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Biomechanical Performance of Rotator Cuff Repairs With Humeral Rotation

A New Rotator Cuff Repair Failure Model

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Background: Traditional biomechanical evaluations of rotator cuff repair techniques employ cyclic loading of the supraspinatus tendon in an isolated medial direction.

Purpose: This study was conducted to evaluate 2 different rotator cuff repair techniques that are currently the subject of debate with cyclic loading and with internal and external humeral rotation to better simulate postoperative rehabilitation.

Study Design: Controlled laboratory study.

Methods: Nine fresh-frozen paired human cadaver shoulders (18 shoulders) were studied. A single-row repair with 2 suture anchors was compared with a double-row repair with 4 suture anchors. The shoulders were tested in a custom device to position the shoulder in neutral, 45° of internal rotation, and 45° of external rotation. Cyclic loading of the supraspinatus tendon was performed with an MTS material testing machine. Gap formation was measured and analyzed for each rotational position using the MTS device.

Results: For the single-row repair, average gap formation per 100 cycles in the positions of neutral, internal, and external humeral rotation was 1.47 ± 0.63, 3.11 ± 1.55, and 2.24 ± 0.94 mm, respectively. For the double-row repair, average gap formation per 100 cycles in the positions of neutral, internal, and external humeral rotation was 1.25 ± 0.54, 2.29 ± 1.10, and 1.57 ± 0.48 mm, respectively. For gapping averaged over all positions, the double-row repair had significantly less gapping than the single-row repair (P = .0109); gapping was greatest for internal rotation, followed by external rotation, and least for neutral (P < .0001).

Conclusion: The testing method of including a rotational component in biomechanical rotator cuff repair testing is a more realistic model of the loading conditions experienced by a repaired rotator cuff as the patient participates in postoperative rehabilitation. Double-row repair has better fixation strength than single-row repairs when exposed to cyclic loading and changes in humeral rotation position.

Clinical Relevance: Humeral rotation affects rotator cuff fixation and should be considered in postoperative rehabilitation.

Keywords: rotator cuff; repair; biomechanics; shoulder; tendon

Rotator cuff tears are a frequent cause of shoulder pain and disability. Arthroscopic rotator cuff repair is now considered a mainstream technique with highly satisfactory clinical results.8,12,16,22,26-28 Although many advantages of arthroscopic techniques exist, concern remains regarding healing failures for large and massive tears.7 These high failure rates are attributed to multiple factors, including severity of tear, poor tendon quality, and degree of retraction. Recent research has focused on improving the strength and durability of rotator cuff repairs to decrease this high rate of failure.

Early all-arthroscopic repair constructs involved a single-row design, in which suture anchors are implanted in the anatomic footprint of the rotator cuff. Double-row repairs employ a medial row of suture anchors placed along the lateral margin of the articular cartilage in addition to a lateral row of anchors placed in the lateral aspect of the footprint.10,25 Advantages of double-row repair include a more anatomical restoration of the footprint, increased tendon-to-bone contact area, decreased tendon-bone interface motion, and improved fixation strength.10,25

As arthroscopic repair techniques have evolved, so have the methods by which these constructs are tested in the...
laboratory. Early biomechanical testing involved single loading of the repair to failure. Burkhart et al were the first to report cyclic loading as the model for studying rotator cuff repair methods. Cyclic loading is thought to better simulate the early postoperative environment and therefore be a better model for evaluating rotator cuff repair fixation strength. Several recent studies compared single-row and double-row repair constructs using cyclic loading. Burkhart et al were the first to report cyclic loading as the model for studying rotator cuff repair methods. Cyclic loading is thought to better simulate the early postoperative environment and therefore be a better model for evaluating rotator cuff repair fixation strength. Several recent studies compared single-row and double-row repair constructs using cyclic loading. These studies employ cyclic loading of the supraspinatus tendon in an isolated medial direction. The postoperative environment of the supraspinatus, however, involves loading the humerus in different positions of rotation. Therefore, humeral rotation incorporated into cyclic loading may better simulate the postoperative shoulder environment and may give further insight into failure properties of rotator cuff repair. The objective of this study is to evaluate single-row and double-row rotator cuff repairs employing cyclic loading with changes in humeral rotation. The hypothesis of the study is that double-row rotator cuff repair will outperform single-row repair using cyclic loading with humeral rotation variations.

