Biomechanical comparison of lesser tuberosity osteotomy versus subscapularis tenotomy in total shoulder arthroplasty

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Background: Total shoulder arthroplasty is traditionally performed through an anterior deltopectoral exposure with subscapularis tenotomy. Postoperative subscapularis dysfunction is common and adversely affects clinical outcomes. Consequently, surgeon interest in lesser tuberosity osteotomy has grown in an effort to improve subscapularis repair strength. This study investigated the biomechanical strength of subscapularis tenotomy vs lesser tuberosity osteotomy in the setting of total shoulder arthroplasty.

Materials and methods: Uncemented humeral prostheses were placed in 20 paired upper extremities from 10 cadavers. For each respective cadaver, 1 limb underwent lesser tuberosity osteotomy and the contralateral limb underwent subscapularis tenotomy. The cadaveric specimens then underwent cyclic displacement and maximum load to failure testing.

Results: The subscapularis tenotomy specimens exhibited significantly less cyclic displacement (0.8 mm) than the osteotomy group (1.8 mm), with a 95% confidence interval (CI) for the difference of 0.5 to 1.5 mm (P = 0.002). The maximum load to failure was 439 ± 96 N for tenotomy and 447 ± 89 N for osteotomy (95% CI for the difference of −58 to 75), which was not significant (P = .78).

Conclusion: Lesser tuberosity osteotomy was not significantly stronger than subscapularis tenotomy in maximum load to failure testing, with minimal clinical significance set at 100 N. Subscapularis tenotomy repair showed statistically significant less cyclic displacement than lesser tuberosity osteotomy. Further research is needed to clarify how the biomechanical results immediately after subscapularis tenotomy and lesser tuberosity osteotomy correlate with clinical outcomes.

Level of evidence: Basic Science Study, Biomechanical Study.

Keywords: Lesser tuberosity osteotomy; subscapularis tenotomy; total shoulder arthroplasty
mobilized with this method, the subscapularis tendon must be directly repaired after prosthesis placement. Unfortunately, many patients who undergo subscapularis tenotomy have postoperative subscapularis dysfunction.8,9,15

Subscapularis dysfunction has been linked with inferior clinical outcomes after TSA.12 The prevalence of postoperative subscapularis dysfunction has led to the development of alternative methods of subscapularis mobilization. In particular, lesser tuberosity osteotomy has gained favor among surgeons performing TSA. The rationale for this exposure technique is that bone-to-bone healing may lead to a stronger subscapularis repair.

Several authors have recently published promising clinical data on the short-term results of lesser tuberosity osteotomy for TSA.8,14,15 However, questions remain about the strength of lesser tuberosity osteotomy repair. There have been few published biomechanical studies comparing lesser tuberosity osteotomy with subscapularis tenotomy. To the best of our knowledge, prior biomechanical studies have not examined uncemented humeral fixation and most have not used paired-specimen analysis. Therefore, we performed this matched-pair study to further investigate and compare the initial biomechanical strength of lesser tuberosity osteotomy and subscapularis tenotomy repair in the setting of uncemented TSA.

Materials and methods

The study used 10 fresh frozen cadavers without pre-existing shoulder pathology. For each respective cadaver, 1 upper extremity was randomly selected to undergo lesser tuberosity osteotomy and the contralateral limb from the same cadaver underwent subscapularis tenotomy. This unique setup using paired upper extremities from respective cadavers provided an internal control for bone density and musculotendinous strength.

The cadaveric shoulders were dissected in preparation for biomechanical testing. Care was taken during dissection to preserve the integrity of the subscapularis myotendinous unit and its humeral insertion. The two humeri from a respective cadaver were dissected and tested sequentially to avoid confusion during data collection.

The humeral shafts were osteomized 15 cm distal to the inferior articular surface of the humeral head and potted into cylinders of bone cement (Hygienic Orthodontic PMMA Resin, Coltène Whaledent, Cuyahoga Falls, OH, USA). Specimens then underwent subscapularis tenotomy or lesser tuberosity osteotomy and repair as randomized.

Subscapularis tenotomy technique

The subscapularis tendon was incised 1 cm medial to its insertion onto the lesser tuberosity. A soft tissue tendon-to-tendon repair was performed using No. 0 Ethibond (Ethicon Inc, Somerville, NJ, USA) sutures in figure-of-eight fashion. Eight sutures were placed in each repair and tightened in neutral shoulder position (Figs. 1-5).
sutures through the subscapularis tendon at the edge of the sub-
scapularis fragment. The 4 No. 2 FiberWire sutures were tied with 
3 stacked square-knots. The construct then consisted of a tight 
suture loop encircling the osteotomy fragment and the proximal 
shaft of the humeral implant (Figs. 6-10).

