

Biomechanical Analysis of Two Tendon Posterosuperior Rotator Cuff Tear Repairs: Extended Linked Repairs and Augmented Repairs

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Purpose: The purpose of this study was to compare single-row (SR), extended double-row (DR), and augmented, extended double-row (aDR) rotator cuff repairs in a two-tendon, posterosuperior rotator cuff tear (RCT) model with intact rotator cuff tendons. **Methods:** RCTs were created and randomly assigned to SR, DR, or aDR repair (5 each) in 20 cadaveric shoulder specimens. A collagen scaffold was used for augmentation. In the remaining 5 specimens, the rotator cuffs were left intact. All specimens were cyclically loaded from 25 to 75 N for 50 cycles. Every 50 cycles, peak load was increased by 25 N until failure occurred. Cyclic stiffness and number of cycles were analyzed. **Results:** The SR (72.9 ± 4.64 N/mm)- and aDR (72.6 ± 11.8 N/mm)-repaired specimens differed significantly in stiffness from the intact specimens (93.1 ± 14.8 N/mm) at ≥ 100 N ($P < .05$). The intact specimens and DR- and aDR-repaired specimens endured more cycles to failure ($1,556 \pm 677$, $1,302 \pm 248$, and $1,211 \pm 95$, respectively) than the SR-repair specimens (388 ± 72 cycles, 260 ± 4 N) ($P < .05$ for all groups). **Conclusions:** Linked DR constructs were significantly stronger than SR repairs in this two-tendon RCT model and approached the strength of the intact rotator cuff. Augmentation with a collagen patch (aDR) did not influence biomechanical repair qualities in this model, but did result in less variability in failure load and more consistency in the mode of failure. **Clinical Relevance:** The biomechanical properties of extended linked DR constructs are superior to those of SR constructs for repair of two-tendon RCTs, and are not compromised by graft augmentation.

Shoulder pain resulting from injury to the rotator cuff is commonly encountered in both primary care and shoulder clinics.¹ The treatment of both partial-thickness and full-thickness rotator cuff tears is generally successful in reducing symptoms and functional

deficits in afflicted patients.²⁻⁵ The success of surgical rotator cuff tendon repair, however, has been correlated to a number of factors, including size of the rotator cuff tear, tendon quality, magnitude of retraction, and fatty infiltration.⁶

Massive rotator cuff tear (RCT) has been previously defined as a tear greater than 5 cm in length or a tear that involves 2 or more rotator cuff tendons.^{7,8} Recent literature would suggest that these tears are relatively common, with a reported prevalence rate between 9% and 25% of arthroscopically treated RCT.^{4,5,9} Although the evolution of double-row repair techniques appears to have enhanced the biomechanical properties of rotator cuff repairs,^{5,10} it has also been established that surgical repair of massive RCT, at a minimum of 1 year after surgery, results in a significant re-tear risk that may be as high as 94%.^{4,11,12} Therefore, it is apparent that satisfactory outcomes after operative management of massive RCT is not uniform, and consequently, new strategies are needed to improve patient outcomes after these injuries.

Ideally, the normal rotator cuff anatomy should be restored during repair. This can, however, be difficult in

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large tears because tendon retraction and muscle atrophy are often present. Though long a topic of debate, recent data finally showed both decreased re-tear rates and improved functional outcome when massive RCT undergoes double-row (DR) rather than single-row (SR) repair.¹³⁻¹⁵ However, both re-tear risk and functional outcome significantly depend on tendon mobilization during the repair.¹³

To this end, repair augmentation with collagen scaffolds has recently been proposed to enhance the quality of repair when tendon quality and mobilization are not optimal. Repair augmentation as such has shown promising histologic and short-term clinical results when applying the scaffold as an "onlay" augmentation technique.¹⁶⁻¹⁹ Questions have been raised, however, as to whether (1) additional suture anchors or (2) a collagen scaffold, as may be required in the repair of massive RCT, would immediately have positive biomechanical effects on repair strength. "Additional suture anchors" refers to the use of 6 rather than 4 anchors in the repair.²⁰

The objectives of this study were to compare, in a massive RCT model, the biomechanical properties of SR repair; extended, linked DR repair; and extended DR rotator cuff repair augmented with a collagen scaffold. In addition, biomechanical properties of intact rotator cuff tendons were analyzed for comparison. The hypothesis was that the biomechanical properties of augmented repairs of massive RCT using a collagen scaffold would be superior to those of traditional SR repairs and equivalent to those of DR reconstructions without augmentation. In addition, the biomechanical properties of intact rotator cuff tendons were expected to be superior to those of any of the repair techniques.

