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A biomechanical cadaveric study of patellar tendon allograft as an alternative graft material for superior capsule reconstruction

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Hypothesis: In a cadaveric irreparable rotator cuff tear model, patellar tendon allograft–superior capsule reconstruction (PT-SCR) will restore glenohumeral stability and reduce subacromial contact pressures without significant graft deformation during testing.
Methods: Eight cadaveric shoulders were tested in a custom shoulder testing system. Rotational range of motion (ROM), superior translation, and subacromial contact pressure were measured in the following experimental conditions: intact rotator cuff, irreparable supraspinatus tear (massive cuff tear [MCT]), and PT-SCR.
Results: MCT and PT-SCR resulted in significantly increased total ROM at all degrees of abduction compared with the intact state ($P < .001$). In both 0° and 30° of glenohumeral abduction, MCT showed a significant increase in superior translation compared with the intact state ($P < .001$). Application of the PT-SCR resulted in a decrease of superior translation compared with MCT ($P < .001$). At 0° abduction/60° external rotation and 0° abduction/90° external rotation, MCT showed significantly greater peak subacromial contact pressure compared with the intact state ($P < .006$). At both of these positions, PT-SCR was able to reduce peak pressure to lower than or no significant difference from the intact state. There was no statistically significant change in graft thickness, length, or width after testing.
Conclusion: PT-SCR was able to reduce superior translation of the humeral head and peak subacromial contact pressure without restricting ROM. Furthermore, there was no significant graft deformation during testing. PT-SCR in this validated cadaveric model demonstrates favorable biomechanical properties and is a viable source of graft material for SCR.

Institutional Review Board approval was not required for this basic science study. Investigation performed at Orthopaedic Biomechanics Laboratory, Tibor Rubin VA Medical Center, Long Beach, California, USA.

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The treatment of irreparable rotator cuff tears presents a challenge for clinicians, especially in the younger patient. Tendon transfers, partial rotator cuff repair, and débridement alone provide unreliable outcomes. Reverse total shoulder arthroplasty is typically reserved for older patients and those with end-stage glenohumeral arthritis in the setting of rotator cuff dysfunction. Superior capsule reconstruction (SCR) was first described by Mihata et al[14] in 2012 using fascia lata autograft (FLA) as a treatment strategy for irreparable rotator cuff tears. Defects in the superior capsule of the shoulder have been shown to increase translation of the humeral head and to increase subacromial contact pressures.[10] SCR restores stability against superior translation and reduces subacromial contact pressures in shoulders that are rotator cuff and capsule deficient.[16]

Mihata et al[13,14] have reported excellent clinical results of SCR with FLA; however, FLA is associated with donor site morbidity. In the United States, human dermal allograft (HDA) has become the graft of choice for SCR.[1,6,24] A biomechanical study demonstrated inferior biomechanical characteristics of HDA compared with fascia lata allograft.[12] Denard et al[9] demonstrated improved functional outcome scores and range of motion (ROM) with SCR with HDA but no improvement in acromiohumeral distance and inferior healing rates compared with the study of Mihata et al with FLA.

Given the results of SCR with HDA, we hypothesized that an allograft that was thicker and stiffer than HDA would display biomechanical properties more similar to an intact shoulder. Thicker SCR grafts have been shown to be more effective in restoring superior stability.[15] Patellar tendon allograft (PTA) is typically >4 mm thick compared with 3 mm for thicker HDAs. PTA is also stiffer and has a higher ultimate load to failure, greater Young modulus, and less ultimate strain than HDA.[3-5,8,17,19-23,26,27] Patellar tendon has a Young modulus and ultimate strain more comparable to fascia lata than to HDA.[7] Mihata et al[12] demonstrated that HDA used for SCR in a cadaveric model elongated by approximately 15% and thinned by about approximately 20% after testing, whereas fascia lata allograft demonstrated minimal deformation. The collagen fiber orientation of the patellar tendon is parallel compared with the random collagen fiber orientation of dermis. Given that the graft will be loaded along these parallel fibers in the setting of an SCR, this may allow faster remodeling during the healing process compared with HDA. This, along with the addition of bone on the glenoid side of the graft, may allow bone to bone healing and thus improve the healing rates of the SCR graft with PTA vs. HDA.

