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Biomechanical similarities among subscapularis repairs after shoulder arthroplasty

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Hypothesis: Many authors suggest that subscapularis deficiency after shoulder arthroplasty has a negative effect on long-term outcomes. Thus, increasing emphasis has been placed on the technique for repair of the tendon. This study evaluated the biomechanical strength of 3 different repairs: osteotomy, tendon to bone, and a combined method.

Materials and methods: Twenty-four paired shoulders from deceased donors were prepared for shoulder arthroplasty. The subscapularis tendon was removed/repaired with the lesser tuberosity in the osteotomy group, was removed periosteally in the bone-to-tendon group, and was tenotomized in the combined group. The tendon-to-bone repair used bone tunnels, and the combined construct added tendon-to-tendon fixation. A materials testing system machine was used for cycling. A digital motion analysis system with spatial markers was used for analysis.

Results: There were no significant differences ($P > .05$) in age, bone mineral density, or construct thickness. No statistically significant differences ($P > .05$) in elongation amplitude ($P = .67$) or cyclic elongation ($P = .58$) were detected within the constructs or between repair techniques. Failure testing revealed no differences in maximum load, stiffness, or mode of failure.

Discussion: There remains no consensus about the optimal method of repairing the subscapularis tendon during shoulder arthroplasty. Furthermore, the results of the current study do not support one technique over another with regard to initial fixation properties. All constructs investigated exhibited comparably robust biomechanical performance. Durability may, therefore, be more a result of healing potential than the specific construct chosen.

Level of evidence: Basic Science Study, Biomechanical Study

Keywords: Shoulder arthroplasty; subscapularis; repair; lesser tuberosity osteotomy; tendon to tendon repair

Shoulder arthroplasty is an effective treatment for patients with end-stage glenohumeral arthritis, and its prevalence has increased in contemporary orthopedics with the availability of new implants and an aging population. Patients are now younger and more active, thus magnifying the issue of prosthetic durability and functionality. Many factors influence the outcome of a shoulder replacement, including rotator cuff functionality, soft-tissue balancing, activity

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demands, bone quality, and component wear. However, recent research has focused on the contribution of the subscapularis muscle.[3,7,8,10]

The standard deltopectoral surgical approach to the shoulder mobilizes the subscapularis tendon with an osteotomy or tenotomy for exposure to the glenohumeral joint. The effect of a compromised subscapularis tendon postoperatively has been the focus of current clinical and biomechanical studies. Miller et al[15] showed by physical examination that approximately 66% of patients have persistent subscapularis dysfunction after shoulder arthroplasty. Gerber and Edwards et al[7,10] have further suggested that subscapularis deficiency has a negative effect on the long-term outcomes for shoulder arthroplasty. Thus, increasing emphasis has been placed on the technique for repair of the tendon.

The 3 predominant methods for releasing the tendon are a tenotomy leaving a cuff of tendon, periosteal release off the proximal humerus, and osteotomy of the lesser tuberosity in its entirety.[9] A variety of techniques have been proposed for reattachment of the subscapularis tendon.[1,6,9,10,20] These include bone-to-bone, tendon-to-tendon, tendon-to-bone, and combination procedures. Each method has its own innate technical complexities, and current biomechanical results do not consistently support one construct over another.

Krishnan et al,[13] using a biomechanical test protocol with progressively increasing cyclic load levels, found bone-to-bone to be stronger than tendon-to-tendon repair, yet Van den Berghe et al[20] demonstrated no difference under conditions of fatigue loading. Ahmad et al[1] have suggested that a combined construct is more resilient than a tendon-to-bone repair; however, this configuration has not been compared against a bone-to-bone technique.

Long-term clinical data are presently unavailable. The objective of the current study was to assess the biomechanical response to cyclic subfailure loading and to quantify the failure properties of a bone-to-bone lesser tuberosity osteotomy, tendon-to-bone, and combined tendon-to-bone subscapularis repair techniques used in shoulder arthroplasty.

Materials and methods

This study was exempt from Investigational Review Board approval.

Testing was done with 24 fresh frozen shoulders from deceased male donors (12 contralateral pairs) who were an average age of 57 ± 8 years. Bone mineral density (BMD) testing was performed on all specimens using a dual-energy x-ray absorptiometry (DEXA) scanner (General Electric Lunar Prodigy, Madison, WI). During the scan, each humerus was specifically positioned so that BMD was assessed near the fixation site. After BMD measurements, the shoulders were randomly divided into 3 groups while ensuring that the same repair technique was not used for both the left and right shoulders of a particular matched pair: a combined bone-to-tendon repair, a tendon-to-bone repair, and a lesser tuberosity osteotomy. Each shoulder was dissected down to the glenohumeral joint. No specimens had evidence of fractures or gross pathology of the rotator cuff, glenohumeral capsule, or surrounding soft-tissue envelope.

