Biomechanical Performance of Medial Row Suture Placement Relative to the Musculotendinous Junction in Transosseous Equivalent Suture Bridge Double-Row Rotator Cuff Repair

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Purpose: To compare the biomechanical performance of medial row suture placement relative to the musculotendinous junction (MTJ) in a cadaveric transosseous equivalent suture bridge (TOE-SB) double-row (DR) rotator cuff repair (RCR) model. **Methods:** A TOE-SB DR technique was used to reattach experimentally created supraspinatus tendon tears in 9 pairs of human cadaveric shoulders. The medial row sutures were passed either near the MTJ (MTJ group) or 10 mm lateral to the MTJ (rotator cuff tendon [RCT] group). After the supraspinatus repair, the specimens underwent cyclic loading and load to failure tests. The localized displacement of the markers affixed to the tendon surface was measured with an optical tracking system. **Results:** The MTJ group showed a significantly higher ($P = .03$) medial row failure (5/9; 3 during cyclic testing and 2 during load to failure testing) compared with the RCT group (0/9). The mean number of cycles completed during cyclic testing was lower in the MTJ group (77) compared with the RCT group (100; $P = .07$) because 3 specimens failed in the MTJ group during cyclic loading. There were no significant differences between the 2 study groups with respect to biomechanical properties during the load to failure testing. **Conclusions:** In a cadaveric TOE-SB DR RCR model, medial row sutures through the MTJ results in a significantly higher rate of medial row failure. **Clinical Relevance:** In rotator cuff tears with tendon tissue loss, passage of medial row sutures through the MTJ should be avoided in a TOE-SB RCR technique because of the risk of medial row failure.

Arthroscopic rotator cuff repair (RCR) provides reliable and reproducible relief of pain and return of shoulder function in majority of the patients.[1] Multiple biomechanical constructs have been described for arthroscopic RCR and include variations of single-row, double-row (DR), and transosseous equivalent (TOE) techniques.[2,3] While the debate and controversy regarding the clinical superiority of DR versus single-row RCR techniques continue, biomechanical studies have demonstrated significantly increased footprint

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area coverage and contact with DR and TOE techniques compared with single-row repairs.[4-17]

Retears after arthroscopic RCR may occur because of mechanical and biological failure of the fixation.[18-24] Revision RCR with tendon tissue loss and chronic retracted rotator cuff tears represents a clinically challenging situation because the working length available to perform the tendon to bone repair is limited. In such a situation, if the tendon can be reduced to the footprint, performing an arthroscopic RCR with TOE DR technique is desirable but can be difficult. The surgeon should avoid passing medial row sutures in close proximity to the musculotendinous junction (MTJ) as this has been shown to predispose to type II failure (medial row failure) of RCR in TOE DR techniques.[25-29] Poor suture holding strength of the tissue in the region of the MTJ and or strangulation of the tissue at the medial row have been proposed as 2 mechanisms explaining medial row failure in TOE DR repair. However, there is limited biomechanical evidence supporting these mechanisms in TOE-SB DR RCR.

The purpose of this study was to compare the biomechanical performance of medial row suture placement relative to the MTJ in a cadaveric TOE suture bridge (TOE-SB) double-row (DR) RCR model. We hypothesized that the supraspinatus tendon repaired with a TOE-SB DR repair technique will demonstrate greater elongation under cyclic loading and a decreased load to failure when the medial suture row is passed through the MTJ compared with the medial row passed 10 mm lateral to the MTJ.

Methods

A total of 9 matched pairs (18 shoulders) of fresh-frozen human cadaveric shoulders with intact rotator cuffs were used in this study. The average age of the specimens was 58.8 ± 5.4 years. There were 7 male donors and 2 female donors, and the average body mass index was 23.2 ± 4 kg/m^2. Computed tomography (CT) scans were performed on all but 2 specimens to determine bone mineral density (BMD) in the region of the humeral head prior to dissection and testing. The 2 specimens could not be scanned because of technical issues with the CT scanner, and the specimens had to be dissected as they were already thawed. The specimens were maintained at −20°C until approximately 12 hours prior to RCR.

