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Biomechanical Evaluation of Transosseous Rotator Cuff Repair

Do Anchors Really Matter?

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Investigation performed at the Rush University Medical Center, Chicago, Illinois

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Background: Suture anchor fixation has become the preferred method for arthroscopic repairs of rotator cuff tears. Recently, newer arthroscopic repair techniques including transosseous-equivalent repairs with anchors or arthroscopic transosseous suture passage have been developed.

Purpose: To compare the initial biomechanical performance including ultimate load to failure and localized cyclic elongation between transosseous-equivalent repair with anchors (TOE), traditional transosseous repair with a curved bone tunnel (TO), and an arthroscopic transosseous repair technique utilizing a simple (AT) or X-box suture configuration (ATX).

Study Design: Controlled laboratory study.

Methods: Twenty-eight human cadaveric shoulders were dissected to create an isolated supraspinatus tear and randomized into 1 of 4 repair groups (TOE, TO, AT, ATX). Tensile testing was conducted to simulate the anatomic position of the supraspinatus with the arm in 60° of abduction and involved an initial preload, cyclic loading, and pull to failure. Localized elongation during testing was measured using optical tracking. Data were statistically assessed using analysis of variance with a Tukey post hoc test for multiple comparisons.

Results: The TOE repair demonstrated a significantly higher mean ± SD failure load (558.4 ± 122.9 N) compared with the TO (325.3 ± 79.9 N), AT (291.7 ± 57.9 N), and ATX (388.5 ± 92.6 N) repairs ($P < .05$). There was also a significantly larger amount of first-cycle excursion in the AT group (8.19 ± 1.85 mm) compared with the TOE group (5.10 ± 0.89 mm). There was no significant difference between repair groups in stiffness during maximum load to failure or in normalized cyclic elongation. Failure modes were as follows: TOE, tendon (n = 4) and bone (n = 3); TO, suture (n = 6) and bone (n = 1); AT, tendon (n = 2) and bone (n = 3) and suture (n = 1); ATX, tendon (n = 7).

Conclusion: This study demonstrates that anchorless repair techniques using transosseous sutures result in significantly lower failure loads than a repair model utilizing anchors in a TOE construct.

Clinical Relevance: Suture anchor repair appears to offer superior biomechanical properties to transosseous repairs regardless of tunnel or suture configuration.

Keywords: rotator cuff; tendon rupture; biomechanical; tendon repair

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Arthroscopic rotator cuff repair is a common orthopaedic procedure and has a high success rate with regard to patient satisfaction and functional improvement. Initially, rotator cuff repairs were performed in an open fashion and utilized a single row of fixation achieved by the creation of transosseous bone tunnels.[3,7,11] With the development of shoulder arthroscopic surgery, suture anchor fixation has become the method of choice for those surgeons performing entirely arthroscopic repairs of rotator cuff tears. Suture anchor repair techniques have evolved from single-row to double-row constructs and recently to a transosseous-equivalent footprint reconstruction in an attempt to more closely reproduce the normal rotator cuff footprint anatomy.[6,15] Current biomechanical data suggest that a transosseous-equivalent repair offers improved ultimate load to failure with reduced gap formation during cyclic loading when compared with either single- or double-row suture anchor repairs.[15] On the clinical front, the literature remains elusive in regard to improved clinical outcomes with more advanced repair techniques.[3,7,11,19,22,23]

More recently, newer techniques for all arthroscopic transosseous repairs of the rotator cuff have been developed. These techniques utilize a custom device (ArthroTunneler, Tornier Inc, Edina, Minnesota) that enters perpendicular to the rotator cuff footprint and then exits at a nearly 90° angle toward *the lateral wall of* the greater tuberosity, creating a more sharply angled transosseous

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TABLE 1
Demographics of Cadaveric Shoulders[a]

	Repair Group (n = 7 per group)			
	TOE	TO	AT	ATX
Age, mean ± SD, y	56.0 ± 10.0	55.7 ± 8.4	62.9 ± 12.1	41.7 ± 11.6
Sex, n				
Male	4	5	5	5
Female	3	2	2	2
Shoulder side, n				
Right	5	2	3	3
Left	2	5	4	4
Bone density, mean ± SD, HU	1141.9 ± 45.2	1171.2 ± 43.0	1123.0 ± 48.7	1150.5 ± 57.0

