A Biomechanical Comparison of 2 Transosseous-Equivalent Double-Row Rotator Cuff Repair Techniques Using Bioabsorbable Anchors: Cyclic Loading and Failure Behavior

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Purpose: A novel double-row configuration was compared with a traditional double-row configuration for rotator cuff repair. **Methods:** In 10 matched-pair sheep shoulders in vitro repair was performed with either a double-row technique with corkscrew suture anchors for the medial row and insertion anchors for the lateral row (group A) or a double-row technique with a new tape-like suture material with insertion anchors for both the medial and lateral rows (group B). Each specimen underwent cyclic loading from 10 to 150 N for 100 cycles, followed by unidirectional failure testing. Gap formation and strain within the repair area for the first and last cycles were analyzed with a video digitizing system, and stiffness and failure load were determined from the load-elongation curve. **Results:** The results were similar for the 2 repair types. There was no significant difference between the ultimate failure loads of the 2 techniques (421 ± 150 N in group A and 408 ± 66 N in group B, $P = .31$) or the stiffness of the 2 techniques (84 ± 26 N/mm in group A and 99 ± 20 N/mm in group B, $P = .07$). In addition, gap formation was not different between the repair types. Strain over the repair area was also not different between the repair types. **Conclusions:** Both tested rotator cuff repair techniques had high failure loads, limited gap formation, and acceptable strain patterns. No significant difference was found between the novel and conventional double-row repair types. **Clinical Relevance:** Two double-row techniques—one with corkscrew suture anchors for the medial row and insertion anchors for the lateral row and one with insertion anchors for both the medial and lateral rows—provided excellent biomechanical profiles at time 0 for double-row repairs in a sheep model. Although the sheep model may not directly correspond to in vivo conditions, all–insertion anchor double-row constructs are worthy of further investigation. **Key Words:** Double row—Rotator cuff—Suture anchor—Biomechanical testing.

The goal of arthroscopic rotator cuff repair is to ensure tendon-bone healing and maintain repair integrity because tendon repair integrity has been linked to improved clinical outcomes.[1-3] Clinical and magnetic resonance imaging–based reports have suggested that a notable postsurgical tear rate still exists.[1,4] Factors that may influence repair success include the severity of the tear, retraction and atrophy of the tendon, and quality of the remaining tissue.[5] An optimal initial repair construct would have a high initial fixation strength, minimize gap formation, maintain mechanical stability under cyclic loading, and re-create the "footprint" of the tendon insertion.[6] Such a construct may allow early postoperative motion while maintaining repair integrity.[7] This has stimulated the development of many novel "double-row" rotator cuff repair tech-

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niques that sought to improve the biomechanical characteristics of rotator cuff repair and increase the area of tendon-bone contact.[5,8-12]

Double-row fixation has been gaining popularity in clinical use because of its reported superior biomechanical properties.[13-15] Previous biomechanical studies have suggested that double-row fixation does have superior biomechanical characteristics when compared with single-row fixation.[5,16,17] Some of the most biomechanically sound double-row techniques used a transosseous tunnel for the lateral row, requiring a mini-open technique.[12,18] In an effort to obtain the advantages of a transosseous construct while using arthroscopic techniques, the "transosseous-equivalent" (TOE) technique (also known as the suture bridge technique) was introduced. The medial row was composed of standard screw-in suture anchors, whereas the lateral row for these constructs is occupied by an insertion anchor, which captures sutures from the medial row. More recently, these techniques have been reported to have superior results with regard to footprint restoration, biomechanical failure, and cyclic loading testing.[19-21]

The optimal configuration for TOE double-row constructs has yet to be determined. Biomechanical studies have evaluated both insertion anchors and tenodesis screws for the lateral row.[7] Our purpose was to evaluate a novel TOE double-row technique using a newly available suture material (FiberTape; Arthrex, Naples, FL) with insertion anchors for both the medial and lateral rows and compare this novel technique with a more conventional TOE suture anchor/insertion anchor construct, which used suture anchors for the medial row and insertion anchors for the lateral row. The novel insertion anchor construct also included a horizontal stitch designed as a blocking cross stitch similar to the massive cuff tear stitch described by Ma et al.[22] and the modified Mason-Allen stitch[23] described by Gerber et al.[24] In addition, the study was designed to use bioabsorbable anchors. Our hypothesis was that the novel double-row construct would exhibit superior biomechanical properties when compared with the more conventional TOE technique based on the additional blocking cross stitch and the new suture material.

