Biomechanical Comparison of 3 Glenoid-Side Fixation Techniques for Superior Capsular Reconstruction

Jonas Pogorzelski,* MD, MHBA, Kyle J. Muckenhirn,* BA, Justin J. Mitchell,*† MD, J. Christoph Katthagen,*‡ MD, Jason M. Schon,* BA, Kimi D. Dahl,* MS, Alan M. Hirahara,§ MD, Joshua S. Dines,‖ MD, Christopher R. Adams,§ MD, Thomas Dooney,‖ MD, Patrick J. Denard,** MD, Travis Lee Turnbull,* PhD, and Peter J. Millett,*†† MD, MSc

Investigation performed at the Department of BioMedical Engineering, Steadman Philippon Research Institute, Vail, Colorado, USA

Background: Superior capsular reconstruction (SCR) was recently introduced as a treatment for irreparable superior rotator cuff tears in younger patients.

Purpose/Hypothesis: The purpose was to assess the biomechanical strength of 3 methods for fixation of the graft to the glenoid for SCR. It was hypothesized that a 4-anchor technique would provide greater load to failure than 3-anchor techniques.

Study Design: Controlled laboratory study.

Methods: Thirty-six cadaveric specimens were randomized into 3 groups of previously established glenoid-side graft fixation techniques: (1) three 3.5-mm knotless screw-in anchors, (2) three 3.0-mm knotless push-in anchors, and (3) a 4-anchor hybrid construct with two 3.0-mm knotted push-in anchors and two 2.9-mm knotless push-in anchors. The repairs were cyclically loaded at 0.5 Hz from 10 to 200 N, then pulled to failure. Elongation, stiffness, maximum load at failure, and mode of failure were recorded and calculated.

Results: There were no significant differences in graft elongation or stiffness among the 3 techniques (P = .37 and P = .26, respectively). Maximum load to failure was significantly greater in technique 1 (mean ± SD, 427.85 ± 119.70 N) than technique 3 (319.5 ± 57.60 N) (P = 0.024). There were no significant differences in load to failure between techniques 1 and 2 or between techniques 2 and 3.

Conclusion: Glenoid-side graft fixation with 3 threaded 3.5-mm suture anchors showed a significant superior pull-out strength when compared with a 4-anchor hybrid technique and thus might be recommended in SCR for patients with irreparable superior rotator cuff tears to achieve maximum stability.

Clinical Relevance: SCR presents a novel alternative for treatment of irreparable superior rotator cuff tears in younger patients. Glenoid fixation is essential to provide adequate fixation of the graft to prevent the humeral head from rising and to restore normal biomechanics.

Keywords: superior capsular reconstruction; SCR; irreparable rotator cuff tear; supraspinatus

Irreparable rotator cuff injuries lead to significant pain and functional impairment.5,9 Loss of the stabilizing structures, such as the rotator cuff and the superior shoulder capsule, may result in superior translation of the humeral head.5,6 While the rotator cuff represents the main dynamic stabilizer of the glenohumeral joint, the capsule is an important static stabilizer14 and is torn off its attachment to the greater tuberosity in the setting of massive posterosuperior rotator cuff tears.21 In chronic tears, repair of both structures may be difficult, as they can be atrophic, retracted with inelasticity, and become infiltrated with fatty tissue.2,11,18,19,26,27

Although muscle tendon transfer surgery and reverse total shoulder arthroplasty have been shown to be reasonable treatment options for irreparable rotator cuff tears,2,3,8,9,25,33-35 a high complication rate and poor clinical outcomes in certain patient populations make stringent patient selection necessary.2,7,9 More precisely, a 38% complication rate has been reported after reverse total shoulder arthroplasty among patients <65 years old,7 and significant osteoarthritic changes have been observed after latissimus dorsi transfer in the long term.10 Understanding that each of these surgical options
may pose a problem in younger patient populations by disrupting the normal anatomy and by limiting future treatments, Petri et al.\textsuperscript{11,15,30} concluded that a joint preserving solution might be desired.