The subscapularis was reflected off the scapula, and the humerus was detached from the glenoid by releasing the capsule with the subscapularis tendon intact. The supraspinatus and infraspinatus musculotendinous complexes were completely detached from their insertions on the proximal humerus, and attention was turned to preparation for the arthroplasty. The subscapularis tendon was removed, as described subsequently, and a reciprocating saw was used to make a bone cut at the anatomic neck of the proximal humerus, ensuring anatomic retroversion.

The humeral canal was prepared with standard arthroplasty broaches (Univers, Arthrex, Naples, FL). Once the canal was broached to the appropriate size, a 2.0-mm drill was used to create bone tunnels for each suture repair, as described subsequently. Prostheses with varying stem sizes according to the anatomic humeral size were then inserted (Univers TSR) for all repair groups, and the subscapularis tendon repair was completed.

Method 1: Combined tendon-to-bone/tendon

In the combined tendon-to-bone/tendon group, a tenotomy of the subscapularis tendon was performed approximately 1 cm medial to the attachment of the lesser tuberosity. The humerus was prepared, and 3 bone tunnels were created just lateral to the subscapularis insertion on the lesser tuberosity that exited in the humeral canal. Three sutures of No. 5 Fiberwire (Arthrex, Naples, FL) were placed through the bone tunnels, and the humeral prosthesis was inserted. The 3 sutures were then sutured to the tenotomized tendon in a modified Mason-Allen configuration. The tenotomy was reapproximated and 3 tendon-to-tendon simple sutures were placed to complete the repair (Fig. 1, A).

Method 2: Tendon-to-bone

In the tendon-to-bone group, the subscapularis was released periosteally off the lesser tuberosity. The humerus was cut and broached, and 4 holes were placed approximately 5 to 8 mm from the edge of the humeral cut. No. 5 Fiberwire suture (Arthrex, Naples, FL) was then placed through the bone tunnels. The prosthesis was inserted and the tendon was repaired with 4 No. sutures through the bone tunnels in a modified Mason-Allen construct (Fig. 1, B).

Method 3: Lesser tuberosity osteotomy

A thin osteotome was used to remove the lesser tuberosity with the subscapularis insertion intact, as described by Gerber et al.[9] The humerus was prepared in a standard fashion and 4 unicortical bone tunnels were created just lateral to the lesser tuberosity.[9] The humeral component was inserted, and the lesser tuberosity osteotomy was repaired by placing 2 No. 5 sutures over the osteotomized fragment. Each suture entered the superficial tendon at the tendon-bone interface and was then brought from deep to superficial in a mattress-type configuration. The needle was passed through the bone tunnel and tapped out of the cortex at the greater tuberosity. The sutures were tied over a small 7-hole titanium plate (Synthes, Paoli, PA), as described by Gerber et al[9] (Fig 1, C).

