Systematic Review

Transosseous-Equivalent Rotator Cuff Repair: A Systematic Review on the Biomechanical Importance of Tying the Medial Row

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Purpose: Double-row and transosseous-equivalent repair techniques have shown greater strength and improved healing than single-row techniques. The purpose of this study was to determine whether tying of the medial-row sutures provides added stability during biomechanical testing of a transosseous-equivalent rotator cuff repair. **Methods:** We performed a systematic review of studies directly comparing biomechanical differences. **Results:** Five studies met the inclusion and exclusion criteria. Of the 5 studies, 4 showed improved biomechanical properties with tying the medial-row anchors before bringing the sutures laterally to the lateral-row anchors, whereas the remaining study showed no difference in contact pressure, mean failure load, or gap formation with a standard suture bridge with knots tied at the medial row compared with knotless repairs. **Conclusions:** The results of this systematic review and quantitative synthesis indicate that the biomechanical factors ultimate load, stiffness, gap formation, and contact area are significantly improved when medial knots are tied as part of a transosseous-equivalent suture bridge construct compared with knotless constructs. Further studies comparing the clinical healing rates and functional outcomes between medial knotted and knotless repair techniques are needed. **Clinical Relevance:** This review indicates that biomechanical factors are improved when the medial row of a transosseous-equivalent rotator cuff is tied compared with a knotless repair. However, this has not been definitively proven to translate to improved healing rates clinically.

Most biomechanical studies evaluating arthroscopic rotator cuff repair techniques have shown that double-row and transosseous-equivalent (TOE) repairs are significantly stronger than single-row repairs.[1] Increased strength and contact area are thought to lead to improved healing.[2] However, there is no conclusive evidence showing that improved biomechanical properties lead to an intact repair at the time of follow-up in clinical studies.[3,4] Though controversial, there is sound clinical evidence that healed rotator cuff tears have improved functional outcomes compared with tears that have not healed after rotator cuff repair.[5] Thus improving healing is the impetus behind development and use of differing repair techniques, yet healing is likely associated with a combination of biomechanical and biological factors.

Double-row repairs have been largely abandoned for the TOE repair because of improved contact area,[6] increased yield load,[7] and reduced operative time. TOE repairs can be performed using various suture configurations but are generally divided between those in which the medial row is tied and all-knotless repairs (Fig 1). Debate on the utility of tying the medial row continues among surgeons performing arthroscopic rotator cuff repairs. Proponents of tying the medial row stress the importance and the improvement of strength of the construct, whereas advocates for the knotless repairs claim no difference in repair strength or clinical outcomes and emphasize the possibility of reduced irritation of the medial knot within the subacromial space. The goal of this systematic review was to examine the

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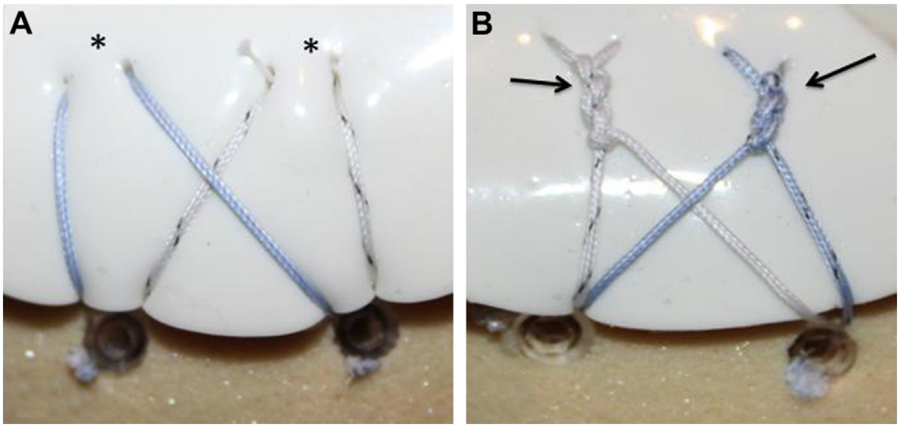


Fig 1. Model of knotless repair versus tying of knots at the medial row shows the 2 repair constructs evaluated in this study, looking from a lateral view, where medial is at the top and lateral is at the bottom. Studies evaluated in the review compared the biomechanical properties of TOE rotator cuff repairs in which the medial-row sutures were not tied (knotless) (A) versus those in which the medial-row sutures were tied together (knotted) (B). The asterisks indicate that no knot is present, and the arrows point to the knots tied in the repair construct.

published literature to determine whether tying of the medial row of a TOE rotator cuff repair results in improved biomechanical properties of the repair construct. We hypothesized that biomechanical studies would show improved ultimate load, contact pressure, stiffness, and hysteresis with reduced gap formation using arthroscopic TOE rotator cuff repair techniques in which the medial row was tied compared with knotless repairs.

