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A Biomechanical Analysis of Shoulder Stabilization

Posteroinferior Glenohumeral Capsular Plication

Shane J. Nho,* MD, MS, Rachel M. Frank,* BS, Geoffrey S. Van Thiel,* MD, MBA,
Fan Chia Wang,*† MS, Vincent M. Wang,* PhD, LCDR Matthew T. Provencher,‡ MD,
MC USN, and Nikhil N. Verma,*‖ MD
*From the *Department of Orthopaedic Surgery, Rush University Medical Center,
Chicago, Illinois, the †Department of Bioengineering, University of Illinois at Chicago,
Chicago, Illinois, and the ‡Department of Orthopaedic Surgery,
Naval Medical Center, San Diego, California*

Background: The use of posterior capsular plication to decrease capsular volume and address capsular laxity for treatment of posterior instability, multidirectional instability, or as an additional technique in the treatment of anterior instability is common. Multiple different suturing techniques have been described.

Hypothesis: The simple stitch will have inferior biomechanical properties compared with either the horizontal mattress or figure-of-8 stitches for suture plication of the posteroinferior quadrant of the glenoid.

Study Design: Controlled laboratory study.

Methods: Twenty-one fresh-frozen shoulders with a mean age of 57.7 ± 12.3 years were randomized into capsulolabral plication of the posteroinferior quadrant using either simple stitch configuration, horizontal mattress configuration, or figure-of-8 configuration. Each shoulder was mounted onto a materials testing machine, preloaded to 5 N for 2 minutes, cycled from 5 to 25 N for 100 cycles (1 Hz), and then loaded to failure at 15 mm/min. Capsular displacement from the glenoid was determined using digital video analysis. Data recorded included mode of failure, ultimate load to failure, load at 2 mm of displacement, as well as displacement during cyclical loading (during the entire 100 cycles and during the final cycle only).

Results: There was a statistically significant difference ($P < .0001$) in mechanism of failure among the 3 groups with the simple stitch group failing more often in the capsular tissue than in the mattress and figure-of-8 sutures, which more commonly failed at the capsulolabral junction. There was no statistically significant difference ($P > .05$) among the 3 groups in gapping (displacement) after cyclical loading, load at 2 mm of displacement, or in ultimate load to failure.

Conclusion/Clinical Relevance: Based on these results, all 3 stitches can be used effectively for capsular plication, although the simple stitch may be preferred for the capsular plication because of technical ease and decreased trauma to the capsulolabral tissue.

Keywords: plication; glenohumeral joint; Bankart; suture anchor

Over the past decade, all-arthroscopic techniques have become an accepted method of performing both anterior and posterior shoulder stabilization procedures, with results comparable with and sometimes better than open procedures.[6,14-16,20,33,34] Furthermore, even though there is a high association between anterior capsular laxity and Bankart lesions, there is no consensus on the association between posterior capsular laxity and the so-called reverse Bankart lesion.[32] Regardless of the cause, the factor most commonly associated with posterior shoulder instability is thought to be laxity of the posterior capsule,[10,28,35,36] and thus treatment has been focused on reducing posterior capsular redundancy via capsular plication in an attempt to restore stability to the shoulder. In addition, capsular plication of the posteroinferior (PI) quadrant of the glenoid is also used to augment

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‖Address correspondence to Nikhil N. Verma, MD, Midwest Orthopaedics at Rush, 1611 W. Harrison Street, Suite 300, Chicago, IL 60612 (e-mail: nverma@rushortho.com).

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stabilization of a concomitant anterior labral repair or in cases of excessive anterior instability without any appreciable labral tear.[31]

Although it is well known that capsular stitches hold well in the labrum and anterior capsule, the posterior capsule is thinner, less robust biomechanically, and may not provide an optimal fixation construct.[5] When addressing laxity, the goal of plication is to arthroscopically create a fold in the capsular tissue, thereby reducing the redundancy created by excessive stretch and/or pull on the capsule. Several methods of capsular plication to the PI quadrant are in current clinical use,[2,9] and several outcome studies describe results of plication[6,30,36,38]; however, no studies in the literature to date compare the biomechanical properties of several different plication techniques to the PI quadrant of the glenohumeral capsule.

