Does transosseous-equivalent rotator cuff repair biomechanically provide a “self-reinforcement” effect compared with single-row repair?

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The concept of a “self-reinforcing” rotator cuff repair has been described and theorized to provide a mechanism of resistance to structural failure in the face of otherwise destructive forces. A repair construct that provides this mechanism has been described to mimic a Chinese finger trap, “in which the system grips more tightly as the tensile longitudinal disruptive force increases.” This concept of “self-reinforcement” in the setting of rotator cuff repair, although theorized, has not been biomechanically verified, quantified, or characterized.

The purpose of the current study was to determine whether a transosseous-equivalent (TOE) repair could provide a self-reinforcing mechanism of preservation and be “self-protective” against potentially destructive forces. Tendon-bridging sutures provide a compression vector over the repaired tendon that may improve footprint contact force with progressive tendon loading. These sutures can potentially provide frictional resistance to increasing gap formation and ultimate failure. However, similarly, with single-row (SR) repair, increasing tendon load will transmit some component of the loading vector onto the repair site as well (Fig. 1). We hypothesized that the TOE repair would provide disproportionately more frictional force with the same progressive tendon-loading sequence compared with SR repair. Is it possible that bridging sutures dissipate the compression force over the tendon so that the theory of self-reinforcement is simply theoretical? If the progressive increase in footprint compression force is not significantly different between both repairs, arguably, the theory of self-reinforcement does not apply to suture tendon-bridging constructs; in this case, tendon loading would simply be providing an obligatory transmission of vector force to the footprint and no exceptional protective force from the bridging sutures themselves.

Materials and methods

Specimen preparation

The study used 10 fresh frozen human cadaveric male shoulders with a mean age of 57.3 ± 9.1 years (range, 46-71 years), without evidence of rotator cuff tear or pathology. Specimens were stored at −20°C and thawed 24 hours at room temperature before dissection. Specimens were dissected of all soft tissue and disarticulated at the glenohumeral joint to isolate the supraspinatus muscle and its tendinous insertion on the greater tuberosity. The humerus was transected approximately 7 cm from the inferior articular margin and potted in a 1.5-inch-diameter polyvinyl chloride pipe with plaster of Paris.

After the plaster was set, the supraspinatus tendon was sharply dissected from its insertion on the greater tuberosity, and the bony footprint of the supraspinatus was treated with a fine rasp. The distal 10 mm end of the supraspinatus tendon was resected from anterior-to-posterior to simulate a single-tendon rotator cuff tear. The proximal end of the supraspinatus tendon was sutured using No. 2 nonabsorbable FiberWire suture (Arthrex, Naples, FL, USA) with an interlocking whipstitch to use for applying various loads to the supraspinatus.

Figure 1  Schematic representation shows how footprint contact increases with increasing tendon load. As tendon load increases from T to T’, the suture loop from a repair that is not fixed medially elongates and narrows (double arrows) creating a “focal loop wedge.” This effect creates a compression vector over the footprint laterally, and the exposed contact area (C) diminishes.

Figure 2  Custom testing apparatus.

The humerus was inserted into a custom testing device designed to allow for humeral abduction and supraspinatus muscle loading (Fig. 2). A normal saline solution was used to keep specimens moist during all phases of dissection, preparation, and testing.

Pressure sensor preparation

Supraspinatus repair contact force, area, and pressure were measured using a Tekscan 4201 sensor (Tekscan Inc, South Boston, MA, USA). Sensors were trimmed to fit the supraspinatus footprint dimensions. The final dimension of the sensors was
sensing elements. The tape was trimmed close to the sensor in moisture from contacting the sensor, which would damage the sensors. They were then sealed between 2 layers of clear tape to prevent contact variables from being measured through all experimental trials. The supraspinatus tendon was ultimately allow for sensor attachment to the greater tuberosity. The knot was tied with a sliding double half-hitch knot first, followed by alternating simple half-hitches, for a total of 5 throws using a knot-pusher. The MP-TOE repair was performed first, followed by the SR repair. Results of pilot testing and a previous study showed the suture-bridging technique did not affect the contact measurements for the subsequent SR repair. For each repair, therefore, the same specimen was used to serve as a reproducible internal control. The same surgeon (M.C.P.) performed all repairs.

