Biomechanical Analysis of Medial-Row All-Suture Suture Anchor Fixation for Rotator Cuff Repair in a Pair-Matched Cadaveric Model

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Purpose: To compare the biomechanical properties of all-suture suture anchors (ASSAs) with conventional suture anchors (CSAs) for double-row rotator cuff repair (RCR). **Methods:** Fourteen fresh-frozen human cadaveric shoulders were randomized into 2 RCR treatment groups: ASSA and CSA. All constructs received a double-row repair, with the lateral-row implants consisting of two 5.5-mm PEEK (polyether ether ketone) Footprint anchors. Each construct was loaded to a 10-N preload for 2 minutes, followed by cyclic loading from 10 to 160 N at a rate of 100 N/s for 100 cycles. Load-to-failure testing was performed immediately after cyclic loading testing at 1 mm/s from the zero position until failure. Cyclic creep, elongation amplitude, maximum load, stiffness, energy, and failure mode were recorded. **Results:** No significant difference in cyclic creep ($P = .117$) or elongation amplitude ($P = .428$) was found between the ASSA and CSA groups during cyclic testing. Three specimens in each group (43% in each) failed by the suture tearing through the tendon. The remaining specimens in each group failed by the anchor pulling out of the humeral head. The mean maximum load was 617.73 ± 177.77 N and 545.13 ± 212.98 N for the ASSA and CSA groups, respectively ($P = .339$). Maximum elongation before failure was not different between groups ($P = .122$). Mean energy and stiffness were not statistically different between the ASSA and CSA groups ($P = .629$ and $P = .973$, respectively). **Conclusions:** In this cadaveric analysis with a simplified unidirectional experimental setup, failure mechanics and maximum load between the ASSA and CSA constructs were similar, with no difference in energy and stiffness. Although the ASSA group showed slightly larger elongation than the CSA group, these differences may not be clinically relevant. **Clinical Relevance:** This study provides a biomechanical head-to-head comparison of ASSAs and CSAs, indicating that ASSAs may be clinically equivalent to CSAs for use in an RCR.

The technical goals of arthroscopic rotator cuff repair (RCR) include achieving high initial fixation strength, minimizing gap formation, minimizing repair construct tension, and maintaining mechanical stability until biological healing occurs. The widely used conventional suture anchors (CSAs) are structurally dissimilar to all-suture suture anchor (ASSA) constructs, which could potentially offer some benefits over CSAs. It is important to determine whether these benefits come at the cost of the mechanical properties of the anchor construct.

The use of suture anchors for tendon fixation has evolved to become the accepted standard of care for most patients undergoing arthroscopic RCR. Suture

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anchor constructs allow for a variety of different fixation constructs, including single-row and double-row repairs, reconstruction with biological augmentation, and transosseous footprint reconstruction. Recently, ASSA constructs have been introduced for use in a variety of soft tissue—to—bone fixation constructs, including biceps tenodesis and labral repairs.[1-6] An all-suture fixation construct theoretically provides the biomechanical benefits of traditional suture anchor fixation while offering a low-profile construct that is less traumatic to the humeral cortex, allowing for less bone removal.[6] With less trauma to the cortex and the smaller-diameter pilot hole ASSAs require, more anchors may be placed within the humeral cortex compared with CSAs. Anchors causing less trauma to the cortex and fewer biological consequences are important to consider in patients with suboptimal bone such as those with osteopenia and osteoporosis as long as those anchors are comparable in terms of pullout strength. After a failed repair with anchor pullout, a CSA may become a hard loose body, creating more damage to the shoulder joint.[5,6] With these potential benefits of ASSAs over CSAs, it is important to understand the mechanical properties of ASSA fixation constructs and compare them with CSAs.

Few studies have investigated all-suture anchor biomechanics compared with traditional anchor methods. In 2016, Dwyer et al.[5] performed a biomechanical study comparing ASSA performance with bioabsorbable screw-in suture anchor performance. Using anchor fixation in both bovine tibia and human cadaveric glenoid specimens, they noted that in glenoid bone, all anchors performed similarly, and in bovine bone, when pre-tensioned, the ASSA performed similarly to the conventional screw-in anchor. Furthermore, Goschka et al.[6] reported comparable biomechanical properties of an all-suture anchor in the setting of an RCR specifically.