Methods

Search Strategy

We applied a text-search strategy using the terms "double row OR medial knot OR double-row fixation" AND "rotator cuff." We searched the Cochrane Central Register of Controlled Trials and Medline for biomechanical studies assessing the strength of medial-knot tie-down in rotator cuff repairs among different suture configurations. Bibliographies were cross-referenced to identify any other pertinent studies for inclusion. The initial search was performed on February 10, 2012, with subsequent searches immediately before submission and during the review process to ensure that additional studies meeting the inclusion criteria had not been published in the interim.

Inclusion Criteria

Inclusion criteria were cadaveric studies examining the biomechanical properties of double-row rotator cuff repairs using a TOE technique. At least 2 of the groups in each study must have been directly comparing a knotless repair with one in which knots were tied using the medial-row sutures. None of the studies included tied knots on the lateral row; however, this was not a specific exclusion criterion. Clinical studies, systematic reviews, and case reports were excluded. We did not exclude studies based on the model used or biomechanical properties tested. However, differences in these aspects were noted and are detailed in the "Results" section.

Study Selection

The initial search yielded 2,247 articles with the term "rotator cuff repair." Terms were applied regarding specific repair ("double row" OR "double-row fixation") and particular fixation ("medial knot") that narrowed the search to 331 studies. Two of the authors (N.A.M. and A.S.L.) evaluated citations and abstracts generated by the literature search and applied selection criteria with regard to inclusion. These 2 reviewers independently assessed each full report to determine relevance to review, quality of methodology, and extracted data. The final yield was 5 studies that met sufficient criteria and provided reliable quantitative data to formulate a strong comparison[8-12] (Fig 2).

Statistical Analysis

All of the biomechanical outcome parameters of interest were continuous variables; however, because of the heterogeneity of human and animal data, a standardized mean difference between the 2 groups of

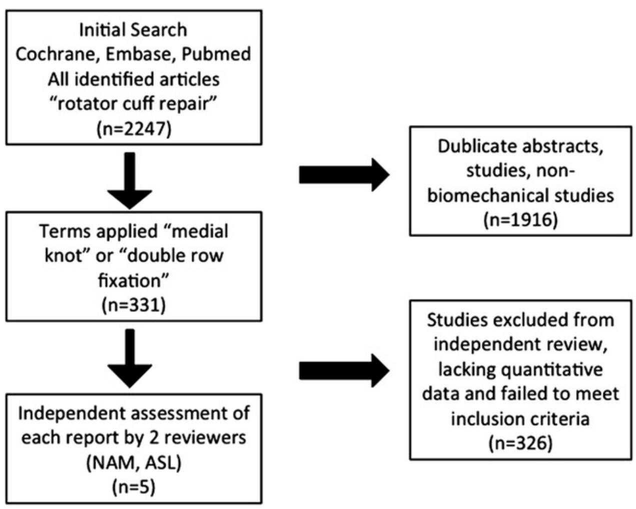


Fig 2. Search strategy for final yield of 5 studies. The right-pointing arrows indicate application of exclusion criteria. The search results were consistent during each search.

interest was calculated. Ninety-five percent confidence intervals (CIs) were calculated for all point estimates. The I^2 statistic was used to quantify heterogeneity, whereas the Cochran χ^2 test of homogeneity (i.e., Q test, $P < .10$) was used to test for heterogeneity.

Data from eligible studies were pooled by use of a random effects model (*v* fixed effects) because of the anticipated heterogeneity across repair techniques at different institutions, as well as types of sutures and anchors used, and because of expected differences in biomechanical models and testing conditions. Subgroup analyses that were planned a priori included analyzing gap formation, ultimate load to failure, and hysteresis based on the types of suture anchors used, as well as the type of suture (e.g., tape *v* suture).

Results

Model and Testing

Of the 5 studies, 3 used cadaveric specimens[8-10] whereas the other 2 used animal models to simulate the human supraspinatus.[11,12] Slightly different protocols were used in all of the studies. Busfield et al.[8] tested 6 matched pairs of cadaveric shoulders with a mean age of 60 years (range, 54 to 65 years). This group used an Instron machine (Canton, MA) with an abduction angle of 30° and a preload of 10 N. Cyclic stress testing was performed from 10 N to 180 N at 1 mm/s for 30 cycles. Tensile test to failure was performed again after a 10-N preload at 1 mm/s.