Biomechanical testing

The humeri were maintained in the custom vise attached to 
a biomechanical testing apparatus (MTS Systems, model 858 
Bionix, Minneapolis, MN, USA). The shoulders were positioned 
for testing in 45° of glenohumeral abduction in neutral rotation, 
with the line of pull directed 135° in relation to the long axis of the
humerus. This positioning served to align the biomechanical testing stress along the subscapularis muscle-tendon axis. After positioning of the humerus, the free subscapularis muscle was then clamped within a cryo-jaw. Liquid carbon dioxide was applied to the clamped muscle belly to deep freeze the muscle in position.

Specimens were loaded cyclically to 100 N at 1 Hz for 3000 cycles. The force of 100 N was replicated from the protocol of Ponce et al., who estimated that this force simulated post-operative rehabilitation forces after TSA. This value is approximately 10% of the maximum voluntary contraction of the subscapularis as estimated by Chang et al. and 40% of the estimated subscapularis contractile force predicted by Bull. The number of cycles was based on an estimated post-operative physical therapy regimen of 70 repetitions daily for 6 weeks.

Cyclic displacement was measured using a 6-mm differential variable reluctance transducer (DVRT; Micro-Strain, Burlington, VT, USA). After the completion of 3000 cycles, the specimens then underwent maximal load to failure testing. Specimens were subjected to a loading rate of 2 mm/s until failure occurred. Maximum load to failure data were recorded, and statistical analysis was performed.

**Statistical analysis**

Descriptive statistics are reported as mean ± standard deviation for the tenotomy and osteotomy groups separately. The 95% confidence interval (CI) for the intracadaver difference of 2 techniques is reported. The paired \( t \) test was used to compare maximal load to failure and cyclic displacement between the tenotomy and osteotomy groups. The conclusions remained consistent if the nonparametric Wilcoxon rank sum test was used. The \( \alpha \) level was set at 0.05 for statistical significance.

We used 100 N as the level of minimal clinical significance for the maximal load to failure power analysis. This value was chosen because it represents the force expected during passive range of motion exercises during postoperative rehabilitation. For the observed standard deviation (SD) of the difference and the number of cadavers available (maximum load: SD, 95 and \( n = 10 \); cyclic displacement: SD, 0.6 and \( n = 8 \)), assessment using a 2-sided paired \( t \) test at an \( \alpha = 0.05 \) provided 80% power to detect a mean difference for maximum load of 100 N or larger and for cyclic displacement of 0.72 mm or larger.
The average results for cyclic displacement were 0.8 ± 0.2 mm (median, 0.7; range, 0.6-1.2 mm) after subscapularis tenotomy repair and 1.8 ± 0.6 mm (median, 1.7; range, 0.93-2.59 mm) after lesser tuberosity osteotomy repair. The mean cyclic displacement values after lesser tuberosity osteotomy were significantly higher than those after subscapularis tenotomy (average difference, 1.0 mm; 95% CI of the differences, 0.5-1.5 mm; \( P = .002 \)).

The average maximal load to failure was 439 ± 96 N (median, 431; range, 299-634 N) after subscapularis tenotomy, compared with 447 ± 89 N (median, 439; range, 309-603 N) after lesser tuberosity osteotomy. With minimal clinical significance set at 100 N, the mean differences in maximal load to failure between the lesser tuberosity osteotomy and subscapularis tenotomy groups were not statistically significant (average difference, 8 N; 95% CI of the differences, −58 to 75 N; \( P = .78 \)).

Mechanical testing malfunction occurred during cyclic displacement testing of 2 tenotomy specimens. The DVRT cyclic displacement sensor exceeded its linear range during testing of 1 tenotomy specimen. Cyclic displacement data from this specimen was discarded from our statistical analysis. Another cadaveric humerus lost fixation within the potting device during cyclic testing. The resulting data were corrupted and therefore not included in our statistical analysis. Careful analysis showed that the subsequent maximal load to failure data from these specimens was consistent with that obtained from other specimens, and load to failure data from these 2 specimens were included in our statistical analysis.

