# Knotless Rotator Cuff Repair in an External Rotation Model: The Importance of Medial-Row Horizontal Mattress Sutures

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**Purpose:** To evaluate the effect of the addition of 2 horizontal mattress knots to the medial row of a knotless rotator cuff construct on the biomechanical properties in terms of both cyclic and failure testing parameters in an external rotation model. **Methods:** In 8 fresh-frozen human cadaveric shoulders, a knotless transosseous repair was performed, whereas in 8 contralateral matched-pair specimens, 2 horizontal mattress knots were added to the medial-row fixation. A custom jig was used that allowed external rotation (0° to 30°) with loading. A materials testing machine was used to cyclically load repairs from 0 to 180 N for 30 cycles and then to failure. Video digitizing software was used for analysis. Data from paired specimens were compared by use of paired Student *t* tests. **Results:** Ultimate load to failure was significantly higher in the modified construct (549 N *v* 311 N, $P = .01$). Linear stiffness in the first cycle, at the 30th cycle, and at failure was significantly higher ($P = .02$, $P = .02$, and $P = .04$, respectively) in the modified construct as well. Energy absorbed by the repaired tissue was significantly less in the modified construct at the first cycle, at the 30th cycle, and at ultimate load to failure ($P = .03$, $P = .02$, and $P = .04$, respectively). Significantly greater anterior gap formation occurred with the knotless technique at the first cycle (4.55 *v* 1.35) and 30th cycle (7.67 mm *v* 1.77 mm) ($P = .02$). **Conclusions:** The modified construct shows improved biomechanical properties when allowing for external rotation during high-load testing. Using an additional horizontal mattress from separate sutures in the medial-row anchors helps to neutralize forces experienced by the repair. **Clinical Relevance:** The addition of medial-row fixation to a knotless construct will enhance the stability of rotator cuff repairs with the goal of improved patient outcomes.

With enhanced understanding of the biomechanics and anatomy of rotator cuff pathology and the stress experienced by the tissues during postoperative rehabilitation, recent focus has been on creating a more durable repair that provides an optimal environment for potential tendon healing. Numerous studies have provided data regarding the high incidence of retears after rotator cuff repair.[1-3] However, recent data have suggested that the retear rate with a transosseous-equivalent suture bridge may be lower.[4] Duquin et al.[5] reviewed 1,252 repairs from 23 studies, finding a significantly lower retear rate for tears greater than 1 cm.

However, the literature comparing single- and double-row techniques remains controversial. Several studies suggest that no difference exists between single- and double-row repairs.[6-8] Burkhart and Cole[9] have recently suggested that these Level I studies comparing techniques yield invalid conclusions with regard to standardizing the method of repair in addition to tear pattern and size. Although there is no controversy regarding the biomechanical superiority

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of the transosseous repair techniques, Level I evidence does not exist to support or refute the claim that these patients have better clinical outcomes. To make that determination, large prospective outcome studies need to be performed comparing patients with similar tear patterns using standardized single and transosseous repair constructs.

A previous study outlined the potential pitfalls using a medial-row anchor loaded with No. 2 high-strength sutures fixated with knotless anchors laterally.[10] This study did not take into account external rotation on the repair, which has been shown by Park et al.[11] to affect gap formation and differential tendon strain.

With recent literature focusing on enhancing the contact between the tendon and footprint, newer technology continues to be developed to accomplish this task.[12] Stronger, wider suture materials and knotless fixation constructs were created to maintain the biomechanics of repair constructs while simplifying the technique.

The purpose of this study was to determine whether the addition of two No. 2 high-strength sutures tied in horizontal mattress fashion in the medial row of a knotless construct would enhance the biomechanical characteristics of the repair. Our hypothesis was that the addition of fixation would enhance the linear stiffness and energy absorbed by the construct while decreasing anterior gap formation during loading in an external rotation model.

## METHODS

### Specimen Preparation

Eight matched pairs of fresh-frozen human cadavers (mean age, 54 years; range, 33 to 68 years) without evidence of rotator cuff pathology or greater tuberosity asymmetry were used in this study. Specimens were stored at –20°C and thawed for 24 hours before use. All soft tissues were carefully dissected from the scapula and proximal humerus. The supraspinatus was sharply dissected from its scapular and humeral attachments. The bony footprint was scraped with a fine rasp, as is routinely done with surgical rotator cuff repair, and a standard rotator cuff tear was created in the specimen by sharply resecting the distal 10 to 12 mm of the supraspinatus tendon in a straight anterior-to-posterior fashion. The humerus was cut in the midshaft region 10 cm distal to the surgical neck.