Early clinical and biomechanical research has shown that superior capsular reconstruction (SCR) can be a beneficial treatment option for irreparable rotator cuff tears to restore glenohumeral stability.\textsuperscript{20-22} Although mid- and long-term outcomes have not yet been reported, several studies have performed for glenoid-side fixation of the graft. It was hypothesized that a 4-anchor technique would provide greater load to failure than 3-anchor techniques.

METHODS

Specimen Preparation

A biomechanical study was performed with 36 nonpaired fresh-frozen human cadaveric shoulders (18 male, 18 female). All specimens were ≤65 years of age (mean ± SD, 55.6 ± 8.0 years), with no history of shoulder injury, surgery, anatomic abnormality, or osteoarthritis. All specimens were distributed by sex and then randomly distributed among the 3 techniques. As a result, a total of 6 male and 6 female specimens were assigned to each group. The dermal allografts were distributed in a similar fashion. To decrease the potential variable introduced by graft thickness and since the 3-mm-thick graft is the preferred thickness to use clinically presently, all allografts were chosen to be 3 mm thick. For a cadaveric study, our institution does not require Institutional Review Board approval. Dual-energy X-ray absorptiometry scans were performed to exclude specimens with osteoporosis and to standardize bone mineral density (total T score, −0.13 ± 1.6). All specimens were stored at −20°C and thawed at room temperature for 24 hours before preparation. The humerus and clavicle were disarticulated from the scapula, and all soft tissue except the labrum was removed for adequate glenoid exposure. The scapula was then potted in polymethyl methacrylate (Fricke Dental International, Inc) to preserve the position of the glenoid during testing.

Surgical Technique

A single orthopaedic surgeon (J.P.) performed all SCRs in an open fashion. To reduce the potential learning effect, several pilot trials were performed for each surgical technique by the same trained orthopaedic surgeon. Three techniques were used to test medial fixation strength with a 3.0-mm-thick acellular dermal allograft (ArthroFlex; Arthrex, Inc). Each graft was trimmed to a width of 35 mm and length of 70 mm before sutures were passed 10 mm from the medial edge.

Technique 1 (Figure 1) was similar to the medial fixation described by the group of Millett et al.\textsuperscript{15,30,36} using three 3.5-mm suture anchors (BioComposite SwiveLock; Arthrex, Inc) to secure the graft to the superior glenoid.\textsuperscript{13,15,30} A central anchor was loaded with labral tape suture and placed at the 12-o’clock position (Figure 2), with both limbs passed centrally through the graft. A No. 2 looped suture was passed through the anteromedial and posteromedial corners of the graft to create cinch stitches. Then, anterior and posterior anchors were placed 17.5 mm from the central anchor, corresponding to the 10- and 2-o’clock positions to secure the corresponding labral tape limb and cinch suture to the glenoid in a knotless fashion.

Technique 2 (Figure 3) consisted of three 3.0-mm knotless anchors (SutureTak; Arthrex, Inc) to secure the graft to the superior glenoid. The anchors were placed on the labrum at the 11-, 12-, and 1-o’clock positions just medial to the labrum. The anterior and posterior anchors were placed precisely 13 mm anterior and posterior from the center anchor. The suture limbs were evenly passed, leaving 3-mm tissue borders between 6-mm mattress stitches. Then, the graft was secured to the glenoid by engaging the knotless mechanism for each anchor.

\textsuperscript{11}Address correspondence to Peter J. Millett, MD, MSc, Steadman Philippon Research Institute, The Steadman Clinic, 181 West Meadow Drive, Suite 400, Vail, CO 81657, USA (email: drmillett@thesteadmanclinic.com).

\textsuperscript{12}Steadman Philippon Research Institute, Vail, Colorado, USA.

\textsuperscript{13}The Steadman Clinic, Vail, Colorado, USA.

\textsuperscript{14}Department of Trauma, Hand, and Reconstructive Surgery, University Hospital Muenster, Muenster, Germany.

\textsuperscript{15}Private practice, Sacramento, California, USA.

\textsuperscript{16}Hospital for Special Surgery, New York, New York, USA.