Kaplan et al.[10] used 8 cadaveric specimens with a mean age of 54 years (range, 33 to 68 years). Their customized MTS machine (MTS Systems, Eden Prairie, MN) allowed for up to 30° of external rotation. A 10-N preload over a 1-minute period was performed, and cyclic loading was performed from 10 N to 180 N at 5 mm/s for 30 cycles. Load to failure was performed after a 10-N preload, and then tension was applied at 1 mm/s to failure.

Chu et al.[9] used 14 pairs of cadaveric shoulders with a mean age of 71.2 ± 8.9 years; the study included bone mineral density testing. An MTS machine was used to load each specimen from 5 N to 180 N of tension at 0.25 Hz using force control for 200 cycles. Load to failure was performed at 1 mm/s.

Maguire et al.[12] tested 6 sheep infraspinatus tendons in each of 4 groups. Testing used an MTS machine (Eden Prairie, MN), with loading between 10 N and 100 N at 1 Hz for 500 cycles. Gapping was assessed with a digital caliper at the end of testing. Failure testing was performed with tensioning at 33 mm/s.

Leek et al.[11] used 14 bovine infraspinatus muscle-tendon units as a model for the human supraspinatus. Again, 10 N was used to pre-tension the constructs, and loading from 10 N to 90 N for 500 cycles at 0.5 Hz was performed. Before failure testing, a 10-N preload was used; then, failure load was applied at 0.5 mm/s (Table 1).

Repair Technique

Busfield et al.[8] used medial 6.5-mm metal Arthrex anchors (Arthrex, Naples, FL) loaded with No. 2 FiberWire (Arthrex). The sutures were passed in a horizontal-mattress fashion approximately 15 mm medial to the tendon edge. Two single-loaded anchors were used medially, and 2 anchors were used laterally. One suture from each medial anchor was brought laterally into two 4.5-mm PushLock anchors (Arthrex) at a position 1 cm lateral to the normal supraspinatus footprint. A manual tensiometer was used to ensure equal tension of 4 kg on the suture limbs before insertion of the lateral anchors.

Kaplan et al.[10] tested 2 constructs, 1 using 4.75-mm medial-row anchors loaded with wide-dimension suture (FiberTape; Arthrex) and then passed up through the tendon and over to a lateral anchor.

Chu et al.[9] examined 3 constructs: (1) a suture bridge construct using single-loaded 5.5-mm Bio-Corkscrew (Arthrex) medially and 4.5-mm PushLock anchors with sutures tied medially, (2) a similar construct using a 5-mm Spiralok medial anchor (DePuy Mitek, Raynham, MA) and 4.9-mm Versalok (DePuy Mitek), and (3) a knotless suture bridge construct using the SutureCross system (KFx Medical, Carlsbad, CA).

Maguire et al.[12] tested 4 groups, including the standard suture bridge construct using 2 medial 5.5-mm Bio-Corkscrew FT anchors (Arthrex) loaded with a single No. 2 FiberWire suture. Laterally, two 3.5-mm PushLock anchors were used. One group had the medial row tied, and in the other group, the same anchor configuration was used without tying of knots. This study also tested a double—suture bridge repair in which double-loaded anchors were used medially, producing 4 horizontal-mattress sutures along the medial row. A fourth construct consisted of two 3.5-mm PushLock anchors used medially and 2 laterally in a knotless repair. The suture was pulled laterally by hand without standardization of the tension.

Leek et al.[11] studied the SutureCross system in both repair constructs. The 3-mm medial nails were used as standard medial-row suture anchors in the knotted group but were driven through the tendon as recommended by the manufacturer in the knotless repair group. Lateral anchors were 5.5 mm in diameter in both groups (Table 1).

Stiffness

Three studies measured stiffness at the initial and final cycles of cyclic testing.[8,10,11] Kaplan et al.[10] and Leek et al.[11] both found significantly stiffer constructs with the presence of knots medially at these 2 time points. A quantitative synthesis of these studies showed significantly improved ($P = .04$) first-cycle stiffness but no significant difference ($P = .23$) in stiffness at the final