Given these potential advantages of PTA as a graft source for SCR, the objective of this study was to assess the effects of SCR using PTA on shoulder biomechanics in a validated cadaveric irreparable rotator cuff tear model. We hypothesized that SCR using PTA would restore glenohumeral stability and subacromial contact pressures without significant changes in graft dimensions.

Materials and methods

Specimen preparation and testing setup

Eight fresh frozen cadaveric shoulders (mean age, 63 ± 7 years [range, 49-70 years]; 7 male and 1 female) were used for this biomechanics study. Specimens were thawed overnight before dissection. All specimens were evaluated thoroughly to ensure no evidence of rotator cuff disease or any other gross abnormalities. Specimens were denuded of skin, soft tissues, and muscles except for the coracoacromial ligament, glenohumeral joint capsule, and tendinous insertions of the rotator cuff, deltoid, latissimus dorsi, and pectoralis major muscles. The humerus was transected 2 cm distal to the deltoid tuberosity. Muscle-tendon insertions were sutured in a Krackow fashion using No. 2 FiberWire (Arthrex, Naples, FL, USA) to allow muscle loading during testing. The number of sutures for each muscle was as follows: supraspinatus, 2; infraspinatus, 2; teres minor, 1; subscapularis, 2; deltoid, 3; pectoralis major, 2; latissimus dorsi, 2.

The scapula was mounted onto a custom scapular plate and fixed rigidly to a previously validated custom shoulder testing system at 20° anterior tilt and 0° abduction (Fig. 1).[11] An intramedullary rod was inserted into the humeral shaft and secured to the testing system. This allowed control of all 6 degrees of freedom of the glenohumeral joint. A rotary variable differential transformer (Novotechnik U.S., Inc., Southborough, MA, USA) was connected to the intramedullary rod for measurement of humeral internal and external rotation (precision: 0.05°); 90° of humeral external rotation was defined where the bicipital groove aligned with the anterolateral edge of the acromion at 60° of glenohumeral abduction. To allow 3-dimensional tracking of the position of the humerus relative to the fixed scapula, 3 screws were placed in the scapula (coracoid, anterior acromion, and posterior acromion) and 3 screws were placed in the proximal humerus.

Muscles were loaded using a braided low-stretch Dacron fishing line (Izorline International, Inc., Paramount, CA, USA) by suturing to the previously Krackow sutured tendinous insertions of