The purpose of the present study was to determine the clinically relevant biomechanical properties (mode of failure, ultimate load to failure, load at 2 mm of displacement, as well as displacement) of suture plication of the PI quadrant of the glenoid, performed using various plication repair constructs to an intact labrum. Specifically, repairs with simple stitch configuration, horizontal mattress configuration, and figure-of-8 configuration were compared. Our null hypothesis was that there would be no biomechanical differences between the different repair constructs.

MATERIALS AND METHODS

A total of 21 independent fresh-frozen human cadaveric shoulders with a mean age of 57.7 ± 12.3 years (range, 33-92 years) were thawed and dissected down to the glenohumeral capsule and labrum. There were 9 right shoulders and 12 left shoulders from 14 male specimens and 7 female specimens. After all soft tissues were dissected, the humeral head was disarticulated from the glenoid via careful dissection of the capsular tissue from its most lateral insertion on the humerus, thereby preserving as much capsular tissue as possible. Each glenoid was then visually inspected. Exclusion criteria were (1) significant degenerative changes, (2) any absent labral tissue, and (3) labral damage to the inferior quadrants including cracks, splitting, fissures, or any other incompetencies; however, no specimens met criteria for exclusion. To analyze the influence of bone density, each specimen also underwent dual-energy x-ray absorptiometry (DEXA) bone density testing with a bone densitometer at the region of the bone intended for fixation as well as at the anatomical neck of the humerus.

For all specimens, the glenoid capsulolabral complex was divided into quadrants, with the focus on the PI quadrant. The posterior half of the complex was defined as the inferior half of the glenoid from 3 o'clock to 9 o'clock (right shoulder) with the 6 o'clock position separating the anteroinferior quadrant from the PI quadrant. The position of interest was thus from 6 o'clock to 9 o'clock (right shoulder). Specimens were randomized to 1 of 3 groups (n = 7 per group): group 1, capsulolabral plication with simple stitch configuration; group 2, capsulolabral plication with horizontal mattress stitch configuration; and group 3, capsulolabral plication with figure-of-8 stitch configuration (Figure 1).

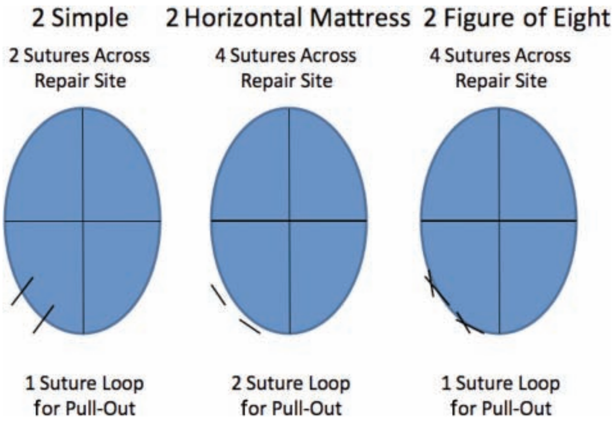

Figure 1. Comparison of specimens repaired with simple stitch configuration, horizontal mattress stitch configuration, and figure-of-8 stitch configuration.

