Biomechanical Comparison of 4 Double-Row Suture-Bridging Rotator Cuff Repair Techniques Using Different Medial-Row Configurations

Stephan Pauly, M.D., Bettina Kieser, M.D., Alexander Schill, Cand.Dipl.Ing., Christian Gerhardt, M.D., and Markus Scheibel, M.D.

Purpose: Biomechanical comparison of different suture-bridge configurations of the medial row with respect to initial construct stability (time 0, porcine model). Methods: In 40 porcine fresh-frozen shoulders, the infraspinatus tendons were dissected from their insertions. All specimens were operated on by use of the suture-bridge technique, only differing in terms of the medial-row suture-grasping configuration, and randomized into 4 groups: (1) single-mattress (SM) technique, (2) double-mattress (DM) technique, (3) cross-stitch (CS) technique, and (4) double-pulley (DP) technique. Identical suture anchors were used for all specimens (medial: Bio-Corkscrew FT 5.5 [Arthrex, Naples, FL]; lateral: Bio-PushLock 3.5 [Arthrex]). All repairs were cyclically loaded from 10 to 60 N until 10 to 200 N (20-N stepwise increase after 50 cycles each) with a material testing machine. Forces at 3 and 5 mm of gap formation, mode of failure, and maximum load to failure were recorded. Results: The DM technique had the highest ultimate tensile strength (368.6 ± 99.5 N) compared with the DP (248.4 ± 122.7 N), SM (204.3 ± 90 N), and CS (184.9 ± 63.8 N) techniques (P = .004). The DM technique provided maximal force resistance until 3 and 5 mm of gap formation (90.0 ± 18.1 N and 128.0 ± 32.3 N, respectively) compared with the CS (72 ± 8.9 N and 108 ± 20.2 N, respectively), SM (66.0 ± 8.9 N and 90.0 ± 26.9 N, respectively), and DP (62.2 ± 6.2 N and 71 ± 13.2 N, respectively) techniques (P < .05 for each 3 and 5 mm of gap formation). The main failure mode was suture cutting through the tendon. Conclusions: Comparing the 4 different suture-bridge techniques, we found that modified application of suture-bridge repair with double medial mattress stitches significantly enhanced biomechanical construct stability at time 0 in this porcine ex vivo model. Clinical Relevance: This technique increases initial stability and resistance to suture cutting through the rotator cuff tendon after arthroscopic suture-bridge repair.
modifications of the suture-bridge technique at time 0, which was initially described by Park et al.\textsuperscript{19} These modifications address the medial row: 1 technique consists of 2 sutures per anchor medially and 3 techniques use 4 sutures per medial anchor, varying only in their respective medial-row suture-grasping techniques.

We hypothesized increased resistance to failure and less gap formation for more complex medial-row constructs with improved tendon-grasping techniques when compared with conventional double-row suture-bridge repairs.

\textbf{METHODS}

\textbf{Shoulder Dissection}

Forty fresh-frozen porcine shoulders (right side and male in all cases; age, 6 months) were stored at $-20^\circ\text{C}$ until thawed at room temperature 5 hours before identical preparation. All soft tissues were dissected to isolate the infraspinatus tendon attached to the humeral head. The infraspinatus tendon was then sharply detached from its bony footprint insertion on the greater tuberosity (with no humeral fibrocartilage attached) to mimic a full-thickness tear of the human supraspinatus tendon.\textsuperscript{13,15,16} Footprint dimensions and tendon thickness/caliber at the proximal and distal end of the bony insertion were obtained with a digital caliper gauge and documented. To prevent tissue dehydration, immediate processing and testing of all shoulders were ensured, and tendon tissue was kept moist with sprayed isotonic saline solution (0.9\% sodium chloride).

All reconstruction techniques consisted of identical numbers and types of anchors (2 medially and 2 laterally) and were performed by a single investigator (S.P., fourth-year resident in orthopaedic surgery).

\textbf{Medial Row}

To achieve suture-bridge repair, 2 medial anchors (Bio-Corkscrew FT 5.5 double loaded with No. 2 FiberWire; Arthrex, Naples, FL) were applied to the footprint according to Park et al.\textsuperscript{19} with respect to the dead man’s angle.\textsuperscript{20} The tendon was reduced and perforated 12 to 14 mm medially with a Scorpion Suture Passer (Arthrex) in 4 different fashions. Each technique was performed in 10 specimens.