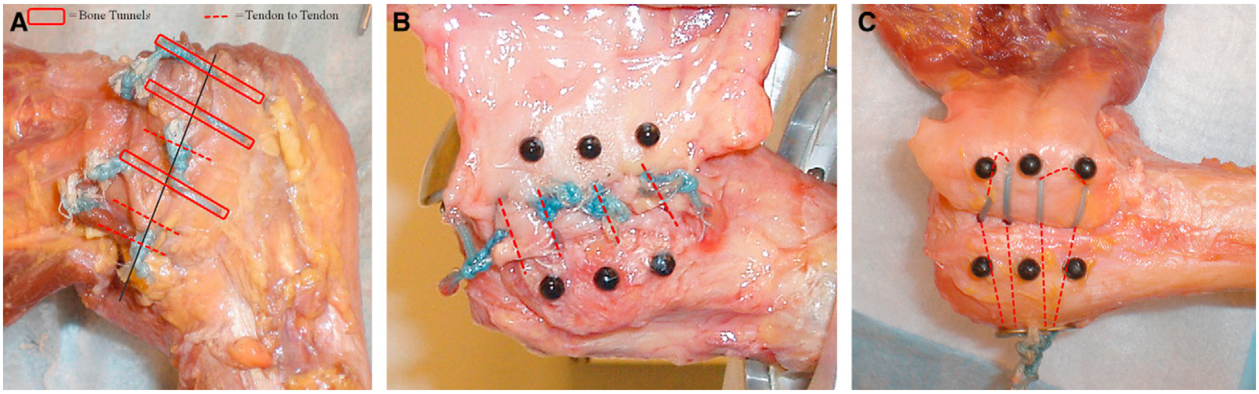

Figure 1 Repair constructs were **(A)** combined tendon-to bone (3 sutures) with modified Mason-Allen sutures and tendon-to-tendon (3 sutures) using a simple suture repair, **(B)** a tendon-to-bone repair with 4 modified Mason-Allen sutures, and **(C)** a lesser tuberosity osteotomy.

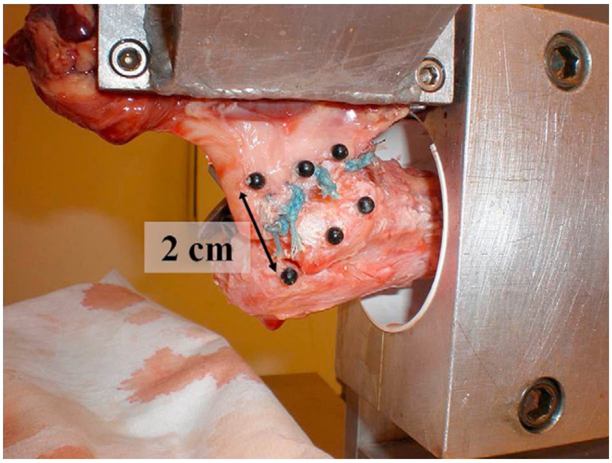

Figure 2 In the experimental setup for digital video tracking of marker positions, pairs of markers were placed at the superior, middle, and central aspects spanning the tendon repair site.

Experimental setup

After each repair technique was completed, tissue thickness at the repair site was measured using a precision caliper with 0.1-mm resolution. The proximal humerus was potted within a plastic cylinder using acrylic cement (Isocryl, Lang Dental, Wheeling, IL) and mounted to a custom alignment fixture secured to the base of an electromechanical materials testing system (MTS Insight 5, Eden Prairie, MN). The subscapularis muscle was secured within a cryogenic clamp such that the long axis of the tendon was aligned vertically, in line with the test actuator.

Specimens were placed in neutral humeral rotation by isolating the anatomic pull of the subscapularis pretenotomy/osteotomy and marking the location of the biceps groove in the testing apparatus. This orientation was then reproduced for the tested condition. Three pairs of spatial markers were placed at the superior, middle, and inferior portions of the tendon, with 1 marker on each side of the repair construct (Fig. 2). Each marker was placed just medial to the suture line on the tendon/muscle side, with the corresponding marker placed 2 cm from its pair on the bone (lateral) side of the repair.

A digital motion analysis system consisting of a high-resolution digital video camera (1000 × 1000 × 48 fps, Imperx IPX-1M48-L, Boca Raton, FL) and digital motion analysis software (Spica Technology Corp, Maui, HI) was used to optically record and measure displacements of each set of markers affixed to the repairs.[11] Each specimen was preloaded to 10 N for 1 minute, loaded for 150 cycles from 10 to 100 N at 0.5 Hz, and finally pulled to failure at 1 mm/s. Throughout cyclic and failure testing, load, actuator displacement, and time were recorded synchronously with the optical data using dedicated MTS TestWorks software. Specimens were regularly moistened using a saline mist spray during testing. Construct failure mode was visually classified as occurring within the bone, tendon, or muscle.

Data analysis

For optical data analysis, segment length was measured regionally at the superior, middle, and inferior positions along each tendon specimen. Because the inhomogeneous structural properties of each repair construct resulted in marker displacements along both horizontal and vertical axes of the recorded digital images, for consistency, segment length was defined as the shortest distance between a pair of markers. Segment lengths were also computed by averaging the data across the 3 regions. The change (increase) in segment length relative to the preloaded state was computed for each anatomic position to describe local construct deformation throughout testing. From the cyclic test, 2 primary parameters were quantified (Fig. 3): (1) cyclic elongation, defined as the increase in segment length from the peak load of the first cycle to the peak load of the final cycle of testing, and (2) elongation amplitude, defined as the peak-to-valley measurement of the segment elongation for the final test cycle. During the pull-to-failure test, maximum load and linear stiffness were determined; stiffness was calculated as the steepest slope of the load-displacement curve spanning 30% of the data points collected between initiation of the load-to-failure test and the maximum load. A repeated measures (within-group) analysis of variance (ANOVA) was used for comparison of tendon regions, and a between-group ANOVA was used to compare properties of the repair techniques. Failure modes were statistically compared using a χ^2 test. Values of $P < .05$ were considered statistically significant.