The mode of failure for the tenotomy repair specimens was suture tear-out through the tendon substance in every case. In the osteotomy specimens, the sutures tore through the bone wafers, with resultant laxity and eventual gross displacement (Table I; Figs. 11-14).
Discussion

Subscapularis release via tenotomy or osteotomy is an essential step in the deltopectoral approach to TSA. As the largest of the rotator cuff muscles, the subscapularis plays a crucial role in soft tissue stability after TSA. In addition to stability, subscapularis integrity and strength is required for shoulder internal rotation and the performance of daily activities such as tucking in a shirt.

Postoperatively, the surgeon must balance the desire for early shoulder range of motion against the concern for subscapularis repair compromise. The subscapularis has traditionally been released via tenotomy. Unfortunately, studies show that many patients exhibit subscapularis dysfunction after TSA and that this correlates with inferior clinical outcomes. The search for a stronger and more stable subscapularis repair has led to the development of lesser tuberosity osteotomy as a means of exposure for TSA.

Several authors have recently published promising clinical data on the short-term results of lesser tuberosity osteotomy for TSA. Scalise et al. conducted a retrospective study comparing lesser tuberosity osteotomy and subscapularis tenotomy in TSA. Patients who underwent osteotomy had higher clinical outcome scores and a lower rate of subscapularis tears postoperatively than those who had undergone subscapularis tenotomy.

Table 1  Lesser tuberosity osteotomy vs subscapularis tenotomy

<table>
<thead>
<tr>
<th>Variables</th>
<th>Tenotomy</th>
<th>Osteotomy</th>
<th>Difference</th>
<th>Difference 95% CI</th>
<th>P</th>
<th>Tenotomy</th>
<th>Osteotomy</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load</td>
<td>439 ± 96</td>
<td>447 ± 89</td>
<td>−8 ± 93</td>
<td>−58 to 75</td>
<td>.78</td>
<td>431 (299-634)</td>
<td>439 (309-603)</td>
<td>.43</td>
</tr>
<tr>
<td>Cyclic displacement</td>
<td>0.8 ± 0.2</td>
<td>1.8 ± 0.6</td>
<td>−1.0 ± 0.6</td>
<td>0.5 to 1.5</td>
<td>.002</td>
<td>0.7 (0.68-1.12)</td>
<td>1.7 (0.93-2.59)</td>
<td>.008</td>
</tr>
</tbody>
</table>

CI, confidence interval.
* Values are shown as mean ± standard deviation or median (range).
† For the measurement of maximum load with 10 cadavers, there was 80% power to detect an effect size of 1.0 (where an effect size of 0.8 is considered to be a “large” effect size according to Cohen*). Assuming a standard deviation of the differences of approximately 95 for maximum load, there was slightly more than 80% power to detect a paired difference in means of 100, which had been thought to be a clinically important difference. Similarly for cyclic displacement (n = 8 cadavers) power to detect an effect size of 1.2, assuming a standard deviation of the differences of approximately 0.6, there was 80% power to detect a difference in cyclic displacement of 0.72 or larger.
‡ Paired t test.
§ Wilcoxon rank sum test.

Figure 11  Graph demonstrates maximum load to failure (N) of subscapularis tenotomy (y axis) and lesser tuberosity osteotomy (x axis) for specimens. The data points above the central line show higher load to failure of tenotomy repair for a given specimen, and data points below the central line demonstrate higher load to failure of the osteotomy repair.

Figure 12  Graph demonstrates cyclic displacement (mm) after subscapularis tenotomy (y axis) and lesser tuberosity osteotomy (x axis) for specimens. The data point cluster below the central line demonstrates greater cyclic displacement after lesser tuberosity osteotomy repair.
Gerber et al\textsuperscript{7} evaluated 39 patients who underwent lesser tuberosity osteotomy during TSA. They reported radiographic osteotomy healing in all patients and normal subscapularis function in 75\% to 89\% of patients postoperatively. However, they did note progressive fatty infiltration of the subscapularis postoperatively.\textsuperscript{8} Qureshi et al\textsuperscript{14} retrospectively reviewed 30 shoulders performed via lesser tuberosity osteotomy and reported improved internal rotation strength after osteotomy compared with an earlier cohort of patients who underwent subscapularis tenotomy.

Despite promising early clinical results, questions remain about the biomechanical strength of lesser tuberosity osteotomy repair. The goal of lesser tuberosity osteotomy is to maximize repair strength while avoiding damage to the subscapularis tendon. Although subscapularis tenotomy repair has been shown to fail at the tendon-to-tendon interface,\textsuperscript{13} lesser tuberosity osteotomy preserves the tendon and allows for bone-to-bone healing.