The purpose of this study was to compare the biomechanical properties of ASSAs with conventional suture anchors (CSAs) for double-row RCR. We hypothesized that there would be no difference in failure mechanisms or biomechanical properties between the ASSAs and CSAs with both cyclic and load-to-failure testing.

Methods

A total of 14 fresh-frozen matched (left and right) human cadaveric shoulders were included in this study after institutional review board exemption was granted. Specimens were selected from the cadaveric registry only if it was documented that there was no history of a rotator cuff tear and/or shoulder surgery. Each specimen underwent computed tomography scanning (BrightSpeed; GE Medical Systems, Fairfield, CT); the images were then imported into our institution's picture archiving and communication system, and bone mineral density (BMD) at the proximal humerus was calculated with a technique used in previous studies.[7] The specific locations for BMD evaluation were marked digitally in the picture archiving and communication system by a single investigator (E.D.B.). BMD between the left and right shoulders of each pair was evaluated to ensure no difference was found. The specimens were block randomized and assigned to 1 of the 2 test groups (ASSA or CSA) with the contralateral shoulder specimen assigned to the opposite group to ensure an equal number of right and left humeri in each group. Methods of fixation included an ASSA (Q-Fix implant 2.8-mm with blue-and-black Cobraid Magnumwire suture; Smith & Nephew, Andover, MA) and CSA (double-loaded Twinfix PK FT 5.5-mm anchor; Smith & Nephew).

Surgical Technique

The skin and muscles excluding the rotator cuff were removed from the specimens. The rotator cuff muscles were then dissected free of skin and soft tissues and were inspected for any signs of injury or previous tears

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by orthopaedic fellows and senior authors R.M.F. and B.R.W. The supraspinatus was isolated by dissecting the infraspinatus posteriorly and the rotator interval anteriorly, leaving only the supraspinatus tendon secured to the greater tuberosity. Once isolated, the supraspinatus was sharply detached from its insertion on the greater tuberosity. The tear was then repaired using 1 of the 2 repair techniques: ASSA or CSA (Fig 1). For all specimens, placement of the medial row was performed according to the implant instructions for the specific group. The first anchor was placed 5 mm posterior to the posterior edge of the long head of the biceps tendon and 5 mm lateral to the articular margin, whereas the second anchor of the medial row was placed 15 mm posterior (center to center) to the first anchor, keeping a distance of 5 mm from the articular margin. Sutures from the implant in the medial row were placed in a horizontal mattress fashion 5 mm lateral to the musculotendinous junction of the supraspinatus tendon, with approximately 3 to 4 mm between suture limbs.

In total, 4 suture limbs were passed through the tendon, being evenly distributed throughout the tendon to fill the width of the tendon consistent with methods performed in a clinical situation. Horizontal mattress sutures were then tied using 5 alternating half-hitch knots with reverse posts to reproduce arthroscopic knot configurations. All constructs received a double-row repair, with the lateral-row implants consisting of two 5.5-mm PEEK (polyether ether ketone) Footprint anchors (Smith & Nephew). The lateral-row anchors were placed 15 mm from the lateral edge of the greater tuberosity, directly lateral, in line with the anterior and posterior medial-row anchors. One suture limb from each of the medial-row mattress sutures was brought through each lateral-row Footprint anchor and affixed into the bone, creating a typical crossing double-row pattern. Sutures were loaded into the Footprint anchor and tensioned.