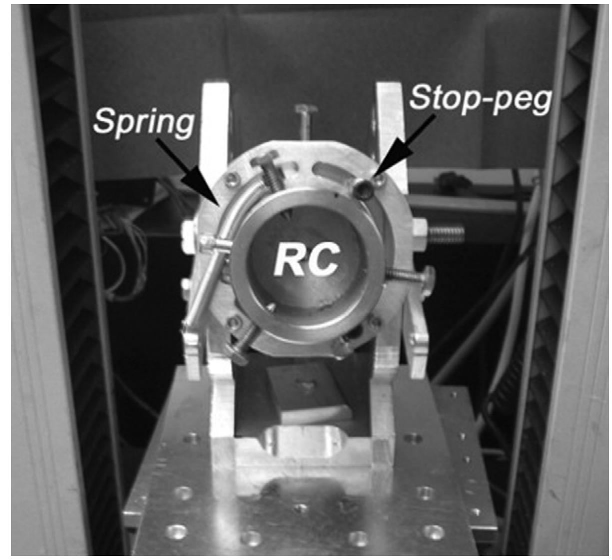


**FIGURE 1.** The testing apparatus allows for specimen rotation as a load is applied by a materials testing machine; the stop peg defines the arc of rotation, whereas the spring allows the specimen to return to the starting position during a return cycle. (RC, rotating clamp.)

A single surgeon performed all dissections and repairs to minimize technique variability between tested specimens. All humeri were mounted and clamped with a custom-machined testing apparatus that was designed to allow humeral external rotation with tendon loading as described by Park et al.[11] in an attempt to more accurately simulate in vivo biomechanics. Prior studies have shown that active external rotation with the arm at the side can result in 30% maximal contraction of the supraspinatus tendon. External rotation is applied to the specimen by the materials testing machine, and the humerus is able to return to the starting position with a built-in loaded spring. The testing apparatus has stop pegs that limit external rotation to 30°, which is comparable to postoperative range of motion seen in patients (Fig 1).

### Rotator Cuff Repair

In 8 specimens the knotless technique was used. Two 4.75-mm anchors loaded with 1 strand of wider-dimension high-strength suture (FiberWire; Arthrex, Naples, FL) were placed in 2 medial bone sockets just lateral to the articular margin 1.2 cm apart. The tail of each wider-dimension high-strength suture was passed through medial supraspinatus rotator cuff tissue. One tail from each medial anchor was then retrieved and inserted with an anchor into a lateral bone socket 1 cm