The comparative strength of subscapularis tenotomy vs lesser tuberosity osteotomy was examined by Ponce et al\textsuperscript{13} in 2005. In their biomechanical study, they reported that lesser tuberosity osteotomy provided a stronger repair than subscapularis tenotomy. Krishnan et al\textsuperscript{11} reported similar findings from their 2009 biomechanical study. Ahmad et al\textsuperscript{1} performed a biomechanical study in 2007 of tenotomy repair methods, but an osteotomy group was not included. They did note, however, that the addition of transosseous sutures to augment direct subscapularis tendon-to-tendon repair resulted in improved biomechanical strength. In 2008, Van den Bergh et al\textsuperscript{17} compared subscapularis tenotomy with osteotomy fixation using a buttress plate.

We performed a cadaveric study to further investigate the relative strength of subscapularis tenotomy and lesser tuberosity osteotomy in the setting of TSA. We used a testing protocol similar to Ponce et al.\textsuperscript{13} However, there were some important differences between our studies, and one of the most significant differences in study design was that we used paired cadaveric specimens. For each respective cadaver, one upper extremity was selected to undergo lesser tuberosity osteotomy while the contralateral limb from the same cadaver underwent subscapularis tenotomy. This unique setup of using paired upper extremities from respective cadavers provided an internal control for bone density and musculotendinous strength.

Ponce et al\textsuperscript{13} found no statistical association between sex, age, or bone mineral density and repair cyclic displacement or load to failure. However, it was unclear whether the study was powered to detect a difference in these variables and whether the statistical analysis was limited to the osteotomy subgroup or included all repair techniques. Krishnan et al\textsuperscript{11} did not perform bone densitometry on specimens, but did use matched pairs for their osteotomy specimens to minimize variability secondary to bone density. Ponce et al\textsuperscript{13} and Krishnan et al\textsuperscript{11} reported that lesser tuberosity osteotomy showed higher maximal load to failure compared with soft tissue subscapularis tenotomy repair.

Our results differ and call into question the biomechanical superiority of lesser tuberosity osteotomy repair. In our study, the lesser tuberosity osteotomy group showed significantly more cyclic displacement than did the soft tissue tenotomy repair. Evaluation of our maximal load to failure data showed no statistically significant difference between our lesser tuberosity osteotomy and subscapularis tenotomy groups.

The reason for the difference between our results and those of Ponce et al\textsuperscript{13} is unclear. Our lesser tuberosity osteotomy and subsequent repair techniques were similar: lesser tuberosity wafers of similar dimensions were repaired using FiberWire sutures that encircled the humeral
medial and lateral drill holes (4). Krishnan et al.11 did not place a humeral prosthesis in their cadaveric specimens; therefore, their osteotomy repair method did not include a suture loop encircling the prosthesis. It is possible that differences in surgical technique contributed to our different outcomes.

One notable difference between studies is that Ponce et al.13 used cemented humeral prostheses (Zimmer Anatomical Shoulder System, Zimmer Inc, Warsaw, IN, USA), whereas we used press-fit humeral components (Biomet Comprehensive Stem). Perhaps cemented humeral components provide an immediate “lock” to the osteotomy sutures that is not present initially with uncemented components. Suture loops placed around a press-fit component may possibly have more creep than those that encircle a cemented humeral component. Perhaps looping the sutures around a press-fit humeral prosthesis does not provide a biomechanical advantage.

Lastly, it is important to note that Krishnan et al.11 used No. 5 Ethibond, Ponce et al.13 used No. 5 FiberWire, and we used No. 2 FiberWire. The greater inherent strength of the larger No. 5 suture may be advantageous in securing the osteotomy fragment and may be a better technique.

Another important difference between our study and that of Ponce et al.13 and Krishnan et al.11 is the technique of subscapularis tenotomy repair. We believe that smaller sutures placed in figure-of-eight fashion may provide a stronger and less bulky repair than larger sutures placed in Mason-Allen fashion. Therefore, we used 8 braided nonabsorbable (size 0 Ethibond) sutures in figure-of-eight fashion rather than fewer (4), larger sutures (No. 5 Fiberwire and No. 5 Ethibond) in the Mason-Allen configuration as used by Ponce et al.13 and Krishnan et al.11 respectively. Our tenotomy load to failure results were greater than those of Krishnan et al.11 and Ponce et al.13, and these data suggest that multiple figure-of-eight sutures may be preferable for subscapularis tenotomy repair.