Methods

Specimen Preparation

Twenty fresh-frozen shoulder specimens from cadavers, mean age 50 years (range, 21 to 59), were randomly divided into 4 groups after matching for bone mineral density (BMD). There was no significant difference in BMD among the 4 specimen groups. Sample size was based on previous studies in which similar biomechanical cadaveric testing was performed and a pre hoc sample size calculation was performed.¹⁰ After being thawed for 24 hours, shoulder specimens were placed upright, simulating the beach chair position.²¹ The skin and deltoid muscle of each specimen were then completely removed, exposing the rotator cuff muscles and their insertions to the proximal humerus.

Intact Specimens

Five specimens were prepared for testing of the intact rotator cuff tendons (Fig 1). The bicipital groove of each specimen was identified, and the rotator interval was opened along the anterior border of the supraspinatus

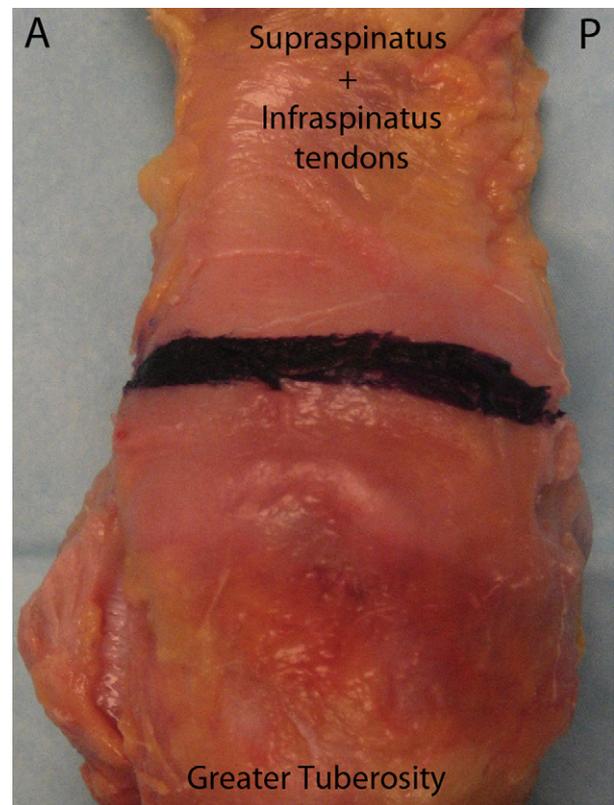


Fig 1. Left-sided specimen with intact supraspinatus and infraspinatus tendon with a tendon width of 35 mm from anterior to posterior. (A, anterior; P, posterior.)

tendon. A digital caliper (Swiss Precision Instrument, Garden Grove, CA) was used to mark a 3.5-cm line along the lateral supraspinatus and infraspinatus muscle insertions, beginning at the anterior border of the supraspinatus.

Simulation of Massive Rotator Cuff Defect

In the remaining specimens, a massive posterosuperior rotator cuff defect was created involving 2 rotator cuff tendons (supraspinatus and infraspinatus). As the size of rotator cuff insertion varies with body size, the decision was made to define a massive RCT for standardization purposes as a two-tendon tear. The bicipital groove was identified, and the rotator interval was opened along the anterior border of the supraspinatus tendon. The same digital caliper was used to mark a 3.5-cm line along the lateral supraspinatus and infraspinatus muscle insertions, beginning at the anterior border of the supraspinatus. The posterior rotator cuff was then divided at this point in line with muscle–tendon fibers. In these specimens the supraspinatus and infraspinatus tendons were incised from anterior to posterior, sharply releasing the supraspinatus and infraspinatus tendons laterally from their insertion sites. The 3 groups of specimens were then randomly assigned to undergo 1 of 3 different massive RCT repair techniques.