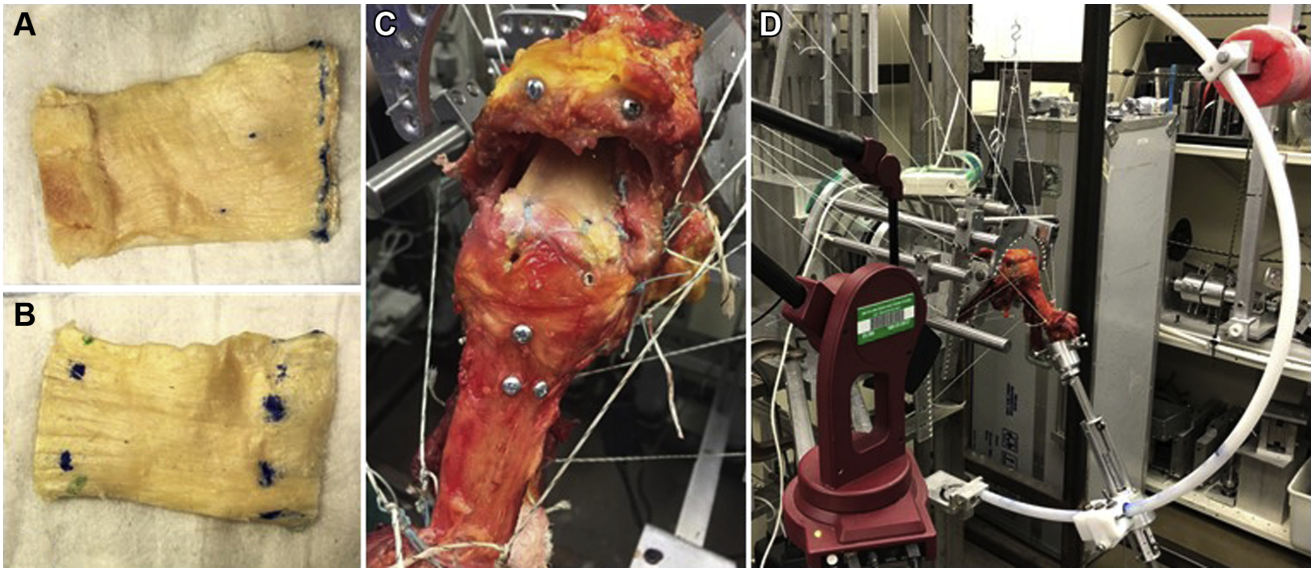

Figure 1 (**A, B**) Preparation of the patellar tendon allograft. (**C**) Surgical placement of the allograft. (**D**) Custom shoulder testing jig.

the muscles on the humerus. Lines were fed through customized muscle plates positioned to mimic physiologic loading conditions, routed over adjustable pulleys, and loaded with weights. Two loading conditions were used in this study: balanced and unbalanced. The forces were predetermined on the basis of physiologic cross-sectional area ratios and electromyographic studies.[2,25] The following muscle forces in the balanced muscle loading condition were used: supraspinatus, 10 N; infraspinatus, 5 N; teres minor, 5 N; subscapularis, 10 N; pectoralis major, 20 N; latissimus dorsi, 20 N; deltoid, 40 N. The unbalanced loading condition was performed to apply a superiorly directed force to the humerus; this was done by applying an additional 40 N to the deltoid and removing the weights from the pectoralis major and latissimus dorsi.

Experimental conditions

The following experimental conditions were tested: intact rotator cuff, irreparable rotator cuff tear encompassing the entire supraspinatus footprint (massive cuff tear [MCT]), and SCR using PTA (PT-SCR).

Irreparable supraspinatus tear

After the intact shoulder condition was tested, an irreparable supraspinatus tear model was created by sharply incising the supraspinatus and the superior capsule at the insertion on the greater tuberosity. The supraspinatus and superior capsule were then resected from the remaining rotator cuff by sharply resecting them from the anterior and posterior cuff, from lateral to medial, to the level of the glenoid.

PT-SCR

On the glenoid, PT-SCR fixation was performed using two 4.5-mm metal Corkscrew FT anchors (Athrex). On the humerus, a double-row transosseous-equivalent technique was performed using two 5.5-mm Bio-Corkscrew suture anchors for the medial row and two 4.75-mm Bio-SwiveLocks for the lateral row (Athrex). All anchors were loaded with No. 2 FiberWire suture. The first medial-row humerus anchor was placed 5 mm posterior to the anterior edge of the supraspinatus footprint, and the second anchor was placed 5 mm anterior to the posterior edge of the supraspinatus footprint. The first glenoid anchor was inserted 5 mm posterior to the anterior edge of the supraspinatus defect, and the second anchor was placed 5 mm anterior to the posterior edge of the supraspinatus defect. Using a MicroScribe (MicroScribe 3DLX; Revware, Raleigh, NC, USA) at 20° of glenohumeral abduction and axial rotation at the midpoint of the total ROM for that specimen, the anteroposterior width of the glenoid anchors, the anteroposterior width of the medial-row humerus anchors, the mediolateral length from the anterior glenoid anchor to the anterior medial-row humerus anchor, and the mediolateral length from posterior glenoid anchor to posterior medial-row humerus anchor were measured.