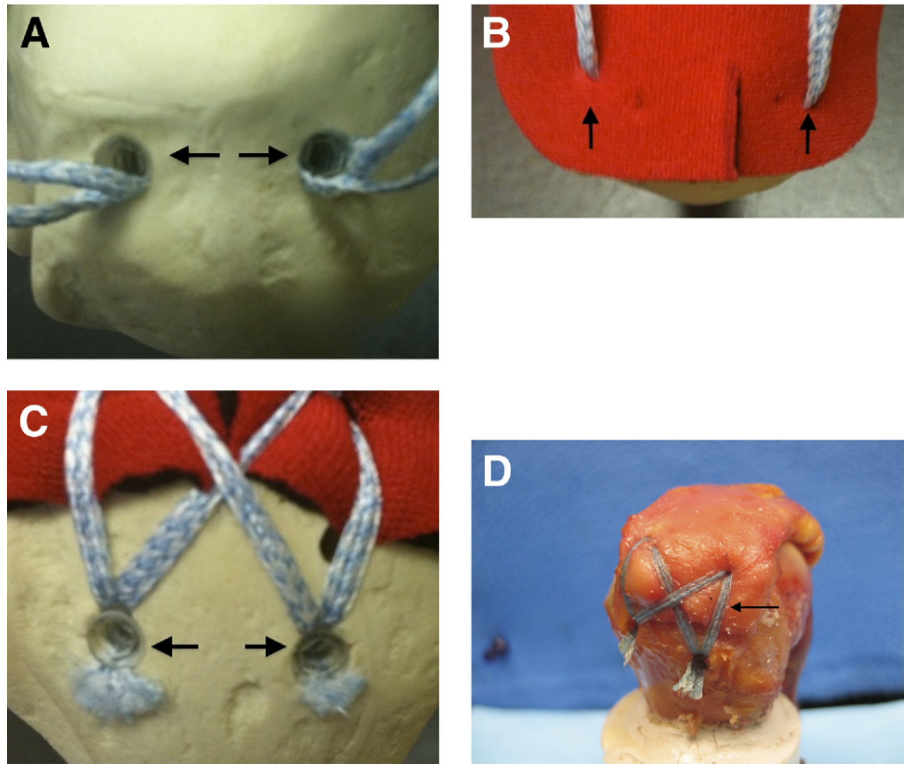


**FIGURE 2.** Knotless technique. (A) Saw bone model with two 4.75-mm anchors (arrows) loaded with wider-dimension high-strength sutures in medial bone sockets. (B) Wider-dimension sutures passed through supraspinatus tissue (black arrows) and (C) then placed in 2 lateral bone sockets with two 4.75-mm anchors (black arrows). (D) Cadaver specimen showing the final repair with wider-dimension high-strength sutures passed through supraspinatus tissue (black arrow) and then placed in 2 lateral bone sockets with 2 anchors.

lateral to the edge of the footprint. The other tail from each medial-row anchor was then retrieved and inserted with an anchor into the other lateral bone socket approximately 1.2 cm from the other lateral bone tunnel (Fig 2).

In 8 matched specimens, the modified construct was used. Two 4.75-mm anchors loaded with 1 strand of wider-dimension high-strength suture and 1 strand of No. 2 high-strength suture (FiberWire; Arthrex) were placed in 2 medial bone sockets just lateral to the articular margin 1.2 cm apart. This construct uses 2 horizontal mattress knots to approximate the rotator cuff to the medial aspect of the rotator cuff footprint. One high-strength suture and 1 wider-dimension high-strength suture were passed through the supraspinatus. This step was repeated for each of the other suture tails. The high-strength sutures from the same anchor, which were in a horizontal mattress configuration, were then tied on top of the rotator cuff, reapproximating it to the footprint. One tail from the wider-dimension high-strength sutures from each medial anchor was then retrieved and inserted with an anchor into a lateral bone socket 1 cm lateral to the edge of the footprint. The other tail from the wider-dimension high-strength sutures from each medial-row anchor was retrieved and inserted with an anchor into the other lateral bone socket approximately 1.2 cm from the other lateral bone tunnel (Fig 3). We named this technique the NET bridge, because the medial-row sutures are used to neutralize the forces on the repair while the wider-dimension high-strength sutures capture the torn tendon, compressing and securing it to the bone.

The previously detailed rotator cuff repair constructs were tested with an Instron materials testing machine (Instron, Canton, MA) with a load capacity of 5 kN, a custom shoulder fixture device, and a video digitizing system. The proximal humerus was potted with plaster of Paris in rigid polyvinyl chloride piping and secured with screws. The potted specimen was secured in the custom-designed rotatory testing apparatus previously described. The humerus was held in 30° of abduction, and to minimize soft-tissue slippage or failure at the tendon-grip interface, a cryoclamp was used to secure the proximal part of the supraspinatus tendon. Care was taken to ensure equal and symmetric tension on the tendon before clamping. When the specimen was mounted securely, nonreflective black paint was used to make 3-mm circular markers on the specimens to be used for the video digitizing system. Seven markers were used: 1 on the clamp, 1 pair medial to the medial-row anchors, 1

**Figure 3.** Modified construct. (A) Saw bone model with two 4.75-mm anchors (arrows) loaded with wider-dimension high-strength sutures and No. 2 high-strength sutures in medial bone sockets. (B) No. 2 high-strength sutures and wider-dimension high-strength sutures from each medial anchor passed through supraspinatus tissue (arrows). (C) No. 2 high-strength sutures tied in horizontal mattress fashion (arrows). (D) Wider-dimension high-strength sutures placed in 2 lateral bone sockets with two 4.75-mm anchors (arrows). (E) Cadaveric specimen showing final repair: dashed arrow, wider-dimension high-strength suture; solid arrows, No. 2 high-strength sutures from same anchor tied to each other in horizontal mattress fashion.

lateral to the medial-row anchors, 1 pair on the tendon edge, and 1 off a fixed marker in the greater tuberosity. A video digitizing system that involves video recording of the markers, computer digitization of the markers, creation of centroids representing the center of the markers, and calculation of distances with ExpertVision software (Motion Analysis, Santa Rosa, CA) was used.