**MP-TOE repair**

A previous study found the MP-TOE was biomechanically equivalent to the original TOE repair, even though the former repair required fewer suture passes through the repaired tendon, and the mode of failure for this repair was also more forgiving at the musculotendinous junction. Two medial-row pilot holes were punched at the medial edge of the greater tuberosity footprint just lateral to the articular cartilage yet medial to the Tekscan sensor; the anterior hole was placed 5 mm posterior to the bicipital groove. Two lateral pilot holes were punched 1 cm distal to the lateral edge of the supraspinatus footprint in line with the medial holes, and the distance between each suture anchor in the same row was 15.0 mm anterior-to-posterior. All holes were placed at a 45° angle relative to the bony surface. The medial row holes received 5.5-mm Bio-CorkscREW Suture anchors (Arthrex), single-loaded with No. 2 nonabsorbable FiberWire suture (Arthrex). However, instead of passing the suture limbs through the supraspinatus tendon via 4 individual passes, anterior and posterior suture limb pairs were passed simultaneously, with only 2 transtendon suture passes. A looped FiberSnare shuttle suture (Arthrex) was used to pass each suture limb pair 12 mm from the lateral tendon edge, simultaneously through the supraspinatus tendon, centered above its respective anchor. To secure the medial tendon, 1 suture limb from the anterior anchor and 1 limb from the posterior anchor were tied with the standard knot over the knot-pusher shaft, and the posterior free suture limb was pulled to bring the knot to the posterior anchor, creating a broad mattress configuration between anchors. The remaining 2 suture limbs were tied with a non-sliding knot over the anterior anchor. This technique creates 2 broad overlapping anterior-posterior suture bridges at the medial aspect of the supraspinatus footprint. The sutures tails were not cut. Two of the posterior sutures from the tied mattresses, 1 from each anchor, were incorporated into a 5.5-mm knotless SwivelLock anchor (Arthrex) and placed posteriorly at the distal-lateral position. With a constant application of tension, the screw was placed at a 45° angle relative to the proximal lateral humerus. This process was repeated with the remaining 2 anterior suture limbs to complete the repair, thus creating an additional 4 suture tendon-bridging construct criss-crossing centrally (Fig. 4). After advancing the lateral anchors, the free suture limbs were cut.

**SR suture anchor repair**

Two lateral holes were punched as far lateral as possible while still remaining on top of the footprint, thus maximizing the potential tendon contact area on the bony insertion. Each anchor was centered 15.0 mm from the other anterior to posterior. Two 5.5-mm Bio-CorkscREW FT anchors were used, which were double-loaded with No. 2 nonabsorbable FiberWire suture. Simple

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**Figure 3** Tekscan sensor secured to the rotator cuff footprint with small screws.
suture configurations were used for the lateral row. The suture passes were approximately 7 mm apart from one another for a given anchor and 10 mm medial to the lateral edge of the simulated tear (Fig. 5), similar to another study. Although middle footprint and medial SR repairs have been described, this laterally based repair configuration was used to maximize footprint coverage without compromising the sensor, thus minimizing bias against this repair.

Biomechanical testing

Fixed within the custom testing apparatus, the humerus was locked in neutral rotation by aligning the supraspinatus footprint dimension (anterior-to-posterior) orthogonal to the loading vector so that the approximate supraspinatus centroid was slightly posterior to the center of the humeral head. The loading vector line of action was defined by a No. 2 whip-stitched interlocking suture aligned with the centroid of the muscle and parallel to the baseplate. The suture was passed through the pulley system from which the loads were applied. To evaluate the effect of increasing supraspinatus load on footprint frictional force, contact measurements were recorded with the following supraspinatus loads: 0, 20, 40, 60, and 80 N. Measurements were performed at 0° and 30° of glenohumeral abduction. The abduction angle was defined relative to lines along the length of the humerus and the supraspinatus muscle and tendon, as previously described. The pulley component was adjusted vertically when the abduction angle was changed to keep the loaded suture parallel with the baseplate.

Before testing, specimens were sequentially ramp loaded using 20-N increments, from 0 to 80 N. The loads applied simulate physiologic loads that may be experienced postoperatively. Measurements were then performed in the same step-wise order for the first trial from 0 to 80 N, and then followed with a second trial; 2 separate trials were performed to confirm repeatability, and the values were averaged.

After testing was completed at both abduction angles for the MP-TOE repair, the repair was carefully removed and the SR repair was performed using the same specimen. Pilot studies demonstrated no gross effect of repair order on contact variables. But we noted that the SR repair would potentially affect the tendon and bone relatively more for a subsequent MP-TOE repair based on where the sutures were passed through the tendon and where the suture anchors were placed on the tuberosity; for the SR repair, the MP-TOE bridging sutures would cross the affected tendon and anchor sites from the SR repair, potentially adding more variability between testing conditions. The Tekscan pad was left attached to the greater tuberosity while the second repair was performed. All measurements were then repeated with the SR repair. For each repair, the footprint contact...
area, contact force, mean contact pressure, and peak contact pressure using a 2 × 2-pixel area were determined and averaged for both trials, and finally, averaged across the specimens. After measurements were completed, each Tekscan pad was removed and then calibrated and tested for functionality and loss of sensitivity using the Instron 4411 materials testing machine. Accuracy after testing was within a range of ±1.5 N, with repeatability at ±0.7 N. Inherent loss of sensitivity and decreased sensitivity with testing duration were both considered when using the Tekscan technology. Pilot studies demonstrated relatively insignificant sensitivity losses, likely related to the number of testing conditions evaluated, and the static (vs cyclic) loading conditions necessitated by the study design.