Table 1. General Characteristics of Selected Studies

Author	Journal (Year)	Cadaver Type and Specimen Quantity	Cycles	Load Used/Failure Load	Mode of Failure	Power Analysis
Busfield et al.[8]	*Am J Sports Med* (2008)	Human supraspinatus 6 male matched pairs (12)	30	10-N preload to 180 N at 1 mm/s Failure: 10-N preload loaded at 1 mm/s	Medial knots: Tendon-clamp interface (all) Completely knotless: Lateral row interface (4/6), tendon-clamp interface (2/6)	Yes
Leek et al.[11]	*Arthroscopy* (2010)	Bovine infraspinatus 14	500	10-N preload for 60 seconds 10 to 90 N at 0.5 Hz Failure: 10 N for 60 s at 0.5 mm/s until gross mechanical failure, failure of instrumentation, or 15-mm total displacement	All constructs failed by suture cutting through tendon or by suture slipping through caps of lateral screw anchors	Yes
Chu et al.[9]	*Arthroscopy* (2011)	Human supraspinatus 14 fresh-frozen matched pairs (28)	200	5 to 180 N at 0.25 Hz Load to failure (1 mm/s)	Completely knotless: 11/14 failed before completing cyclic loading, 5 suture tears through tendon with load to failure, 1 suture tear through tendon with fatigue loading, and 1 case of hardware pulling of bone Spiralok/Versalok: all specimens survived cyclic loading, 7 suture tears through tendon with load to failure Corkscrew/PushLock: 6/7 survived throughout cyclic loading SutureCross: 8/11 occurred during first loading cycle; 11 suture slips from lateral anchors, 3 suture tears through tendon with load to failure	No
Kaplan et al.[10]	*Arthroscopy* (2011)	Human supraspinatus 8 fresh-frozen matched pairs (16)	30	10 to 180 N at 5 mm/s Failure: 10 N applied and loaded to failure at rate of 1 mm/s	Majority of knotless constructs failed at anteromedial anchor; majority of modified repair constructs failed intramuscularly	Yes
Maguire et al.[12]	*Knee Surg Sports Traumatol Arthrosc* (2011)	Ovine infraspinatus 24	500	10 to 100 N at 1 Hz Failure: after cycle loading, 33 mm/s after cyclical testing, defined as decreasing load with increasing displacement	Predominant failure mode was tendon tearing through suture material; in 1 double Sb repair, suture pulled free of 1 PushLock anchor and tore through tendon on other side	Yes

Sb, suture bridge.

cycle of cyclic testing with constructs using medial knots. Four studies evaluated ultimate stiffness at failure,[8-10,12] with 2 of the 4 showing significant differences between groups.[9,10] A pooled analysis of ultimate stiffness showed a nonsignificant increase in stiffness at failure in the TOE group with medial knots (standardized mean difference, 0.52; 95% CI, −0.20 to 1.25; $P = .16$; $I^2 = 62\%$) (Fig 3A).

Hysteresis

Two studies performed hysteresis testing.[8,10] Both studies evaluated hysteresis during the first cycle and with testing to failure. Both studies found significantly more energy absorbed during load-to-failure testing in groups with medial knots. These studies were combined with no statistical heterogeneity, and the pooled analysis showed significantly more energy capable of being absorbed in the constructs with medial knots (standardized mean difference, 1.39; 95% CI, 0.54 to 2.25; $P = .001$; $I^2 = 0\%$) (Fig 3B). Kaplan et al.[10] reported that significantly more energy was dissipated laterally with hysteresis testing at the first and 30th cycles as well, whereas Busfield et al.[8] found no difference between groups with first-cycle testing.

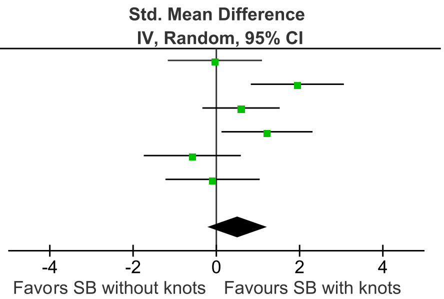
Gap Formation

In the study by Leek et al.,[11] medially knotted tendons took a mean of 200 cycles (± 227) to reach 3-mm stretch compared with only 25 cycles (± 52) in the knotless repair group; however, this was not significant with the numbers they had ($P = .07$). Heterogeneity in defining gap formation, measuring techniques, and specifying

A

Study or Subgroup	SB with knots Mean	SD	Total	SB without knots Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Busfield	42.38	2.23	6	42.7	11.88	6	16.2%	-0.03 [-1.17, 1.10]
Chu Pushlok	230	82	7	112	43	14	16.4%	1.95 [0.83, 3.06]
Chu Versalok	138	40	7	112	43	14	18.6%	0.59 [-0.34, 1.52]
Kaplan	241.78	54.62	8	182.53	35.38	8	16.7%	1.22 [0.12, 2.31]
Maguire FT	99.06	16.83	6	108.39	12.71	6	15.8%	-0.58 [-1.74, 0.59]
Maguire PL	116.09	15.28	6	117.71	17.8	6	16.2%	-0.09 [-1.22, 1.04]
Total (95% CI)			**40**			**54**	**100.0%**	**0.52 [-0.20, 1.25]**