\textsuperscript{17}NCH Physician Group, Naples Community Hospital, Naples, Florida, USA.

\textsuperscript{18}Arthrex, Inc, Naples, Florida, USA.

\textsuperscript{19}Southern Oregon Orthopedics, Medford, Oregon.

One or more of the authors has declared the following potential conflict of interest or source of funding: Arthrex, Inc. provided partial study funding and an in-kind donation of surgical supplies. A.M.H. has received intellectual property royalties, speaking fees, and research support from and is a paid consultant for Arthrex Inc and has received speaking fees from LifeNet Health Inc. J.S.D. has received speaking fees and research support from and is a paid consultant for Arthrex Inc; is a paid consultant for ConMed Linvatec and Trice; has received intellectual property royalties from Linvatec; and has received publishing royalties and financial or material support from Wolters Kluwer Health—Lippincott Williams & Wilkins, C.R.A. is an employee of and paid consultant for and has received speaking fees from Arthrex Inc. P.J.D. has received intellectual property royalties, speaking fees, and research support from and is a paid consultant for Arthrex Inc and has received publishing royalties and financial or material support from Wolters Kluwer Health—Lippincott Williams & Wilkins. P.J.M. has received research support from Arthrex Inc, Ossur, Siemens, and Smith & Nephew; has received intellectual property royalties from and is a paid consultant for Arthrex Inc; has stock or stock options in Game Ready and VuMedi; and has received intellectual property royalties from Medbridge.
Technique 3 (Figure 4) used 4 anchors in a hybrid knotted-knotless technique. Two 3.0-mm biocomposite anchors (SutureTak) were placed just medial to the labrum 15 mm apart at the 11- and 1-o’clock positions. The sutures from these anchors were passed through the graft at 5-mm intervals. A No. 2 looped suture was also passed through the anteromedial and posteromedial corners of the graft to create cinch stitches. The 2 central sutures and the 2 peripheral sutures from the anchors (SutureTak) were tied together, creating a double pulley. Then, the cinch sutures were secured to the glenoid in a knotless fashion with two 2.9-mm knotless anchors (PushLock; Arthrex, Inc) placed 35 mm apart at the 10- and 2-o’clock positions.

Biomechanical Testing

Each SCR medial fixation construct was biomechanically assessed with a dynamic tensile-testing machine (Instron ElectroPuls E10000; Instron Systems). Before the ArthroFlex graft was clamped in a custom fixture, it was whip-stitched 3 cm from the lateral graft margin and further reinforced with multiple wraps of steel wire to prevent slippage during testing. This method of mechanical clamping has been validated and is supported by several biomechanical studies in the literature.4,17,23 Before testing, the clamp was positioned at 3 cm from the lateral margin for each specimen, and the Instron crosshead displacement was zeroed. The graft and fixture were then mounted in the testing machine, with the potted scapula securely fixed to the stationary base. The testing setup was oriented such that the SCR graft was pulled directly lateral, in line with the perpendicular plane of the glenoid. After the graft was pre-loaded to 10 N, care was taken to ensure that it was aligned vertically (Figure 5). Specimens from each technique group were cyclically loaded at 0.5 Hz from 10 to 60 N until 10 to 200 N (20-N stepwise increase after 50 cycles each), based on a testing protocol from previously performed studies that biomechanically evaluated humeral fixation after supraspinatus tendon repair.16,28,29 If the repair was still intact after cyclic loading (400 cycles), it was pulled to failure at 500 mm/min. Failure was defined as suture breakage, loosening of the suture >5 mm, or any perceived movement of the implanted anchors. Failure mode was observed and defined in each case by 2 reviewers. Elongation and stiffness at the conclusion of cyclic loading were determined, as were
the maximum load during pull to failure and the mode of failure. Elongation was taken as the accumulated actuator displacement from the start of cyclic loading (0th cycle) to the end (400th cycle). Stiffness was calculated as the slope of the load versus the displacement curve at the final cycle of cyclic loading during the increase in load from 10 to 200 N. For constructs that did not survive cyclic loading, only the failure cycle and range of loading could be recorded, as the exact load of failure could not be defined. For all others, the maximum load during the pull-to-failure event was recorded.