Technique 1 was a medial-row single-mattress suture-bridge repair (SM technique). According to Park et al.\textsuperscript{19} 1 suture was retrieved from each anchor to leave a single-loaded anchor. The remaining suture perforated the tendon in a horizontal mattress stitch configuration (distance, 4 mm horizontally as measured with a digital caliper gauge), followed by an identical procedure for the second medial anchor (Fig 1). To achieve maximum loop and knot security, a fisherman’s sliding knot was used and reinforced with 3 reversed-post half-hitches to maximize knot-holding capacity.\textsuperscript{21,22}

Technique 2 was a medial-row double-mattress suture-bridge repair (DM technique). Both limbs from each of the 2 sutures perforated the tendon medially (distance, 4 mm horizontally) to establish horizontal mattress stitches in a parallel fashion for each medial anchor (Fig 2). Knot tying for each mattress stitch was performed according to the SM technique.
Technique 3 was a medial cross-stitch suture-bridge repair (CS technique). Both limbs from each of the 2 sutures perforated the tendon medially in a cross fashion: first, a regular horizontal mattress stitch (distance, 4 mm) was established and tied (as in the SM technique), followed by another perpendicular, vertical mattress stitch (distance, about 4 mm) and identical tying technique (Fig 3).

Technique 4 was a double-row double-pulley suture-bridge repair (DP technique). First, 1 end of both FiberWires per medial anchor was passed through the tendon simultaneously, representing the fashion of 1 regular horizontal mattress stitch with 2 free ends each (as in the SM technique). Then, 1 end of 1 medial inner FiberWire was split, loaded with a contralateral corresponding FiberWire, and shuttled through 1 anchor eyelet as described previously to achieve a horizontal reinforcement in between both medial anchors (Fig 4). Suture crossing and application of the lateral row were identical to the SM technique.

Lateral Row

For establishment of the lateral row, a transosseous-equivalent lateral-row repair in suture-bridge fashion was applied with knotless anchors (Bio-PushLock 3.5), fully inserted at a perpendicular angle to the cortical surface of the humerus. Application of the lateral row was identical for all techniques (Figs 1-4).19

Biomechanical Testing

For biomechanical testing, the medial free limb of the tendon was wrapped with a cotton bandage to increase friction. Subsequently, it was attached to a steel-wired extension hull ("Chinese finger trap") and then cross-suture secured (No. 5 FiberWire) to avoid
tendon slippage. In a previous study, this fixation method showed solid tendon fixation up to 600 N and superior interface grip when compared with other soft-tissue fixation techniques.24

The humerus was then sawed and adjusted to vertical load application to simulate physiologic load conditions as seen in the human supraspinatus tendon.14 It was fixed to biomechanical testing molds by use of bone cement (Beracryl; Fa. Troller, Fulenbach, Switzerland).

Before biomechanical testing, ultraviolet light–reflecting trackballs were attached to the tendon-bone construct: (1) medially to the medial row, (2) in between both suture rows, (3) to the greater tuberosity, and (3) to the fixation mold (Fig 5). An optical 3-dimensional tracking device with an accuracy of 0.1 mm 3-dimensionally was used for detection of gap formation (Qualisys AB, Gothenburg, Sweden).

**Loading Evaluation**

Preload was set at 10 N, followed by cyclic loading of all reconstructions with 50 cycles of 10 to 60 N on a material testing device (model 1455; Zwick, Ulm, Germany). Subsequently, load was increased with 20 N stepwise for another 50 cycles (50 × 10 to 80 N, 50 × 10 to 100 N, 50 × 10 to 120 N, and so on) until 50 × 10 to 200 N. Specimens surviving 50 cycles of 10 to 200 N were tested until maximum load to failure.13 The pulling speed was set to 350 mm/min for regular test cycles and to 500 mm/min for ultimate tensile strength beyond 200 N.

**Parameters**

The definition of failure was gap formation of both 3 and 5 mm between the medial tendon marker and the marker at the bony tuberosity.11,25,26 Definition of ultimate failure was either complete tendon tear or loss of load applied of greater than 50% (as obtained by the material testing device). Mode and focus of failure were documented.

**Statistical Analysis**

An a priori power analysis with an effect size of 0.347 and a post hoc power analysis based on the ultimate failure loads and standard deviations showed a power greater than 0.85 with \(\alpha = 0.05\) if 10 specimens per reconstruction were tested.

Statistical analysis was performed with SPSS software for Windows, version 14 (SPSS, Chicago, IL). Statistical testing for nonparametric variables was used (Kruskal-Wallis and \(\chi^2\) tests). Analysis of variance and the Scheffé and Dunnett tests were used to compare different groups for continuous variables. The level of significance was set at \(P \leq 0.05\). All data were given as means and standard deviations.