No labral preparation or tears were created in any of the specimens. For each specimen, 2 stitches were positioned at 7 o'clock and 8 o'clock. The capsular plication stitch was placed in the posterior capsule 10 mm from the capsulolabral junction using a 45° suture lasso (Arthrex Inc, Naples, Florida). The suture lasso was directed so that the tip exited at the labral-articular surface interface, and the nitinol wire was advanced. A No. 2 Fiberwire (Arthrex) suture was placed in the nitinol wire loop from the articular side and passed through the capsulolabral tissue to exit on the capsular side. For specimens in group 1, capsulolabral plication was repaired with a simple stitch configuration and tied with reverse half-hitches on alternating posts. For specimens in group 2, the initial suture limb was passed as described for the simple stitch. The suture lasso was used to penetrate the capsule a second time at 5 mm from the first suture limb, and the suture limb from the articular side was passed to the capsular side. A horizontal mattress stitch configuration was tied on the capsular side with reverse half-hitches on alternating posts. For the specimens in group 3, the initial suture limb was passed as described for the simple stitch. Next, the suture lasso was used to penetrate the capsule a second time at 5 mm from the first suture limb, and the suture limb from the capsular side was passed to the articular side creating a figure-of-8 stitch configuration. The knot was also tied with reverse half-hitches on alternating posts (Figure 2).

After repair, the glenoid was separated from the remainder of the scapula by sawing 1 cm below the infraglenoid ridge along the infraspinatus fossa in a medial direction, cutting along the medial border of the scapula just under the spine. Each specimen was then potted in dental acrylic (Isocryl, Lang Dental, Wheeling, Illinois) so that the glenoid fossa was parallel with the surface of the potting container. After potting, the capsular tissue was cut with a scalpel at the 6 o'clock and 9 o'clock positions to isolate the PI quadrant. Before testing, 2 markers

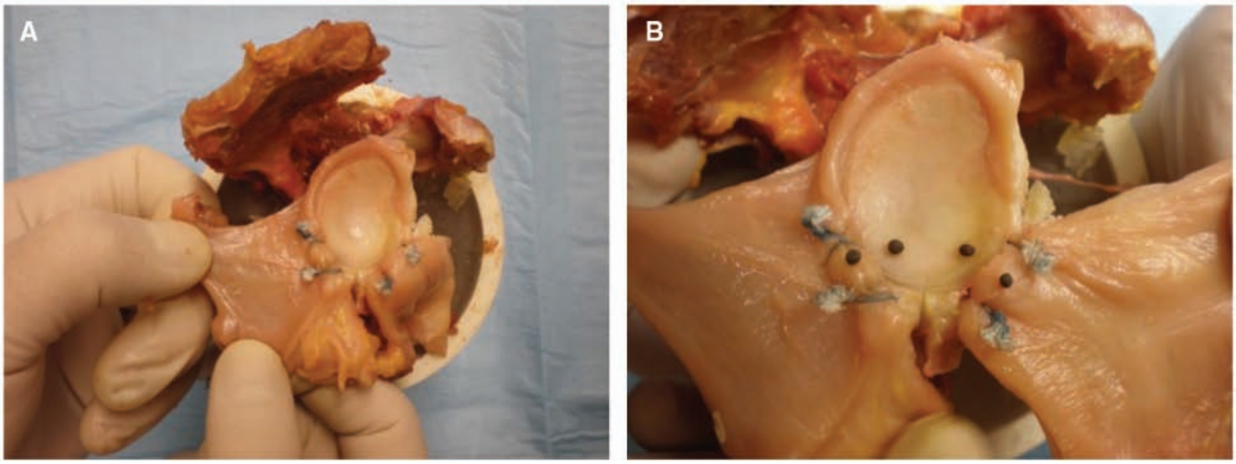

Figure 2. A, specimen preparation. Shown is figure-of-8 stitch configuration (also shown is anteroinferior quadrant repair). B, markers on specimen to enable optical determination of capsular tissue displacement during testing.

were placed on the surface of the specimen to optically determine capsular tissue displacement during testing, with one marker on the surface of the glenoid and the other marker 1 cm away on the surface of the labrum between the 2 sutures (Figure 2). Digital calipers (with 0.1 mm resolution) were used to ensure consistent placement of the markers among specimens.