MATERIALS AND METHODS

Nine fresh-frozen paired human cadaver shoulders (18 shoulders; mean age, 61 years; range, 37-81) were used. The shoulders were dissected free of skin and soft tissue, leaving only the proximal humerus and supraspinatus tendon (Figure 1). The remaining diaphysis of the humerus was potted into a polyvinyl chloride pipe using expansion cement. There was no evidence of gross rotator cuff injury in any specimen. The supraspinatus tendon of each shoulder was then sharply dissected off at its insertion site on the humerus. One shoulder from each pair was randomized to either a single-row or double-row repair, which was performed by a single fellowship-trained shoulder specialist. The single-row repair was performed by placing two 5.5-mm fully threaded metal corkscrew suture anchors (Arthrex Inc, Naples, Florida) loaded with a single No. 2 Fiberwire (Arthrex). The anchors were placed in the center of the insertional footprint in the coronal plane and in the anterior third and the posterior third of the insertional footprint in the sagittal plane. The single No. 2 Fiberwire suture was passed through the tendon in a simple fashion 7 mm from the tendon edge. For the double-row repair, the medial anchors were placed adjacent to the humeral head articular cartilage edge, 1 in the anterior third and 1 in the posterior third. The lateral row of anchors was placed at the lateral edge of the insertional footprint with 1 in the anterior third and 1 in the posterior third. The lateral row of anchors was placed at the lateral edge of the insertional footprint with 1 in the anterior third and 1 in the posterior third. The medial row sutures were passed in a mattress fashion with 7 mm of tissue captured and the lateral row sutures were passed in a simple fashion 7 mm of tissue captured (Figure 1). All anchors in both techniques were placed 45° to the line of pull of the supraspinatus tendon according to the “deadman theory.”

The shoulders were tested in a custom-built jig to position the shoulder in 30° of abduction (Figure 2) and allow the humerus to be rotated to positions of neutral rotation (NE), 45° of external rotation (ER), and 45° of internal rotation (IR). To change humeral rotation, the potted humerus was rotated within its clamp. The exact position of rotation was determined using a goniometer and verified by 2 experimenters. Cyclic loading of the supraspinatus tendon was performed with an MTS material testing machine (858 Bionix Test System, MTS Systems Corporation, Eden Prairie, Minnesota). The potted humerus was set in the jig and the supraspinatus muscle belly was rigidly fixed to the MTS device via a liquid carbon dioxide–cooled cryoclamp. The supraspinatus muscle belly was placed in the cryoclamp such that the distance between the head of the humerus and the cryoclamp was approximately 12 mm for all specimens. During testing, the supraspinatus was frequently bathed in saline warmed to 37°C to keep the tendon in the repaired region near physiologic conditions and to establish a more gradual temperature gradient between the muscle in the cryoclamp and the repaired tendon. The temperature of the supraspinatus tendon was frequently measured during experimentation to ensure that the proper temperature was being maintained.

An initial 1-N tare or preload was applied and a digital image was taken (5.1 megapixels) of the tendon and clamp with the digital camera mounted perpendicular to the tendon.
The tendon was then briefly loaded to 25 N as a tare force (where a second digital image was collected) before undergoing cyclic loading (100 cycles) at 50 N. After 100 cycles, a digital image was taken with the tendon again under 25 N of load. The rotational position was then changed and the cyclic loading repeated as well as the digital image under 25 N of load. The rotational position was then changed again and the cyclic loading and digital image repeated. Therefore, the specimen was loaded in each rotational position for each load magnitude. The initial position was randomized and the iteration pattern of humerus position was NE, then ER, then IR. As shown in Figure 3, after the initial 50-N load magnitude, the cyclic loading magnitude was increased from 50 N to 200 N in 25-N increments, then by 50-N increments thereafter to failure (defined as the point at which the tendon repair pulled completely off the humerus, with no remaining attachment). Since several pilot experiments demonstrated failure of single row specimens at 150 N, an initial static load of 25 N was chosen to be more than 10% of the lowest failure, but not so large as to cause additional damage during the static gapping measurements.

