rotation, it has been shown to initiate external rotation when starting in neutral rotation.[15]

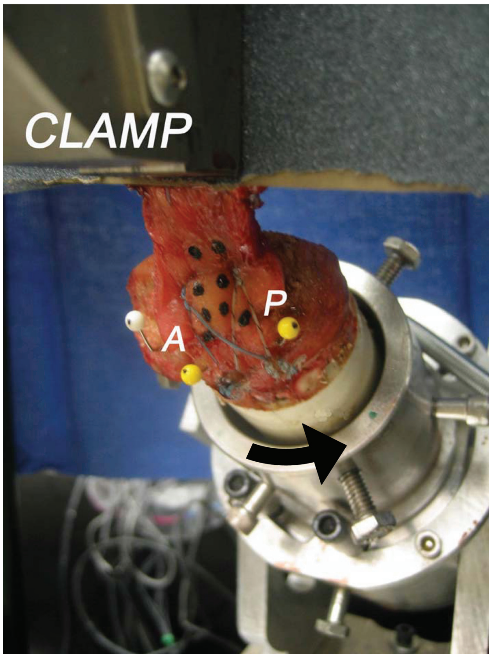

Figure 5. Tendon markers for measuring gap formation. Black "dots" were used as tendon markers for the video-digitizing system. A, anterior tendon; P, posterior tendon. Arrow indicates direction of rotation with tendon loading.

The testing apparatus has stop-pegs that control the amount of rotation arc that can be produced; the arc chosen for testing was 30°, as may be commonly performed postoperatively during rehabilitation.

To minimize soft-tissue slippage or failure at the tendon-grip interface, a modified soft-tissue clamp supplemented with double-sided fine sandpaper was used to secure the proximal part of the supraspinatus tendon, approximately 1 cm proximal to the musculotendinous junction, as previously described.[16] Care was taken to ensure equal and symmetric tension across the tendon before clamping. Once the specimen was mounted securely, markers were placed on the surface of the tendon, humerus, and clamp for the video-digitizing analysis (Figure 5).

With rotation, the tendon moved out of plane to varying degrees, depending on the specimen. Because the VDS was limited to 2 coordinate planes, studies were performed in our laboratory to determine the accuracy of the marker distances with rotation; rotation created an obligatory third dimension that potentially could misrepresent the marker distances. For both the anterior and posterior tendon regions, the out-of-plane correction factor was on the order of less than 0.01 mm, and therefore considered negligible using both 30° abduction and a 30° rotation arc as in the current study.

Tensile Testing. Before testing to failure, cyclic loading was performed; a 10-N preload was applied for 60 seconds, and then each specimen was cyclically loaded[6] from 0 N to 90 N at a loading rate of 1 mm/s for 30 cycles. Supraspinatus tendon loading created rotation up to 30° of external rotation. After cyclic testing, the clamp was rechecked for tightness. The specimens were then loaded to failure at a rate of 1 mm/s. The structural properties of linear stiffness at yield load, yield and ultimate failure loads, and energy absorbed to failure were determined from the load-elongation curves. Yield load is the load beyond which a given repair construct is permanently deformed and will not retain its original shape. Using the VDS, gap formation of the repairs was measured at "end rotation" and at yield load; "end rotation" was defined by the 1 videoframe just before engaging the stop-peg (30° humeral external rotation); by defining end rotation, the effects of dynamic rotation alone could be isolated and measured. In contrast, after the stop-peg has been engaged, the humerus cannot actively rotate; therefore, the effects of static rotation were measured at higher loads, such as at yield and ultimate loads.