The specimen was then loaded into a materials testing system ([MTS] MTS Insight 5, MTS Systems Corp, Eden Prairie, Minnesota) for biomechanical testing. The potted glenoid was placed in a custom-made jig fixed to the platform of the MTS. The repaired PI quadrant was placed in a custom soft tissue clamp, attached to an in-line 1000-N load cell. The clamp gripped the specimen 1.5 cm above the marker on the labrum (again, verified with digital calipers to ensure consistency across specimens). The specimen was oriented such that the vector of labral translation force was directed from the glenoid in a PI direction (Figure 3). A 1 megapixel digital video camera was used to optically track the specimen markers throughout testing.[11] The recorded video (48 frames per second) was analyzed with Digital Motion Analysis Software (Spica Technology Corporation, Maui, Hawaii), which was synchronized to the force and actuator displacement data from the MTS software. On the basis of our calibration studies of marker displacements similar to those seen in the present study, the measurement precision and accuracy of our optical imaging system was 3 μm and 60 μm, respectively. Based on previous studies[27,31] and our own pilot data, the following testing conditions were used for each specimen: preload at 5 N (constant load) for 2 minutes, followed by cyclical loading for 100 cycles from 5 to 25 N at 1 Hz, followed by pulling to failure load at 15 mm/min.

Data analyzed included mode of failure, ultimate load to failure, load at 2 mm of tissue displacement, as well as tissue displacement during cyclical loading (during the entire 100 cycles and during the final cycle only). For tissue displacement analyses, using the optical tracking software a segment was defined as the shortest distance between the 2 surface markers. From the cyclic test, 2 primary parameters were quantified, including *cyclic elongation,* defined as the relative increase in segment length from the peak load of the first cycle to the peak load of the final cycle of testing, and *elongation amplitude,* defined as the peak to valley measurement of the segment elongation for the final test cycle. Load at 2 mm of tissue (optical) displacement as well as ultimate load to failure were determined via the synchronized digital motion analysis software and MTS data from the pull-to-failure test. After failure occurred, the failure mode was determined (eg, suture tear, tear at glenolabral junction, tear at capsulolabral tissue).

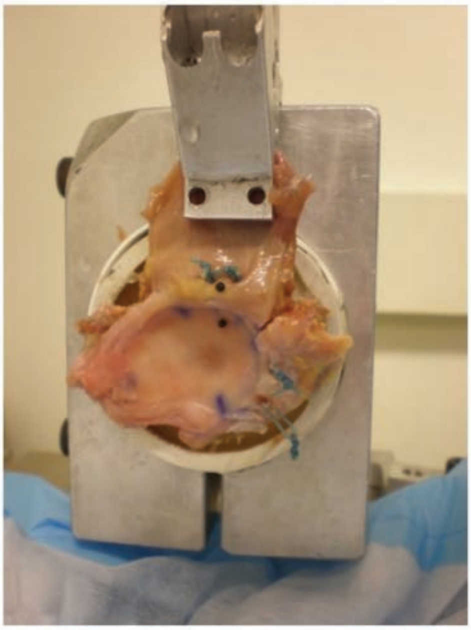

Figure 3. Specimen testing setup.

TABLE 1
Specimen Characteristics

Patient Detail	Simple Stitch	Horizontal Mattress	Figure-of-8	*P* Value
Age, y	56.0 ± 6.0	60.1 ± 10.8	57.0 ± 19.3	.83
Bone mineral density, g/cm^2	0.61 ± 0.10	0.61 ± 0.11	0.62 ± 0.21	.99
Gender	M: 6 of 7 (86%) F: 1 of 7 (13%)	M: 5 of 7 (71%) F: 2 of 7 (29%)	M: 4 of 7 (57%) F: 3 of 7 (43%)	
Side	L: 4 of 7 (57%) R: 3 of 7 (43%)	L: 5 of 7 (71%) R: 2 of 7 (29%)	L: 3 of 7 (43%) R: 4 of 7 (57%)	