Gap formation was a measure of displacement of the actuator of the MTS machine (±0.5 mm accuracy). The 100 cycles per rotational position combined for a total of 300 cycles for all 3 positions tested before incrementing to the next higher load magnitude. The difference between the displacement of the tendon when statically loaded with 25 N and the displacement immediately after the 100 cycles of loading, again when statically loaded with 25 N, was considered as the gapping per 100 cycles for that position. The “average gapping” per 100 cycles was obtained by summing all the gapping that occurred for a particular position and dividing by the number of times the shoulder was tested in that position.

The total energy required to completely pull the repair off the humerus was computed by integrating the area under the load-displacement curve. To ensure that there was no slippage of the tendon in the freezing clamp throughout testing, the region of the tendon immediately adjacent to the clamp was speckled with a number of small paint dots. The digital photographs of the tendons in the clamps taken before testing and throughout the testing were used to monitor for potential slippage of the tendon in the clamp. The distances between the edge of the freezing clamp and several of the dots were measured from the photographs using the digital image analysis program Scion (Scion Corp, Frederick, Md).

Statistical Analysis

The shoulders were considered matched pairs during statistical analysis. A 2-way repeated-measures analysis of variance was performed on both factors, with repair type as 1 factor (single vs double row) and rotation position (NE, ER, IR) as the second factor. A Student-Newman-Keuls multiple comparisons test was used to evaluate differences between the 3 levels of rotational position (NE, ER, and IR). Average gap per loading cycle and total energy to failure were taken as the dependent variables.

RESULTS

When gapping was averaged over all rotational positions, the single-row repair had a greater average tendon gap formation per 100 cycles than the double-row repair (2.27 mm ± 1.04 vs 1.70 mm ± 0.71; \( P = .0109 \)). Rotational position was also found to have a statistically significant effect on tendon gapping (\( P < .0001 \)). Average gapping for IR was significantly greater than for ER, which in turn was significantly greater than for NE (Figure 4). In addition, there was a trend (\( P = .1047 \)) for rotational position to have a more pronounced effect on average gapping for the single-row suture technique than for the double-row technique. Figure 5 demonstrates the energy to failure for single-row and double-row repairs at each humeral position. When

Figure 3. Graph of displacement (gapping) versus time as an example of a single-row repair construct undergoing cyclic loading. The load starts at 50 N and increases in 25-N increments. At each loading magnitude, the repair is cyclically loaded and iterated through all 3 rotational positions. At the 150-N load magnitude, the repair failed in the internal rotation position for this specimen.

Figure 4. Comparison of average gapping between single-row versus double-row repair for internal rotation (IR), external rotation (ER), and neutral rotation (NE). The figure shows means ± standard deviation.
DISCUSSION

The novel feature of this study is the addition of humeral rotation to the cyclical loading model. The optimal position for minimizing gapping for rotator cuff repairs was neutral rotation. This may be explained by the fact that when the humerus is in neutral, the line of pull of the supraspinatus is directly perpendicular to a line connecting the anterior and posterior anchors. This means that the load is evenly distributed between the anterior and posterior anchors. However, when the humerus is rotated, the load is not symmetrically distributed and there is greater strain and hence stress on the more distal suture construct (eg, the anterior side when the humerus is externally rotated) (Figure 6). When the humerus is rotated, tension on the rotator cuff repair preferentially loads the anchor furthest from the test machine. This is analogous to the findings of Burkhart et al,5 who introduced the concept of tension overload. They observed that for a U-shaped tear repaired directly to the greater tuberosity, the central suture in a repair always failed first and by the greatest amount when subjected to cyclic loading and this was because it correlated with the portion of the tendon repaired under the greatest tension. It should also be noted in our study that the double-row repair had 2 additional anchors and the mere addition of 2 anchors for the double-row repair may also explain the superior fixation strength.