Statistics

As a simplification of the full analysis of variance, an a priori power calculation was conducted with the assumption of independent comparison of means and an alpha of 0.0167 (Bonferroni correction for 3 pairwise comparisons).

Usage of 12 specimens per group was found to be sufficient to detect an effect size ($d$) of 1.41 with 80% statistical power. All continuous variables were not observed to be skewed or overdispersed, so parametric testing methods were used. One-factor analysis of variance models were built for each dependent variable, and pairwise comparisons were made between groups with Tukey’s method. All statistical analyses and graphics were produced with the statistical programming language R (v 3.3.2).32

RESULTS

No significant differences were observed in elongation or stiffness among the 3 techniques after pull to failure ($P = .39$, $P = .99$, and $P = .36$, respectively). After the 400 cycles, analysis of the maximum load at failure indicated that technique 1 was significantly stronger (133.9%, $P = .024$) than technique 3 (Tables 1 and 3). There was no significant
difference in maximum load to failure between techniques 1 and 2 (Tables 1 and 2). There was no significant difference in strength determined between techniques 2 and 3 (Tables 2 and 3). Of note, there was a trend toward a higher load to failure for technique 2 as compared with technique 3 (Tables 2 and 3). One graft fixation with technique 1, 2 graft fixations in technique 2 (Table 2), and 3 graft fixations of technique 3 (Table 3) failed before reaching the pull-to-failure threshold after 400 cycles.

**DISCUSSION**

The most important findings of the study were that elongation and stiffness were not significantly different among the 3 tested techniques. However, concerning maximum load to failure, technique 1 (with 3 suture anchors) was significantly superior to technique 3 (with 4 suture anchors) \((P = .024)\). These findings refute our hypothesis and support the use of 3 suture anchors for glenoid-side fixation of the graft during SCR.

SCR was originally described as being used with a fascia lata autograft; however, several authors have now proposed using a dermal allograft for the procedure.\(^ {13,15,30} \)

The reliable performance of acellular dermal allograft, in terms of elongation and stiffness properties, makes it a practical replacement for autologous tissue. Benefits for patients include reduced surgical time and the elimination of the morbidity of graft harvest. Importantly, dermal allograft has demonstrated the potential for biological incorporation with minimal immunologic risk.\(^ {37,39} \) While most techniques use a 4-anchor bridging double row to secure the graft to the greater tuberosity,\(^ {24,38} \) there is considerable variability with regard to the number of anchors

**TABLE 1**

Overview of Technique 1\(^ a \)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cycles to Failure</th>
<th>Elongation After 400 Cycles, mm</th>
<th>Stiffness During PTF, N/mm</th>
<th>Maximum Load, N</th>
<th>PTF</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PTF</td>
<td>21.46</td>
<td>51.29</td>
<td>297.41</td>
<td>Yes</td>
<td>Anterior anchor pulled out</td>
</tr>
<tr>
<td>2</td>
<td>PTF</td>
<td>14.06</td>
<td>56.36</td>
<td>298.62</td>
<td>Yes</td>
<td>Posterior suture broke</td>
</tr>
<tr>
<td>3</td>
<td>PTF</td>
<td>15.04</td>
<td>52.03</td>
<td>476.79</td>
<td>Yes</td>
<td>Posterior suture broke</td>
</tr>
<tr>
<td>4</td>
<td>PTF</td>
<td>15.47</td>
<td>72.34</td>
<td>408.35</td>
<td>Yes</td>
<td>Posterior suture broke</td>
</tr>
<tr>
<td>5</td>
<td>PTF</td>
<td>15.07</td>
<td>65.53</td>
<td>315.20</td>
<td>Yes</td>
<td>Posterior suture broke</td>
</tr>
<tr>
<td>6</td>
<td>PTF</td>
<td>11.03</td>
<td>65.54</td>
<td>489.31</td>
<td>Yes</td>
<td>Superior anchor pulled out</td>
</tr>
<tr>
<td>7</td>
<td>PTF</td>
<td>13.05</td>
<td>47.84</td>
<td>636.68</td>
<td>Yes</td>
<td>Superior anchor broke</td>
</tr>
<tr>
<td>8</td>
<td>PTF</td>
<td>16.00</td>
<td>51.35</td>
<td>322.35</td>
<td>Yes</td>
<td>Posterior suture broke</td>
</tr>
<tr>
<td>9</td>
<td>PTF</td>
<td>15.41</td>
<td>70.54</td>
<td>367.53</td>
<td>Yes</td>
<td>Posterior anchor pulled out</td>
</tr>
<tr>
<td>10</td>
<td>PTF</td>
<td>10.82</td>
<td>67.40</td>
<td>588.43</td>
<td>Yes</td>
<td>Posterior suture broke</td>
</tr>
<tr>
<td>11</td>
<td>304 (10-180 N)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>Anterior suture broke</td>
</tr>
<tr>
<td>12</td>
<td>PTF</td>
<td>11.32</td>
<td>71.37</td>
<td>505.62</td>
<td>Yes</td>
<td>Anterior anchor pulled out</td>
</tr>
</tbody>
</table>