### Statistical analyses

A paired t test was used to statistically compare the values between the MP-TOE repair and the SR repair. A paired t test was also used to compare between abduction angles and also between supraspinatus loading conditions for a given repair. The slopes of contact force vs supraspinatus force and contact pressure vs supraspinatus force were calculated to evaluate the effect of increasing muscle load. Multivariate regression analysis was performed to compare the differences in slopes between the 2 repair groups. A P value of <.05 was used as the level of significance for all comparisons.

In a previous study using the same testing apparatus and similar methods, a power analysis was performed for contact area measurements for a TOE repair comparing positions of abduction at 0°, 30°, and 60°. On the basis of analyses in our laboratory that involved measuring contact area by use of our Tekscan sensor and software, the standard deviation was approximately 7 mm². To detect a minimum 14 mm² (8.75% of the sensor) difference in contact area between abduction positions with a 5% level of significance (α = .05), at least 6 specimens were determined to be necessary for achieving a power of 95%.

### Results

The MP-TOE repair had significantly larger footprint force, contact area, mean contact pressure, and peak contact pressure compared with the SR repair at each supraspinatus load for 0° (Table I) and 30° (Table II) abduction (P < .05). The MP-TOE repair resulted in an average 86.2% increase in contact force, 219.7% increase in contact area, 93.5% increase in contact pressure, and 143.7% increase in peak contact pressure compared with the SR repair when averaged across supraspinatus loads and abduction angles.

For a given repair, there were no significant differences in contact characteristics between the 2 abduction angles. The SR repair had significant (P < .05) increases in footprint force (N) between every tendon-loading condition (1.4 ± 0.5, 2.9 ± 0.8, 4.6 ± 1.3, 6.0 ± 1.6, and 7.6 ± 2.1 N for tendon loads of 0, 20, 40, 60, and 80 N, respectively; Fig. 6). For the SR repair group, this same relationship between all measurements was seen with contact area at both abduction angles and at 0° abduction for pressure (Fig. 7). The MP-TOE repair demonstrated the same significant relationships (P < .05) for footprint force with increasing tendon load (5.9 ± 1.2, 10.6 ± 1.7, 14.1 ± 2.2, 16.6 ± 2.6, and 18.4 ± 3.1 N for each progressive tendon load, respectively; Fig. 6). For the MP-TOE repair group,
this same relationship between all measurements was also seen for contact pressure (Fig. 7) at both abduction angles and at 30° abduction for area.

With increasing supraspinatus loads, the MP-TOE repair had a significantly higher progression (slope) of footprint contact force compared with the SR repair at 0° (P = .025) and 30° (P = .014) abduction (Fig. 6). The MP-TOE repair also had a significantly higher progression (slope) of footprint contact pressure compared with the SR repair at 30° abduction (P = .034) (Fig. 7). For each abduction angle, the slopes for force and pressure were averaged over the 10 measurements (obtained from each of 10 specimens) for both the MP-TOE and SR repairs; the ratio of the repair averages (MP-TOE slope average/SR slope average) for a given abduction position were 1.99 (footprint force at 0° abduction), 1.72 (footprint pressure at 0° abduction), 2.20 (footprint force at 30° abduction), and 2.07 (footprint pressure at 30° abduction). For a given repair, there were no significant differences in slope comparing 0° and 30° of abduction.