**Cyclic and Tensile Testing:** A 10-N preload was applied for 1 minute, and each specimen was cyclically loaded from 10 to 180 N at a rate of 5 mm/s for 30 cycles. After cyclic loading for 30 cycles, the clamp and the custom fixture device were rechecked for tightness to ensure that there was no tendon slippage. A 10-N preload was then reapplied, and the specimen was loaded to failure at a rate of 1 mm/s.

### Statistical Analysis

Paired Student *t* tests were performed to compare the paired specimens based on their biomechanical properties. As with other studies in our laboratory,

**Table 1.** *Cyclic Load Data From Materials Testing Machine for Knotless Repair and Modified Repair Showing Higher Stiffness at All Time Points for Modified Repairs*

| Cyclic Data | Knotless Repair | Modified Repair | *P* Value |
|---|---|---|---|
| First cycle stiffness (N/mm) | 38 ± 18.95 | 75 ± 27.35 | .02 |
| 30th cycle stiffness (N/mm) | 143 ± 33.45 | 226 ± 58.13 | .02 |
| First cycle hysteresis (N-mm) | 521 ± 297.01 | 189.81 ± 78.59 | .03 |
| 30th cycle hysteresis (N-mm) | 24 ± 10.49 | 10.78 ± 8.09 | .02 |

paired *t* tests were used given that matched-pair specimens were randomized to repair constructs. The level of statistical significance was set at $P < .05$.

## RESULTS

All measurements and calculations were made by a computer-digitized analysis of the video recording of the testing. Initial and linear stiffness for the first and last cycles was calculated by use of data acquisition and analysis software (Series IX; Instron). The initial stiffness was defined as the slope of the toe region of the load-elongation curve, whereas the linear stiffness was defined as the slope of the linear region of the load-elongation curve. The energy absorbed by the first and 30th cycles was defined as the area under the load-elongation curve. Linear stiffness of the NET construct was significantly greater at the first and 30th cycles ($P = .02$). In addition, energy dissipated through the lateral repaired rotator cuff tissue was significantly greater in the knotless technique at the first and 30th cycles ($P = .03$ and $P = .02$, respectively) (Table 1).

Gap formation of the repair and surface strain over the footprint area were calculated for the first and last cycles. The gap formation was defined as the space (measured in millimeters) created at the lateral edge of the tendon at the repair site. This gap was calculated by measuring the change in the position of the markers on the lateral edge of the tendon relative to the stationary markers on the lateral humerus. Gap formation showed significant difference between groups. The modified constructs showed significantly less anterior gap formation at the first cycle (1.35 mm *v* 4.55 mm, $P = .02$) and 30th cycle (1.77 mm *v* 7.67 mm, $P = .02$) (Table 2).

The structural properties of linear stiffness at failure, ultimate failure load, and hysteresis at failure were calculated by use of data acquisition and analysis software (Series IX; Instron). Linear stiffness at failure was calculated as described previously, and the ultimate failure load was defined as the peak force of the load-elongation curve. The energy absorbed to failure was defined as the area under the load-elongation curve from the start of loading until the ultimate failure was reached. Linear stiffness at failure was significantly higher in the modified constructs compared with the knotless technique ($P = .04$). In addition, the ultimate load to failure was significantly higher for the modified construct (mean, 549 N *v* 311 N; $P = .01$). Repaired lateral rotator cuff tissue was also protected to a significantly greater degree at ultimate load as shown by the ultimate hysteresis values ($P = .04$) (Table 3).

The mode of failure for the majority of the knotless constructs occurred at the anteromedial anchor, whereas the majority of NET constructs failed intramuscularly (Figs 4 and 5). As with similar biomechanical studies on rotator cuff repairs, the observed failure mechanisms are merely observations and not statistically significant findings of the 8 matched-pair specimens.