Biomechanical Testing

After completion of the tendon repairs, the humerus was transversely cut 6 inches distal to the supraspinatus insertion and potted in a polyvinyl chloride pipe using acrylic cement (Isocryl; Lang Dental, Wheeling, IL). The humerus was secured to an adjustable-angle mount positioned at a 30° angle to simulate the anatomic position of the supraspinatus with the arm in 60° of abduction[8] (Fig 2A). Specimens were placed in neutral humeral rotation using the biceps groove as a reference for each specimen (Fig 2B). The humeral mounting fixture was secured to the base of an Insight 5 Materials Testing System (MTS, Eden Prairie, MN). A custom freezer clamp was used to grip the supraspinatus muscle at the musculotendinous junction to apply tensile loading to the tendon repair constructs. Optical makers were placed on the specimens as well as the testing apparatus as a backup method of calculating outcome variables, such as cyclic creep, cyclic elongation, and elongation amplitude, but were not ultimately used in the analysis.

The repaired tendons were biomechanically assessed[8-11] using a 10-N preload for 2 minutes, followed

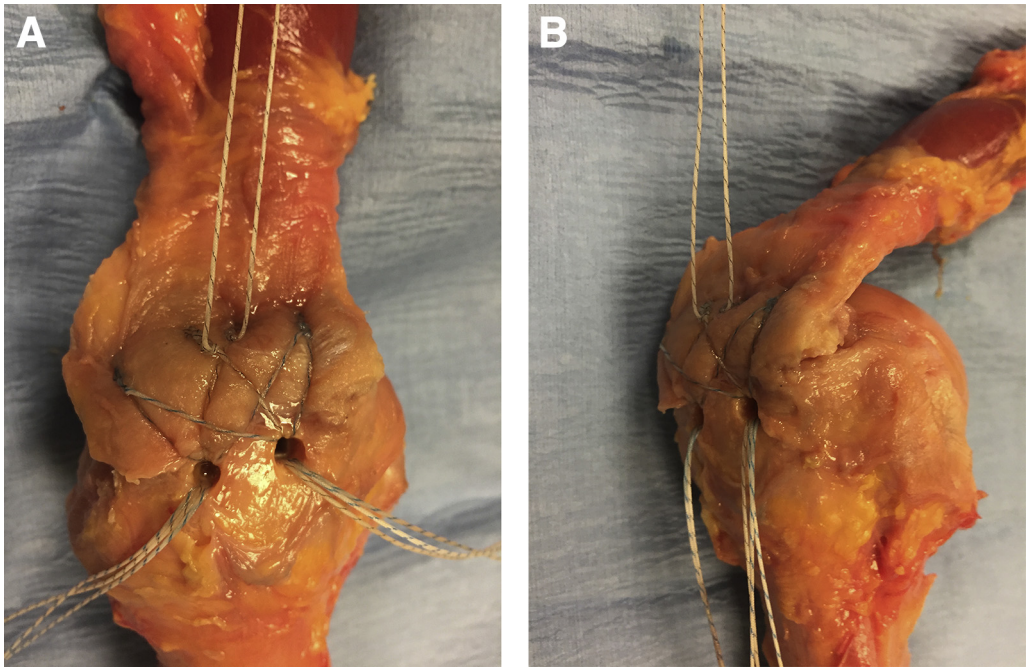

Fig 1. Lateral view (A) and anterior view (B) of cadaveric humerus and supraspinatus dissected out and repaired using a double-row repair technique with the medial row consisting of all-suture suture anchors or conventional suture anchors and the lateral-row implants consisting of two 5.5-mm PEEK Footprint anchors.