METHODS

In this study 20 Merino sheep shoulders (10 pairs; mean age, 1 year) were harvested and frozen at −20°C before testing. Each specimen was allowed to thaw before dissection, surgical site preparation, and testing. The infraspinatus muscle is the most developed rotator cuff muscle in the sheep and has been used in prior studies for evaluation of anchoring constructs.[18,22,23] The infraspinatus tendon and humeral attachment were carefully dissected and isolated, and the remaining rotator cuff tendons were completely removed. The humerus was cut transversely just above the elbow. Matched-pair shoulder specimens allowed each anchor technique to be performed on the same animal. Repairs were alternated from left to right throughout testing. Each specimen was carefully examined to ensure that the rotator cuff musculature was intact, and the infraspinatus tendon was of sufficient size (minimum width at least 20 mm) to support a double-row rotator cuff repair. The humerus was potted with Ureol (Ciba Specialty Chemicals, Basel, Switzerland) to allow for proper fixation during testing. The infraspinatus was then completely released from its insertion site. During the course of the study, specimens were kept moist with periodic sprays of saline solution.

Surgical Techniques

All rotator cuff repairs were carried out by a single surgeon (J.T.S.). The conventional TOE surgical technique—using suture anchors for the medial row and insertion anchors for the lateral row—used two 5.5-mm Bio-Corkscrew FT2 anchors (Arthrex) double loaded with No. 2 FiberWire (Arthrex) for the medial row and SwiveLock insertion anchors (Arthrex) with a closed-end loop for the lateral row (group A) (Fig 1). A template was formed from moldable plastic that had 4 holes in a 12 × 12–mm box configuration. The template was applied to the tuber-

FIGURE 1. Closed-loop SwiveLock insertion anchor (Arthrex) with FiberTape suture (Arthrex).

osity of the humerus, and the position of the holes was marked onto the humerus. A tap was used to create 4 anchor holes before the tendon was attached. The same template was used for the novel anchor technique, allowing consistently reproducible anchor placement for both the medial and lateral rows in both surgical techniques. For the conventional technique, the suture anchors were inserted in the medial row at a 45° angle to the bone surface. The tendon was draped over the humerus so that its lateral border ended at the lateral row. For each suture anchor of the medial row, 2 horizontal mattress sutures were placed medially in the tendon. Six alternating half-hitches were tied for each knot. The suture from the more lateral knot on each side was cut, whereas the sutures from the more medial knots were used to create the suture bridge (Fig 2). The SwiveLock insertion anchors were loaded with the suture bridge sutures and inserted to create the lateral row. Tension was applied to each suture so that all slack was removed from the suture before placement of the lateral-row insertion anchor.