Discussion

The concept of “self-reinforcement” in rotator cuff repair has been theorized to apply to tendon-bridging constructs between medial and lateral rows. The theory postulates that increasing footprint frictional forces can be generated with progressive and yet counterproductive tendon-loading forces. The purpose of the current study was to biomechanically validate this theory and characterize frictional force at a repaired rotator cuff footprint as it relates to progressively increasing failure loads. Burkhart et al described the self-reinforcement concept involving a “wedge” effect created by tendon-bridging sutures that are fixed between both

Table II  Supraspinatus repair contact characteristics for a single-row repair and medial-pulley transosseous equivalent repair with increasing supraspinatus load at 30° abduction

<table>
<thead>
<tr>
<th>Supraspinatus load</th>
<th>Area (mm²) Mean (SE)</th>
<th>Force (N) Mean (SE)</th>
<th>Pressure (kPa) Mean (SE)</th>
<th>Peak pressure (kPa) Mean (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-row</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 N</td>
<td>33.0 (6.8)</td>
<td>1.4 (0.5)</td>
<td>33.1 (7.2)</td>
<td>46.0 (14.3)</td>
</tr>
<tr>
<td>20 N</td>
<td>56.5 (9.4)</td>
<td>2.9 (0.8)</td>
<td>46.9 (6.4)</td>
<td>77.0 (14.6)</td>
</tr>
<tr>
<td>40 N</td>
<td>69.3 (9.9)</td>
<td>4.6 (1.3)</td>
<td>59.2 (9.0)</td>
<td>102.5 (22.3)</td>
</tr>
<tr>
<td>60 N</td>
<td>77.8 (9.4)</td>
<td>6.0 (1.6)</td>
<td>71.9 (11.7)</td>
<td>128.0 (29.2)</td>
</tr>
<tr>
<td>80 N</td>
<td>84.2 (8.8)</td>
<td>7.6 (2.1)</td>
<td>84.0 (14.4)</td>
<td>156.5 (33.7)</td>
</tr>
<tr>
<td>MP-TOE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 N</td>
<td>89.0 (13.7)</td>
<td>5.9 (1.2)</td>
<td>61.5 (9.0)</td>
<td>120.5 (22.3)</td>
</tr>
<tr>
<td>20 N</td>
<td>109.8 (8.6)</td>
<td>10.6 (1.7)</td>
<td>93.2 (11.2)</td>
<td>186.5 (27.5)</td>
</tr>
<tr>
<td>40 N</td>
<td>118.4 (6.5)</td>
<td>14.1 (2.2)</td>
<td>116.5 (15.1)</td>
<td>234.0 (33.6)</td>
</tr>
<tr>
<td>60 N</td>
<td>120.8 (6.0)</td>
<td>16.6 (2.6)</td>
<td>135.2 (19.0)</td>
<td>273.5 (39.1)</td>
</tr>
<tr>
<td>80 N</td>
<td>120.7 (6.0)</td>
<td>18.4 (3.1)</td>
<td>149.6 (22.1)</td>
<td>298.0 (43.5)</td>
</tr>
</tbody>
</table>

MP-TOE, medial-pulley transosseous equivalent repair; SE, standard error.

Figure 6  Contact force and slope with increasing supraspinatus load. With increasing supraspinatus loads, the medial pulley transosseous-equivalent (MP-TOE) repair had a significantly higher progression (slope) of footprint contact force compared with the single-row (SR) repair at 0° (P = .0249) and 30° (P = .01404) abduction. For a given repair, there were no significant differences in slope comparing 0° and 30° of abduction. “Repair #,” where the # (0° or 30°) represents the abduction angle, followed by the linear equation quantifying the slope.
medial and lateral bony anchors: the tendon is increasingly “wedged” between the sutures and bony footprint as progressive tendon loading occurs. Baseline footprint compression comes from distal-lateral anchor placement that creates an obligatory normalizing force that is perpendicular to the axis of tendon loading; the current study has shown that tendon loading actually enhances this footprint compression effect rather than promote construct failure, as intuition may suggest.

With respect to SR repair, the anchor is not distal-lateral to the footprint, and compression to bone is more likely arising from the suture loop knot itself. With tendon loading, this loop elongates, with the superior limb creating a relative compression vector and a “focal loop wedge” effect. This elongation is obligatory with tendon loading for any suture loop (Fig. 1). Because there is no medial fixation for this loop and more complete footprint “self-protection” cannot occur with relatively less footprint contact area involved (and therefore less frictional resistance to tendon distraction), tendon loading could coincidently contribute directly to construct failure (eg, gapping, decreased yield loads) in the SR repair setting.

The current study has shown that increasing tendon loads do in fact increase footprint compression and frictional force; in addition, area and pressure significantly increases as well for a given repair. This was seen for both TOE and SR repairs. A prior study showed that footprint contact significantly increases with the TOE repair compared with double-row and SR repairs with both abduction and rotation; in that study, the load was kept constant. Arguably, the most significant finding in the current study is that the progressive footprint force increases (slopes of measurements) were significantly different between TOE and SR repairs, highlighting the additional contribution tendon-bridging sutures convey to the self-reinforcing mechanism. If the slopes of the increasing footprint forces were not different between repairs, the effect would be considered obligatory and not novel; so beyond the absolute contact differences between repairs, which was characterized in a prior study, the differences in slopes verify that disproportionate frictional forces are created with TOE repair, even in the face of increasing tendon-loading forces. In fact, for both 0° and 30° abduction, average footprint force ratios between MP-TOE and SR repairs (MP-TOE:SR) were 1.99 and 2.20, respectively, suggesting TOE repair can provide approximately twice as much “self-reinforcing” effect.