## DISCUSSION

Rotator cuff repairs have evolved from open techniques to mini-open repairs and, presently, are commonly being performed arthroscopically. Initial arthroscopic repairs were done with a single-row technique. However, through detailed anatomic studies, surgeons began to better understand the rotator cuff footprint on the humerus.[13]

Double-row rotator cuff fixation was thought to enhance tendon-to-bone contact. Although the exact

**Table 2.** *Anterior Gap Data From Video Digitizing System (VDS) Analysis for Knotless Repair and Modified Repair Showing Higher Gap Formation in Knotless Repairs*

| VDS Data | Knotless Repair (N) | Modified Repair (N) | *P* Value |
|---|---|---|---|
| First cycle gap | 4.55 ± 2.25 | 1.35 ± 1.82 | .02 |
| 30th cycle gap | 7.67 ± 5.14 | 1.77 ± 2.45 | .02 |

**Table 3.** *Failure Loading Data From Materials Testing Machine for Knotless Repair and Modified Repair Showing Higher Load, Linear Stiffness, and Hysteresis in Modified Repairs*

| Failure Data | Knotless Repair | Modified Repair | *P* Value |
|---|---|---|---|
| Ultimate load (N) | 311.30 ± 107.26 | 549.49 ± 163.23 | .01 |
| Linear stiffness (N/mm) | 182.53 ± 35.38 | 241.78 ± 54.62 | .04 |
| Ultimate hysteresis (N-mm) | 1,147.01 ± 1,058.99 | 3,056.69 ± 1,511.76 | .04 |

time period for tendon-to-bone incorporation has not been defined in the literature, animal studies have shown the importance of tendon-to-bone contact for healing.[14-16] Charousset et al.[17] used computed tomography arthrography to compare double- and single-row constructs and found better healing rates with the former. The transosseous-equivalent technique was developed to maximize compression of the tendon to the footprint, to optimize the contact dimensions, and to provide increased repair strength.[18] This technique has been shown to have a significantly greater ultimate load to failure and similar gap formation and stiffness when compared with a double-row technique.[19] Frank et al.[20] used magnetic resonance imaging to show high healing rates using the transosseous-equivalent repair. Outcome studies have shown promising early results using these techniques.[4,5,21-28]

As the volume of shoulder arthroscopy continues to increase, technology used for rotator cuff repair has followed suit. High-strength sutures are more durable and are used to minimize a potential weak point in repair constructs. The wider-dimension sutures aid in rotator cuff compression across the anatomic footprint. Finally, in attempts to simplify the surgical technique, the knotless technique eliminates the need to tie arthroscopic knots. However, as shown in this study, knotless fixation may lead to increased gap formation and failure of the repair. Thus this simplification of the procedure may be detrimental to patient outcomes.

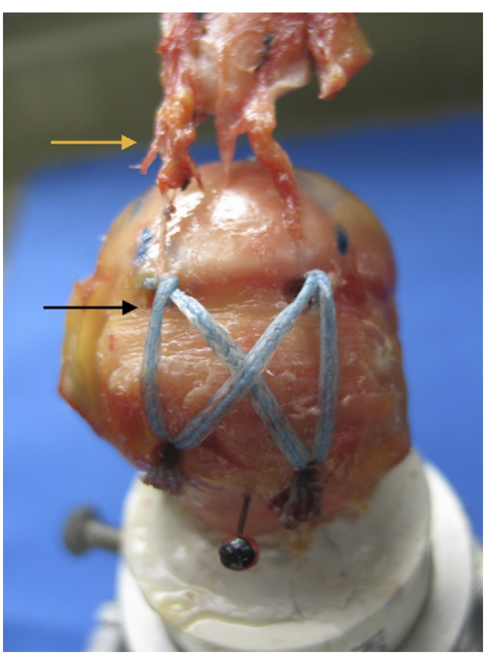

**Figure 4.** View of lateral aspect of potted humerus after ultimate failure of knotless construct. The tendon (light arrow) has torn away from the footprint (dark arrow). Initial failure occurred anteriorly due to the external rotation and differential strain on the rotator cuff.