**RESULTS**

**Tendon Caliber and Footprint Dimensions**

There was no significant difference between all 4 groups \((P > .05)\) with respect to footprint dimensions, insertional areas, or tendon caliber (Table 1).
Mode of Failure

Documented failures were suture cutting through the tendon in all but 1 case, initiated at the medial row and combing toward the more lateral aspects of the tendon until failure of the lateral row. In only 1 case, construction strength was stronger than bone and survived humeral neck fracture. No anchor pullout was observed.

Different numbers of reconstructed units survived all test cycles until 10 to 200 N and were submitted to subsequent maximum load-to-failure evaluation: 4 shoulders from the SM group, 8 from the DM group, 1 from the CS group, and 4 from the DP group.

Gap Formation of 3 and 5 mm

The mean force to create 3 mm of gap formation between the medial tendon reflector and the humeral head was \(66.0 \pm 8.9\) N (95% confidence interval [CI], 60.3 to 71.7 N) for the SM technique, 72 ± 8.9 N (95% CI, 65.9 to 78.1 N) for the CS technique, and 62.2 ± 6.2 N (95% CI, 58.3 to 66.1 N) for the DP technique. With a mean load of 90 ± 18.1 N (95% CI, 78.5 to 101.4 N), the DM technique showed significantly higher resistance compared with all other techniques (\(P < .05\)) (Fig 6A).

The mean force to create 5 mm of gap formation between the medial tendon reflector and the humeral head was 90 ± 28.6 N (95% CI, 72.2 to 107.7 N) for the SM technique, 108 ± 22.3 N (95% CI, 94.2 to 121.8 N) for the CS technique, and 71.1 ± 13.7 N (95% CI, 62.6 to 79.6 N) for the DP technique. With a mean load of 128 ± 32.5 N (95% CI, 107.8 to 148.1 N), the DM technique showed significantly higher resistance compared with all other techniques (\(P < .05\)) (Fig 6B).

With a mean load of 90 N, 5 mm of gap formation was seen with the SM technique (Fig 6B) whereas only 3 mm of gap formation occurred with the DM technique (Fig 6A). In other words, application of a second mattress suture per medial anchor prevented 2 mm of gap formation at a mean load of 90 N.

Maximum Load to Failure

The mean force until total failure was 204.3 ± 90 N (95% CI, 148.5 to 260.1 N) for the SM technique, 184.9 ± 63.8 N (95% CI, 145.3 to 224.5 N) for the CS technique, and 248.4 ± 122.7 N (95% CI, 172.9 to

### Table 1. Footprint and Tendon Dimensions for Each Technique

<table>
<thead>
<tr>
<th>Technique</th>
<th>Footprint Width (mm)</th>
<th>Footprint Length (mm)</th>
<th>Insertional Area (mm²)</th>
<th>Tendon Caliber Medially (mm)</th>
<th>Tendon Caliber Laterally (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>17.5 ± 1.4</td>
<td>14.7 ± 0.7</td>
<td>259.8 ± 21.1</td>
<td>3.0 ± 0.4</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>DM</td>
<td>16.3 ± 0.9</td>
<td>13.8 ± 0.6</td>
<td>228.7 ± 16.5</td>
<td>2.3 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>CS</td>
<td>17.1 ± 0.9</td>
<td>14.8 ± 0.8</td>
<td>254.1 ± 19.9</td>
<td>2.6 ± 0.4</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>DP</td>
<td>16.3 ± 0.9</td>
<td>13.9 ± 0.6</td>
<td>226 ± 18.1</td>
<td>2.3 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
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323.8 N) for the DP technique. With a mean load of 368.6 ± 99.5 N (95% CI, 306.9 to 430.3 N), the DM technique showed significantly higher resistance compared with all other techniques (P < .004) (Fig 7). The CS technique was less resistant than single medial mattress sutures (P > .05).

DISCUSSION

Double-row suture-bridge repair allows quick arthroscopic transosseous-equivalent cuff repair with improved footprint coverage, reduced knot impingement, and improved biomechanical properties compared with conventional double-row techniques.19,27,28 This study showed differences in construct stability when modifying the medial row of standard suture-bridge repairs as described initially. In particular, application of a second medial mattress suture increased resistance against gap formation and load to failure significantly. Compared with the technique using a single medial mattress suture (204.3 ± 90 N), the addition of a second augmentation almost doubled construct stability against load to failure (368.6 ± 99.5 N). We found that by just adding a second medial mattress suture, the mean applied force of 90 N caused 3 mm of gap formation for the DP technique but 5 mm of gap formation for the SM technique. Traction from the musculotendinous unit hits the reconstruction medially first; hence, improved medial force transmission to the underlying bone may therefore increase construct stability.