Our protocol for biomechanical testing was nearly the same as that of Ponce et al.13 The cadaveric arm position was identical. They used a 9-mm DVRT whereas we used a 6-mm DVRT. Although it may be technically easier to place the 6-mm DVRT closer to the area of repair gap formation and thus obtain more accurate displacement data, we believe this difference is likely negligible. The cyclical loading protocols of 100-N load at 1 Hz for 3000 cycles were identical. Different testing velocities were used in the load to failure analyses: we loaded the specimens at 2 mm/s, whereas Ponce et al.13 loaded their specimens at 33 mm/s. Because our experiment was designed to simulate time 0 postoperative conditions when high-velocity motion is not a consideration, we performed a low-velocity analysis to minimize the effects of tissue viscoelasticity on mechanical testing. Given the different viscoelastic properties of bone and tendon, it may be that loading rate differentially affected tenotomy or osteotomy specimens and led to a different outcome than that obtained by Ponce et al.13

Krishnan et al.11 used a different biomechanical testing protocol. In their study, specimens underwent 400 cycles of 180-N loading at 0.5 Hz. Load was then successively increased by 180-N every 400 cycles until failure was reached. This different biomechanical testing protocol may have influenced outcomes and may make direct comparison of these results less valuable.

The clinical significance of our results remains to be determined. It is unclear how displacement under cyclic load correlates with in vivo clinical risk of subscapularis dysfunction or rupture. Lesser tuberosity osteotomy introduces a site of potential displacement in a naturally rigid bone-to-bone interface. In contrast, tenotomy causes tendon-to-tendon displacement in an area that is naturally less rigid than a bone-to-bone interface. It may be that suture repair of subscapularis tenotomy closely replicates the natural tensile strength of the subscapularis tendon, whereas suture repair of the lesser tuberosity osteotomy introduces relative instability in a naturally rigid bone-to-bone interface with subsequent increased cyclic displacement.

Several authors have reported consistently high rates of osteotomy healing clinically.8,15 so it is likely that osteotomy site displacement is within the range tolerated for bony healing. It is possible that the rigid tenotomy repair is less tolerant of cyclic displacement than the osteotomy repair. This could lead to tenotomy repair with low cyclic displacement but rupture the moment a given threshold displacement occurs. In our series, tenotomy fixation consistently failed at lower displacement values than osteotomy repairs. Therefore, the decreased cyclic displacement in our tenotomy specimens may not connote a clinically decreased rate of subscapularis tendon rupture. In fact, a recent study that used ultrasound imaging to evaluate the integrity of subscapularis tenotomy repairs found a high rate of failure at patient follow-up.9

How maximal load to failure of a subscapularis construct affects clinical results is also unknown. One might infer that increased maximal load to failure of a subscapularis repair correlates with decreased risk of subscapularis compromise. However, it is not known whether subscapularis rupture/dysfunction most often occurs after a single stress that exceeds maximal load to failure or instead after repetitive loads that exceed the construct’s endurance limit.

Our data show no clear difference in maximal load to failure between subscapularis tenotomy and lesser tuberosity osteotomy in an in vitro model. It is important to note, however, that our study was performed on cadaveric specimens and does not account for changes in the biomechanical construct over time as may occur in vivo. Specifically, our study does not provide information about how bony and ligamentous healing will affect construct
Subscapularis tenotomy vs osteotomy

strength. Further investigations will be necessary to reach a more definitive conclusion.

Conclusion

Subscapularis mobilization in TSA can be performed via subscapularis tenotomy or lesser tuberosity osteotomy. Surgeon interest in lesser tuberosity osteotomy has grown, and prior biomechanical data suggests that osteotomy provides a stronger repair than tenotomy. In our study, however, there was no significant difference in maximum load to failure between lesser tuberosity osteotomy and subscapularis tenotomy repair with minimal clinical significance set at 100 N. Furthermore, the lesser tuberosity osteotomy group showed significantly greater displacement under cyclic load than the subscapularis tenotomy repair group. Further research is needed to clarify the biomechanical and clinical results of subscapularis tenotomy and lesser tuberosity osteotomy in TSA.

Acknowledgments

The authors thank William S. Harmsen, MS, and Cathy D. Schleck, BS, for help with statistical analysis, Donna Riemersma for her assistance with manuscript preparation, and Carl Clingman for his medical illustrations.

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The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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