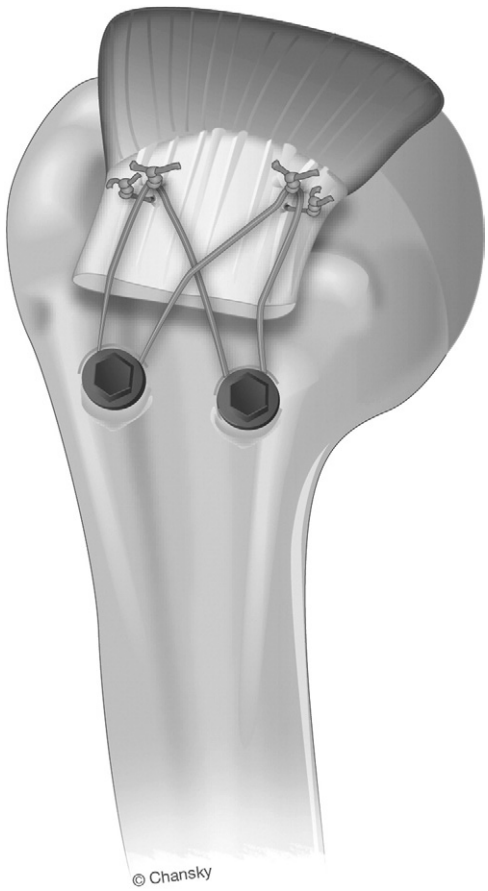
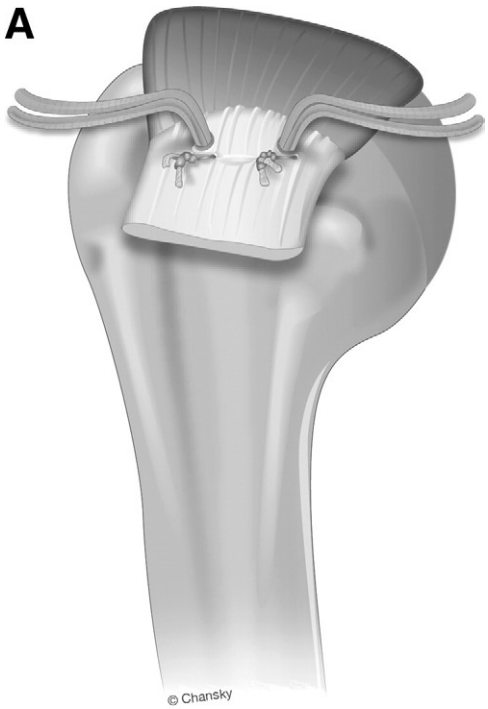


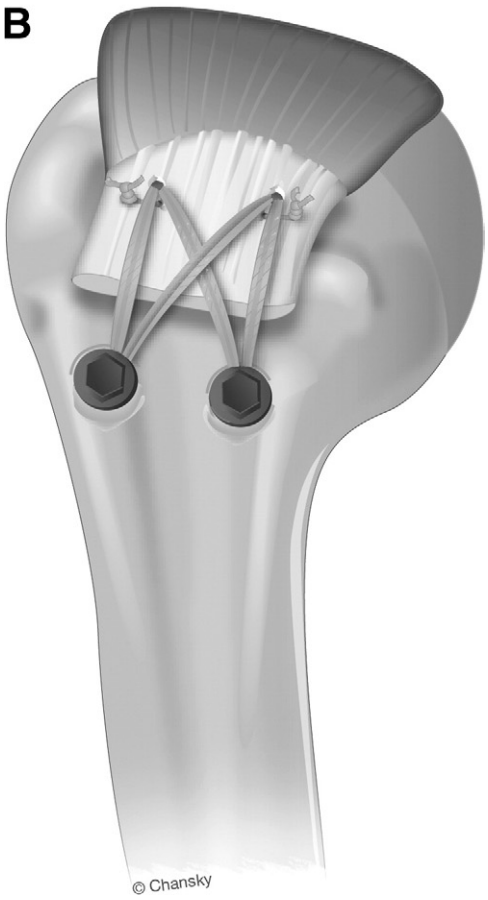
Figure 2. Final conventional double-row construct. The medial row comprised 2 suture anchors, and the lateral row comprised 2 insertion anchors capturing sutures from the medial-row suture anchors.