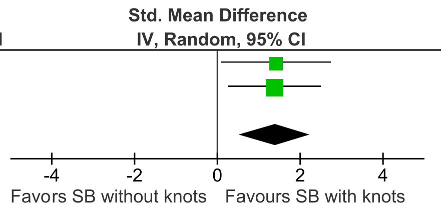
Heterogeneity: Tau² = 0.51; Chi² = 13.27, df = 5 (P = 0.02); I² = 62%
Test for overall effect: Z = 1.41 (P = 0.16)



B

Study or Subgroup	SB with Knots Mean	SD	Total	SB without Knots Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Busfield	2,805	796	6	1,648	711	6	41.8%	1.42 [0.09, 2.74]
Kaplan	3,056	1,512	8	1,157	1,059	8	58.2%	1.38 [0.25, 2.50]
Total (95% CI)			**14**			**14**	**100.0%**	**1.39 [0.54, 2.25]**

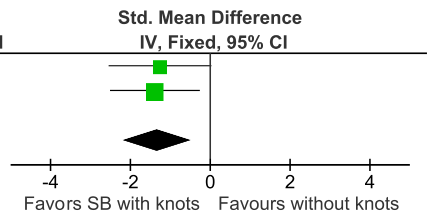
Heterogeneity: Tau² = 0.00; Chi² = 0.00, df = 1 (P = 0.96); I² = 0%
Test for overall effect: Z = 3.18 (P = 0.001)



C

Study or Subgroup	SB with knots Mean	SD	Total	SB without knots Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Busfield	4.22	1.44	6	8.1	3.76	6	43.3%	-1.26 [-2.55, 0.03]
Kaplan	1.77	2.45	8	7.67	5.14	8	56.7%	-1.39 [-2.51, -0.26]
Total (95% CI)			**14**			**14**	**100.0%**	**-1.33 [-2.18, -0.48]**

Heterogeneity: Chi² = 0.02, df = 1 (P = 0.88); I² = 0%
Test for overall effect: Z = 3.08 (P = 0.002)



D

Study or Subgroup	SB with knots Mean	SD	Total	SB without knots Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Busfield	353	73	6	254	61	6	14.4%	1.36 [0.05, 2.67]
Chu Pushlok	310	82	7	166	87	14	19.0%	1.62 [0.56, 2.68]
Chu Versalok	337	44	7	166	87	14	17.0%	2.16 [1.00, 3.32]
Kaplan	549	163	8	311	107	8	16.7%	1.63 [0.46, 2.81]
Maguire FT	283.76	118.77	6	281.34	94.79	6	17.5%	0.02 [-1.11, 1.15]
Maguire PL	394.9	70.71	6	328.65	37.72	6	15.4%	1.08 [-0.17, 2.33]
Total (95% CI)			**40**			**54**	**100.0%**	**1.31 [0.71, 1.91]**

Heterogeneity: Tau² = 0.20; Chi² = 7.78, df = 5 (P = 0.17); I² = 36%
Test for overall effect: Z = 4.29 (P < 0.0001)

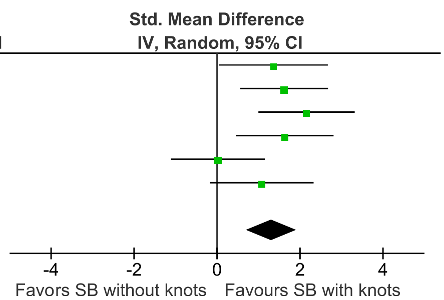


Fig 3. Forest plots created for various biomechanical properties of the 5 studies. The study by Leek et al.[11] did not include data for stiffness at failure or ultimate load to failure and thus could not be added to the analysis. However, the data from this study were evaluated with the systematic review component of this study. (A) Stiffness at failure comparisons. (B) Hysteresis comparisons. (C) Gap formation comparisons. (D) Ultimate load to failure.

the time at which gap was measured resulted in a variance in interpretation, which made it difficult to combine the data. First-cycle gapping and final-cycle gapping were measured in 2 studies.[8,10] A quantitative synthesis of these 2 studies showed that the final-cycle gapping was significantly less in the groups with medially tied knots (standardized mean difference, −1.33; 95% CI, −2.18 to −0.48; $P = .002$; $I^2 = 0\%$) (Fig 3C). Maguire et al.[12] measured gap formation but failed to define the cycle at which this was measured. Consequently, they found no difference among the 4 groups. Leek et al.[11] found no difference in gapping across the repair site (gauge displacement) but did note a significant difference in total gap formation. This group also studied the number of cycles before 3 mm of gap was seen. Thus gap was noted after 25 cycles (± 52) in the knotless repair group and after 200 cycles (± 227) in the medially knotted group; however, this was not found to be statistically significant, likely because of the wide variability in the data. Chu et al.[9] defined conditioning elongation as the displacement of the repair site from cycles 1 to 50 and peak-to-peak elongation as the mean peak-to-peak amplitude for cycles 48 to 50. This study found no difference in gap formation with conditioning, but the authors did note that a significant difference was seen with peak-to-peak testing. Busfield et al.[8] reported a difference in gap at yield load, but the difference at ultimate load did not reach statistical significance ($P = .053$) (Table 2).