Specimen Preparation

The shoulder specimens were obtained from Lifelegacy Foundation (Tucson, AZ). The specimens were prepared according to a previously published protocol.[27,30] The shoulders were stripped of all soft tissues except for the supraspinatus muscle and tendon, which was left intact. The shoulder fellow (B.B.) visually inspected all the specimens for supraspinatus tendon tears. Specimens with partial or full-thickness rotator cuff tears were excluded. The supraspinatus muscle attachment was elevated off the supraspinatus fossa of the scapula. The length and width of the supraspinatus tendon footprint on the greater tuberosity was measured with digital calipers. The supraspinatus tendon insertion was then sharply elevated off its footprint on the proximal humerus. The MTJ was identified visually from the superior view, as would be seen arthroscopically from the subacromial space. An indelible marker was used to create a reference line perpendicular to the tendon fibers at the midpoint of the anterior-posterior margins on the tendon at the MTJ. Two lines parallel to this were drawn at 10 mm (1L) and 20 mm (2L) lateral to the MTJ (Fig 1). The thickness of the tendon was measured separately 3 times with digital calipers at the MTJ, 1L, and 2L positions. The right shoulder for each matched pair was then randomized by coin flips to either the MTJ repair group (medial row of sutures passed through the MTJ) or RCT repair group (medial row of sutures passed transtendinously 10 mm lateral to the MTJ), and the contralateral shoulder received the alternate repair.

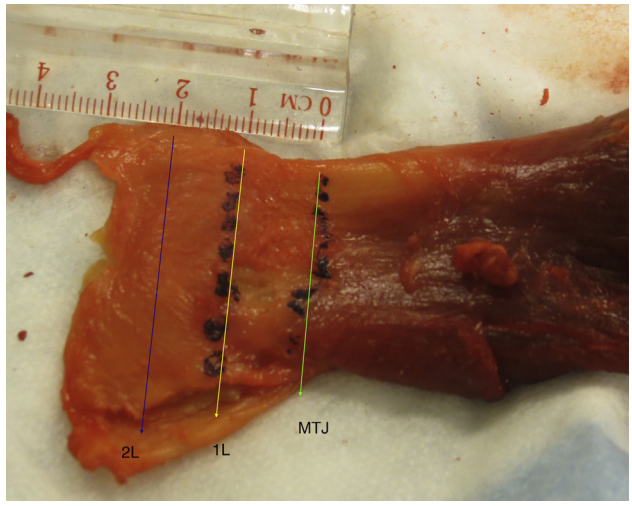

Fig 1. Supraspinatus musculotendinous unit after dissection off the footprint and scapula. The medial row sutures in the musculotendinous junction (MTJ) group were passed through the MTJ junction, and the medial row sutures in the rotator cuff tendon (RCT) group were passed at 1 cm lateral to the MTJ (1L). (1L, 1 cm lateral to the musculotendinous junction; 2L, 2 cm lateral to the MTJ.)

RCR

A consistent technique was used to perform RCRs in each group, except for varying the position of the medial row of sutures. The TOE-SB DR supraspinatus repairs were performed in each group with 4.5 mm BioCorkscrew anchors (Arthrex, Naples, FL) single loaded with No. 2 FiberWire medially and 4.5 mm Pushlock anchors laterally (Arthrex). Planned anchor sites were marked on the greater tuberosity. The medial