\( a \)Elongation, stiffness, maximum-load PTF, and failure mode are presented for each specimen individually. N/A, not available; PTF, pull to failure.

**Figure 5.** Anterior view of a right-side scapula secured in a polymethyl methacrylate block, demonstrating the setup within the Instron machine. The polymethylmethacrylate block is secured to the lower portion of the Instron machine, while the graft is secured to the clamp of the Instron. AC, acromion; C, coracoid process; G, glenoid.
and methods for glenoid-side fixation, with limited biomechanical information about each technique.

Regarding the results of our study, an explanation of why the 3-anchor constructs performed as well or better than the 4-anchor constructs may not be obvious, but some arguments can be made. Technique 1 showed the greatest pull-out strength, most likely because of the use of threaded anchors, which perform better than push-in anchors in weaker bone.1 This is of certain interest, as the bone quality of patients undergoing SCR might not be as good as that of patients of comparable age, owing to disuse from the massive rotator cuff tear. Additionally, the use of wider suture (tape) in this technique may have improved fixation and reduced the chance of cut-through and failure. In general, the most common mode of failure in this construct was suture breakage, thus demonstrating that threaded anchors with a 3.5-mm diameter are sufficient for glenoid-side fixation of the graft.

Technique 2 consisted of 3 suture anchors with horizontal mattress sutures that were independently secured within the knotless mechanism of each anchor. The use of independent sutures—aside from bridging configurations,

### TABLE 2
Overview of Technique 2

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cycles to Failure</th>
<th>Elongation After 400 Cycles, mm</th>
<th>Stiffness During PTF, N/mm</th>
<th>Maximum Load, N</th>
<th>PTF</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>206 (10-140 N)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>No Superior anchor pulled out</td>
</tr>
<tr>
<td>2</td>
<td>PTF</td>
<td>11.19</td>
<td>90.82</td>
<td>445.31</td>
<td>Yes</td>
<td>Anterior anchor pulled out</td>
</tr>
<tr>
<td>3</td>
<td>PTF</td>
<td>18.88</td>
<td>73.22</td>
<td>420.95</td>
<td>Yes</td>
<td>Anterior suture broke</td>
</tr>
<tr>
<td>4</td>
<td>PTF</td>
<td>18.11</td>
<td>80.33</td>
<td>444.19</td>
<td>Yes</td>
<td>Posterior anchor pulled out</td>
</tr>
<tr>
<td>5</td>
<td>PTF</td>
<td>16.71</td>
<td>54.62</td>
<td>290.67</td>
<td>Yes</td>
<td>Anterior anchor broke</td>
</tr>
<tr>
<td>6</td>
<td>PTF</td>
<td>16.99</td>
<td>64.54</td>
<td>459.65</td>
<td>Yes</td>
<td>Anterior suture broke</td>
</tr>
<tr>
<td>7</td>
<td>PTF</td>
<td>15.98</td>
<td>66.35</td>
<td>449.55</td>
<td>Yes</td>
<td>Anterior anchor pulled out</td>
</tr>
<tr>
<td>8</td>
<td>PTF</td>
<td>18.79</td>
<td>71.85</td>
<td>355.31</td>
<td>Yes</td>
<td>All anchors pulled out</td>
</tr>
<tr>
<td>9</td>
<td>357 (10-200 N)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>No All anchors pulled out</td>
</tr>
<tr>
<td>10</td>
<td>PTF</td>
<td>23.01</td>
<td>48.18</td>
<td>354.46</td>
<td>Yes</td>
<td>Superior anchor pulled out</td>
</tr>
</tbody>
</table>