The single-mattress suture-bridge technique as described by Park et al.19 and tested in our study showed inferior biomechanical properties (gap formation, maximum load to failure) compared with the classical double-row technique (medial and lateral corkscrew anchor fixation).13 Because double-loaded suture anchors are mechanically superior to open transosseous and arthroscopic single-loaded anchor repairs, the currently tested DM technique was developed.29 Compared with maximum load to failure for the DM technique with the present approach (368.6 ± 99.5 N), Lorbach et al.13 found 398 ± 98 N for double-row double-corkscrew anchor fixation in a similar cadaveric model with an identical cyclic testing protocol. However, the latter approach may cause remarkable knot impingement and is technically more demanding to perform.

Loosening and gap formation occurred at the site of medial tendon perforation first. Hence techniques with increased mechanical friction during the medial-row penetration (such as the DP technique with 3 FiberWires passing through simultaneously) create tendon substance defects at the medial-row interface, which resulted in early movement and weakest resistance to 3 and 5 mm of gap formation. From our observations,
it is also crucial that 1 FiberWire serves as a shuttle for a further 2 suture limbs before penetrating tendon and passing the eyelet. Three strong fiberglass sutures wear out the stitch canal while passing through and furthermore cause tremendous friction of the biological material. Suture blocking with subsequent eyelet breakage occurred once. In such a case the prepared medial mattress suture may be lost, and application of an additional anchor may be necessary. Furthermore, addition of a horizontal medial suture with a separate knot does not increase biomechanical stability but may cause knot impingement medially.

Our data result from time 0 ex vivo analysis. Footprint insertions for human supraspinatus tendon have been described and are comparable to insertions that were obtained in this animal cadaveric investigation.30,31 Neither tendon nor footprint dimensions differed significantly between the tested techniques, which must be considered a precondition for biomechanical comparison because, otherwise, construct stability may be influenced. However, even similar anatomic references allow only limited transfer to human conditions because tendon tissue strength and bone density may not represent findings in the elderly patient population with advanced degenerative tissue changes. Nearly all specimens showed the sutures cutting through the tendon as the primary failure mode. No anchor breakage or loosening occurred. This may be explained by strong trabecular and cortical strength in the juvenile porcine humeral head. Anchor loosening may occur more often in weaker, osteopenic human bone as a consequence of inactivity, which evolves in chronic tears.32 Because the anchor-bone interface as a potential failure site was ruled out, our study focused on the tendon-suture interface for comparing biomechanical stability.

Failure or tear of the reconstructed tendon-bone units occurred medially first at the site of load transmission from muscle by tendon to bone and then combing the tendon toward the lateral row. The second lateral fixation row accounts for superior strength compared with single-row repairs in time 0 cadaveric studies.7-10,13 However, prospective clinical and radiographic follow-up studies found only marginal or no advantage with double-row reconstructions at 6 months or at 2 years compared with single-row repair.3,4,33 At 12 months’ radiographic follow-up, tendon integrity was reported for 88% of suture-bridge repairs (SM technique).34 Structural defects of the tendon medially to the footprint (medial rotator cuff failure) were reported from revision cases at a mean of 9 months after double-row repair, matching with observations from the present in vitro study.17

Study Limitations

Biomechanical improvements of double-row reconstructions do not necessarily translate into superior clinical performance. The assumption of strangulation through strong tissue adaptation to the bony insertion by use of double-row techniques with multiple tendon perforations, strong synthetic suture, and knot types is possible.35,36 Maximized biomechanical construct stability at time 0 providing strong tissue adaptation may deteriorate microcirculation and hence biological regeneration, which is mandatory for durable tendon-bone reintegration. Only midterm to long-term clinical and radiographic results for these new techniques will help to evaluate their respective value in rotator cuff repair.

As a further weakness, only 1 double-row technique featuring the same material (anchors, knotless anchors, and suture material) was performed, which does not represent the full spectrum of double-row techniques available.

A further limitation is that porcine cadaveric investigations do not allow direct transfer to clinical situations in humans because stronger tendon material must be assumed to be present. Lorbach et al.13 described comparable bone density in 8-month-old porcine and middle-aged human shoulders. However, a strength of this model is that it allows standardized comparison of different surgical techniques with less variations in age and causes of death than in human cadavers.

For the sake of increased initial strength, we consider the slightly enhanced operating procedure and time justified. Additionally, used suture materials cause no additional expense because suture anchors are provided with 2 suture limbs anyway.

CONCLUSIONS

Comparing the 4 different suture-bridge techniques, we found that modified application of suture-bridge repair with double medial mattress stitches enhances biomechanical construct stability at time 0 in this porcine ex vivo model under cyclic loading.

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REFERENCES