[a]TOE, transosseous-equivalent repair with anchors; TO, traditional transosseous repair with curved bone tunnel; AT, arthroscopic transosseous repair technique using simple suture configuration; ATX, arthroscopic transosseous repair technique using X-box suture configuration; HU, Hounsfield units.

tunnel with potentially increased bone bridge length. Potential advantages of arthroscopic transosseous repairs include the associated decreased cost, elimination of suture anchors, and a similar ability to re-create the rotator cuff footprint. Potential disadvantages include increased surgical complexity, risk of fracture of the greater tuberosity, and suture cutout through bone, which is a known limitation of traditional open transosseous repairs. To our knowledge, there have not been any published reports comparing the differences in initial biomechanical performance between these techniques. The purpose of this study was to evaluate the differences in initial biomechanical performance including ultimate load to failure and localized elongation with cyclic loading between transosseous-equivalent repair with suture anchors (TOE), anchorless designs of the traditional transosseous repair with curved bone tunnels (TO), and the arthroscopic transosseous repair technique utilizing a simple (AT) or X-box suture configuration (ATX). The hypothesis was that TOE suture anchor repair would demonstrate superior initial biomechanical performance in comparison to the transosseous repair techniques.

MATERIALS AND METHODS

Twenty-eight fresh-frozen, human cadaveric shoulders were utilized in this study. Twenty-one were randomized to 1 of 3 repair groups (7 specimens per group): TOE, TO, and AT using the ArthroTunneler. Seven of the 28 specimens were assigned to the ATX group utilizing the ArthroTunneler. The ATX specimens were added to the study after randomization for the other 3 groups had occurred and therefore were unable to be included in the randomization process. The TOE, TO, and AT groups were randomized, in order of priority, according to bone density, age, and sex. The random number generator in Microsoft Excel (Microsoft, Redmond, Washington) was used for this process. Mean ages for the repair groups were 56.0 years (range, 45-68) for TOE, 55.7 years (range, 47-68) for TO, 62.9 years (range, 47-86) for AT, and 41.7 years (range, 25-50) for ATX. Quantitative computed tomography was used to determine the bone density at the greater tuberosity of the humerus (Table 1). Table 1 further summarizes the demographics of the cadaveric shoulders.

Specimen preparation included first dissecting the humerus and rotator cuff muscles free of skin and any underlying soft tissues. The supraspinatus was isolated by clearly dissecting the infraspinatus posteriorly and the rotator interval anteriorly, leaving only the supraspinatus tendon secured to the greater tuberosity. Once isolated, the supraspinatus was sharply detached from its insertion on the greater tuberosity. The tear, as seen in Figure 1, was then repaired using 1 of the 4 repair techniques described below (TOE, TO, AT, ATX). The same suture type was utilized for all groups to minimize suture strength as a potential confounder. All repairs were performed by a single surgeon (M.J.S.).

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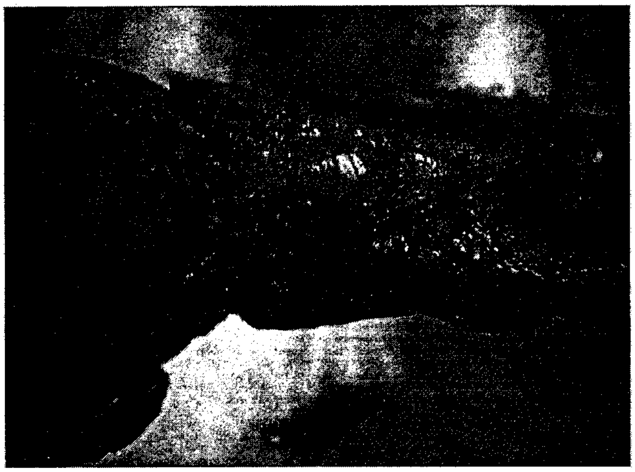

Figure 1. Supraspinatus tear.