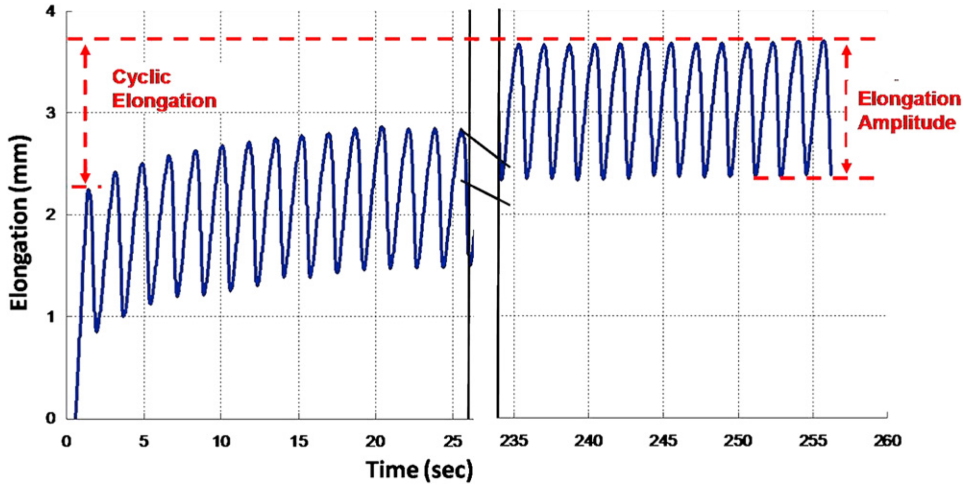

Figure 3 Optical displacement vs time plot illustrates peak-valley calculations.

Table I Demographic data of cadaveric specimens

	Tendon-to-bone	Combined	Lesser tuberosity osteotomy
	(n = 7)	(n = 7)	(n = 8)
Variable	Mean ± SD	Mean ± SD	Mean ± SD
Age, y	57 ± 6	56 ± 3	59 ± 12
BMD, g/cm^2	0.65 ± 0.18	0.57 ± 0.08	0.61 ± 0.10
Construct thickness, mm	4.9 ± 1.3	4.6 ± 0.9	4.8 ± 1.2

BMD, Bone mineral density.

Results

Data for 2 samples were lost due to MTS failure or optical tracking software failure (1 specimen each) during experimentation. For consistency of analysis, the data reported reflect those from specimens for which complete data sets were available for the mechanical and optical results for cyclic and failure tests. Demographic, BMD, and geometric data are summarized in Table I. ANOVA revealed no significant differences ($P > .05$) in age, bone mineral density, or construct thickness between the groups.

Regional marker elongation data for each construct are provided in Table II. No statistically significant differences ($P > .05$) in elongation amplitude or cyclic elongation were detected intraconstruct or among the repair techniques.

Cyclic testing results (Table III) revealed no significant differences among repair groups with regard to the mean (ie, averaged over the 3 regions) elongation amplitude ($P = .67$) or the mean cyclic elongation ($P = .58$). After failure testing, no differences were noted for maximum load and stiffness (Table III).

Ultimate failure mechanism results are displayed graphically in Fig. 4. Bone failure in the lesser tuberosity group occurred by the plate pulling through the cortex of the greater tuberosity. Bone failure in the tendon-to-bone group was defined as breach of the bone tunnels at the edge of the humeral cut. Tendon failure represented loss of soft tissue integrity at the site of repair and muscle failure, indicated tearing of the muscle belly. No statistical difference was found in failure mode among the 3 groups ($P = .125$).