The loading conditions used in the current study are based on electromyography studies that have shown a range of maximal contraction during postoperative rehabilitation; passive external rotation does not generate more than 5% of maximal supraspinatus contraction,[8] while active external rotation with the arm at the side can be approximately 30% of maximal supraspinatus constraction.[27] The maximal supraspinatus contraction has been estimated to be approximately 300 N.[4] Given these parameters, the supraspinatus load during postoperative exercises should range from 15 N to 90 N at most with external rotation exercises. While the humerus was externally rotating (before engaging the stop-peg), we chose a spring constant from pilot studies to allow external rotation with loads not exceeding 45 N on average. The relatively low loads applied in this model were chosen to best simulate the actual in vivo postoperative loading situation with active external rotation. Previous studies have employed relatively higher loads with the humerus fixed in space.[6,16,18,26]

Similar to another study that used 20 cycles,[19] we chose 30 cycles based on previous studies at our institution where cyclic behavior stabilized at 25 cycles. The number of cycles can be arbitrary, [6] but the early cycles likely give the most accurate information in cadaveric specimens, which deteriorate with use and time. Because we found that the gap data during cyclic loading was relatively small, and not different from the gap determined at "end rotation," the cyclic loading of each specimen was ultimately performed only to standardize the tendon conditioning before tensile loading to failure.

The gap of interest was defined as the space (measured in mm) between the lateral edge of the repaired tendon and the lateral edge of the insertion footprint; markers were placed symmetrically anteriorly and posteriorly, flanked by the suture knots from the repair. This gap was calculated by measuring the change in position of the markers on the lateral edge of the tendon relative to the stationary markers on the lateral humerus; the relative gap between tendon edge and markers estimated the gap that would be created between the tendon edge and lateral footprint insertion.

Statistical Analysis

A paired Student t test was used to compare the biomechanical properties between repair constructs. The paired t test was chosen based on the fact that match-paired specimens were

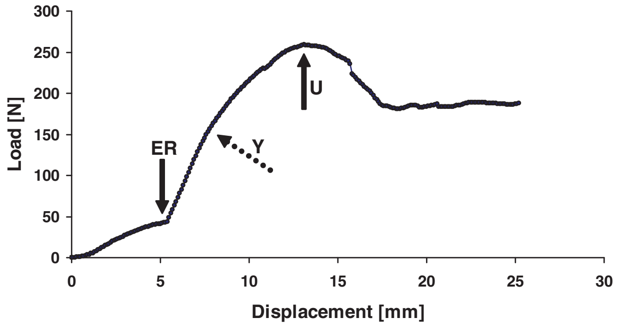

Figure 6. Representative stress-strain curve. "Rotational stiffness" was measured from the portion of the curve to the left of the down-arrow; linear stiffness was measured using the remaining curve. ER, down-arrow = end rotation (1 video frame before engaging the stop-peg); Y, dotted-arrow = yield load; U, up-arrow = ultimate load.

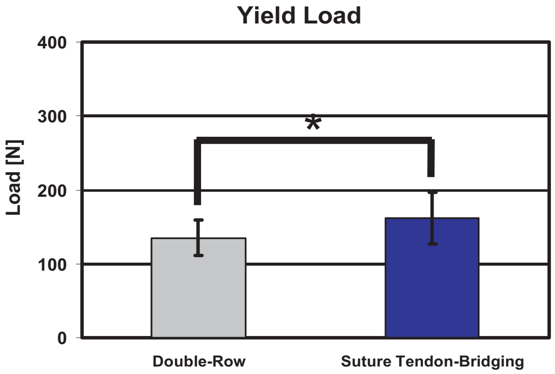

Figure 7. Comparison of yield load between repair constructs at 30° of humeral external rotation. *$P < .05$.

randomized to right versus left (the type of testing method was not randomized), and that the study was designed to take advantage of dependence between paired extremities from 1 common cadaver. The level of statistical significance was set at $P < .05$.

A power analysis was performed for gap formation measurements to assess for sample size. To detect a difference in averages within a minimum of 2 standard deviations between the 2 repair constructs, with a power of at least 95%, using a 5% level of significance ($\alpha = .05$), the required sample size was 12 specimens (6 matched pairs). Because the standard deviation was approximately 0.5 mm for both repair constructs, our results are able to detect a minimum 2 standard deviations (approximately 1 mm) of difference in gap formation between the 2 testing conditions with a probability of at least 95%.

RESULTS

Notably, rotation created 2 stiffness regions on the load-elongation curves. As the humerus rotated through the 30° arc, "rotational" stiffness was calculated from the stress-strain curve; after the rotating apparatus abutted the stop-peg at 30° of external rotation, linear stiffness was calculated from the corresponding portion of the curve (Figure 6). End rotation was defined on the video 1 frame before engaging the stop-peg, thus providing a means to isolate the effect of dynamic external rotation on gap formation.