For the TOE repair using suture anchors, 2 single-loaded PEEK Twinfix full-thread 5.0-mm suture anchors (Smith & Nephew, Andover, Massachusetts) were used for the medial row and two 5.5-mm PEEK Footprint anchors were used for the lateral row. For the medial row, the first anchor was placed 5 mm posterior to the posterior edge of the long head of the biceps tendon and 5 mm lateral to the articular margin. The second anchor of the medial row was placed 15 mm posterior (center to center) to the first anchor, keeping 5 mm from the articular margin. No. 2 Ultrabraid sutures (Smith & Nephew) from the medial row were placed in a horizontal mattress fashion 5 mm lateral to the musculotendinous junction of the supraspinatus tendon, with approximately 3 to 4 mm between suture limbs. In total, 4 suture limbs were passed through the tendon, evenly distributed throughout the tendon to fill the width of the tendon as would be produced in the clinical situation. Horizontal mattress sutures were tied using 5 alternating half-hitch knots to reproduce arthroscopic knot configurations. The lateral-row anchors were placed 15 mm from the lateral edge of the greater tuberosity directly lateral in line with the anterior and posterior medial-row anchors. One suture limb from each of the medial-row mattress sutures was brought through each lateral-row Footprint anchor and affixed into the bone, creating a crossing pattern (Figure 2). Sutures were loaded into the Footprint anchor and tensioned manually.

For the TO repair, a large, curved trocar needle was used to create the bone tunnel in a curved fashion. Entrance and exit targets for the tunnel to be created by the needle were marked at the same position as the TOE anchor placement. Two No. 2 Ultrabraid sutures were passed through each tunnel. Sutures from the medial tunnel aperture were placed in a simple fashion 5 mm medial to the musculotendinous junction of the supraspinatus tendon. Four total suture limbs were passed through the tendon, similar to the previous TOE technique. From the anterior tunnel, 1 suture was passed through the anterior tendon, and another suture was passed through the posterior tendon. A similar configuration was used for the posterior tunnel to reproduce the crossing pattern of the TOE technique (Figure 2).

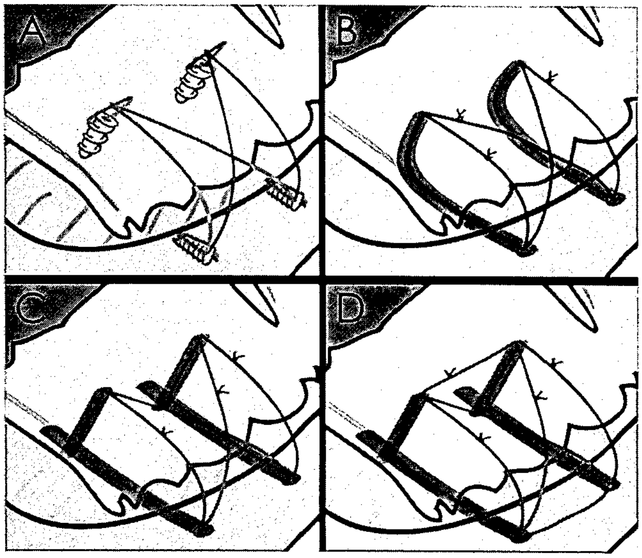

Figure 2. Suture configurations: (A) transosseous equivalent (TOE), (B) transosseous (TO), (C) ArthroTunneler (AT), and (D) ArthroTunneler X-box (ATX).

For the AT repair, the ArthroTunneler was used to create 2 repair tunnels with the same entrance and exit targets as the TO repair. To create the 90° tunnel, a drill was first used to create the medial tunnel, and the hook (with loop actuator) of the ArthroTunneler was inserted into the tunnel. To create the lateral tunnel, the drill was introduced through the ArthroTunneler device and inserted to the full depth of the drill. The suture inserter was loaded with 2 No. 2 Ultrabraid sutures and introduced through the ArthroTunneler, and then the loop actuator was retracted to capture the sutures. The sutures were placed in the rotator cuff and tied in the same configuration as the TO repair above (Figure 2).

The ATX repair also used the ArthroTunneler to create 2 repair tunnels as described above. However, an X-box suture configuration was utilized instead. Three No. 2 Ultrabraid sutures were placed in the posterior tunnel. One No. 2 Ultrabraid suture and 1 shuttle suture were placed in the anterior tunnel. Medial suture limbs from both tunnels were passed through the tendon in a simple suture configuration so that the 3 sutures from the posterior tunnel exited through 1 hole in the posterior cuff and 2 sutures from the anterior tunnel exited through 1 hole in the anterior cuff. The lateral end of 1 suture and the medial end of 1 suture in the posterior tunnel were shuttled through the anterior tunnel, lateral to medial. At this point, only 4 No. 2 Ultrabraid sutures remained, similar to the other techniques. The suture with the lateral end shuttled was then tied to its medial end in a medial mattress fashion. The medial and lateral ends of the 3 remaining sutures were tied together, forming an "X" pattern with a surrounding "box" (Figure 2).