Yield Strength and Ultimate Load

Ultimate load was measured in 4 of the 5 studies, with 3 of these 4 showing that a knotted medial row had significantly higher ultimate load[8-10] and 1 showing that a double-knotted medial row had significantly improved load to failure[12] (Table 2). A pooled analysis showed that the ultimate load to failure was significantly higher in constructs in which medial knots were tied (standardized mean difference, 1.31; 95% CI, 0.71 to 1.91; $P <$ .0001; $I^2 = 36\%$) (Fig 3D). Leek et al.[11] measured yield strength of their construct at 650 N (± 530 N) in the medially knotted group compared with 350 N (± 270 N) in the knotless repairs; however, this was not significantly different with the numbers available in the study and the large variability in results. Busfield et al.[8] also studied yield load, showing a significant difference between the medial knotted group (233 ± 27 N) and the knotless construct (182 ± 41 N) ($P = .02$).

One study measured contact area using pressure sensors between the rotator cuff and the greater tuberosity.[12] The authors found that the suture bridge constructs in which the medial row was tied had greater contact area; however, only the double−suture bridge construct with 4 knots tied medially was statistically greater than the knotless repairs.

Failure Mechanism

Busfield et al.[8] observed that all repairs in which the medial-row suture was tied failed at the clamp-tendon interface, whereas 4 of 6 shoulders undergoing knotless repair failed at the lateral anchors. Leek et al.[11] found that constructs failed either by the suture cutting through the tissue or loosening from the lateral anchors, but no trends in mode of failure between the groups were detected. Maguire et al.[12] also reported no difference in failure mechanisms among their 4 groups, with the majority of specimens failing by the sutures cutting through the tendon. In the study by Kaplan et al.,[10] the majority of knotless repairs failed at the anteromedial anchor whereas the knotted constructs failed intramuscularly (Table 1).

Bias

Inherent bias existed through each report because studies were formulated with different aims and configurations. Busfield et al.[8] used millimeters of gap to determine the number of specimens, determining that 6 specimens in each group would be needed to detect a 4-mm difference. Maguire et al.[12] did not mention an a priori power analysis and briefly discuss a post hoc power analysis that was not used in the study. The remaining studies also did not perform power analyses.[9-11] Sheep[12] and bovine[11] infraspinatus tendons were used as a model for the human supraspinatus; however, both of these models have been shown to be good substitutes for human rotator cuff tendons.[13-20] Although these models have similar tendon properties, the absolute values of loads and gaps may vary because of their species-specific size difference. The double−suture bridge technique used in the study by Maguire et al.[12] was slightly different from other studies that used single-loaded anchors medially, and thus several variables were being tested in this group—the medial knots and the addition of an extra knot, as well as an extra 2 sutures from each anchor. However, this study also had a group with a standard single-loaded medial-anchor knotted suture bridge repair construct. The numbers available for the different types of sutures and anchors precluded the planned subgroup analyses.

Discussion

The strength of rotator cuff repairs was improved biomechanically with the transition from single-row to double-row techniques.[1] Contact area and pressure increased with TOE repairs,[21,22] and surgical times were reduced with the addition of knotless repair techniques.[23,24] However, there is concern that the benefit of additional strength observed with double-row and TOE techniques may be lost without tying of medial knots. The goal of this systematic review of the literature was to evaluate the biomechanical properties of tying medial knots during TOE rotator cuff repairs by comparing yield load, load to failure, failure mechanism, and displacement after knotless and knotted TOE rotator cuff repairs.