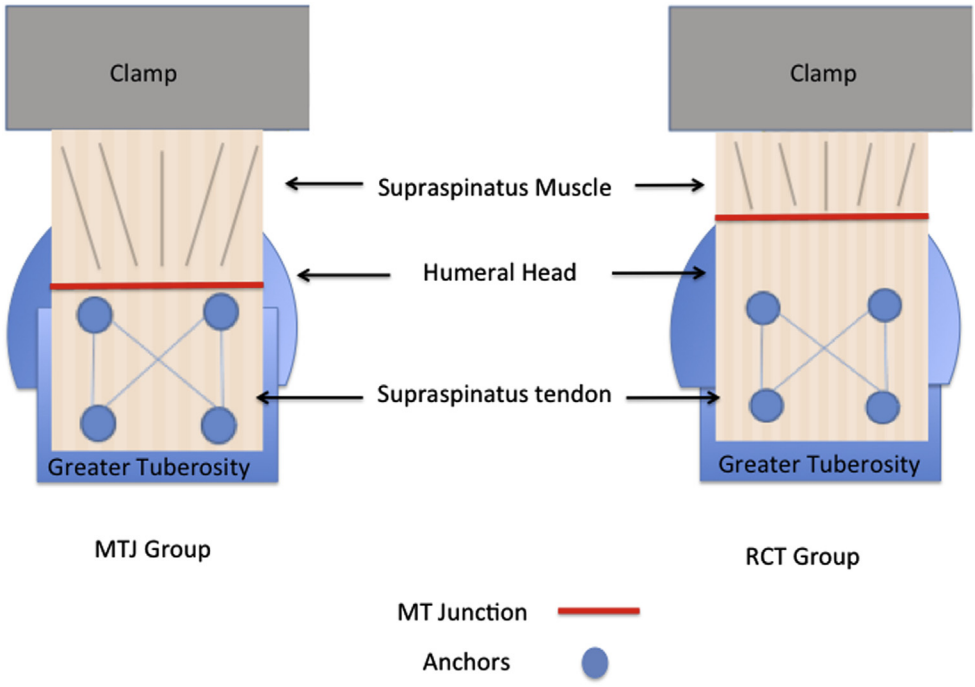

Fig 2. Simulated repair of the supraspinatus tendon using the double-row transosseous equivalent technique. A suture bridge construct was created using 2 suture anchors and mattress suture for the medial row. One limb of suture from each anchor was then used to trap the tendon next to the footprint and secured using 2 swivel locks laterally. (MTJ, musculotendinous junction repair group; RCT, rotator cuff tendon repair group.)

row anchors were placed just lateral to the articular margin. The anterior-medial anchor site was consistently placed 5 mm posterior to the posterior lip of the bicipital groove. The posterior-medial anchor site was marked 15 mm posterior to the bicipital groove, at the articular margin. The 2 lateral anchor sites were marked 15 mm lateral to the 2 medial anchors on the proximal humerus. A punch was used to create 2 holes in the previously marked spots, and the Biocorkscrew anchors were screwed into these holes. A free needle was used to pass the No. 2 FiberWire through the designated area to form a horizontal mattress pattern of medial row sutures. In the RCT group, the medial row of sutures were placed 10 mm lateral to the MTJ through the supraspinatus tendon. In the MTJ group, the medial row sutures were placed in the vicinity of the MTJ of the supraspinatus (Fig 1). In order to standardize the amount of tendon lateral to the medial row, the tendon was cut 1 cm lateral to the medial row (at the 1L position for MTJ group and the 2L position for RCT group). The mattress suture was tied with a slipknot followed by 3 alternating half hitches. A punch for the lateral row was used to create holes in the planned anchor sites. One limb from each anchor was taken across and fixed to the lateral greater tuberosity with a 4.5 mm Pushlock anchor in a criss-cross pattern (TOE-SB construct; Fig 2).

Biomechanical Testing

The specimens for biomechanical testing were prepared according to a previously published protocol.[27,30] Each humerus was cut at 15 cm below the medial calcar and potted in a polyvinyl chloride pipe using acrylic cement (Isocryl, Lang Dental, Wheeling, IL). 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 muscle belly was then placed in a custom freezer clamp to grip the musculotendinous unit medial to the MTJ.[27,30] The humeral mounting fixture was then secured to the base of an Insight 5 materials testing system (MTS, Eden Prairie, MN).

For the optical analysis, 2.5-mm circular markers were glued on both the anterior and posterior construct surfaces to observe localized elongation during testing (Fig 3). Five rows of markers were placed across the specimens in the RCT group: on the greater tuberosity, in between the medial and lateral suture rows, just medial to the medial row of suture anchors, on the muscle belly, and on the cryogenic clamp. Four rows of markers were placed across the specimens in the MTJ group: on the greater tuberosity, in between the medial and lateral suture rows, just medial to the medial row of suture anchors, and on the custom clamp. Digital video was captured at 40 Hz with a 2.82 megapixel camera (Prosilica GX1920, Allied Vision Technologies, Exton, PA) and a 25-mm lens, using Digital Motion Analysis Software (DMAS, Spica Technology Corporation, Maui, HI) to track markers (accuracy, 40 μm) for each specimen.