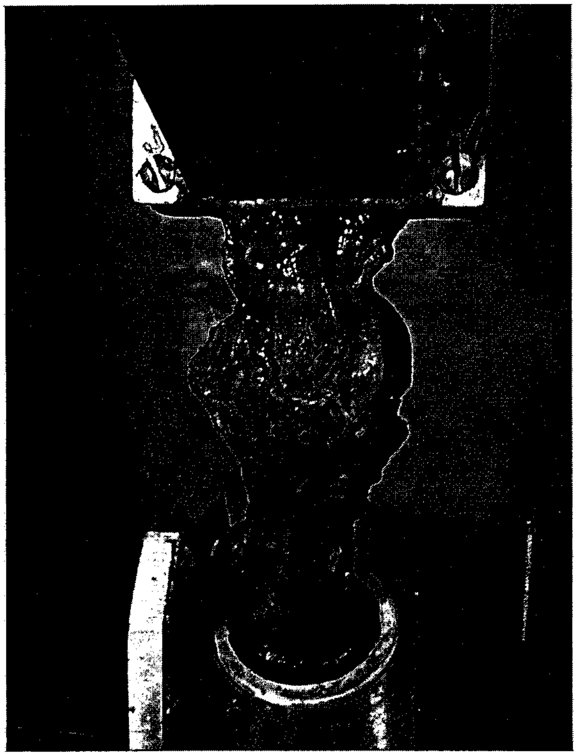

Figure 3. Mechanical testing set-up with optical markers placed.

After completion of the tendon repairs, the humerus was transversely cut 6 inches distal to the supraspinatus insertion and then potted in a polyvinyl chloride (PVC) pipe using acrylic cement (Isocryl, Lang Dental, Wheeling, Illinois). The humerus was secured to an adjustable-angle mount positioned at a 30° angle to simulate the anatomic position of the supraspinatus with the arm in 60° of abduction. Specimens were placed in neutral humeral rotation using the biceps groove as an anatomic reference for each specimen. The humeral mounting fixture was then secured to the base of an Insight 5 materials testing system (MTS Inc, Eden Prairie, Minnesota). A custom freezer clamp was used to grip the supraspinatus muscle at the musculotendinous junction to apply tensile loading to the tendon repair constructs[24,25] (Figure 3).

To determine tissue displacement optically, 2 rows of 2.5-mm-diameter circular markers were affixed to the tendon surface: a medial row in line with the medial-row knots and a lateral row at the lateral tunnel aperture (Figure 3). For the more narrow tendons (in which 2 markers were placed per row), segment length was measured at the anterior and posterior tendon locations, while a third central region was added for wider specimens. One-megapixel digital images were captured at a rate of 48 Hz throughout testing using an Imperx IPX-1M48-L video camera (Imperx, Boca Raton, Florida).[10,24] Subsequently, using ImageJ software (National Institutes of Health, Bethesda, Maryland) and the MTrack2 plug-in (http://valelab.ucsf.edu/~nico/ijplugins/MTrack2.html), the X-Y coordinates of the individual markers were tracked for all recorded frames.

A modified protocol published by Park et al[16,18] was utilized for mechanical testing of the constructs, with an increase in the cyclic interval upper loading limit and number of cycles. Each specimen was preloaded to 10 N for 2 minutes, loaded between 10 and 160 N at 100 N/s for 100 cycles, and then loaded to failure at 1 mm/s. Throughout cyclic and failure testing, load, crosshead displacement, and time were recorded synchronously with the optical data using dedicated MTS TestWorks software (MTS, Eden Prairie, Minnesota). Specimens were regularly moistened using a saline mist spray during testing. Construct failure mode was visually classified as occurring within the tendon, suture, or bone. Suture failure included suture breakage or knot failure, bone failure included avulsion and anchor advancement, and tendon failure consisted of sutures tearing through the tendon.