Implants

To improve the reproducibility of tear simulation and repair and optimize consistency, we opted for open but arthroscopically reproducible repair techniques. The repairs were performed using standard arthroscopic equipment, including suture anchors and shuttling devices. The suture anchors used for all repair constructs were 4.75-mm biocomposite suture anchors (Arthrex, Naples, FL). Suture anchors used in double-row repairs were loaded with one strand of No. 2 continuous braided polyethylene/polyester multifilament suture (FiberWire, Arthrex) and 1 strand of No. 2 continuous braided polyethylene/polyester multifilament 2-mm-wide tape (Fibertape, Arthrex). Anchors for single-row repairs were loaded with only No. 2 continuous braided polyethylene/polyester multifilament suture. An arthroscopic shuttling device was used to pass the nonabsorbable sutures through the tendons. All surgical repairs were performed by an orthopaedic sports medicine fellow (T.R.G.) with the assistance of an orthopaedic resident (O.A.v.d.M) after standardizing tear simulation and repair methodology with a board-certified orthopaedic surgeon (P.J.M.). For repair augmentation in the augmented double-row (aDR) group, an acellular dermal collagen scaffold of human origin was used (Arthrex and Lifenet Health, Virginia Beach, VA). The 3 different two-tendon RCT repairs are illustrated in Fig 2.

Surgical Repairs

Single-Row Repair Technique. With a waterproof marker, the positions of 3 suture anchors were marked 0.75 cm lateral from the articular margin. The anchors were spaced evenly along the footprint approximately 1.5 cm apart, thereby ensuring that a bone bridge of 1 cm was

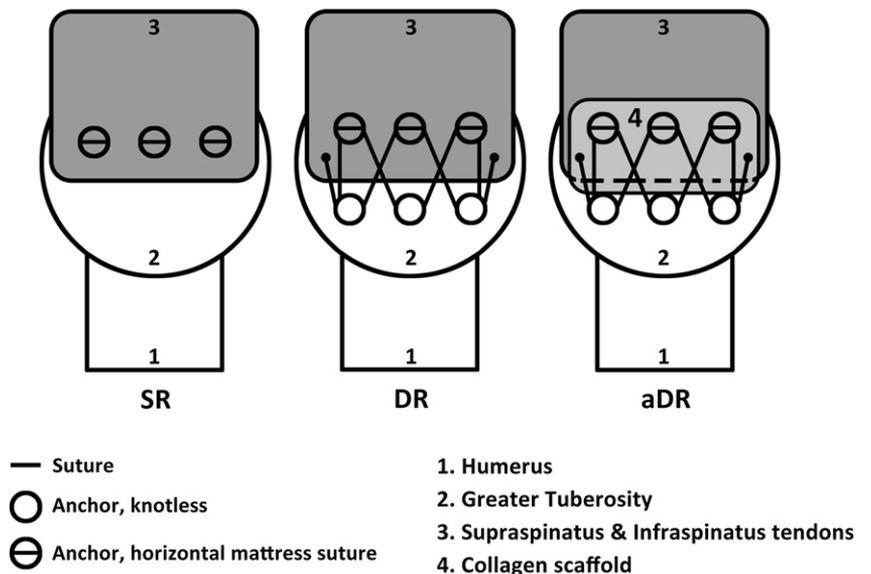
maintained between the suture anchors. Measurements were performed using the previously described digital caliper. After preparation of the anchor sites with a punch, the suture anchors were screwed into place, loaded with a single suture. Subsequently, each suture was individually passed through the rotator cuff tissue, 0.5 cm from the edge of the tendon, using a standard shuttling device in a mattress fashion. Suture limbs were then tied using 5 throws of a standard surgeon’s square knot, resulting in 3 horizontal mattress stitches (Fig 3A).

Double-Row Repair Technique. Extended, linked double-row rotator cuff repair was achieved using an extended speed-bridge repair technique.²⁰ With a waterproof marker, the positions of 3 medial row suture anchors along the articular cartilage junction were marked. Again, these anchors were centered 1.5 cm apart to ensure that a bone bridge of approximately 1 cm was maintained. Three lateral row suture anchors were similarly marked 1.5 cm lateral to the medial row anchors. The digital caliper was used to confirm that the spacing between medial and lateral anchors was 1.5 cm, and the separation between anchors of the medial and lateral rows was 1.75 cm.

The anchor sites were prepared with a punch, and the medial row of suture anchors loaded with No. 2 suture and 2-mm suture tape was placed. One strand of the suture and one strand of the tape were passed through the rotator cuff along the medial portion of the anatomic footprint of the rotator cuff, in single fashion, 2 cm from the lateral edge of the tendon, using a standard shuttling device. This resulted in 6 tendon perforation sites, each containing a strand of suture and a strand of tape.

Similarly to the single-row technique previously described, the sutures were tied creating a horizontal

Fig 2. Three different types of massive rotator cuff tear repair.