TABLE 2
Biomechanical Results

	Simple Stitch	Horizontal Mattress	Figure-of-8	*P* Value
Ultimate load to failure, N	290.1 ± 142.0	246.6 ± 155.0	246.1 ± 93.2	>.05
Load at 2 mm displacement, N	75.2 ± 19.3	84.9 ± 37.8	84.9 ± 24.4	>.05
Stiffness, N/mm	40.1 ± 11.6	32.5 ± 19.9	35.9 ± 11.1	>.05
Cyclic elongation, mm	0.85 ± 0.56	0.87 ± 0.54	0.65 ± 0.40	>.05
Elongation amplitude (of final cycle), mm	0.65 ± 0.30	0.58 ± 0.10	0.75 ± 0.25	>.05
Method of failure	Glenolabral: 3 of 7 (43%) Capsule: 4 of 7 (57%)	Glenolabral: 6 of 7 (86%) Capsule: 1 of 7 (14%)	Glenolabral: 5 of 7 (71%) Capsule: 2 of 7 (29%)	<.0001

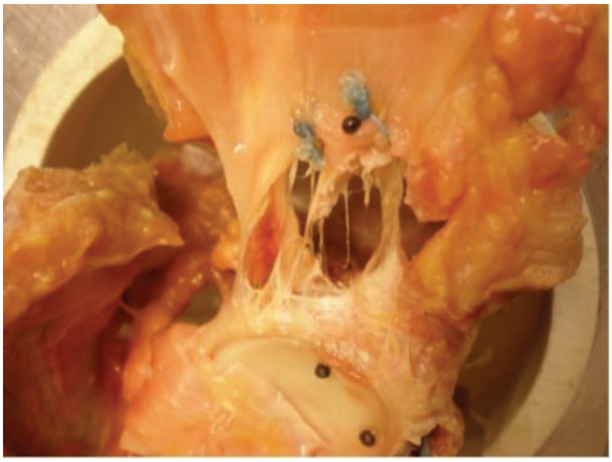

Figure 4. Glenolabral failure after pull-to-failure testing.

Figure 5. Capsular tissue failure after pull-to-failure testing.

One-way analysis of variance with Tukey post hoc testing was used to analyze data from the 3 different groups using SPSS software (SPSS Science Inc, Chicago, Illinois), with statistical significance at $P < .05$. Chi-square testing was used to analyze modes of failure between the testing groups, with statistical significance at $P < .05$.

RESULTS

There was no significant difference in age or average bone mineral density between the 3 groups of shoulder specimens, as indicated in Table 1. No specimens failed during cyclic testing.

The ultimate load to failure in the simple stitch, horizontal mattress, and figure-of-8 groups was 290.1 ± 142.0 N, 246.5 ± 155.0 N, and 246.1 ± 93.2 N, respectively, which was not statistically different. Similarly, the load required to reach 2 mm of displacement during the failure testing was also not statistically different among the 3 groups. The biomechanical results are summarized in Table 2.

The modes of failure differed among the 3 groups, as shown in Figures 4 (glenolabral failure) and 5 (capsular rupture failure). In the simple stitch group, failure occurred by capsular rupture outside the construct, between the clamp and the stitch in 4 specimens (57.1%) and by tearing at the glenolabral junction in 3 specimens (42.9%). In the horizontal mattress group, failure occurred at the glenolabral junction in 6 specimens (85.7%) whereas a single specimen failed by capsular rupture (14.3%). In the figure-of-8 group, failure at the glenolabral junction again accounted for 5 failures (71.4%) while rupture of the capsule was responsible for 2 failures (28.6%). Statistical analysis with chi-squared contingency table testing showed a significant difference ($P < .0001$) among the failure mechanisms among the 3 groups.

From the cyclical loading data, there was no statistically significant difference in elongation of the repair construct among the 3 groups. There was also no statistically significant difference in the gapping of the final cycle (of 100) among the 3 groups, as shown in Table 2.