Graft preparation consisted of bone removal from the tibial tubercle until a 1-cm-wide and approximately 1- to 2-mm-thick enthesis remained. This thin bone layer allowed the graft to be malleable to the superior surface of the glenoid, on which it was placed. On occasion, cracks to the bone layer occurred during graft placement but did not compromise fixation. The graft was sized to leave 5 mm of the tendon and bone medial to the glenoid anchors and 10 mm of tendon lateral to the medial-row anchors of the humerus (Fig. 1). The sutures limbs of the glenoid and medial-row humerus anchors were passed through the graft in a horizontal mattress fashion at the defined points and were tied with a sliding-locking knot and 3 reversing half-hitches on alternating post knots.

Once the graft had been secured to the glenoid and the medial-row anchors of the humerus, the suture limbs from the humerus anchors were placed in a knotless transosseous-equivalent fashion into the 2 SwiveLock anchors 1 cm distal to the distal edge of the graft in line with the medial-row anchors. Two additional posterior side-to-side No. 2 FiberWire sutures were used to secure the graft to the remnant posterior rotator cuff tissue (Fig. 1).

Biomechanical measurements

All measurements were obtained at 0°, 30°, and 60° of glenohumeral abduction, corresponding to 0°, 45°, and 90° of shoulder abduction, respectively. Humeral rotational ROM was measured under the balanced loading condition by measuring maximum internal rotation and external rotation, applying 2.2 Nm of torque. Total ROM was calculated as the sum of maximum internal and external rotation. Superior translation of the humeral head in the unbalanced loading condition was measured as the change of the humeral position along the y-axis of the global coordinate system. Subacromial contact characteristics were measured in the unbalanced muscle loading condition only, using a Tekscan sensor (model 4000; saturation pressure, 10.3 MPa; Tekscan, Inc., Boston, MA, USA) with sensitivity set at 35 and equilibrated before testing. The Tekscan was placed in the subacromial space, and the contact force, contact area, and peak pressure were measured. Contact pressure was calculated as contact force/contact area.

Graft dimensions

Measurements of graft dimensions were performed before and after biomechanical testing. A digital caliper was used to measure the medial width, lateral width, anterior length, posterior length, and anterior and posterior graft thickness in the medial, central, and lateral portions of the graft.

Data analysis and statistics

For each specimen, 2 trials of each measurement were performed and averaged. These measurements were then averaged across all 8 specimens. For humeral rotational ROM, humeral head translation, and subacromial contact characteristics, statistical analysis was performed using a repeated-measures analysis of variance test, followed by a Tukey post hoc test for pairwise comparisons. Graft dimensions were compared both before and after testing by a paired Student *t*-test. A *P* value of < .05 was set for statistical significance.

Table I Range of motion

Measurement position	Condition		
	Intact	MCT	PT-SCR
	Rotation (°)	Rotation (°)	Rotation (°)
Internal rotation			
0° abduction	11.8 ± 3.9	12.9 ± 3.5	12.5 ± 3.4
30° abduction	14.7 ± 3.3	15.5 ± 3.3	15.6 ± 3.4
60° abduction	3.8 ± 3.3	9.3 ± 3.7*	6.4 ± 3.8*,†
External rotation			
0° abduction	94.6 ± 6.1	103.0 ± 6.9*	103.4 ± 7.0*
30° abduction	109.5 ± 4.4	115.0 ± 4.6*	114.1 ± 5.2*
60° abduction	116.0 ± 3.1	119.0 ± 3.3	119.9 ± 3.2*
Total rotation			
0° abduction	106.5 ± 9.3	115.9 ± 9.3*	115.8 ± 9.4*
30° abduction	124.2 ± 7.2	130.4 ± 7.0*	129.6 ± 7.9*
60° abduction	119.8 ± 5.6	128.2 ± 5.9*	126.3 ± 6.0*

MCT, massive cuff tear; *PT-SCR*, patellar tendon allograft–superior capsule reconstruction.
Values are presented as means ± standard error.
* Statistically significant difference compared with intact condition ($P < .05$).
† Statistically significant difference compared with massive cuff tear ($P < .05$).