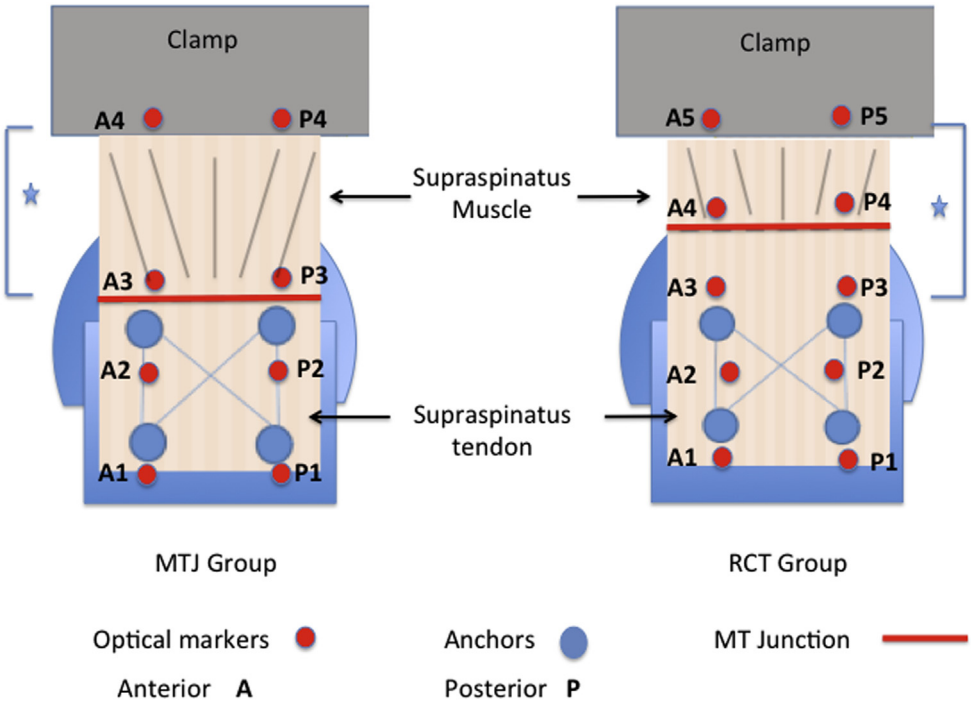

Fig 3. Methodology for optical tracking of surface markers. The position of the markers for the optical analysis for the MTJ group (anterior/posterior; A/P1, greater tuberosity; A/P2, tendon between medial and lateral suture rows; A/P3, tissue just medial to medial suture row; A/P4, cryogenic clamp) and RCT group (A/P1, greater tuberosity; A/P2, tendon between medial and lateral suture rows; A/P3, tissue just medial to medial suture row; A/P4, muscle belly; A/P5, cryogenic clamp). Optical measurements were reported between the medial suture row and clamp (★) markers A/P3 and A/P4 for the MTJ group and markers A/P3 and A/P5 for the RCT group. (MTJ, musculotendinous junction repair; RCT, rotator cuff tendon repair.)

The testing protocol was based on methods published by Salata et al. and Park et al.[30,31] Prior to the testing sequence, each specimen was preloaded to 10 N for 2 minutes. The specimen was subsequently loaded cyclically between 10 and 160 N at 100 N/second for 100 cycles. After cyclic testing, specimens were loaded to failure at 1 mm/second. Load and actuator displacement data were acquired synchronously with the optical marker data using MTS Test Works 4 software and DMAS, respectively. Specimens were regularly moistened using saline mist spray during testing. Construct failure mode was visually classified as occurring (1) within medial row, where no suture involvement occurred; (2) within anchor, due to suture pulling out of anchor; or (3) due to anchor advancement from bone.

Data Analysis

For cyclic testing, 2 primary parameters were quantified from the MTS load and displacement output: (1) first cycle construct excursion, defined as the increase in construct length from the initial preloaded testing state to the peak extension of the first cycle; and (2) secant stiffness, defined as the slope of the line joining minimum and maximum points of the loading phase of the force-deformation curve; secant stiffness was separately evaluated as the average of the first 5 cycles and the last 5 cycles. In addition, localized strain during cyclic testing was measured between optical markers placed at the medial anchor line and crosshead. The outcome was termed optical cyclic elongation and was defined as the increase in segment length between the defined markers from the mean peak displacement of the first 5 cycles captured to the mean peak displacement of the last 5 cycles relative to the initial segment length.

From the load to failure test, 4 parameters were quantified, the first 3 from the MTS output: (1) maximum load; (2) extension at maximum load, defined as the crosshead displacement at maximum load relative to the preloaded state; and (3) linear stiffness, calculated as the maximum slope of the load-displacement curve spanning 40% of the data points collected between initiation of the failure test and the maximum load.[30] The fourth outcome, measured optically, was the localized strain between the markers placed at the medial anchor and top grip when the maximum load was achieved. This was termed as optical strain at maximum load and was calculated by optically measuring the segment length between the aforementioned 2 markers at maximum load and dividing that length by the segment length measured under the initial preload. All optical measurements were calculated separately for anterior and posterior regions of each construct in order to determine whether there was a regional difference in outcomes.