Mean ± SD | N/A | 16.60 ± 3.70 | 67.98 ± 11.51 | 410.00 ± 57.60 |

*Elongation, stiffness, maximum-load PTF, and failure mode are presented for each specimen individually. N/A, not available; PTF, pull to failure.

### TABLE 3
Overview of Technique 3

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cycles to Failure</th>
<th>Elongation After 400 Cycles, mm</th>
<th>Stiffness During PTF, N/mm</th>
<th>Maximum Load, N</th>
<th>PTF</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380 (10-200 N)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>No Posterior (PushLock) suture broke</td>
</tr>
<tr>
<td>2</td>
<td>PTF</td>
<td>6.84</td>
<td>74.26</td>
<td>280.34</td>
<td>Yes</td>
<td>Anterior superior suture (SutureTak) broke (PushLock) broke</td>
</tr>
<tr>
<td>3</td>
<td>251 (10-160 N)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>No Anterior and posterior inferior sutures (PushLock) broke</td>
</tr>
<tr>
<td>4</td>
<td>254 (10-160 N)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>No Anterior inferior anchor (PushLock) broke</td>
</tr>
<tr>
<td>5</td>
<td>PTF</td>
<td>12.58</td>
<td>53.01</td>
<td>295.93</td>
<td>Yes</td>
<td>Anterior and posterior superior sutures (SutureTak) broke</td>
</tr>
<tr>
<td>6</td>
<td>PTF</td>
<td>12.85</td>
<td>46.15</td>
<td>288.24</td>
<td>Yes</td>
<td>Anterior inferior suture (PushLock) broke</td>
</tr>
<tr>
<td>7</td>
<td>PTF</td>
<td>13.42</td>
<td>38.63</td>
<td>364.07</td>
<td>Yes</td>
<td>Anterior and posterior inferior anchors (PushLock) broke</td>
</tr>
<tr>
<td>8</td>
<td>PTF</td>
<td>13.94</td>
<td>62.76</td>
<td>337.12</td>
<td>Yes</td>
<td>Anterior and posterior inferior sutures (PushLock) broke</td>
</tr>
<tr>
<td>9</td>
<td>PTF</td>
<td>13.89</td>
<td>46.17</td>
<td>319.5 ± 57.60</td>
<td>Yes</td>
<td>Anterior inferior suture (PushLock) broke</td>
</tr>
<tr>
<td>10</td>
<td>PTF</td>
<td>20.76</td>
<td>61.34</td>
<td>351.81</td>
<td>Yes</td>
<td>Anterior inferior suture (PushLock) broke</td>
</tr>
<tr>
<td>11</td>
<td>PTF</td>
<td>21.05</td>
<td>41.73</td>
<td>439.12</td>
<td>Yes</td>
<td>Anterior inferior suture (PushLock) broke</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>N/A</td>
<td>14.20 ± 4.70</td>
<td>57.48 ± 16.61</td>
<td>319.5 ± 57.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Elongation, stiffness, maximum-load PTF, and failure mode are presented for each specimen individually. N/A, not available; PTF, pull to failure.
as seen in the other constructs—may prove advantageous, as the overall construct is not compromised with the failure of 1 anchor. In other words, with its particular spacing, this construct may help share the load more evenly. Although not studied, a particular advantage of this anchor technique is the ability to percutaneously place all 3 anchors through a guide at the preferred location before the graft is shuttled arthroscopically. However, it is notable that the most common mode of failure was anchor pullout, thus supporting the presumption that fixation strength might have been improved by either increasing anchor size or adding threaded fixation, as in technique 1.