Results

Rotational ROM

At 0° and 30° of glenohumeral abduction, there were no statistically significant differences in internal rotation between the intact shoulder condition, MCT, and PT-SCR ($P > .541$) (Table I). At 60° of abduction, internal rotation for MCT was significantly greater than for the intact state ($P < .001$). Internal rotation for PT-SCR was also significantly greater than for the intact state ($P = .027$) but significantly less than for MCT ($P = .013$). For external rotation, MCT and PT-SCR were significantly greater than the intact state at 0° and 30° of abduction ($P < .013$), but only PT-SCR was significantly greater than the intact state at 60° of abduction ($P = .038$). For total rotation, MCT and PT-SCR were significantly greater than the intact state at all degrees of abduction ($P < .005$).

Glenohumeral superior translation in unbalanced condition

At all degrees of external rotation in both 0° and 30° of glenohumeral abduction, MCT showed a significant increase in superior translation compared with the intact state ($P < .001$). At these abduction angles, PT-SCR resulted in a significant decrease of superior translation at all degrees of external rotation compared with MCT ($P < .001$) (Table II). Whereas PT-SCR restored superior translation to no significant difference from the intact state at 0° ($P > .551$) and 30° ($P > .192$) of external rotation at these abduction angles, it still showed a significant increase in superior translation compared with the intact state at 60° ($P < .036$) and 90° ($P < .007$) of external rotation. At 60° of abduction, neither MCT nor PT-SCR showed a statistically significant difference from the intact state ($P > .11$).

Subacromial peak contact pressure

MCT showed significantly greater peak pressure compared with the intact state at 0° abduction/60° external rotation (279.1 kPa greater; $P = .006$) and 0° abduction/90° external rotation (643.9 kPa greater; $P < .001$) (Fig. 2). At 0° abduction, PT-SCR demonstrated significantly less peak contact pressure compared with MCT at 30° external

Table II Superior translation under unbalanced load

Measurement position	Condition		
	Intact	MCT	PT-SCR
	Translation (mm)	Translation (mm)	Translation (mm)
0° glenohumeral abduction			
0° external rotation	2.6 ± 0.4	6.0 ± 1.1*	3.6 ± 0.6†
30° external rotation	2.0 ± 0.3	6.3 ± 0.8*	3.4 ± 0.8†
60° external rotation	1.8 ± 0.2	6.1 ± 0.4*	3.4 ± 0.6*,†
90° external rotation	1.7 ± 0.3	6.3 ± 0.6*	3.4 ± 0.4*,†
30° glenohumeral abduction			
0° external rotation	2.7 ± 0.3	5.4 ± 0.9*	3.5 ± 0.8†
30° external rotation	2.0 ± 0.3	5.3 ± 0.6*	3.3 ± 0.6†
60° external rotation	1.4 ± 0.3	5.6 ± 0.7*	3.4 ± 0.8*,†
90°external rotation	2.0 ± 0.5	5.7 ± 0.6*	3.5 ± 0.5*,†
60° glenohumeral abduction			
0° external rotation	1.6 ± 0.3	1.8 ± 0.3	1.8 ± 0.2
30° external rotation	1.6 ± 0.4	2.5 ± 0.4	1.8 ± 0.4
60° external rotation	1.8 ± 0.3	2.0 ± 0.2	1.7 ± 0.4
90° external rotation	2.3 ± 0.5	2.5 ± 0.6	2.0 ± 0.5

MCT, massive cuff tear; *PT-SCR*, patellar tendon allograft–superior capsule reconstruction.
Values are presented as means ± standard error.
* Statistically significant difference compared with intact condition ($P < .05$).
† Statistically significant difference compared with massive cuff tear ($P < .05$).