The yield load for the tendon suture-bridging technique (161.88 ± 35.09 N) was significantly larger than the double-row technique (135.17 ± 24.03 N) ($P = .026$) (Figure 7). There were no differences for stiffness, ultimate load to failure, and energy absorbed to failure ($P > .05$) between the double-row and suture-bridging techniques (Table 1). The average load at end rotation was 43.42 ± 21.39 N for the double-row technique and 44.95 ± 19.18 N for the suture-bridging technique ($P = .92$).

The end-rotation gap between the tendon and lateral footprint was significantly greater anteriorly than posteriorly (1.27 ± 0.75 mm and 0.56 ± 0.32 mm, respectively) for the tendon suture-bridging technique ($P = .026$) but was not for the double-row technique (0.97 ± 0.35 mm and 0.71 ± 0.61 mm, respectively) ($P = .34$). The yield gap between the tendon and lateral footprint was significantly greater anteriorly than posteriorly (1.62 ± 0.82 mm and 0.68 ± 0.47mm, respectively) for the suture-bridging technique ($P = .024$) but was not for the double-row technique (1.35 ± 0.52 mm and 1.05 ± 0.50 mm, respectively) ($P = .34$). Similarly, when stratified between anterior and posterior gaps, there were no differences between the 2 groups ($P > .05$) (Table 2).

TABLE 1
Stiffness, Load, and Energy Absorbed During Failure Testing

	Double Row	Suture Bridging	*P* Value
Rotational stiffness (N/mm)	12.60 ± 11.01	14.26 ± 10.11	.569
Linear stiffness (N/mm)	52.26 ± 10.91	49.90 ± 12.83	.692
Yield load (N)	135.17 ± 24.03	161.88 ± 35.09	.026
Ultimate load (N)	227.49 ± 52.36	355.84 ± 162.05	.168
Energy absorbed (Nmm)	1828.37 ± 1353.58	2800.70 ± 1696.43	.363

At 30° of external rotation, the anterior tendon region was the first to fail in all constructs in both the double-row and tendon suture-bridging groups. The double-row construct failed at the suture-tendon interface for the anterior-medial anchor first in 5 of the 6 specimens. Five of the specimens failed at the suture-tendon interface in the following order: anterior-medial, then anterior-lateral; 4 of these failed at the posterior-medial anchor next in sequence. In 3 double-row specimens, the posterior-lateral anchor at the suture-tendon interface was the last to fail, with another 2 specimens failing finally at the musculotendinous junction posteriorly. Only 1 double-row construct failed completely at the musculotendinous junction, with the anterior region failing first. The suture-bridging repair remained interconnected between implant fixation points via the tendon-bridging sutures for all repairs except 1. Four of the

TABLE 2
Gap Formation at End Rotation and at Yield Load

	Double Row			Suture Bridging			Double Row vs Suture Bridging (*P* Value)	
Gap Formation (mm)	Anterior	Posterior	*P* Value	Anterior	Posterior	*P* Value	Anterior	Posterior
End rotation (30° external rotation)	0.97 ± 0.35	0.71 ± 0.61	.34	1.27 ± 0.75	0.56 ± 0.32	.026	.40	.63
Yield	1.35 ± 0.52	1.05 ± 0.50	.34	1.62 ± 0.82	0.68 ± 0.47	.024	.57	.33

constructs failed first at the suture-tendon interface anteriorly. The remaining 2 constructs failed at the musculotendinous junction, with the anterior region failing first in both.

DISCUSSION

Improving rotator cuff repair techniques may be enhanced by better understanding what occurs at a repair site when subjected to motion commonly encountered in a postoperative setting. Cyclic loading with the humerus fixed has been an accepted method for testing rotator cuff repairs.[5,6,16,18,21,26] However, a fixed humerus does not allow motion that the supraspinatus is capable of generating, particularly in a postoperative rehabilitation setting. Therefore, the objective of this study was to elucidate the effects of external rotation on both double-row and tendon suture-bridging repair sites. Notably, Park et al[25] have shown that tendon loading that allows rotation (similar to the method employed in the current study) creates significantly more gap and strain at the anterior supraspinatus tendon after repair, when compared to testing with the humerus fixed.