Technique 3, which used more anchors than techniques 1 and 2, was surprisingly not superior in terms of pull-out strength. Technique 3 utilized a hybrid construct of 2 knotless anchors on the periphery (2.9-mm PushLock) and 2 knotted anchors in the center (3.0 SutureTak). In 10 of 12 cases, the peripheral anchors or suture failed. This implies that the strain came from the outer boundaries of the graft and progressed inward. Once the outer anchors failed, the central anchors were left to overcome the applied forces. These positional forces can be explained by the definition of the Poisson ratio, which is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. This is a set ratio for each tissue, depending on the dimensions and thickness. Even though the tissues were identical, the fixation at the glenoid side was not. This implies that if the sides of the graft would have been stabilized, the amount of contraction and elongation could have been reduced. This effect, quantified by applying margin convergence sutures intraoperatively, could in theory help share the load between the glenoid anchors and strengthen the overall repair construct.

In summary, this biomechanical study demonstrates that 3 threaded anchors with a diameter of 3.5 mm showed the most stable fixation for glenoid-side fixation of the graft during SCR at time zero. This has several advantages, especially since the 4-anchor techniques used in our study showed a lower threshold of pull-out resistance. First, placement of 3 anchors is more technically efficient than placement of 4 anchors. Second, glenoid bone stock is limited, so it is encouraging that 3 anchors provided fixation that was superior to the 4-anchor technique tested in this study regarding pull-out strength. Finally, it is notable that techniques 1 and 2 relied on completely knotless fixation, whereas technique 3 utilized a hybrid knotted and knotless construct. A previous study demonstrated that arthroscopic knots have high variability in terms of strength, thereby indicating that knotless techniques have the potential to not only deliver more consistent fixation strength but also reduce suture management issues, which are a concern given the number of anchors and points of fixation needed for an SCR procedure.

While this biomechanical study provides utility by removing many external variables that may affect results, there are inherent limitations to a cadaveric biomechanical study that cannot be controlled. The uniaxial forces laterally applied to the graft from the glenoid may not accurately reflect the dynamic loads experienced throughout a full range of motion of the arm. Moreover, we did not evaluate the contact area of the 3 techniques as well as the gap formation, which might have an effect on the postoperative healing process. The results of this study demonstrate that there was approximately 15 mm of mean elongation after the cyclic loading protocol regardless of surgical technique. However, the clinical implication of these sizable values has yet to be determined and is difficult to assess in a cadaveric model. Moreover, the effect of graft elongation on glenohumeral stability (superior translation) is presently unclear and was not specifically evaluated in the present study. In general, without the contribution of healing, scarring, or muscle contractions, the measured fixation strength only simulates reconstruction immediately after surgery. However, simulating the threshold of fixation strength immediately postoperatively may provide useful information for developing appropriate rehabilitation protocols and is foundational for subsequent clinical studies. Another limitation might be that specimens that failed during cyclic loading were excluded from the failure analysis; therefore, the reported failure results reflect only specimen trials that succeeded past cyclic loading. But given that we wanted to find out about the number of anchors needed to successfully fixate a graft at the glenoid side, we believe that it was more expedient that way.

CONCLUSION

In the present study, glenoid-side graft fixation with 3 threaded 3.5-mm suture anchors showed a significant superior pull-out strength as compared with a 4-anchor hybrid technique and thus might be recommended in SCR for patients with irreparable superior rotator cuff tears to achieve maximum stability.

ACKNOWLEDGMENT

The authors thank William Pennington, MD and Daniel C. Marchetti, BA for their support of and contribution to the study.

REFERENCES

19. Melis B, Wal B, Walch G. Natural history of infraspinatus fatty infiltra-

For reprints and permission queries, please visit SAGE’s Web site at http://www.sagepub.com/journalsPermissions.nav.