Discussion

The standard deltopectoral approach for shoulder arthroplasty releases the subscapularis tendon for exposure to the glenohumeral joint. Recently, subscapularis deficiency and dysfunction in total shoulder arthroplasty has been shown to be both prevalent and problematic.[8,14,16,18] Sperling et al[19] illustrated the importance of the subscapularis muscle by showing that 72% of patients with painful arthroplasties and a rotator cuff tear had a deficient subscapularis. This was further substantiated by Edwards et al[7] in a multicenter study that revealed degeneration of the infraspinatus and subscapularis adversely affected total shoulder arthroplasty outcomes. Moreover, Moeckel et al[16] suggested that a torn subscapularis tendon can lead to instability, and Miller et al[15] showed potentially how prevalent subscapularis deficiency is by reporting that 66% of arthroplasty patients had an abnormal belly press. However, the latter study must be viewed in the context of the work by Armstrong et al[2] that concluded by ultrasound evaluation that physical

Table II Intraspecimen and interspecimen comparison of paired markers

		Column			Average
		Superior	Middle	Inferior	
Repair	Marker, mm	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Tendon-to-bone	Elongation amplitude	1.4 ± 0.4	1.3 ± 0.4	1.3 ± 0.6	1.3 ± 0.4
	Cyclic elongation	1.9 ± 0.6	1.8 ± 0.7	1.6 ± 0.8	1.8 ± 0.7
Combined	Elongation amplitude	1.0 ± 0.5	1.3 ± 0.5	1.2 ± 0.7	1.2 ± 0.5
	Cyclic elongation	1.7 ± 2.0	1.7 ± 1.5	1.7 ± 1.7	1.7 ± 1.7
Lesser tuberosity osteotomy	Elongation amplitude	1.4 ± 0.4	1.4 ± 0.4	1.3 ± 0.3	1.4 ± 0.4
	Cyclic elongation	1.3 ± 0.5	1.2 ± 0.6	1.2 ± 0.5	1.2 ± 0.5

Table III Results of cyclic and load-to-failure testing

		Tendon to Bone	Combined	Lesser tuberosity osteotomy	
		(n = 7)	(n = 7)	(n = 8)	
Testing	Variable	Mean ± SD	Mean ± SD	Mean ± SD	*P*
Cyclic	Elongation amplitude, mm	1.3 ± 0.4	1.2 ± 0.5	1.4 ± 0.4	.67
	Cyclic elongation, mm	1.8 ± 0.7	1.7 ± 1.7	1.2 ± 0.5	.58
Failure	Max load, N	431.2 ± 131.3	487.1 ± 68.3	543.3 ± 187.4	.33
	Stiffness, N/mm	48.7 ± 5.2	48.4 ± 6.8	51.5 ± 11.6	.75

examination has low sensitivity and specificity for subscapularis tendon tears in arthroplasty patients. Nonetheless, the contribution of an intact subscapularis tendon to a successful shoulder replacement has been borne out in the contemporary literature.

There remains no consensus about the optimal method of repairing the tendon after it has been mobilized for implantation of the prosthesis. Recent biomechanical and clinical studies have suggested that a variety of procedures can provide acceptable outcomes.[6,17] Ahmad et al[1] evaluated the tendon-to-bone and combined repair techniques using load-controlled tests with optical measurement of gapping. The results of their cadaveric study indicated that the combined tendon-to-bone/tendon repair construct produced less gapping than the tendon-to-bone configuration. Krishnan et al[13] biomechanically compared a modified lesser tuberosity osteotomy (bone tunnels through the bicipital groove) with a tendon-to-tendon repair and found that the osteotomy repair was significantly stronger when cycled to 180 N. Van den Berghe et al[20] evaluated tendon-to-tendon, tendon-to-bone, and bone-to-bone repairs of the subscapularis by cyclically loading constructs initially to 150 N and then at 300 N until failure. The bone-to-bone repair was stronger than the tendon-to-bone, but no significant differences were noted when compared with the tendon-to-tendon repair. They also noted that the tendon-to-tendon repair shortened the subscapularis, whereas the tendon-to-bone repair lengthened it. In contrast to the latter findings, the current study's results (obtained using a different loading protocol from those cited above) suggest similar biomechanical resiliency among all of the constructs.

The biomechanical loading protocol used in the current study, unlike prior subscapularis repair studies,[1,13,20] was specifically designed to facilitate quantification of subfailure and ultimate failure properties from 2 distinct loading regimens: load-controlled cycling and displacement-controlled test to failure, respectively. The aforementioned studies used load-controlled cycles with progressively increasing load magnitudes, focusing on achieving a desired amount of gap formation at discrete cycles or aiming to achieve failure during cyclic loading. In contrast, the protocol in the present study consisted of 150 loading cycles from 10 to 100 N at 0.5 Hz, followed by a load-to-failure test at 1 mm/s.