DISCUSSION

In this study, the biomechanical properties of several different repair constructs for plication to the PI quadrant of the glenoid capsule were compared. Although there are several biomechanical studies describing properties of repair constructs for anterior shoulder instability repair, to our knowledge this is the first study to report on these same properties for the posterior portion of the capsule. The structural and mechanical properties of the posterior capsule differ from those of the anterior capsule, thus making it important to study and understand the biomechanical properties as they relate to plication techniques.[5] In particular, this is the only study to date to examine the biomechanical properties of plication repair constructs after cyclical loading of the repair construct. It is important to analyze such results after cyclical loading as this type of load applies a repetitive, yet modest, force to the repair construct, which may be more clinically relevant and consistent with early passive range of motion compared with the one-time, more intense force applied during an ultimate load to failure test.[3,4]

The principal findings of this study support our null hypothesis, as there were no biomechanical differences between each of the 3 repair constructs. The ultimate load to failure for the 3 groups was approximately 260 N, which is consistent with the data presented in other studies analyzing the properties of the anterior portion of the capsule.[12,22,23,25,37] The only other study[31] reporting on the failure loads of plication repair constructs to the PI quadrant reported values of 275.8 ± 50.9 N for plication alone (intact labrum) and 309.7 ± 68.6 N for plication with anchors (torn labrum), again similar to the data reported in the present study. No comparisons can be made regarding the results after cyclical loading because there are no current studies that report this type of information for the posterior capsule.

With regard to mechanism of failure, we found that none of the constructs failed at the arthroscopic knot, and that all specimens failed either at the glenolabral junction or in the midsubstance of the capsular tissue itself. Interestingly, while only 2 modes of failure occurred in this study, failure at the glenolabral junction occurred predominantly in repairs using horizontal mattress and figure-of-8 repairs, while failure via capsular rupture accounted for nearly half of the failed simple stitch repairs. When failure occurs outside the repair construct, such as at the midsubstance of the capsular tissue, the repair is thought to be stronger than the tissue. In contrast, when failure occurs within the repair construct, either at the capsulolabral-suture interface, suture loop, knot, suture-capsular tissue interface, then the repair is thought to be weaker than the tissue. After biomechanical testing, the mode of failure occurred at the weakest point of the repair construct. Simple stitch configuration failed in 57.1% of cases at the midsubstance of the capsular tissue compared with 14.3% in the horizontal mattress group and 28.6% in the figure-of-8 group ($P < .0001$). These results suggest that the weakest point of the simple stitch repairs occurred at the midsubstance of the capsular tissue, which was outside the plication repair construct. One possible explanation is that simple repair constructs only require 1 passage of the suture limb through the capsulolabral junction, whereas horizontal and figure-of-8 require 2 per stitch. Perhaps multiple penetrations by the suture lasso and placement of suture material do not add additional strength to the repair and may, in fact, be detrimental at the time of initial fixation. We have previously reported that a single pass through the intact labral offers the same fixation strength as a suture anchor, but multiple passes were not evaluated.[31] Further animal studies and/or in vivo studies are needed to determine whether multiple penetrations into the capsular tissue may heal over time or whether the multiple penetrations may compromise the strength of the healed tissue.

The pull to failure of 15 mm/min was chosen based on previous studies as well as our own pilot data. During pilot studies, slower pull-out rates (3 and 10 mm/min) resulted in substantially increased capsular stretching, and thus the strength of the actual repair was unable to be quantified. Faster pull-out rates (20 and 30 mm/min) tended to cause significant stretching of the suture loops, which was never experienced at our chosen rate of 15 mm/min. In addition to determining the ultimate load to failure as well as gapping during cyclical loading, load at 2 mm displacement was also addressed. This data point was chosen as previous studies have determined that failure of arthroscopic knots occurs at 1 to 3 mm of displacement,[8,18] and the results indicate that posterior capsular plication repairs with simple stitch, horizontal mattress, and figure-of-8 configurations perform similarly at this 2 mm mark.