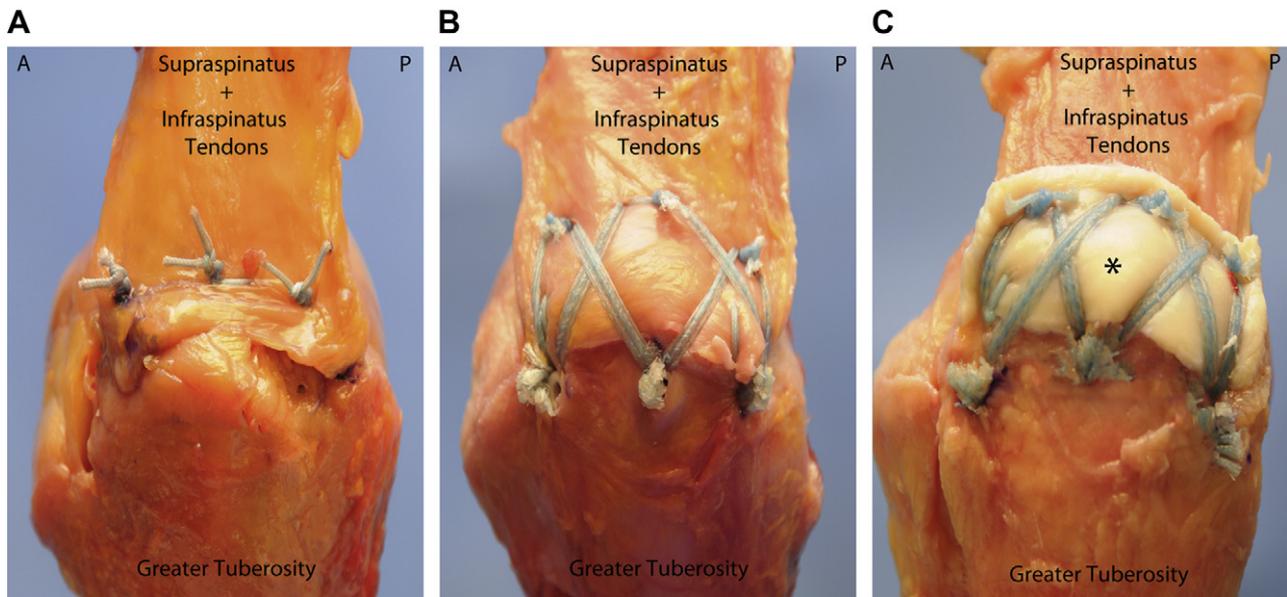


Fig 3. All left-sided specimens: (A) single-row repair; (B) extended, linked double-row repair; and (C) extended, linked double-row repair augmented with a collagen scaffold (*). (A, anterior; P, posterior.)

mattress stitch anchoring the medial cuff row. To minimize the formation of “dog-ears” or bulging of the lateral tension aspect, 2 additional No. 2 continuous braided polyester/polyethylene suture loops (Fiberlink, Arthrex) were passed through the anterolateral and posterolateral tendon, one at each corner, 0.5 cm from the edge of the tendon. The tapes and suture loops were then tensioned and secured within the lateral row of anchors in a standard extended bridging fashion (Fig 3B).

Double-Row Repair Technique Augmented With Collagen Scaffold. The same extended, linked double-row rotator cuff repair previously described was also used for the augmented repair. The original scaffold measured 40 × 70 mm and was 1.25 to 1.75 mm thick. However, a scaffold measuring 20 × 35 mm covered the repair site sufficiently; therefore, each implant was sized accordingly before incorporation into the repair. Incorporation was accomplished by passing the sutures and tapes from each medial anchor through both the rotator cuff tissue and the medial side of the graft in the same single fashion as in the described double-row technique using the shuttling device, again resulting in 6 tendon perforation sites. The sutures were tied on top of the scaffold, creating 3 horizontal mattress stitches medially. Tapes and suture loops were secured laterally using the same bridging fashion as in the nonaugmented double-row technique (Fig 3C).

Specimen Preparation and Potting

After surgical repairs, the proximal scapular insertions of the supraspinatus and infraspinatus muscles were sharply released, and remaining musculature was

removed from the humerus. The repair site and attached tendons and muscles were wrapped in water-soaked gauze to keep the repairs moist. Final specimen preparation of the intact specimens was similar.