Repair strength is critical for optimizing healing at a repaired rotator cuff footprint, insofar as it determines maintenance of tendon-to-bone integrity during postoperative exercises.[12] Based on our results, the suture-bridging repair had a significantly higher yield load than the double-row repair (Table 1). Interestingly, in a previous study comparing the same constructs with the humerus fixed, there were no differences found in yield load, although the suture-bridging repair had a significantly higher ultimate load to failure and energy absorbed to failure.[26] This suggests that the addition of external rotation to the testing model may allow the discernment of yield strength differences for footprint-restoring repair constructs, and highlights how an interconnected construct such as the suture-bridging repair may share load better than a double-row repair that has 4 separate fixation points. While the ultimate load may not have reached statistical significance between the 2 repair techniques, yield load to failure may be more relevant because this theoretically marks a threshold to where the construct is not permanently deformed, and thus may be a better measure for maintenance of gap formation.

Gerber et al[12] have emphasized the importance of minimizing gap formation to avoid poor healing and failure. In the current study, there were no significant differences in gap formation between the double-row and suture-bridging repair constructs in response to dynamic external rotation (Table 2); our power analysis suggests that the nondifference is real to within ~1 mm. The gap formation at the anterior tendon region compared with the posterior region was significantly higher for the suture-bridging repair technique at both end rotation (30° external rotation) and yield load. This may be due to the fact that this technique does not use lateral tendon fixation points. However, the double-row repair does rely on direct lateral tendon fixation; gap formation was not significantly different for the double-row repair at both end rotation and yield load when comparing the anterior versus posterior tendon regions in the current study. Also, the larger anterior gap formation for the suture-bridging repair was on the order of 1 mm, which is a minimal amount. This small amount of gapping may in fact be exaggerated to a certain degree insofar as the markers on the bursal side of the tendon qualitatively moved more than the tendon at the tendon-bone interface. Our results point to the fact that under relatively low loads as may be seen in a rehabilitation setting, as reproduced at end rotation and yield load, both repair constructs limit gap formation. A threshold of "acceptable" gap formation is yet to be determined.

Studies have shown that the anterior supraspinatus muscle and tendon is anatomically different than the posterior portion.[28,29] There is a thick tubular tendon anteriorly that tapers to a flat tendon posteriorly; the anterior tendon is an intramuscular "cord" onto which the fusiform muscle fibers attach.[28] This cord is not to be confused with the "rotator cable," which is a transverse thickening of capsular tissue that subtends the insertions of the supraspinatus and infraspinatus.[3] A rotator cuff tear that does not involve the anterior cord may explain a "functional" rotator cuff tear. When considering the effect of rotation on rotator cuff healing, this difference in anterior versus posterior anatomy becomes more relevant. For example, based on our results that the suture-bridging repair had more anterior tendon gap formation than the posterior region with rotation, direct lateral fixation through the anterior tendon may be necessary to optimize the biomechanics, particularly when a tear involves the most anterior supraspinatus tendon at the rotator interval. Augmenting repair of the anterior tendon cord of the supraspinatus,[28,29] perhaps employing additional lateral fixation, may improve the ability to re-create a functional repair. Interestingly, the anterior supraspinatus tendon has been shown to better withstand nonrotational loading than the posterior tendon after rotator cuff repair.[18] Based on the current study, the anterior cord of the supraspinatus may be more vulnerable to rotational stresses, and this may warrant altering the postoperative rehabilitation regimen. The effect of variable anterior versus posterior supraspinatus tendon anatomy on gap formation, with varying kinematic parameters, requires further study.