The novel anchor technique—using insertion anchors for both the medial and lateral rows—used 2 open-loop SwiveLock insertion anchors for the medial row and 2 closed-loop SwiveLock insertion anchors for the lateral row (group B). For the medial row, an insertion anchor internally loaded with No. 1 FiberWire (Arthrex) was used. The FiberTape (Arthrex) (a new braided ultrahigh-strength suture) (Fig 1) was captured by the loop of the SwiveLock, and the SwiveLock was screwed into place in both medial anchor locations. With removal of the insertion handle, 2 FiberTape ends and 2 No. 1 FiberWire ends exited each medial anchor location. Initially, the No. 1 FiberWire suture was placed through the tendon in a horizontal mattress stitch tied by use of 6 alternating half-hitches (Fig 3A). Both ends of the FiberTape were then brought through the tendon just medial to the horizontal mattress stitch. One end of the FiberTape from each medial anchor was then fixed to the lateral row after passage through the closed-loop SwiveLock to finish the suture bridge (Fig 3B). Tension was applied to each FiberTape suture limb so that all slack was removed before placement of the lateral-row insertion anchor.

Biomechanical Testing

The rotator cuff repair constructs were tested with a Zwick 1120 testing machine (Zwick, Ulm, Germany). A Vicon video digitizing system (Vicon, Los Angeles, CA) was used for analysis of gapping phenomenon. The humerus was placed at an angle of 135° to the vertical axis, allowing tendon testing to approximately re-create the vector of force that would occur after a rotator cuff repair (Fig 4). The video digitizing system (3 specialized cameras) was placed off the lateral side of the construct, viewing the repair from outside the joint. The tendon was grasped in a specially designed soft-tissue clamp, which had sufficient grip and eliminated tendon slippage. After secure mounting of the specimen, 6 video markers were placed on the tendon. One pair of video markers was placed just medial to the lateral tendon border, one pair was placed just medial to the medial suture, and one pair was placed on the humerus just lateral to the tendon edge (Fig 5). The Vicon video digitizing system included video recording of the markers, digitization of the markers, creation of centroids representing the center of the





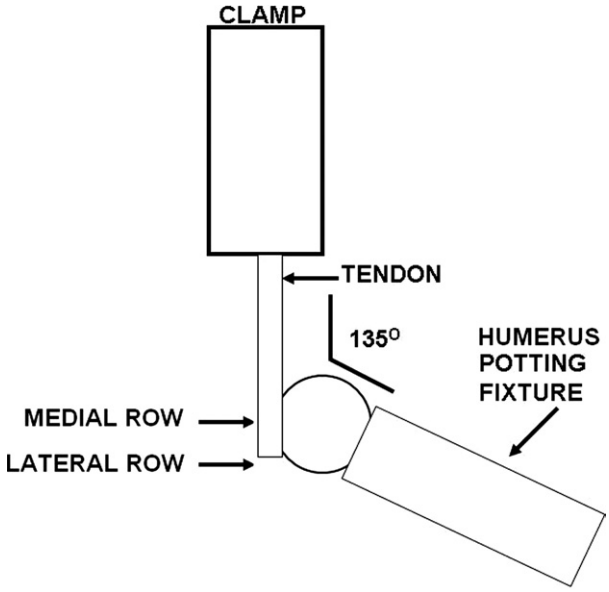


FIGURE 4. Testing setup showing alignment of humerus to testing fixture.

markers, and computer calculation of distance as well as movement during the testing process.

Cyclic Loading

A 10-N preload was applied for 1 minute for preconditioning of the tendon–suture anchor construct. The specimens were then cyclically loaded from 10 to 150 N at a rate of 0.25 H for 100 cycles. Other authors have noted that 150 N represented between one half and two thirds of the load that could be delivered by maximal muscle contraction of the human supraspinatus, so our applied load was well within the physiologic range.[25] Gap formation at the lateral border of the tendon was recorded. It was defined as the distance (measured in millimeters) created at the lateral edge of the tendon. The 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. Gap formation was recorded for the first and last cycles. In

FIGURE 3. (A) Step 1: Novel double-row construct. The medial insertion anchors were placed with tape-like suture exiting the rotator cuff just medial to the previously tied blocking stitch. (B) Step 2: Completed insertion anchor construct. The medial and lateral rows comprised insertion anchors; tape-like suture crosses the blocking stitch medially and is captured by the lateral row of insertion anchors.