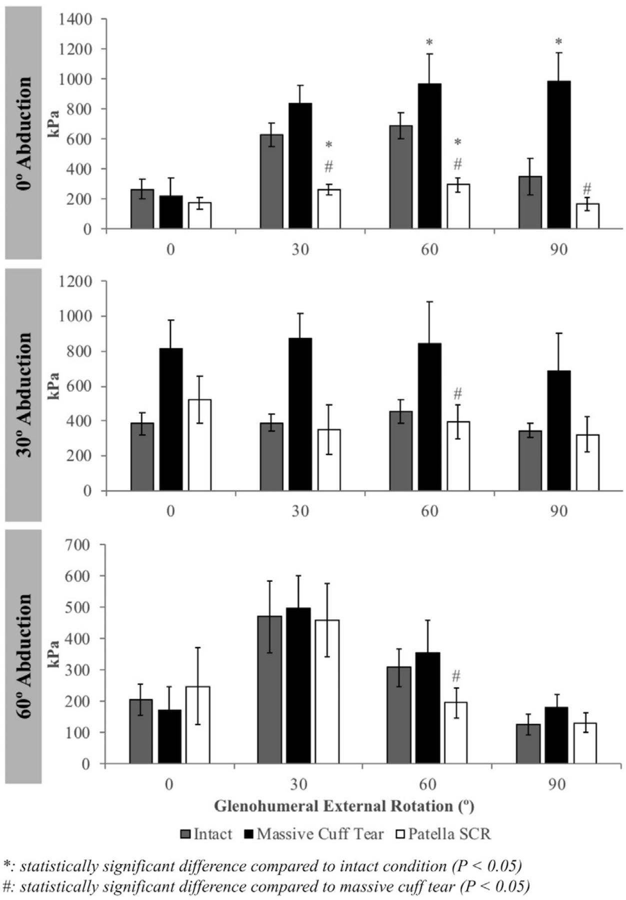

Figure 2 Subacromial peak contact pressure. *SCR*, superior capsule reconstruction.

rotation (574.3 kPa less; $P < .001$), 60° external rotation (671.9 kPa less; $P < .001$), and 90° external rotation (818.9 kPa less; $P < .001$). In 60° external rotation at both 30° abduction (445.7 kPa less; $P = .046$) and 60° abduction (161.8 kPa less; $P = .046$), PT-SCR also demonstrated significantly less peak contact pressure compared with MCT. PT-SCR reduced peak contact pressures to levels below the intact state at 0° abduction/30°external rotation (370.3 kPa less; $P = .008$) and 0° abduction/60°external rotation (392.8 kPa less; $P = .017$) and to no significant difference from the intact state (818.9 kPa less than MCT; $P < .001$) at 0° abduction/90° external rotation.

Graft dimensions

There was no statistically significant change in any graft dimension before and after testing (Table III). Overall mean graft thickness was 4.3 mm before testing and 4.2 mm after testing ($P = .65$). There was also no statistically significant difference in anterior length ($P = .93$), posterior length ($P = .97$), medial width ($P = .65$), or lateral width ($P = .92$).

Discussion

Arthroscopic SCR using both FLA and HDA has been shown to reduce pain, to improve functional outcome scores, and to improve ROM for irreparable rotator cuff tears.[9,13,14,18] However, initial clinical results of SCR with

Table III Change in graft dimensions

	Anterior length	Posterior length	Medial width	Lateral width	Medial thickness	Central thickness	Lateral thickness
Before (mm)	52.5	58.5	34.8	35.5	4.2	4.3	4.4
After (mm)	52.8	58.7	35.8	35.8	4.1	4.2	4.2
Change (mm)	0.3	0.2	1.0	0.3	−0.1	−0.1	−0.2
% Change	0.6	0.3	2.9	0.8	−2.4	−2.3	−4.5
P value	.929	.970	.653	.923	.784	.614	.594

HDA have been inferior to those performed with FLA. Denard et al[9] showed no improvement in acromiohumeral distance at final follow-up and healing rates of almost half of those reported for FLA. In addition, 19% of their cohort required additional surgery and 12% were converted to reverse total shoulder arthroplasty at an average follow-up of 18 months. At final follow-up, 68% had a successful outcome, defined as an American Shoulder and Elbow Surgeons score >50, at least a 17-point postoperative improvement in American Shoulder and Elbow Surgeons score, and not requiring revision surgery. However, results were superior for those with thicker grafts and those that showed healing of the graft on postoperative magnetic resonance imaging.[9] Given these clinical results, this study investigated the biomechanical characteristics of an alternative allograft source for SCR, specifically PTA.