Data Analysis

For optical data analysis, segment length was defined as the medial-lateral distance between a pair of markers in a particular region.[24] For the more narrow tendons (in which 2 markers were placed per row), segment length was measured at the anterior and posterior tendon locations, while a third central region was added for wider specimens. For each specimen, the mean segment length was calculated from the peaks of the initial (L_i) and final (L_f) 5 cycles; cyclic elongation was then determined as $(L_f - L_i)/L_p$, where L_p is the segment length at the preloaded state. In the present study, the cyclic elongation value reported for each specimen represents the average across its anatomic regions. From the MTS load and crosshead displacement output, the first-cycle construct excursion was defined as the elongation of the construct from the preloaded state to the peak of the first cycle; construct excursion was therefore considered to be the initial "slip" of the construct (ie, all tissue, including the repair, between the potted bone and the clamped tendon) as an initial load was engaged.

Maximum load and linear stiffness were determined from the pull to failure test, with the latter calculated as the steepest slope of the load-displacement curve spanning a minimum of 40% of the data points from test initiation to maximum load. Maximum load was defined as the highest load value achieved during failure testing. Statistical analysis was performed using GraphPad Prism 5 (GraphPad Software Inc, La Jolla, California). A 1-way analysis of variance (ANOVA) with a Tukey post hoc test for multiple comparisons was performed to compare the statistical difference between repair groups with respect to bone density, age, and the biomechanical outcome measures. Results were considered statistically significant at $P < .05$. Correlations between specimen bone density, age, sex, and outcome were also assessed.

RESULTS

Data are expressed as mean ± standard deviation. There was a statistical difference between the AT and ATX

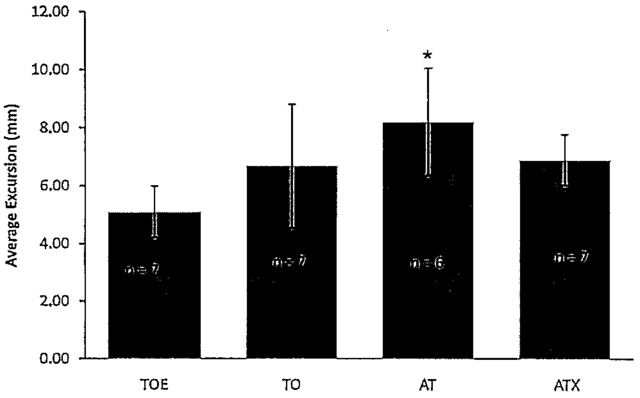

Figure 4. First-cycle construct excursion with standard deviation. *The excursion for the ArthroTunneler (AT) group was significantly larger than that for the transosseous-equivalent (TOE) group. TO, transosseous group; ATX, ArthroTunneler X-box group.

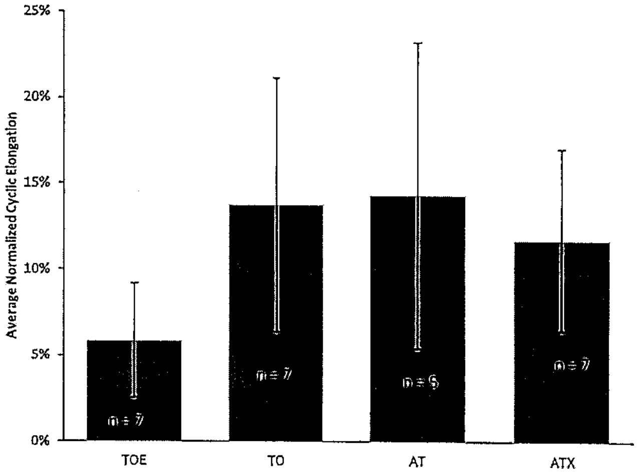

Figure 5. Normalized optical cyclic elongation with standard deviation. TOE, transosseous-equivalent group; TO, transosseous group; AT, ArthroTunneler group; ATX, ArthroTunneler X-box group.

groups with respect to age, where the AT group had a significantly higher mean age (62.9 ± 12.1 years) compared with the ATX group (41.7 ± 11.6 years) ($P < .05$). However, there was no statistical difference between groups with respect to bone density. It was found that among female specimens, higher age correlated with lower bone density ($r^2 = 0.3172$), but there existed relatively no correlation among male specimens with respect to bone density ($r^2 = 0.0181$).