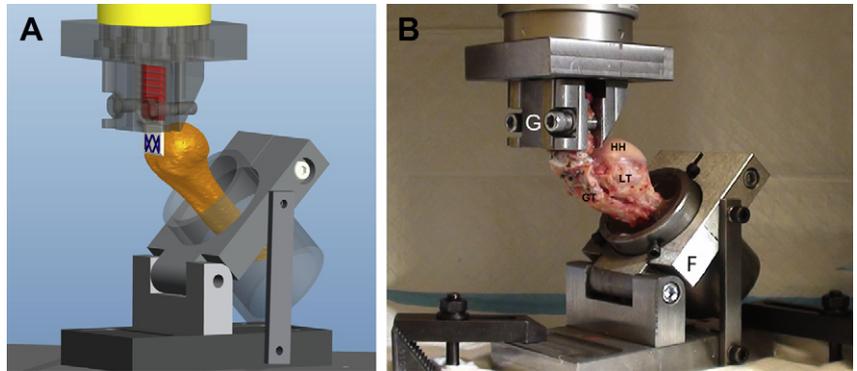
All humerus specimens were then placed in a specially designed metal potting cylinder and potted in polymethyl methacrylate (PMMA) (Dentsply, York, PA), with the humerus axis aligned with the potting cylinder axis. The proximal end of muscle–tendon interface was prepared for clamp fixation using No. 3 braided polyester sutures (Ethibond, Johnson & Johnson, New Brunswick, NJ), metal wire, and super glue. This created a secure construct for a rigid clamp interface with the mechanical clamps and ensured consistent tendon incorporation into the clamps, preventing tendon slippage.

The prepped specimen was then locked into a rigid fixture to ensure the tendon would be pulled in-line with the load actuator and into a dynamic tensile testing machine (Instron E10000 ElectroPuls Dynamic Testing System, Instron Systems, Norwood, MA) (Fig 4A and B). The digital caliper was used to ensure that the surgical repair was parallel to the load actuator face so that loading was even throughout the tendon. The tendon was clamped into a custom-made mechanical grip connected to the machine’s load actuator so as to tension the repair construct at a 135° angle in relation to the humerus (Fig 4A and B).^{10,22}

Biomechanical Testing

After tuning the tensile testing machine for tendon stiffness (N/mm), a tensile load gradually applied a preload of 25 N for 10 seconds to remove possible creep; sinusoidal cyclic loading was then applied to the

Fig 4. (A) Humerus potted in-line with the cylinder and placed in the designed fixture. The humerus is aligned at a 135° angle with the load actuator. The potted specimen and fixture are then rigidly clamped in the Instron E10000 testing machine, and the rotator cuff tendons are clamped in the mechanical grips. (B) Potted specimen and fixture clamped down into the Instron E10000 testing machine. (HH, humeral head; GT, greater tuberosity; F, fixture; LT, lesser tuberosity; G, grips.)



tendon. The first 50 cycles were applied in the force range 25 to 75 N. After 50 cycles, the applied peak load increased to 100 N for another 50 cycles; the load range in this second step was therefore 25 to 100 N. Subsequently, peak load was increased by 25 N after completion of each 50-cycle segment until failure occurred. This method has been described by Schneeberger et al.²² and is clinically relevant in simulating the strength of rotator cuff repairs at time-zero during increasing exercise efforts.

The tendon and repair sites were moistened during the test because studies have shown that tissue desiccation may influence biomechanical properties.²³ Data were recorded by Instron WaveMatrix software (Instron Systems, Norwood, MA). Cyclic displacement (mm) and cyclic stiffness (N/mm) were determined after 10, 60, 110, 160, 210, and 260 cycles. These points were chosen to allow the repair to settle into a steady state after increasing the maximum load range after every 50 cycles. In addition, number of cycles to failure, maximum load range at failure (N), and mode of failure were recorded. These measurements were analyzed and plotted with Microsoft Excel Software (Microsoft, Seattle, WA).

Statistical Analysis

Statistical analysis was performed with Predictive Analytics Software (PASW) Statistics Version 18 (IBM Corp, Armonk, NY). The study compared data for each

group using a one-way analysis of variance (ANOVA). For ANOVAs that showed a statistically significant difference, a post hoc Tukey honestly significant difference (HSD) test was conducted to assess the location of the means that differed statistically significantly between the groups. Significance was established at $P \leq .05$.