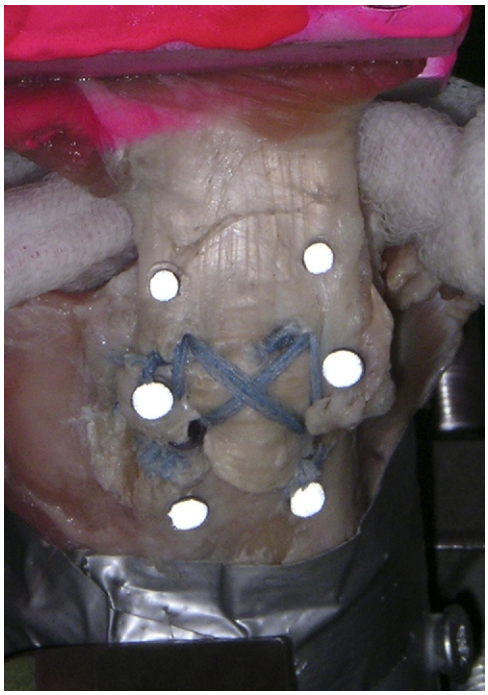


FIGURE 5. Superior view of rotator cuff repair with video markers in place. Two markers were placed on the lateral humerus, two inside the cuff repair, and two medial to the cuff repair.

addition, strain was defined as the deformation per unit length of the tendon. The original distance was defined as the initial distance between the markers. The change in distance was calculated as the maximal distance between the markers minus the original distance. Strain was calculated by the standard formula ($\Delta L/L$) by use of the Vicon software package and Microsoft Excel (Microsoft, Redmond, WA).

Tensile Testing to Failure

After cyclic loading, the construct was returned to the preload of 10 N. The specimen was loaded until structural failure at a rate of 1 mm/s. The structural properties of linear stiffness and ultimate failure load were calculated by use of data acquisition and analysis software included on the materials testing machine. The ultimate failure load was defined as the peak force of the load-elongation curve. Stiffness was calculated by use of the most linear portion of the failure curve.

Statistical Analysis

Student *t* tests were used to compare the biomechanical properties of the conventional repair (group A) and the novel technique (group B). The level of statistical significance was set at $P < .05$.

RESULTS

Cyclic Loading

There were no statistically significant differences noted between group A and group B during the cyclic loading test (Table 1). Gap formation was not significantly different between the 2 groups in either the first or last cycle. Strain recorded over the repair area was also not significantly different between the 2 groups in either the first or last cycle. For both group A and group B, all specimens survived the cyclic loading testing without obvious defect or deformity.

Tensile Testing to Failure

Overall, the results for tensile testing to failure were similar for the 2 repair types (Table 2). There was no significant difference between the ultimate failure loads of the 2 techniques. The stiffness in group B was increased compared with group A, but the result was not significant. For group B, all specimens failed at the tendon-suture junction, whereas 1 specimen in group A failed with pullout of the anchors. All other specimens in group A failed at the tendon-suture junction.

TABLE 1. *Cyclic Loading Results*

	Group A	Group B	*P* Value	Confidence Interval
Gap formation (mm)				
First cycle	1.37 ± 0.6	1.16 ± 0.7	$P = .40$	−0.367 to +0.789
Last cycle	2.22 ± 0.7	2.14 ± 0.8	$P = .83$	−0.696 to +0.856
Strain				
First cycle	6.40 ± 3.4	6.84 ± 2.5	$P = .76$	−2.475 to +3.337
Last cycle	2.13 ± 0.7	2.11 ± 0.8	$P = .94$	−0.709 to +0.749

TABLE 2. *Failure Testing Results*

	Group A	Group B	*P* Value	Confidence Interval
Ultimate load (N)	421 ± 150	408 ± 66	$P = .31$	−101.5 to +127.5
Stiffness (N/mm)	84 ± 26	99 ± 20	$P = .07$	−11.94 to +18.06

DISCUSSION

There were no major statistical differences between the novel stitch configuration using 4 insertion anchors and the conventional TOE double-row construct using 2 suture anchors and 2 insertion anchors. Therefore our initial hypothesis must be rejected.