Two specimens failed during cyclic loading, both in the AT group. One specimen failed via the suture knot unraveling on the first cycle and was excluded from the data analysis. A second specimen, from an 86-year-old woman, failed via bone fracture during the 74th cycle. The data from this specimen included in the analysis consisted only of first-cycle construct excursion.

Construct excursion results are presented in Figure 4, where there was a significantly larger first-cycle construct excursion in the AT group (8.19 ± 1.85 mm) compared with the TOE group (5.10 ± 0.89 mm) ($P < .05$). The TO and ATX groups resulted in larger first-cycle excursions than the TOE group, but not significantly so, with construct excursions of 6.67 ± 2.13 mm and 6.88 ± 0.88 mm, respectively.

Cyclic elongation (ie, relative increase in marker segment length from initial to final cycles) demonstrated no statistical differences between repair types (Table 2). However, there was a statistical trend ($P = .087$) toward lower cyclic elongation in the TOE group (Figure 5).

Load to failure testing indicated that the TOE group exhibited a statistically greater maximum load (558.4 ± 122.9 N) than each of the other 3 constructs, with maximum loads of 325.3 ± 79.9 N, 291.7 ± 57.9 N, and 388.5 ± 92.6 N for the TO, AT, and ATX groups, respectively ($P < .05$) (Figure 6). There was no statistical difference between groups with respect to construct pull-out stiffness (Table 2).

The yield load was determined as the load at the first occurrence of a zero slope along the load-extension curve. This resulted in yield loads of 245.2 ± 35.9 N (AT), 534.0 ± 116.0 N (TOE), 273.5 ± 68.9 N (TO), and 350.8 ± 83.7 N (ATX). As in the maximum load results, the TOE group showed a significantly greater yield load than any of the other 3 repair groups ($P < .05$).

Failure mode results are presented in Table 3. Failure modes were primarily the suture in the TO group; tendon in the ATX group; tendon or bone in the TOE group; and tendon, bone, or suture in the AT group. Load versus displacement curves from failure testing generally exhibited 3 distinct shapes. The curves corresponding to tendon failure were smooth with relatively large displacements at high loads. In contrast, suture failure curves exhibited sudden load decreases less than 50 N, commonly with stepwise decrements in load, whereas bone failure resulted in a load-displacement curve with sudden, large (100 N or greater) decreases in load during failure.

In the TOE and AT groups, a relationship was found between bone density and failure mode. In both of these groups, the specimens with the lowest bone density resulted in bony avulsions, which were classified as bone failures. One specimen of high bone density in the TOE group was also classified as a bone failure, but this specimen failed as a result of the anchor being pulled out of the bone rather than a bony avulsion. There was no correlation in either the TO or the ATX groups between failure mode and bone density. However, in both of these groups, there was primarily 1 failure mode (TO: 6/7 failed by suture; ATX: 7/7 failed by suture tearing through the tendon).

DISCUSSION

The results of this study demonstrate that TOE repairs for the supraspinatus are biomechanically superior at time zero with regard to ultimate load to failure when compared with anchorless repair techniques using transosseous sutures including newer arthroscopic transosseous repairs.

TABLE 2
Biomechanical Performance Comparison of Repair Techniques[a]

	TOE	TO	AT	ATX
Load to failure testing				
Maximum load, N	558.4 ± 122.9[b]	325.3 ± 79.9	291.7 ± 57.9	388.5 ± 92.6
Stiffness, N/mm	56.9 ± 11.8	59.4 ± 7.0	56.7 ± 16.1	59.2 ± 10.6
Cyclic testing				
First-cycle construct excursion (crosshead), mm	5.10 ± 0.89	6.67 ± 2.13	8.19 ± 1.85[c]	6.88 ± 0.88
Normalized cyclic elongation (optical), % change	5.9 ± 3.3	13.7 ± 7.4	14.3 ± 8.9	11.7 ± 5.3

[a]Data are expressed as mean ± SD. TOE, transosseous-equivalent repair with anchors; TO, traditional transosseous repair with curved bone tunnel; AT, arthroscopic transosseous repair technique using simple suture configuration; ATX, arthroscopic transosseous repair technique using X-box suture configuration.