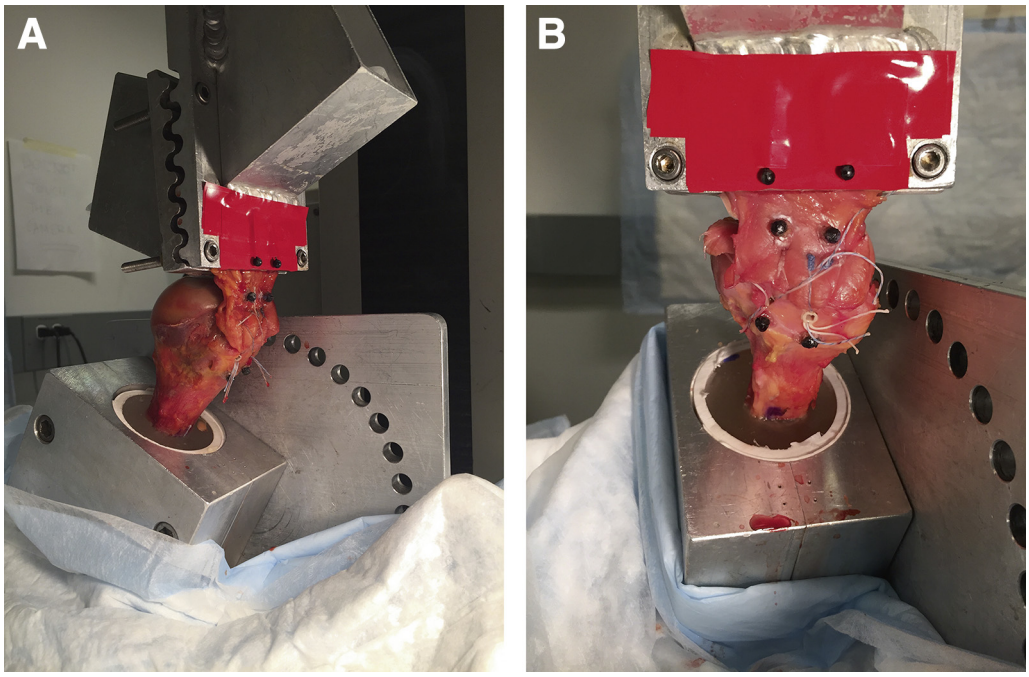

Fig 2. Side view (A) and front view (B) of the specimen secured to an adjustable-angle mount positioned at a 30° angle to simulate the anatomic position of the supraspinatus with the arm in 60° of abduction. The humeral mounting fixture was secured to the base of an Insight 5 Materials Testing System, and a custom freezer clamp was used to grip the supraspinatus muscle at the musculotendinous junction to apply tensile loading to the tendon repair constructs.

by cyclic loading from 10 to 160 N at a rate of 100 N/s for 100 cycles. Load-to-failure testing was performed immediately after cyclic loading testing at 1 mm/s from the zero position until failure. Maximum elongation was recorded as the distance the crosshead moved from the zero position to the point of failure, with the crosshead defined as the mounting fixture and freezer clamp. Specimens were regularly moistened using a saline solution mist spray during testing. Gauge length was defined as the distance from the most proximal suture-tendon interface to the freezer clamp, which was placed just proximal to the musculotendinous junction; this gauge length is assumed to be the strain-sensitive length of the testing apparatus. Cyclic creep was defined as the distance the crosshead moved from the preload to cycle 100, whereas cyclic elongation was defined as the distance the crosshead moved from cycle 1 to cycle 100. Elongation amplitude was defined as the distance the crosshead moved while the construct was loaded from 10 N to 160 N during the last cycle. Stiffness was calculated as the steepest slope spanning 30% of the data points from initial to maximum load during the failure test.[8,12] Total energy to failure was calculated as the area under the stress-strain curve until failure. Construct failure mode was visually classified as occurring within the tendon, suture, or bone. The timing (during cyclic or pull-to-failure testing) and mode of failure (screw, screw-tendon interface, or suture) were recorded. The method of fixation construct failure was grossly recorded.

Statistical Analysis

An a priori power analysis based on data using a similar methodology performed in our laboratory indicated that 14 specimens (i.e., 7 per group) would provide 80% power to detect a significant difference in mean load to failure between the 2 groups with an effect size of 0.6 and significance level of $P < .05$.[8] The statistical analysis was performed using IBM SPSS software for Windows (version 23.0.0; IBM, Armonk, NY). An independent-samples t test was used to compare groups, and a simple linear regression analysis was used to determine the relation between the independent variables BMD and gauge length and the dependent variables cyclic creep, cyclic elongation, elongation amplitude, maximum load, maximum elongation, energy, and stiffness to determine whether a linear relation existed between the variables. The adjusted R^2 value and P value were used to assess variation and significance. The Fisher exact test was used to determine whether failure modes were different between groups. Statistical significance was set at $P < .05$.