Abduction, as a kinematic variable, did not statistically affect footprint contact forces for a given repair technique. In general, increasing abduction has been shown to decrease footprint contact forces. Statistically significant differences were seen for 0° and 60°, not 0° and 30°, which is consistent with the current study. It is possible that at abduction angles of 60° or higher, SR repair would demonstrate less footprint force transmission with increasing tendon loads compared with the 0° and 30° conditions.

The current study can be considered “part 2” of a prior study that analyzed the failure load characteristics of a technically optimized TOE repair— analogous to the original 2-part biomechanical characterization of the TOE repair; “Part 1” of the current study highlighted the benefit of a technically optimized TOE repair requiring only 2 suture passes vs 4 for the original description of the TOE repair. Yet, both repairs were biomechanically equivalent. The current study verifies the theory of self-reinforcement using this simplified 2-suture pass TOE repair that uses a single, broad medial mattress configuration, which is relatively technologically efficient yet potentially less traumatic at the musculotendinous junction. Medial mattress fixation has been shown to improve biomechanical performance and whether knotless repair constructs are clinically sufficient is debatable.

This raises the question: Do focal medial mattress knots tenodese the rotator cuff such that the self-reinforcing effect is actually limited or neutralized? From the results of the current study we know the MP-TOE repair with a broad interimplant mattress does not have this tenodesis effect. In contrast, prior studies have shown the importance of focal medial knots. However, clinically, knotless repair medially has shown promising results. It is possible that knotless repair that uses tendon-bridging sutures creates a self-reinforcing environment that supplants the need for focal medial knots. Furthermore, the anterior “cord” of the supraspinatus tendon, which also represents the anterior portion of the rotator cable, has been shown to be important, particularly in external rotation. Additional anterior fixation has been theorized to improve biomechanical performance. The question of whether...
this additional fixation potentially neutralizes the “self-reinforcement” effect requires further study as well. Insofar as the SR repair does create increased footprint contact forces and pressure with increasing physiologic tendon loads, it could be argued that SR repair is also self-reinforcing, with some degree of structural self-preservation occurring. SR repair would not be self-reinforcing if tendon loading primarily and coincidently created loss of structural integrity with suture loop elongation (and more gap formation). In contrast, progressive tendon loading with TOE repair disproportionately (P < .05) increases repair site frictional resistance to failure compared with SR repair. However, other SR repairs have been described with improved loading and contact variables. These repairs that lack linked footprint-spanning sutures anchored medially are not optimizing footprint contact area restoration. Therefore, a mechanism for optimal self-reinforcement in these more technically involved SR repairs would not exist.

The limitations to this study include those inherent to all cadaveric studies, with only time-zero information available. In addition, biological and healing factors cannot be included; for example, tendon vascularity cannot be tested. However, intratendinous blood flow has been shown to be preserved after suture tendon-bridging repair, and blood supply has been shown to come from the peribursal tissue and bony anchor sites. Despite this, there has been concern about medial tendon strangulation and necrosis with failure after TOE repair fixed medially. The MP-TOE repair was designed to create a broad zone of fixation vs multiple focal spot-welds of fixation, demonstrating less tendon cutout with improved load-sharing capacity. This medial interimplant mattress suture-bridge may help to maintain vascularity and structural integrity, without compromising load-to-failure biomechanics. Although cadaveric studies are limited in assessing healing potential, laboratory studies can provide relevant information from highly controlled variables, limiting confounding factors and bias.

Conclusions

The results from the current study show that the force transmission from muscle to footprint appears to be obligatory, with tendon loading for both SR and TOE repair. However, the TOE repair demonstrated significantly more progressive frictional force and pressure transmission based on the differences in slopes (Figs. 6 and 7); arguably, given the slope ratios between repairs, the TOE repair can provide approximately double the reinforcing effect. Because the progressive increase in footprint compression force is significantly different between both repairs, arguably, the theory of self-reinforcement does apply to suture tendon-bridging constructs with relatively exceptional protective forces arising from the bridging sutures themselves. This characterization helps to verify the theory of self-reinforcement and provides another reason why transosseous-equivalent repair performs well biomechanically. This may explain the favorable outcomes seen clinically with interconnected, tendon-bridging constructs that restore the entire footprint.

References

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