Rotator cuff repairs are performed to reduce pain and restore function. Although pain may improve despite lack of healing, functional improvement has been related to the rotator cuff tendon(s) healing back down to bone.[5,25,26] Healing is complex and has been shown to be affected by tissue quality, age, smoking status, retraction, tear size, chronicity, tension of repair, contact area, and strength of repair. Many of these factors cannot be controlled by the surgeon; however, repair technique and repair strength are potential ways to directly affect patient outcomes. Charousset et al.[27] found significantly better healing in their double-row repair group compared with single-row repairs. Several other studies reported improved healing with double-row[25] and TOE/suture bridge[28] repairs compared with prior reports of single-row repairs. A systematic review also found significantly fewer retears when double-row techniques were used.[29] The goal of any repair technique is to achieve enough

Table 2. Biomechanical Characteristics of Studies

Author	Stiffness (N/mm)	Hysteresis (N • mm) (First Cycle/Failure)	Creep (mm)	Gap Formation (mm) (First Cycle/Last Cycle)	Load to Failure
Busfield et al.[8]	First cycle ($P = .07$) Medial knots: 24.72 ± 4.92 Completely knotless: 21.35 ± 5.74 Failure ($P = .97$) Medial knots: 42.38 ± 2.23 Completely knotless: 42.7 ± 11.88	Medial knots: 562 ± 145 Completely knotless: 705 ± 217		First cycle ($P = .048$)* Medial knots: 3.47 ± 1.48 Completely knotless: 5.05 ± 1.93 Failure ($P = .053$)* Medial knots: 7.58 ± 2.6 Completely knotless: 13.94 ± 6.89	Energy absorbed (N • mm) ($P = .047$)* Medial knots: 2,805 ± 796 Completely knotless: 1,648 ± 711 Yield load ($P = .022$) (N)* Medial knots: 233 ± 27 Completely knotless: 183 ± 41 Ultimate load ($P = .048$) (N)* Medial knots: 353 ± 73 Completely knotless: 254 ± 61
Leek et al.[11]	First cycle ($P < .001$)* Medial knots: 55 ± 9 Transtendon construct: 45 ± 5 Final cycle ($P < .001$)* Medial knots: 79 ± 8 Transtendon construct: 66 ± 7	NA		No. of cycles to 3 mm stretch ($P = .07$) Medial knots: 200 ± 227 Transtendon construct: 25 ± 52 Gauge displacement ($P = .12$) Medial knots: 0.52 ± 0.8 Transtendon construct: 0.77 ± 0.06 Total displacement ($P = .02$)* Medial knots: 650 ± 530 Transtendon construct: 350 ± 270	Yield load ($P = .50$) (N) Medial knots: 650 ± 530 Transtendon construct: 350 ± 270
Chu et al.[9]	PushLock: 230 ± 82 Versalok: 138 ± 40 Refrigerated SutureCross: 112 ± 43	NA		Peak-to-peak elongation PushLock: 0.8 ± 0.3* Versalok: 1.3 ± 0.3 Refrigerated SutureCross: 1.5 ± 0.45* Conditioning elongation PushLock: 2.4 ± 1.3 Versalok: 1.7 ± 1.1 Refrigerated SutureCross: 4.6 ± 1.8	Ultimate load (N) PushLock: 310 ± 82 Versalok: 337 ± 44* Refrigerated SutureCross: 166 ± 87
Kaplan et al.[10]	First cycle ($P = .02$)* Modified repair: 75 ± 27.35 Knotless repair: 38 ± 18.95 30th cycle ($P = .02$)* Modified repair: 226 ± 58.13 Knotless repair: 143 ± 33.45 Linear stiffness ($P = .04$)* Modified repair: 241.78 ± 54.62 Knotless repair: 182.53 ± 35.38	First cycle ($P = .03$)* Modified repair: 189.81 ± 78.59 Knotless repair: 521 ± 297.01 30th cycle ($P = .02$)* Modified repair: 10.78 ± 8.09 Knotless repair: 24 ± 10.49 Ultimate hysteresis ($P = .04$*) Modified repair: 3,056.69 ± 1,511.76 Knotless repair: 1,147.01 ± 1,058.99		First cycle ($P = .02$)* Modified repair: 1.35 ± 1.82 Knotless repair: 4.55 ± 2.25 30th cycle ($P = .02$)* Modified repair: 1.77 ± 2.45 Knotless repair: 7.67 ± 5.14	Ultimate load ($P = .01$) (N)* Modified repair: 549.49 ± 163.23 Knotless repair: 311.30 ± 107.26
Maguire et al.[12] (approximate values)	Stiffness Untied SBwFT: 110 ± 10 Untied SBwPL: 120 ± 15 Standard SB: 90 ± 15 Double SB: 120 ± 15		Untied SBwFT: 8 ± 3 Untied SBwPL: 8 ± 3 Standard SB: 10 ± 6 Double SB: 6 ± 2	NA	Tensile failure load (N) Untied SBwFT: 281 ± 95 Untied SBwPL: 329 ± 38 Standard SB: 284 ± 119 Double SB: 398 ± 71