Results

Cyclic Testing

There was a significant difference in stiffness between intact and aDR-repaired specimens for all maximum load ranges examined and between intact and SR-repaired specimens at maximum load ranges of ≥ 100 N ($P < .05$) (Table 1, Fig 5). There were no differences between the repair groups in stiffness at the maximum load ranges analyzed.

Intact and DR- and aDR-repaired specimens endured significantly more cycles to failure and had a higher maximum load range at failure than SR-repaired specimens ($P < .05$) (Fig 6). There were no differences in these parameters between intact and DR-repaired specimens or between nonaugmented and augmented DR-repaired specimens.

Mechanism of Failure

The mechanism of repair failure was most consistent for SR and aDR repairs (Table 2). The suture construct failed in all SR repairs, and the tendons tore through

Table 1. Results of Cyclic Testing

Load Range	Rotator Cuff Repair Technique			
	Intact	Single-Row	Double-Row	Augmented Double-Row
Stiffness (N/mm)				
25–75 N	83.9 ± 0.4	68.1 ± 0.4	75.3 ± 0.4	65.5 ± 0.4
25–100 N	93.1 ± 0.5	72.9 ± 0.5	82.4 ± 0.5	72.6 ± 0.5
25–125 N	104.1 ± 0.6	80.1 ± 0.6	93.4 ± 0.6	81.0 ± 0.6
25–150 N	113.7 ± 0.8	84.3 ± 0.8	98.8 ± 0.8	88.4 ± 0.8
25–175 N	122.3 ± 0.9	90.2 ± 0.9	107.2 ± 0.9	95.0 ± 0.9
25–200 N	127.4 ± 1.0	96.6 ± 1.0	114.4 ± 1.0	101.4 ± 1.0
Number of cycles to failure	1,756	388	1,302	1,211
Maximum load range at failure (N)	25–935 ± 4.7	25–260 ± 1.3	25–715 ± 3.6	25–670 ± 3.4

NOTE. Results are averages ± standard error of the mean.

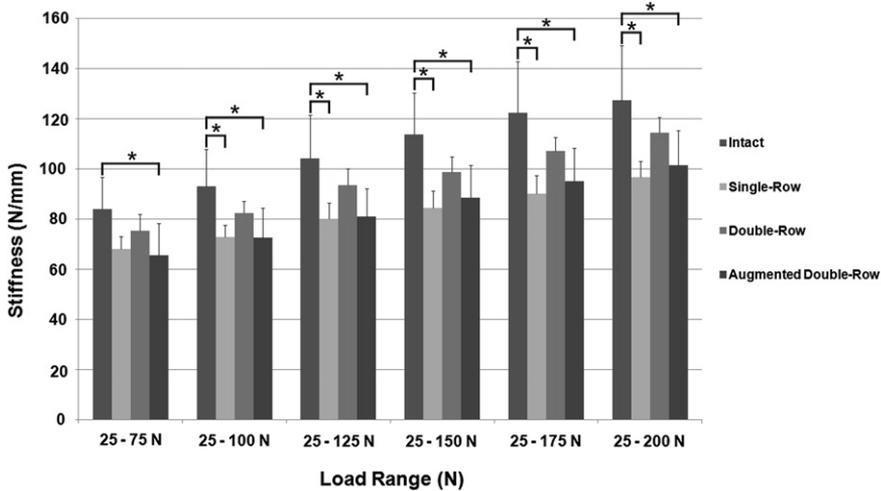


Fig 5. Average stiffness per specimen group for each maximum load range analyzed. *Significant difference.

the sutures in all aDR repairs. Pullout of the lateral row of anchors was observed in 2 DR-repaired specimens.

Discussion

The goal of this study was to compare the biomechanical properties of various rotator cuff repair techniques in a two-tendon posterolateral RCT model. The results support the hypothesis that extended, linked two-tendon RCT repairs augmented with a collagen scaffold are biomechanically superior to traditional SR repairs and equivalent to extended, linked DR repairs without augmentation. The aDR repairs provided the most consistent repair construct, but were not stronger than DR repairs. In addition, the biomechanical properties of the DR group did not differ significantly from those of the intact rotator cuff tendons. Biomechanically, augmented repairs are strong and the method of applying the collagen patch could provide the strength needed to withstand the initial loading so that biological healing and remodeling can occur.