Results

Demographic Characteristics

Fourteen matched male cadaveric shoulder specimens were used for this study. The average age of the specimens was 52 ± 13 years, and the average body mass index was 29.49 ± 5.36 (Table 1). No significant difference in tendon gauge length was found between

Table 1. Cadaveric Demographic Characteristics

	Data
Age, yr	52 ± 13.0
Height, in	71.4 ± 2.1
Weight, lb	215.2 ± 40.7
BMI	29.5 ± 5.4
BMD, HU	
ASSA	257.0 ± 86.8
CSA	266.7 ± 83.2

NOTE. Data are presented as mean ± standard deviation.
ASSA, all-suture suture anchor; BMD, bone mineral density; BMI, body mass index; CSA, conventional suture anchor; HU, Hounsfield units.

the ASSA (15.18 ± 4.18 mm) and CSA (18.41 ± 3.11 mm) groups ($P = .563$). No significant difference in BMD was noted between the ASSA (256.97 ± 86.82 Hounsfield units) and CSA (266.63 ± 83.16 Hounsfield units) groups ($P = .999$).

Cyclic Testing

No significant difference in cyclic creep from preload to cycle 100 ($P = .117$) or elongation amplitude of the last cycle ($P = .428$) was found between the ASSA and CSA groups during cyclic testing (Table 2). Cyclic elongation from cycle 1 to cycle 100 was statistically significant between the ASSA (3.27 ± 0.43 mm) and CSA (3.03 ± 1.04 mm) groups ($P = .023$), with the ASSA group showing slightly larger elongation than the CSA group. However, the cyclic creep from preload to cycle 100 was not statistically significant between the ASSA (7.88 ± 1.32 mm) and CSA (8.49 ± 2.73 mm) groups ($P = .117$). Elongation during the first cycle, from preload to 160 N, trended toward statistical significance ($P = .060$), with the CSA group (5.47 ± 1.90 mm) moving farther than the ASSA group (4.61 ± 0.81 mm).

Failure Testing

During tendon testing, 3 specimens in the ASSA group (43%) and 3 specimens in the CSA group (43%) failed by the suture tearing through the tendon. The remaining 4 specimens in each group failed by the ASSA or CSA pulling out of the humeral head bone. The mean maximum load was 618 ± 178 N and 545 ± 213 N for the ASSA and CSA groups, respectively, with no difference between groups ($P = .339$). Maximum elongation before failure was not different between groups ($P = .122$). An association trended toward significance between higher BMD and higher maximum load in the CSA group ($P = .053$) but not in the ASSA group ($P = .125$). Mean energy and stiffness were not statistically different between the ASSA (5,383 ± 2,717 Nmm and 63 ± 11 N/mm, respectively) and CSA (3,733 ± 1,835 Nmm and 68 ± 10 N/mm, respectively) groups ($P = .629$ and $P = .973$, respectively).

Linear Regression Analysis

On linear regression analysis, statistically significant linear relations were not observed between BMD and cyclic creep, cyclic elongation, elongation amplitude, maximum load, maximum elongation, energy, and stiffness regardless of treatment group. However, in the CSA group, a trend toward significance was noted, with those specimens with a higher BMD achieving a greater maximum load ($P = .053$); this trend toward significance was not found in the ASSA group ($P = .125$) (Fig 3). A statistically significant linear relation was found in the CSA group between the gauge length of the tendon and cyclic elongation from cycle 1 to cycle 100 ($P = .022$), as well as elongation amplitude of cycle 100 ($P = .026$), but this relation was not found between the ASSA gauge length and cyclic elongation ($P = .666$) or elongation amplitude ($P = .967$). No significant linear relations were found between gauge length and any of the other variables tested in either group.

Discussion

The principal findings of this study show that failure mechanics and maximum load between constructs were similar, with no difference in cyclic creep, elongation amplitude, maximum load, and maximum elongation, as well as energy and stiffness at the point of failure, with similar failure modes between the ASSA and CSA groups. Cyclic elongation from cycle 1 to cycle 100 was statistically significant between the ASSA and CSA groups, with the ASSA group showing slightly larger elongation than the CSA group. These findings support the hypothesis that the biomechanical properties of the ASSA and CSA constructs for RCR are largely comparable.