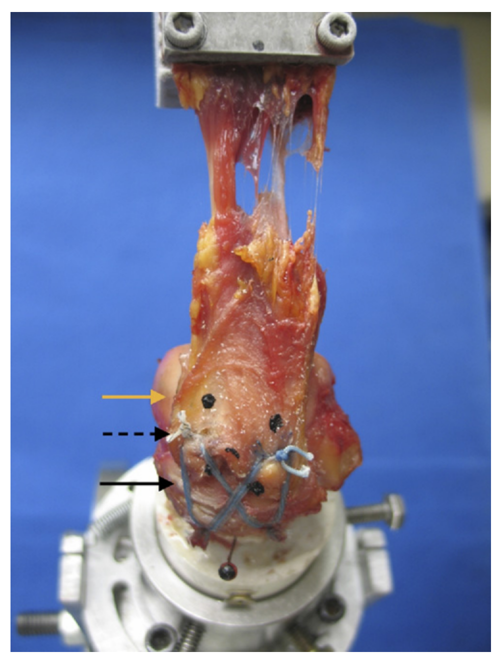

**Figure 5.** View of lateral aspect of potted humerus after ultimate failure of modified construct. The medial-row sutures (dashed arrow) have neutralized the forces acting on the repair. (Light arrows, tendon; dark arrow, footprint.) The load to failure was significantly higher with this technique, with a significantly lower anterior gap formation.

Early biomechanical testing of rotator cuff repairs did not account for the rotational motion (such as external rotation) that patients' typically experience during postoperative rehabilitation. Thus Park et al.[11] created a model, used in this study, that provides cyclic external rotation. The literature has shown the significant effect that rotation has on repair constructs. Double-row repairs were shown to have better fixation strength than single-row repairs when exposed to cyclic loading and changes in humeral rotational position.[29,30] In addition, recent literature has shown differential tension between anterior and posterior sutures when allowing for rotational motion during laboratory testing.[31] This study is the first to compare a modified transosseous-equivalent suture repair technique with a knotless technique in an external rotation model.

This study shows that the addition of medial-row fixation to a knotless repair construct significantly increases the biomechanical characteristics of the repair (linear stiffness, ultimate load, and hysteresis) while significantly decreasing gap formation regardless of tissue quality. Thus the medial-row horizontal mattress sutures neutralized the force experienced by the repaired tissue. This finding was also proven at ultimate load, with the majority of failures in the transosseous repair group occurring intramuscularly, at times leaving rotator cuff tissue under the repair construct.

It is known that the maximal load during supraspinatus contraction is approximately 302 N.[32] In younger specimens, with better tissue quality by gross examination, the knotless construct failed at loads higher than the maximal contraction. However, with poor tissue quality observed by gross examination, the constructs failed at lower loads. In addition, as expected, the majority of failures in the knotless construct occurred at the anterior medial anchor, given the increased differential stress on this area during external rotation. We believe that to provide the best biomechanical environment for healing regardless of tissue quality, medial-row knot fixation is paramount.

Although it was not part of our study, we hypothesize that the addition of medial-row knot fixation acts to seal the footprint from egress of synovial fluid, which may aid in the healing of tendon to bone. A recent study by Ahmad et al.[33] used a fluid-infusion model to show that a single-row repair exposes the healing zone to a larger amount of fluid than a transosseous repair technique. Future studies need to be performed with this type of model on the modified construct to determine its effect on footprint protection during tendon healing.

The main limitation of this study is the use of cadaveric specimens. Obviously, information regarding healing and long-term construct durability was unable to be determined as a result. We also removed the infraspinatus and subscapularis from our specimens, which may have affected our biomechanical results. As with previous studies using an external rotation model, external rotation loading is a simplification of the complex kinematics involved in postoperative motion, but it has been shown to replicate 1 commonly experienced shoulder motion after rotator cuff repair.

Strengths of our study include the utilization of matched-pair specimens in an attempt to eliminate variations in tissue quality being tested by the 2 techniques. Moreover, 1 surgeon performed all repairs to decrease variability in surgical technique. In addition, unlike previous experiments in our laboratory, the utilization of a cryoclamp provided a more stable construct for the experimental origin of the supraspinatus. This modification improved our ability to analyze the cyclic load and load-to-failure data.

## CONCLUSIONS

The modified construct shows improved biomechanical properties when allowing for external rotation during high-load testing. Using an additional horizontal mattress from separate sutures in the medial-row anchors helps to neutralize forces experienced by the repair.

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