Our results after failure testing highlight the importance of regional supraspinatus tendon anatomy. For the double-row repairs, the anterior-medial fixation point tended to fail first through the suture-tendon interface; in general, the medial fixation points failed before their associated lateral fixation points, anterior then posterior. This suggests that the medial row may be critical for tension reduction over the footprint laterally. Notably, the suture-bridging repair remained interconnected after failure testing for 5 of 6 specimens; it relies on medial tendon fixation, and interconnected tendon-compressing sutures that share load.[26] For both repair constructs, the anterior tendon region failed first in all specimens, consistent with the larger average gap formations in the anterior tendon. This suggests that additional anterior fixation may be necessary to optimize repair integrity. Also, gap formation anteriorly could be magnified with larger loads, as may be seen with uncontrolled motion; limiting postoperative external rotation may therefore be significant. Furthermore, increased tension may accentuate gap formation, as may be seen with repaired tendons that have been retracted. A fixed sling with an abduction pillow may minimize gap and strain effects compared to a freely moving sling; Hatakeyama et al[14] found decreased strain with 30° of abduction and neutral or external rotation. This is consistent with the fact that the supraspinatus lies just posterior to the center of rotation.[15]

While the current study highlights the effects of external rotation on yield load and gap formation, other considerations may affect ultimate technique choice. Park et al[24] have shown that the tendon suture-bridging repair provides improved contact dimensions when compared with a double-row technique. Ultimate load and energy absorbed to failure were also found to be higher for the suture-bridging repair.[26] From a technical standpoint, the suture-bridging repair requires fewer tendon suture passes; it maximizes the use of a medial single-row repair by creating tendon-bridging sutures from the same medial implants, and may reduce operative time compared with a double-row technique.[23] Furthermore, the suture-bridging repair does not rely on the lateral-most tissue for fixation; this tissue tends to be of poor quality, especially in chronic tears. Also, the suture-bridging repair brings the medial-row knots flush to the tendon and compresses the lateral tendon edge, which may reduce the likelihood for "edge instability" against the acromio-coracoacromial ligament arch.[3]

The primary limitation of this study is that human cadavers were used. Only time-zero information after repair can be obtained in the absence of healing. Also, the repairs were performed tension-free given the method of preparation; this may alter the tension across a given repair and underestimate our gap formation results, especially when faced with retracted tears as is often the case in vivo. Furthermore, we only simulated an external rotation maneuver; internal rotation was only pilot-tested because the supraspinatus theoretically does not actively contribute to external rotation while internally rotated, as in a sling.[15] Modeling an in vivo shoulder requires accounting for multiple muscle-tendon units and varying kinematics, which we did not fully re-create. Ultimately, the kinematic parameters used in the current study cannot completely model an in vivo shoulder, but may isolate the effect of external rotation on a single repaired tendon when comparing 2 different repair constructs. Finally, the effect of stiffness on rotator cuff repair healing is yet to be elucidated, but is presented in the Results section above, although there were no significant differences between the 2 repair constructs tested.

We sought to simulate a commonly encountered postoperative motion using relatively low loads to elucidate biomechanical effects likely experienced postoperatively. We found a significantly greater yield load in favor of the tendon suture-bridging rotator cuff repair; the concept of medial tendon fixation (providing lateral tendon "shielding") with distal-lateral suture fixation (providing lateral tendon compression) creating an interconnected, load-sharing construct should be considered as new rotator cuff repair constructs are developed.[23,24,26] Gap formation was not different between constructs, although the anterior tendon region experienced more gapping compared to the posterior region at end rotation and yield load for the suture-bridging repair. The improved contact area and pressure afforded by this technique[24] may outweigh the small anterior versus posterior gap differential found in the current study. There was no gap difference between tendon regions for the double-row repair. Notably, gap formation for both constructs may be underestimated, as our specimens were repaired tension-free, while in vivo repair often involves a retracted tear under tension. The effects of anterior versus posterior supraspinatus tendon anatomy becomes more relevant when considering external rotation.[28,29]

Clinically, based on the current study, there are arguments to reinforce the repair anteriorly, and limit external rotation postoperatively, depending on the tissue quality and tension encountered for a given repair. Insofar as the tendon suture-bridging repair has a higher yield load, and no difference in gap formation than a double-row repair based on the current study, with improved footprint contact characteristics[24] and potentially less operative time than a double-row repair,[23] the suture-bridging repair may be the favorable repair. The goal is to optimize healing potential between tendon and bone to decrease persistent tear rates after repair[1,2,10,11,13] and ultimately improve patient outcomes.

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