It has been suggested that the suture-tendon interface remains the most likely site of failure of rotator cuff repair.[26] Indeed, in our study 19 of 20 specimens failed at the tendon-suture interface. Multiple studies have concluded that double-row rotator cuff fixation may provide biomechanical advantages compared with conventional single-row techniques.[5,16,17] Other authors have concluded that so-called TOE rotator cuff repair techniques have an advantage over the originally described double-row techniques[7,27]; however, the optimal double-row configuration has yet to be established.

When prior studies are considered,[5,16,17] our data show quantitatively comparable results. Despite the fact that prior studies used 6.5-mm metallic anchors[5] or 6.5-mm bioabsorbable anchors,[7] the mechanical properties recorded in group A and group B were similar to those in the aforementioned studies. Kim et al.[5] reported gap formation between 1.7 and 3.6 mm and an ultimate load of 516 ± 121 N, whereas Park et al.[7] reported gap formation between 2.87 and 3.74 mm and an ultimate load of 443 ± 87 N for their TOE construct. Our gap formation (between 1.16 and 2.22 mm for both groups) and ultimate load (421 ± 150 N in group A and 408 ± 66 N in group B) results compare favorably with prior works. In addition, the group B construct was stiffer than the group A construct. The difference was not statistically significant ($P = .07$) but could indicate an advantage for future insertion anchor–FiberTape constructs. Future testing would have to be conducted to more explicitly determine whether insertion anchor constructs have an inherent advantage over suture anchor constructs because of the potential for suture creep or knot slippage in suture anchor repairs.

Our novel repair technique used 4 insertion-type anchors (with 2 closed-loop types for the lateral row) and a horizontal stitch. To our knowledge, this is the first biomechanical study that has examined a double-row technique that does not use conventional screw-in suture anchors for the medial row. Given the fact that the results of this construct were similar to those of the more conventional double-row construct, it would be easy to make the next technical step and evaluate the novel technique without the benefit of the horizontal stitch. In this fashion, an arthroscopic insertion anchor technique could be used, which would obviate the need for knot tying in arthroscopic procedures. This should be the subject of future biomechanical studies.

The novel TOE double-row rotator cuff technique described previously was the biomechanical equal of a conventional TOE double-row technique in our study. The medial insertion anchors appear to have suture-holding power and failure strength comparable to screw-in anchors based on our gap formation and failure data. Furthermore, we have confirmed that TOE double-row rotator cuff repair techniques using 2 different nonmetallic anchors exhibit similar biomechanical properties to previously published works using metallic anchors, which have been established as the gold standard for biomechanical rotator cuff testing. Our results suggest that future research is warranted on knotless, insertion anchor–only TOE double-row rotator cuff repairs.

Our study has multiple strengths. The video capture system has been proven reliable in prior studies[5,17] and captures movement within the repair area well. We used a matched-pair technique for specimens, which should eliminate intersample differences. In the sheep model both the bone and the tendon are of excellent quality, placing the focus of the study directly on the repair constructs themselves.

Our study does have weaknesses. We used a sheep model instead of a human cadaveric model. Although the healthy tendon of the sheep does not approximate the degenerative human tendon likely encountered in clinical practice, it has been cited as a "good model and has been used extensively for the evaluation of rotator cuff tendon repairs."[22,23] Testing in human cadaveric specimens may yield additional information about insertion and suture anchor behavior in older bone and suture behavior in human tendon, especially

if altered tendon quality and osteopenia are present. However, other authors have noted similar results for human and sheep studies with similar testing techniques.[17] Additional weaknesses include the limitations inherent in single-direction testing. Recently, authors have included a rotational moment in rotator cuff evaluations,[28] but our construct line of pull was unidirectional. Our study also used in vitro time 0 testing, and thus the in vivo performance of each repair construct is unknown.

CONCLUSIONS

Both tested rotator cuff repair techniques had high failure loads, limited gap formation, and acceptable strain patterns. No significant difference was found between the novel and conventional double-row repair types.

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