To our knowledge, this is the first study assessing the biomechanical characteristics of two-tendon RCT repairs. The difference in testing protocols between this study and prior studies makes it even more difficult to compare the present results with previously reported values. Other studies investigating cadaveric, ovine, and porcine shoulder models report ultimate failure loads of 339 to 457 N, which are lower than those encountered in this study.²⁴⁻²⁷ These studies indicate that double-row, linked constructs with 2 sutures and/or mattress sutures at the medial row of suture anchors can possibly strengthen the rotator cuff repair as a result of load sharing.^{24,25,28} Perhaps the addition of the 2 dog-ear stitches, the use of additional suture anchors, and the use of suture tape may explain the increased failure loads found in this study, although it should again be stressed that the different testing protocols make it hard to compare values.

Contrary to the results of this study, Shea et al. report that application of an extracellular matrix to a rotator cuff repair may actually increase the load to failure and decrease gapping because of load sharing.²⁸ Their study, however, did not involve massive RCT, although it did involve the reinforcement of SR repairs and a different onlay technique.²⁸

When looking at the failure loads of SR repairs, the present results are similar to those previously reported, 256 to 290 N, although both surgical techniques and testing protocols vary.^{10,29}

The comparison of stiffness parameters with previous studies is even more difficult because of the different testing protocols, the types of shoulders used, and even the angles at which the rotator cuff tendons were loaded.^{26,27,29} In the attempt to mimic material properties of the native tissue, stiffness plays an essential role. Surgical technique plays an important role in restoring stiffness to the native state, and stiffness remains an important biomechanical parameter, especially in comparisons of the repaired state with the intact state.

In general, stiffness for the 3 types of repair—SR, DR, and aDR—was higher than in previous studies.^{26,27,29} Yet it should be emphasized that an objective comparison is difficult because of the variety of test setups and foremost because prior literature was focused mainly on smaller rotator cuff tears and repairs. Little has been reported previously concerning the stiffness of intact rotator cuff tendons.

The reported mechanisms of failure have all been previously described and encountered in similar frequencies; most failures were caused by sutures cutting through the tendon at the medial row of the repair.^{10,24,25,27,29} This is very concerning from a clinical standpoint because revision repairs become increasingly difficult. SR and aDR repairs were most consistent in their mechanism of failure.

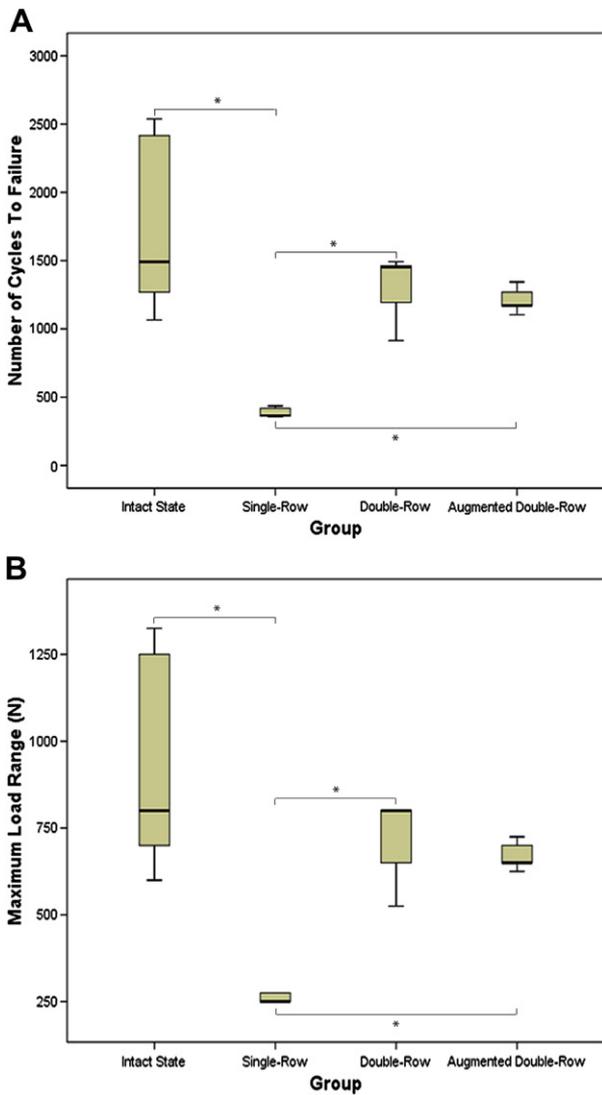


Fig 6. (A) Average number of cycles to failure per group. The horizontal line indicates the median, the box extends from the 25th to the 75th percentile, and the bars indicate the largest and smallest observed values. (B) Average maximum load range at failure. The horizontal line indicates the median, the box extends from the 25th to the 75th percentile, and the bars indicate the largest and smallest observed values. *Significant difference.