Plication of the posterior capsule via arthroscopic surgical techniques has become an accepted method of performing shoulder stabilization.[6,7,24,32,39,40] Capsular plication must be performed correctly, as less than optimal plication results in redundancy while overtightening of the capsule may result in labral damage and loss of motion with potentially deleterious consequences.[13] Repair techniques involving anchors have been used; however, techniques without anchors are also commonly used, especially in the case of an intact labrum. Capsular plication can be performed in isolation or as an adjunct to capsulolabral repair. In a prior study,[31] we studied the difference in repair strength of capsular plication using either an intact labrum or an injured labrum (Bankart lesion) with suture anchor repair, and determined that there was no difference in ultimate load to failure. The clinical application of this study was to test the biomechanical strength of commonly used suture configurations for capsular plication because no other study in the literature has determined the superiority of one method over another. None of the specimens used in this study had evidence of partial labral avulsion ("Kim's lesion")[17-19] or other labral damage; however, it is critical to rule out any evidence of labral injury in the operating room setting as plication with suture anchors might provide a more secure repair in this situation.

In the present study, there was no difference in ultimate load to failure between any of the 3 groups. Taken with the results from our previous study, the results from this study would suggest that the simple stitch configuration, horizontal mattress configuration, and figure-of-8 stitch configuration would all be appropriate choices for plication repair without the use of suture anchors. However, there seems to be no significant advantage to more complex stitch configurations. Simple stitch capsular plications may be preferred because of the relative ease of use as well as a single capsular penetration with a single suture loop, which causes less trauma to the intact capsulolabral tissue. Plication of the posterior capsule may be employed in the arthroscopic management posterior capsular laxity, or as an adjunct in cases of anterior glenohumeral instability.[21,38]

There were several limitations to this study. As with any cadaveric study, this was a time zero in vitro analysis and there was no opportunity for capsular tissues to heal following the plication. Because both the time and method of healing that occur between the tissues after plication, as well as the repair construct fixation strength needed to allow for early postoperative rehabilitation are unknown, the results from this study may differ from what occurs in an in vivo setting. We are not aware of any study describing the in vivo healing of arthroscopic capsular plication, and further study is clearly needed on this topic. The capsular tissue in each specimen was not stretched before testing, and it is possible that more laxity may better replicate clinical situations. In addition, despite visually inspecting each specimen to ensure that it was free of glenohumeral disease, it was not possible to determine whether the specimens had any history of prior instability. In order to minimize the effects of age on blood supply and degeneration to the glenoid,[1,29] cadavers with a relatively young mean age of 57.7 ± 12.3 years were included in this study.

Strengths of the current study were multiple. The study was appropriately powered to determine if there were differences between 3 different suture configurations for capsular plication using the labrum as a point of fixation. Specifically, based on previous data from part 1[27] of this 2-part study with 21 specimens, the study had 80% power with an alpha error level of .05 to detect a difference in means between the 3 different suture configuration groups. In addition, there were no differences in terms of age or bone mineral density. The repairs differed only by the suture configuration, and all repairs were performed using the same instruments, suture material, and arthroscopic knot-tying technique. The biomechanical testing parameter was performed with cyclic loading to replicate clinical conditions akin to a postoperative situation.

CONCLUSION

The optimal fixation construct for posterior glenohumeral capsular laxity has not yet been determined and several different techniques have been described. In the present study, we determined that there was no difference between capsular plication with simple stitch, horizontal mattress, or figure-of-8 repairs in terms of displacement, load at 2 mm of displacement, and ultimate load to failure. Based on these results, all 3 stitches can be used effectively for capsular plication. Simple stitch capsular plication may be preferred because of its equivalent biomechanical strength and because it is technically easier to perform and less traumatic to the capsulolabral tissue. However, in vivo capsular healing following arthroscopic placation and effect of stitch configuration has yet to be determined.

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