Table 1. Anatomic Measurements of the Supraspinatus Tendon in the Study Groups

Anatomic Parameters	MTJ	RCT	*P* Value
Tendon length, mm	32.3 ± 1.4 (29.2-39.5)	33.5 ± 2.7 (27.3-39.6)	.71
MTJ thickness, mm	3.3 ± 0.1 (3-3.7)	3.2 ± 0.1 (2.8-3.5)	.5
Supraspinatus footprint, mm			
Length, medial to lateral	13.5 ± 0.7 (11.9-15)	13.1 ± 0.9 (11-15.1)	.72
Width, anterior to posterior	28.3 ± 1.3 (25.3-31.2)	25.7 ± 0.9 (23.5-27.8)	.11

NOTE. All measurements reported as mean ± standard error of mean (95% confidence interval).
MTJ, musculotendinous junction; RCT, rotator cuff tendon.

Statistical Analysis

The anatomical and biomechanical data were reported as mean ± standard error of mean. The data were compared between the 2 groups using Student's *t*-test (Graphpad Prism 5, Graph Pad, LaJolla, CA). The categorical data were compared using the chi-square test. Correlation between the thickness of the tissue at the medial row and peak load, cyclic elongation, or linear stiffness was calculated by Pearson's correlation coefficient. The level of significance was set at $P < .05$.

Results

Anatomical Data

The anatomical data for the MTJ and RCT groups are shown in Table 1. No supraspinatus tendon tears were found in the 9 matched specimens, and none of the specimens were excluded from the study. The anatomical parameters showed no significant differences between the 2 groups. The tendon length and thickness at the MTJ was consistent between the repair groups. There were no significant differences between the footprint width and length in the MTJ and RCT group specimens. There was no significant difference ($P = .70$) in the average BMD in the humeral head between the specimens in the 2 groups.

Biomechanical Testing Data

Cyclic Loading Data

During cyclic loading, 3 specimens from the MTJ group failed proximally at the MTJ compared with no specimen failing in the RCT group. The mean numbers of cycles completed by the specimens were higher in the RCT group (n = 100) compared with in the MTJ group (n = 77; $P = .07$). The specimens in the MTJ group that failed during cyclic loading were excluded from the remaining comparative data analysis between the 2 groups. Considering only those specimens that completed the cyclic testing in the 2 groups, there was no statistical difference between the 2 groups when comparing construct initial excursion, secant stiffness, and optical cyclic elongation in the anterior and posterior regions of the construct (Table 2).

Load to Failure Data. The 3 specimens in the MTJ group that failed during cyclic testing were excluded from load to failure testing. Load to failure testing resulted in no significant difference between the MTJ specimens (6/9) and RCT specimens (9/9) for all the testing parameters (Table 3). Additionally, there was no significant difference between the 2 repair types when comparing localized optical strain at maximum load or regional differences between anterior and posterior regions within either repair type. There was no correlation between the thickness of the tissue at the

Table 2. Cyclic Testing in the Study Groups

Parameters*	MTJ (n = 9)	RCT (n = 9)	*P* Value
Mechanical cyclic data			
Relative initial excursion, %	0.19 ± 0.4 (0.1-0.3)	0.17 ± 0.3 (0.09-0.2)	.66
Linear stiffness, N/mm	66.2 ± 4.4 (55-77.4)	78.9 ± 8.9 (57.9-99.9)	.27
Secant stiffness, N/mm			
Initial phase	40.8 ± 3.3 (32.8-48.8)	52.3± 4 (42.9-61.6)	.053
Final phase	43.5 ± 4.3 (32.4-54.7)	54 ± 4.9 (42.8-65.2)	.16
Optical cyclic data†			
Cyclic elongation, anterior, %	14.8 ± 4.5 (3.3-26.2)‡	11.1 ± 3.9 (1.5-20.6)§	.54
Cyclic elongation, posterior, %	16.9 ± 5.4 (3-30.8)‡	14.3 ± 4.8 (2.4-26.1)§	.73

MTJ, musculotendinous junction; RCT, rotator cuff tendon.
*Data reported as mean ± standard error of mean (95% confidence interval).
†Data reported are determined from displacements in the *y* direction between the clamp and markers placed just medial to the medial anchor. Anterior and posterior pertain to measurements from markers placed on the anterior and posterior regions of the tendon.
‡Three specimens in the MTJ group failed during the cycling testing, thus data were not included.
§Files from 2 specimens in the RCT group were missing or corrupt.