Outcomes after RCR are generally good to excellent for the vast majority of patients. However, the risk of failure is not insignificant, particularly in the setting of a revision RCR. Some authors have suggested that patients may experience high satisfaction ratings after

Table 2. Comparison of Biomechanical Outcomes Between Groups

	ASSA	CSA	*P* Value
Gauge length, mm	15.2 ± 4.2	18.4 ± 3.1	.56
Cyclic creep, mm	7.9 ± 1.3	8.5 ± 2.7	.12
Cyclic elongation, mm	3.3 ± 0.6	3.0 ± 1.0	.02
Elongation amplitude, mm	2.9 ± 0.4	2.9 ± 0.6	.43
Maximum load, N	617.7 ± 177.8	545.1 ± 213.0	.34
Maximum elongation, mm	17.0 ± 4.7	15.5 ± 1.7	.12
Energy, Nmm	5,383.0 ± 2,716.6	3,733.0 ± 1,835.4	.63
Stiffness, N/mm	62.4 ± 11.1	68.1 ± 10.8	.97

NOTE. Data are presented as mean ± standard deviation.
ASSA, all-suture suture anchor; CSA, conventional suture anchor.

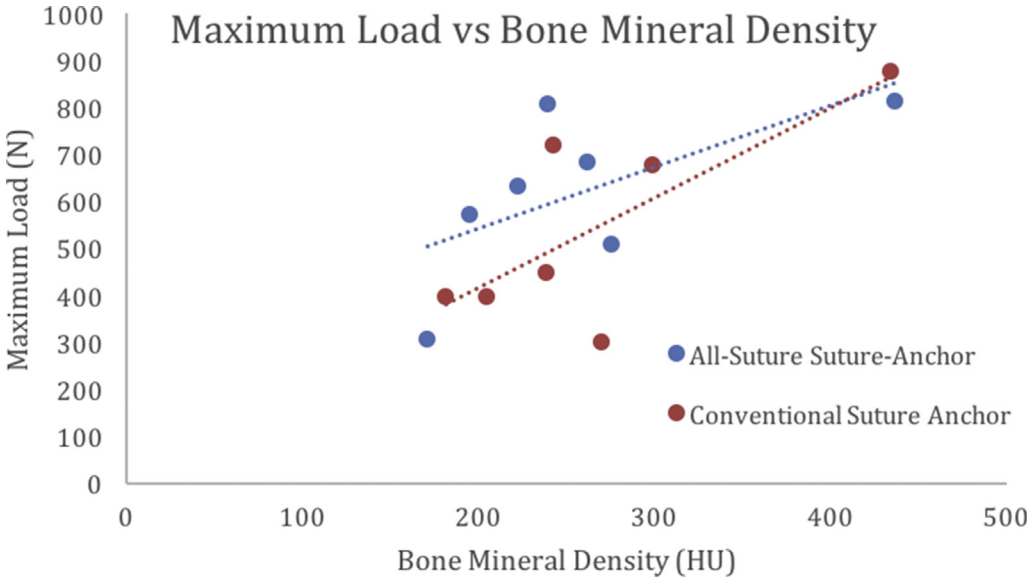

Fig 3. Linear regression analysis showed a trend toward significance with positive correlation between bone mineral density and maximum load ($P = .053$) in the conventional suture anchor group. This trend was not found in the all-suture suture anchor group ($P = .125$). (HU, Hounsfield units.)

RCR surgery even in the setting of a "failed" anatomic repair as documented by imaging modalities and physical examination findings.[12] Other authors, however, have reported that repair integrity correlates with improved outcomes, especially with respect to strength and functional recovery.[13,14] Knowing how the choice of fixation component affects the biomechanical properties of a rotator cuff may be particularly important in the setting of a revision RCR. Use of an all-suture fixation construct in this population may be beneficial because it is a low-profile construct that is less traumatic to the humeral cortex—a method of fixation that may be beneficial for an already traumatized humeral cortex after a failed repair. However, our study design did not investigate this population, and a humeral cortex undergoing revision RCR may be compromised and not mechanically sound enough to support an ASSA.