Although some authors suggest partial rotator cuff repair is sufficient to improve pain and motion in patients with massive rotator cuff tears,³⁰ an anatomic repair is likely optimal. Tendon quality and mobility, however, can result in tenuous rotator cuff repairs. In the past decade, adverse clinical outcomes have been reported after use of porcine patches for rotator cuff tear augmentation.³¹⁻³³ However, biological remodeling and promising short-term clinical follow-up with low complication rates have recently been reported after repairs of massive retracted rotator cuff tears of poor tissue quality augmented with dermal bioimplants of human dermal origin.^{16,34,35}

Table 2. Mechanism of Failure for Each Specimen

Repair Technique	Mechanism of Failure
SR No. 1	Suture construct
SR No. 2	Suture construct
SR No. 3	Suture construct
SR No. 4	Suture construct
SR No. 5	Suture construct
DR No. 1	Tendon–suture interface
DR No. 2	Musculotendinous junction
DR No. 3	Lateral row anchor pullout
DR No. 4	Tendon–suture interface
DR No. 5	Lateral row anchor pullout
aDR No. 1	Tendon–suture interface
aDR No. 2	Tendon–suture interface
aDR No. 3	Tendon–suture interface
aDR No. 4	Tendon–suture interface
aDR No. 5	Tendon–suture interface
Intact No. 1	Tendon–bone interface
Intact No. 2	Musculotendinous junction
Intact No. 3	Musculotendinous junction
Intact No. 4	Musculotendinous junction
Intact No. 5	Tendon–bone interface

SR, single-row; DR, double-row; aDR, augmented double-row.

The worst case scenario testing at time zero used here did not allow for any biological healing, which could influence the biomechanical characteristics of the repair in vivo. The rationale behind the use of human demis-based collagen scaffolds is the enhancement of early vascularization and cellular repopulation and reduction of inflammatory responses in augmented repairs of tendons of poor quality. However, it is hard to simulate a chronic massive rotator cuff tear model in the chosen setup.

The outcome of this study supports the concept that scaffold augmentation indeed may solely enhance biological healing in the weeks after repair and does not play a role in repair strength enhancement immediately after repair, at least when the repair is augmented using an onlay technique. Further histologic and biomechanical analysis of augmented repairs in a chronic massive rotator cuff tear model is mandatory to assess the biological influence of collagen scaffolds on tendon-to-bone healing and, in return, the effect on biomechanical characteristics over longer periods.

Several additional limitations to the study should be mentioned. The choice of mattress sutures instead of multiple simple stitches, with 2 sutures per anchor for SR repairs and a medial anchor row in DR and aDR repairs, was a methodology decision as the goal was to maintain as much similarity as possible between repair constructs. DR and aDR repairs used the same medial stitch configuration as a portion of the repair. Thus, the only difference between these DR repair constructs was the bridging sutures. Otherwise, a difference between single/double rows could have resulted from altered suture configuration.

Another limitation that should be pointed out is the lack of analysis of gap formation in this study. This may

have been clinically relevant considering that a gap of more than 5 mm is considered a clinical failure. However, the authors believe that the reported data on repair displacement and stiffness as measured with the Instron actuator, which is accurate to $\pm 0.5\%$, not only are accurate but are also clinically relevant. The tight standard deviations signify the level of precision. In addition, the authors believe that comparison with the native tendon strength of our repair groups is essential and that the level of significance in the differences found illustrates clinically meaningful differences.

Finally, the position of the Instron actuator used to determine tendon cyclic displacement and stiffness during testing should be mentioned. Previous biomechanical research on the rotator cuff has made use of markers placed on the tendons and video analysis, which perhaps is more accurate for reporting displacement because it limits the influence of tendon slippage from the testing clamps. The authors are confident, however, that the construct of sutures, metal wire, and glue prevented gross tendon slippage from the clamps.

Conclusions

Linked double-row constructs are significantly stronger than single-row repairs in this two-tendon rotator cuff tear model and approach the strength of the intact rotator cuff. Augmentation of double-row repair with a collagen patch does not influence biomechanical repair qualities, but does result in less variability in failure load and more consistency in the mode of failure.

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