Our approach, consisting of a fixed number of loading cycles to a single peak load magnitude, followed by a failure test in displacement control, is similar to that used in published studies of initial biomechanical properties of supraspinatus tendon repairs[5,11] and in a multitude of knee reconstruction tendon graft studies. As reported in Table III, our loading approach yields 4 clinically relevant biomechanical parameters: 2 derived from subfailure loading and 2 from failure testing. In contrast, prior subscapularis studies typically report 2 or 3 parameters, primarily focusing on descriptions of failure.

Our results revealed no differences in cyclic and failure properties or modes of failure among the 3 procedures examined. For the parameters reported in Table III, statistical power ranged from 11% (for stiffness) to 20% (maximum load). Post hoc sample size determination revealed that 129 samples per group would be required to achieve 80% power for the parameter of maximum load. There are practical limitations to the number of specimens

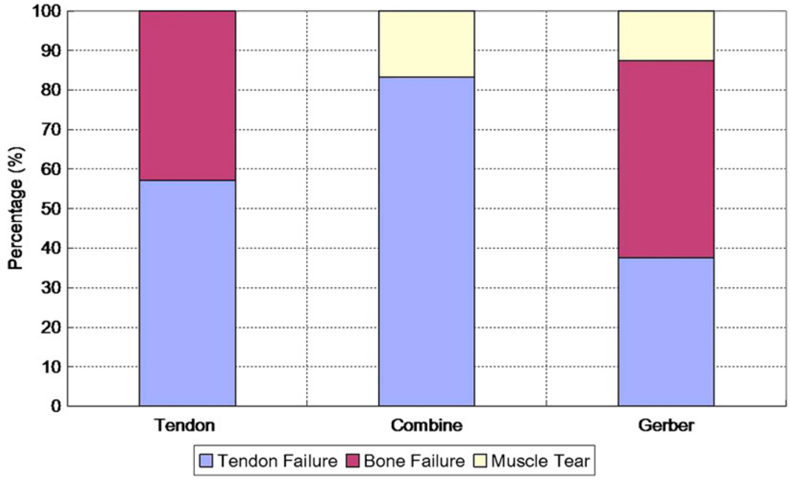

Figure 4 Distribution of modes of failure for each construct are shown.

that can be assessed in a study. The sample size in the current study of 7 or 8 per group is comparable to that of the 3 similar studies in the literature that had 5 or 6 specimens per experimental group.

Discrepancies between the results of the present study and those described are likely attributable to the different experimental approaches. Each of the mentioned 3 biomechanical studies used tensile loading protocols that featured increasing cyclic load magnitudes until a failure criterion was reached. In contrast, a single prescribed amplitude of cyclic loads was applied in the current study before a displacement-controlled elongation to failure test. Hence, a comparison of failure loads across these studies is neither reliable nor advisable. Furthermore, the present study and that of Ahmad et al[1] differed with respect to surface marker location and measurement technique.

The current cadaveric study examines the ‘‘time zero’’ biomechanical properties of tendon-to-bone, combined repair, and lesser tuberosity osteotomy constructs. We acknowledge that the lesser tuberosity osteotomy, as proposed by Gerber et al,[9] can be more difficult in a surgical setting; however, this technique has recently been proposed as a stronger and more durable repair technique with good clinical results.

Our results indicate minimal differences among the 3 groups with respect to tissue displacements during subfailure loading and structural properties during monotonic load-to-rupture testing. The use of the specific test parameters in this study reflected numerous considerations. We selected 150 test cycles owing to computer memory limitations inherent to continuous video recording of the surface markers. The cyclic load range of 10 to 100 N was chosen on the basis of our pilot experiments that revealed specimen failure within 100 cycles of cyclically loading to 150 N as well as our knowledge of the range of subscapularis tendon forces in vivo during passive arm motion (maximum value of approximately 250 N with low demand values of 100 N).[4,12]

Conclusion

The results of the current study do not support one technique over another with regard to initial fixation properties. All constructs investigated exhibited comparably robust biomechanical performance immediately postoperatively. Durability may therefore be more a result of healing potential than specific construct chosen. Each of the examined repair techniques represent a different mode of healing, including bone-to-bone, tendon-to-tendon, and tendon-to-bone. There is also early evidence that suggests fatty degeneration of the subscapularis may be important in ultimate function.[7,10] This may or may not be influenced by the tenotomy technique, and additional histologic and clinical data are required.

Disclaimer

Anthony R. Romeo, MD, is a consultant for Arthrex. The remaining 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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