Table 3. Load to Failure Testing in the Study Groups

Parameters*	MTJ†	RCT	*P* Value
Mechanical failure data			
Maximum load, N	311.6 ± 30.7 (232.7-390.5)	388.3 ± 40.6 (294.8-481.9)	.19
Linear stiffness, N/mm	66.2 ± 4.4 (55-77.4)	78.9 ± 8.9 (57.9-99.9)	.27
Extension at maximum load	0.46 ± 0.6 (0.3-0.6)	0.42 ± 0.3 (0.3-0.5)	.53
Optical failure data‡			
Maximum strain, anterior, %	114 ± 3.5 (104.2-123.8)	121.3 ± 4.8 (109.9-132.7)§	.3
Maximum strain, posterior, %	120.6 ± 3.2 (111.8-129.4)	121.9 ± 5.8 (107.7-136.2)§	.86

MTJ, musculotendinous junction group; RCT, rotator cuff tendon group.
*Data reported as mean ± standard error of mean (95% confidence interval).
†Three specimens failed during the cycling testing, thus no failure tests were run on these specimens.
‡Maximum strains that are reported are determined from displacements in the *y* direction between the clamp and markers placed just medial to the medial anchor. Anterior and posterior pertain to measurements from the markers placed on the anterior and posterior regions of the tendon.
§Data from one specimen were not included because of corruption of the optical file.

medial row and peak load, cyclic elongation, or linear stiffness.

In all 3 specimens in the MTJ group, which failed early during cyclic testing, failure occurred at the medial row construct. Of the remaining 6 specimens in the MTJ group, 2 specimens also failed within the medial tissue during load to failure testing. No specimens in the control group (RCT) failed within this tissue region. The MTJ group showed significantly higher frequency of failures ($P = .03$) in the region of the medial row (3 during cyclic testing and 2 during pull to failure testing) compared with the RCT group. The other mechanisms of construct failure during load to failure testing included suture tearing through the tendon, anchor advancement from the bone, or suture pulling out of the anchor, as shown in Table 4.

Discussion

The results of this cadaveric study demonstrate that in a TOE-SB DR RCR technique, medial sutures placed through the MTJ have a higher frequency of failure during cyclic loading compared with medial sutures placed transtendinously (10 mm lateral to the MTJ) at time zero. For specimens that completed cyclic testing, there was no significant difference in the peak load, cyclic elongation, or linear stiffness between the 2 groups.

This study reflects the initial biomechanical performance of the TOE-SB DR construct at time zero. The data demonstrate that the medial row suture passage through the MTJ may result in mechanical failure of the medial row in the early stages after repair. This is an important finding with clinical relevance to the arthroscopic management of rotator cuff tears accompanied by varying amounts of tendon tissue loss. This situation is frequently encountered during revision RCRs and repair of chronic retracted RC tears and may be additionally complicated by compromised or poor tendon tissue quality.[32] It is highly desirable to use DR repair in these situations for better footprint contact and footprint compression so as to promote tendon to bone healing. In their original description of TOE DR technique, Park et al.[33] recommended that medial row sutures should be passed at least 10 to 12 mm medial to the lateral border of the rotator cuff tendon. Cho et al.[34] have made similar recommendations regarding the location of passage of medial row sutures. However, it is known from the anatomic studies that the tendon length is variable, with the posterior part of the supraspinatus tendon shorter than the anterior. The mean minimum medial-lateral supraspinatus tendon length varies between 20 and 23 mm.[35-40] Hence, if the remnant length of the tendon is short, the surgeon can inadvertently pass the medial row sutures through or medial to the usculotendinous junction in order to have

Table 4. Failure Modes in the 2 Study Groups

	MTJ		RCT	
Failure Mode	Cyclic Testing	Failure Testing	Cyclic Testing	Failure Testing
Failure at the medial row construct*	3	2	0	0
Suture cut through the tendon	0	3	0	6
Suture pull out from anchor	0	0	0	1
Anchor pull out from bone	0	1	0	2
Total	3	6	0	9

MTJ, musculotendinous junction group; RCT, rotator cuff tendon group.
*$P = .03$ *v* RCT group.

a sufficient tendon tissue lateral to the medial row for a TOE-SB DR repair technique. In our study, we recreated this situation in the MTJ group by leaving a 10-mm length of tendon tissue lateral to the MTJ. The results of our study demonstrate that medial row sutures close to the MTJ in TOE-SB DR repair constructs have the potential to compromise fixation and result in a type II failure.