On linear regression analysis of the data, several statistically significant and trending relations were found between the dependent and independent variables. The maximum load's dependency on BMD was found to trend toward significance in the CSA group but not the ASSA group, whereas the maximum load was similar between groups. This could mean that the CSA requires better BMD to function properly and is less forgiving of poor bone quality. An interesting finding was that gauge length had an effect on both cyclic elongation and elongation amplitude in the CSA group, with larger gauge lengths showing smaller cyclic elongation and elongation amplitude. This relation was not found in the ASSA group. A larger gauge length of the tendon is likely inherent in larger specimens with a larger cross-sectional area of the tendon, resulting in less tissue elongation during loading; however, this does not explain why the relation appears in the CSA group and not the ASSA group, nor has the relation of the cross-sectional area's effect on elongation of the tendon been thoroughly described in the literature.

As described by Salata et al.,[8] the first-cycle excursion of cyclic testing is a measure of the initial stability of the repair construct or the compliance of the testing apparatus. Assuming that the compliance of the testing apparatus was the same between the 2 groups, any difference in first-cycle excursion likely indicates the stability of the construct. Although no difference in first-cycle excursion was found between groups, it did trend toward significance, with the CSA group moving more than the ASSA group. This also may explain the statistically significant difference in cyclic elongation from cycle 1 to cycle 100, with the ASSA group elongating more, but no difference in cyclic creep from preload to cycle 100 between groups. Although the repair construct in the CSA group may not be as stable initially, this difference is absorbed throughout cyclic loading. However, clinically, if patients begin to load their RCR before it has had time to heal, those with ASSAs may have a looser construct. Although the difference may be statistically significant, the actual amount of difference in cyclic elongation between the ASSA and CSA groups is small, 3.27 mm and 3.02 mm, respectively, and may be clinically insignificant. In addition, no difference was found in maximum elongation before failure between groups, which may mean these early differences in cyclic elongation may not be clinically relevant. Assuming there were no differences in the testing apparatus between specimens in each group, the difference in first-cycle excursion likely signifies an inherent behavior of the 2 types of anchors. Additional research may be necessary to determine this behavioral difference.

Given similar biomechanical properties of both fixation constructs, ASSAs have the potential to lead to advanced clinical and surgical outcomes owing to their

low-profile and less traumatic design. However, clinical studies need to be performed to determine whether there is a clinical difference in functional outcomes between the ASSA and CSA constructs.

Limitations

This study has several limitations. Because of the time-zero nature of this study, it does not allow for the time necessary for the body to create scar tissue and link the rotator cuff tendon to the bone,[15,16] which ultimately may alter the biomechanics and fixation strength of the RCR construct. Owing to the cadaveric design of this study, it was not possible to evaluate the effects of healing and scarring or to assess how intraosseous versus onlay constructs affect fixation strength. Adjunctive measures such as abrasion, decortication, or creation of vent holes were not performed during the surgical technique used. This was a fixed-angle traction force–based study, which may oversimplify the forces experienced in vivo and does not account for torsional and distraction stresses. This simplification may underestimate the true biomechanical strength of the suture anchors tested and may have preferentially tested the lateral row of Footprint anchors.

Another limitation of this study is due to the small sample size, which may have had an effect on the statistical analysis. A larger number of specimens per group would improve the robustness of the regression analysis and may have an effect on the outcomes that trended toward significance. A post hoc analysis may be warranted. An a priori power analysis suggested a power of 80% would be achieved with 14 paired specimens; however, this was based on a failure-to-load outcome only.

Conclusions

In this cadaveric analysis with a simplified unidirectional experimental setup, failure mechanics and maximum load between the ASSA and CSA constructs were similar, with no difference in energy and stiffness. Although the ASSA group showed slightly larger elongation than the CSA group, these differences may not be clinically relevant.

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