[b]TOE had significantly greater load to failure than TO, AT, and ATX ($P < .05$).

[c]AT had a significantly larger first-cycle excursion than TOE.

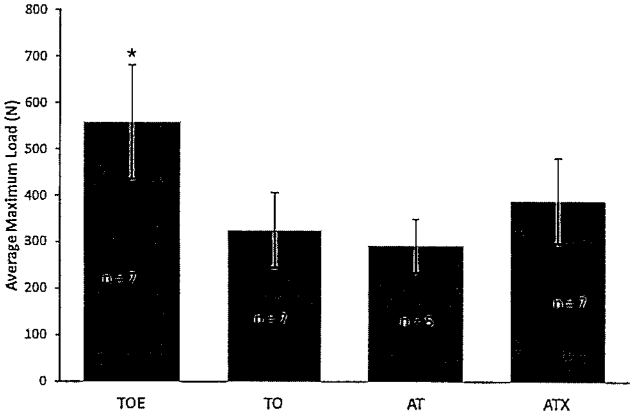

Figure 6. Maximum load to failure with standard deviation. *The transosseous-equivalent (TOE) group exhibited a statistically greater maximum load than the transosseous (TO), ArthroTunneler (AT), and ArthroTunneler X-box (ATX) groups.

TABLE 3
Sites of Repair Failure[a]

	TOE	TO	AT	ATX
Tendon failure, n	4	0	2	7
Suture failure, n	0	6	1	0
Bone failure, n	3	1	3	0

[a]TOE, transosseous-equivalent repair with anchors; TO, traditional transosseous repair with curved bone tunnel; AT, arthroscopic transosseous repair technique using simple suture configuration; ATX, arthroscopic transosseous repair technique using X-box suture configuration.

According to Gerber et al,[8] an ideal repair has high fixation strength, minimal gap formation, and sufficient mechanical stability for tendon-bone healing. Previous studies have demonstrated that suture anchor fixation has equivalent or superior biomechanical properties relative to transosseous techniques.[2,9,13,20,21] Most recently, a cadaveric investigation by Behrens et al[1] comparing the initial tensile fixation strength of a transosseous-equivalent suture bridge rotator cuff repair construct to a traditional transosseous suture construct reported arthroscopic TOE techniques can achieve initial fixation strength comparable with traditional TO techniques performed without suture anchors. Several reasons have been given for the superior fixation and higher failure loads achieved by TOE versus anchorless constructs. One hypothesis, published by Burkhart et al[4] in 1997, attributed the increased failure load to the ability of suture anchors to transfer the weak link from bone to tendon. In more recent biomechanical studies, the TOE repair was shown to improve the pressurized contact area and mean pressure between the tendon and footprint when compared with a double-row technique, with subsequent findings of superior ultimate failure loads and similar gap formation when compared with double-row repair.[16,18] Christoforetti et al[5] demonstrated a decreased but preserved blood supply in the rotator cuff following lateral-row anchor placement in a suture bridge construct, which in a clinical setting may result in more rapid healing and increased stability. The authors of the current study believe that a combination of improved contact area and a transfer of forces from the bone to tendon contribute to the increased stabilization, strength, and biology of TOE repairs.

With an increasing number of surgeons utilizing arthroscopic anchor repairs for rotator cuff fixation, attention has been placed on comparing single- versus double-row versus TOE repair techniques. In the current study, TOE was performed in accordance with the authors' clinical preference. Historically, double-row repairs were introduced as a method to provide the footprint restoration seen with the traditional transosseous repair, combined with the potential for improved tendon-bone healing as seen with single-row anchor repair. Several biomechanical and clinical outcome studies have since found that double-row suture anchor fixation is significantly stronger and has greater footprint contact than single-row fixation.[13,14,17,19,23] However, studies have also shown that TOE repairs have significant advantages when compared with single- and double-row anchor repair techniques.[16,18] In the largest clinical study to date looking at TOE repair, results for clinical outcomes and structural integrity of TOE repairs at 1 year compare favorably with those reported for other double-row suture anchor techniques.[22] Long-term follow-up will be necessary to determine if the durability of these repairs and the structural integrity of these constructs maintain their performance over time. These studies, combined with our biomechanical findings of superior TOE fixation when compared with anchorless techniques, provide further support for the increased utilization and investigation of TOE techniques for rotator cuff repair.