Several reasons help explain why ER had less gapping and required more energy to failure than the IR position. The cross-sectional anatomy of the supraspinatus tendon demonstrates a thicker, rounder edge anteriorly than posteriorly.20 Sutures placed through the more stout anterior tendon were therefore stronger than sutures placed through the weaker, thinner posterior tissue. When the arm was placed in IR, the posterior suture anchor was preferentially loaded, and the gapping occurred more readily through this weaker tissue when compared with the position of ER, in which the suture is placed through the more stout anterior tissue.

Clinically, the finding that the repair exhibits greater amounts of gapping in the rotated (especially the internally rotated) position is relevant to optimize postoperative management. Shoulders are positioned in a sling after rotator cuff surgery and usually in an internally rotated position. The data from our study suggest a benefit from positioning the arm in neutral rotation to minimize failure potential.

We also found that the single-row group exhibited a trend toward increased average gapping in positions of rotation when compared with the double-row group. This is important because it indicates that double-row repair may allow increased postoperative rotation before clinically detrimental gapping compromises the repair. The clinical implication of this is that if humeral rotation is believed to be an important factor affecting gapping, then double-row repairs may provide a benefit in terms of minimizing failure potential in the early stages of healing before allowing full motion.

Figure 5. Bar graph of total energy required to tear the tendon repair off the humerus. The average energy required was significantly higher for the double-row (DR) repair than for the single-row (SR) technique (P < .00002). Internal rotation (IR) energy was significantly greater than external rotation (ER) and neutral (NE). The figure shows means ± standard deviation.

Figure 6. Schematic representation of the supraspinatus tendon being loaded in the neutral position (right) and in rotation (left). In the neutral position, the loads seen by the suture construct (F1, F2) are equal (F1 = F2). Rotation causes greater strain and hence greater stress on the more distal suture construct as that side of the tendon (eg, anterior aspect with arm in external rotation) is under more tension.
part of postoperative rehabilitation, double-row repair may minimize the gapping that occurs in rotation.

Burkhart et al. introduced the technique of cyclic loading to evaluate rotator cuff repairs, and they believed it better simulates the postoperative environment to which the shoulder is exposed. After that study, many other investigators also adopted the cyclic loading technique to evaluate rotator cuff repair biomechanics with better simulation of postoperative conditions. Several biomechanical studies have also compared single- and double-row rotator cuff repair constructs directly using this methodology. Mazzaocca et al. found that there was no significant difference between single- and double-row repairs in load to failure, cyclic displacement, or gap formation, while Ma et al. and Kim et al. showed that double-row fixation was significantly stronger than single-row repair. Although these last 2 studies have observed increased fixation strength for double-row repairs with cyclic loading in a single direction and no change in humeral rotation, they are consistent with our data that have employed cyclic loading with changes in humeral rotation.

Several limitations regarding this study should be considered. First, many variations in rotator cuff repair exist for both single- and double-row rotator cuff repair. This study does not attempt to determine the best possible configuration, but rather is a comparison of basic single- and double-row configurations in the context of humeral rotation. In addition, this study only addresses the biomechanical properties of these constructs, but the biological properties may be of equal or greater importance in terms of healing potential. It is known that double-row constructs have favorable footprint contact characteristics, which may increase the surface area over which healing occurs. Other factors that may be important include tendon-bone pressure distributions, tendon-bone interface motion, and vascularity of the tendon at the repair site. It is likely that all of these factors must be collectively taken into account in determining the best possible construct to promote tendon-to-bone healing.

CONCLUSION

Double-row repair has better fixation strength than single-row repair when exposed to cyclic loading and changes in humeral rotation position. The novel method of including a rotational component in biomechanical rotator cuff repair testing provides a more realistic model of the loading conditions experienced by a newly repaired cuff as the patient participates in postoperative rehabilitation.

REFERENCES