The mode of failure of TOE-SB DR repair construct in the 2 groups in this study provides insight into the difference in repair quality between the MTJ and RCT groups. All the specimens underwent a similar kind of repair, and there were no significant differences in the BMD among the specimens in the 2 groups. When sutures were placed through the MTJ, 5 of the 9 specimens failed within the MTJ tissue, of which 3 failed during early stages of the cyclic testing. The remaining 2 failures in this region were during the load to failure testing phase and resulted in the lowest peak forces within the group. Furthermore, the cyclic and load to failure testing parameters were higher in the RCT group compared with in the MTJ group, although differences were not significant.

Trantalis et al.[26] reported on 5 patients who demonstrated a type II failure after arthroscopic DR RCR. The authors postulated that a more medial passage of medial row sutures potentially contributed to the medial row failure. We believe that the reasons for higher failure rate of the TOE-SB DR repair technique with medial row sutures passing through the MTJ is related to poor holding strength of the MTJ tissue compared with the tendinous tissue lateral to the MTJ. Kim et al.[28] demonstrated that there was a significantly higher retear rate with DR TOE RCRs in patients with remnant tendon length <10 mm compared with a single-row repair. However, there was no significant difference in retear rates between single-row and TOE when the remnant tendon length was >10 mm. Voigt et al.[41] reported that 46% of the supraspinatus failures (6/13) in a series of 51 patients with DR SB constructs were medial row failures. In a retrospective analysis of a case series of 123 rotator cuff tears repaired with SB DR construct, Cho et al.[29] reported a higher type II failure at the MTJ. The current study provides a biomechanical proof of concept in a laboratory setting of the clinical findings related to type II (medial row) failure in TOE RCRs reported in the aforementioned clinical studies.

In a recent cadaveric study, Kullar et al.[42] demonstrated inferior mechanical properties (increased gapping and lower mean loads to failure) in the simulated supraspinatus repair constructs with single-row mattress sutures passed through the MTJ compared with the sutures passed 5 mm lateral to the MTJ. The findings in our study are similar to the results of the cadaveric study by Kullar et al. with some methodological differences. Kullar et al. used custom fabricated metal block to reattach the supraspinatus tendons, but we reattached the supraspinatus tendon back to its footprint on the proximal humerus, which we believe simulates what happens in real life. Kullar et al. used a single row of 4 horizontal mattress sutures as their repair constructs, and we used a TOE-SB DR repair technique. Nonetheless, both studies highlight the importance of avoiding suture passage through the MTJ in RCR constructs.

Limitations

The results of this study should be interpreted with the following experimental limitations. First, rotational testing of the constructs was not performed, which may have more closely simulated the in vivo situation. Second, this study has the limitations associated with any other cadaveric biomechanical study, in which the bone and tendon quality is likely different from in vivo situations. The quality of the tendinous tissue in the setting of a revision RCR and chronic retracted tears would be less structurally sound than in this cadaveric study. Third, the peak load may not be a clinically relevant marker to predict RCR failure. We used optical marker system for detecting differences in local displacement between the 2 types of repairs. However, there were limitations with the use of the optical system with this cadaveric RCR model, including difficulty analyzing surface strains in repair tissue constructs and localized marker placement. For instance, a small change in a tissue marker placement medially could result in large segment differences depending on relative location of tissue failure to the marker. Fourth, we did not evaluate broader suture constructs (suture tape, knotless DR repair) with this repair, which have been shown to minimize suture cutout through the tendon. Furthermore, we did not test different locations within the tendon (5 mm *v* 10 mm). Although the complete detachment of an isolated supraspinatus tendon from the greater tuberosity does not accurately model a true rotator cuff tear, our goal in this study was to assess the biomechanical properties of 2 different medial row suture locations in a simulated but controlled environment. Moreover, this study does not take into account the biological aspect of repair including tendon to bone healing and stabilization of construct by the adjacent intact tissue.

Conclusions

In a cadaveric TOE-SB DR RCR model, passage of medial row sutures through the MTJ results in significantly higher rate of medial row failure.

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