First-cycle excursion is a measure of initial stability of the construct, measuring the amount of initial gapping between the insertion site and repaired tendon. This excursion parameter may also serve as a measure of compliance of the experimental set-up. Assuming the compliance of each construct is equal, any difference in first-cycle excursion would be because of the initial fixation integrity of the repair. In the current study, there was a significantly larger amount of first-cycle excursion in the AT group compared with the TOE group, with an initial average difference of approximately 3 mm ($P < .05$). The excursion in the AT group was largely seen at the repair site secondary to tissue sliding along the sutures, differing from later excursions with a primary mechanism of suture tearing through the tendon. Hence, our findings demonstrate the TOE group as having superior initial fixation stability versus the AT group.

The trend toward lower normalized optical cyclic elongation in the TOE group is possibly consistent with prior studies that have demonstrated a trend toward decreased gapping with suture anchor constructs relative to transosseous tunnel constructs.[21] However, because our markers were placed medial to the suture repair and not on the tendon end, we have not measured actual gapping. Tashjian et al[21] found that gapping significantly increased from the anterior to posterior region. We hypothesize that the trend toward decreased cyclic elongation is attributed to the fact that suture anchors offer point fixation, with sutures tied across a short distance along the medial row and then fixed for a second time at the lateral row. This is in contrast to the long suture loops that are required when using transosseous tunnels, regardless of tunnel angle.

The ArthroTunneler has been proposed as an alternative repair method that allows for arthroscopic placement of a near 90° transosseous tunnel. Our results show that the maximum load sustained by the AT repair is similar to that of the traditional transosseous technique but still inferior to the TOE technique. Changing the suture configuration from the 2 medial mattress suture configuration to an X-box configuration increased the AT transosseous technique construct maximum load from 292 N to 388 N, although this was not statistically significant and still significantly lower than the corresponding value for the TOE repair. The lack of bone failures in the ATX group is likely because of the ATX specimens being significantly younger than the AT group. In fact, it is quite likely that the bone failures in all groups are most often because of poor bone quality. However, despite the lower age, the ATX group still exhibited significantly lower load to failure than the TOE group.

The primary limitation of this study is that it is an in vitro rather than an in vivo study, and results cannot be extrapolated to the potential impact of repair configuration on tendon healing. The question remains: how strong is strong enough? There is likely some minimum value that repair constructs must exceed to tolerate early passive range of motion after which additional strength does not result in improved tendon healing. In addition, the study specimens had intact rotator cuff tendons that do not replicate normal tendon degeneration, which may occur in the setting of rotator cuff tears.

Although the TOE, AT, and ATX techniques could be performed arthroscopically, we used an open technique for all 4 repairs. We do not believe that open repair would result in different initial biomechanical performance of the repair configuration. We also did not measure footprint restoration of the supraspinatus. Although specimens were randomized according to age for 3 groups, the ATX group was significantly younger than the AT group. However, this bias would potentially skew the results in favor of the ATX repair; yet, despite this difference, our results demonstrated better performance with the TOE construct. On the subject of specimen age, a single cadaveric specimen in the AT group was 86 years of age, older than the typical patient undergoing rotator cuff repair. However, bone and tendon were of acceptable quality in the specimens in the study, with no statistical significance in bone density found between the groups. Other specimens in the AT group were 47 to 68 years of age, with no significant difference in age found between the groups with the 86-year-old specimen excluded. Finally, we used an isolated supraspinatus tear model, which does not necessarily replicate the clinical situation in which the remainder of the anterior and posterior cuff remains intact, in the setting of an isolated supraspinatus tear. However, this model has been used in prior studies for biomechanical testing of repair constructs.[11,12,14]

CONCLUSION

The results of this study showed that anchorless repair techniques using only transosseous sutures resulted in lower failure loads than a repair model utilizing anchors in a TOE construct. The orientation of the bone tunnel created with the varying techniques does not appear to be relevant in the ultimate load to failure or for the more physiological forces that are represented by cyclic loading. Changing to an X-box suture configuration led to a trend of increased construct failure load, although this increase did not reach statistical significance. The TOE repair results in superior failure loads compared with transosseous repairs regardless of tunnel or suture configuration.

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