NA, not applicable; SBwFT, suture bridge with Bio-Corkscrew FT Anchors; SBwPL, suture bridge with PushLock.
*Denotes statistical significance ($P < .05$).

strength to allow some early motion while protecting the repair site against the pull of the rotator cuff muscles. Several studies have evaluated the force of the intact rotator cuff. Burkhart[30] calculated a force of 302 N for the rotator crescent based on the area of contracting muscle. Itoi et al.[31] divided the supraspinatus into its anterior, middle, and posterior components and found that forces of 411 N, 152.6 N, and 88.1 N, respectively, were needed to cause a tear in the rotator cuff tendons. Two other studies found forces ranging from 190 N[32] to 353 N.[33] A tendon repair that can resist 300 to 350 N ought to be able to allow some early motion to help prevent stiffness and maximize healing potential. In this systematic review, all knotted repair techniques other than the standard suture bridge in the study by Maguire et al.[12] achieved ultimate loads or yield loads over 300 N. Only 3 of the 7 comparisons showed ultimate or yield loads greater than 300 N for knotless repairs.[10-12] The meta-analysis found a significant improvement in hysteresis, gap formation, and ultimate load to failure when knots were tied down to the medial-row anchors.

Tendon-to-bone healing requires contact between the 2 structures, and the greater surface area of this contact, the better chance of healing.[34-36] Thus gap formation would inhibit rotator cuff healing, and improved contact area should improve the likelihood of healing. Ahmad et al.[37] noted significantly more fluid in the healing zone when using a single-row repair compared with a TOE repair, which could prevent healing. Combining the 2 studies that evaluated initial-cycle and final-cycle gapping showed a significant reduction in gap formation with tying the medial-row sutures before crossing the sutures to the lateral anchors.[8,10] Several other studies looked at total gap formation or gap formation with load to failure, with mean gaps ranging from 1.7 to 13.9 mm. Gap formation was significantly greater with knotless repair in 1 study[11] and a strong trend ($P = .053$) toward greater gapping with knotless repair in another study.[8] Chu et al.[9] also found gapping to be greater during peak-to-peak testing of the knotless repair. Several other studies were not powered accurately to assess for significance in gap formation. Only the study by Maguire et al.[12] evaluated contact, noting significantly greater contact area in their double-knotted repair construct compared with knotless repair techniques. Park et al.[22] found improved contact area and pressure using a medial knotted TOE suture bridge compared with standard double-row techniques. Mazzocca et al.[21] found that all constructs had decreased pressure and contact after 160 minutes; however, a TOE construct with medial knots had greater pressure and contact area initially and persisted better over time. The knotless repair construct tested in this study performed similarly to a standard double-row repair. Therefore, gap formation and contact area also seem to favor tying the medial-row knots of a TOE rotator cuff repair, although further comparison of these parameters is warranted.

Limitations

There are several limitations to this study, many of which are noted in the section on bias in the "Results" section. Only 1 study performed an a priori power analysis; however, this study only used gap formation to determine group size, despite having evaluations of stiffness and ultimate load as other major goals. Next, there was significant statistical heterogeneity in the pooled analysis for stiffness at failure, as indicated by I^2 values greater than 50%. To account for this anticipated heterogeneity, we used a random effects model for our pooled analyses. The magnitude of biomechanical data could differ based on the model (animal and human), and thus we calculated a standardized mean difference. In some cases the systematic differences in testing conditions and measurement parameters precluded a pooled analysis, and in these cases only a systematic review of the data could be performed. Only 1 study evaluated bone mineral density, and it only reported that this was not different between groups. In addition, reporting of whether matched-pair cadavers were used in all studies. Each of these factors could influence the results of this analysis and are limitations because of the quality and information provided by the original studies.

Biomechanical studies are limited in that these are only time zero characteristics, and healing and other environmental factors cannot be factored into the outcome. In addition, with rotator cuff repairs, the ultimate goal is healing, and although biomechanical studies can test factors that may improve the likelihood of tendon-to-bone healing, there are many other factors that cannot be tested. Specifically, we have not answered the question "How strong is strong enough?" to determine the clinical significance of our biomechanical data. We must assume that greater strength, stiffness, and contact area, as well as less gap formation, ultimately improve the ability of the rotator cuff to heal.

Conclusions

The results of this systematic review and quantitative synthesis indicate that the biomechanical factors ultimate load, stiffness, gap formation, and contact area are significantly improved when medial knots are tied as part of a TOE suture bridge construct compared with knotless constructs. Further studies comparing the clinical healing rates and functional outcomes between medial knotted and knotless repair techniques are needed.

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