In this study, SCR with patellar tendon was able to restore the superior stability of the glenohumeral joint at 0° and 30° of abduction with 0° and 30° of external rotation. At higher degrees of external rotation, the PT-SCR did show increased superior translation of the humerus compared with the intact state, which was still reduced compared with the MCT condition. PT-SCR restored subacromial contact pressures to the intact state and even lower than in the intact state for certain testing conditions. There was also no restriction in ROM with PT-SCR with posterior-only side-to-side suturing. Furthermore, there was no significant graft deformation after testing.

Mihata et al[12] previously compared the biomechanical characteristics of fascia lata allograft and HDA with a similar cadaveric testing protocol. Fascia lata allograft and HDA with anterior and posterior side-to-side suturing were both able to restore ROM to the intact condition. In comparison, HDA SCR with posterior side-to-side sutures showed increased ROM compared with the intact state and fascia lata allograft. In our study, PT-SCR with posterior side-to-side suturing also resulted in increased ROM, similar to the HDA SCR with posterior side-to-side suturing.

In the study of Mihata et al,[12] superior translation of the humerus with the fascia lata allograft SCR was less than or not significantly different from the intact state for all testing conditions, whereas neither of the HDA experimental conditions restored superior stability to the intact state at 0° and 30° of abduction. The HDA SCRs showed between 4 and 5.5 mm of superior translation, whereas the PT-SCR showed consistent superior translation of approximately 3.5 mm. However, given that these were different cadaveric specimens, direct comparisons of magnitude of translation should be made cautiously.

Similar to the fascia lata allograft of Mihata et al[12] and both HDA SCRs, the PT-SCR was able to restore subacromial contact pressures at 0° abduction. However, only the PT-SCR and fascia lata allograft SCRs demonstrated reduction in peak contact pressures at 30° and 60° of abduction. The fascia lata allograft showed a small amount of significant thinning (5.6%-11%) and posterior elongation (2.7%) after testing, whereas the HDAs demonstrated more significant thinning (17.1%-26.4%) and elongation (13.7%-15.2%). The PT-SCR demonstrated no significant thinning or elongation. This graft deformation may be even more important clinically than in a cadaveric model because the grafts may demonstrate even more pronounced deformation during an extended time. Given the results of these studies, graft thickness and limited graft deformation may be the 2 most important determinants of superior stability of SCRs.

In addition to the biomechanical characteristics and reduced graft deformation, PT-SCR may have other advantages over the other graft choices. FLAs and thinner HDAs require folding or layering to achieve optimal graft thickness. Although the clinical effects of layering are unclear, graft layers may experience shear forces that could inhibit graft to graft healing. In contrast, PT-SCR is a naturally thicker graft option than single-layer FLA or HDA. Furthermore, having bone on the glenoid side of the graft may enhance healing over the HDA SCRs because of bone to bone contact. This seems especially important given the healing rate of 45% for HDA SCR shown by Denard et al.[9] In addition, there may be an economic advantage of PTA with reduced graft costs compared with HDA, especially because longer PTAs are typically unable to be used for anterior cruciate ligament reconstruction.

Our study has several limitations. This study examines only time-zero effects, which is inherent to all biomechanical cadaveric studies. It does not consider the effects of graft healing or remodeling. This cadaveric model examined only 2 static muscle loading conditions, which is different from the dynamic muscle loading seen under normal physiologic conditions. This model considers only a large irreparable supraspinatus tear and does not consider the effects of additional tears of either the infraspinatus or subscapularis that are often seen clinically. However, partial repair of the posterior rotator cuff and subscapularis is often performed before SCR. In addition, only posterior side-to-side suturing of the PT-SCR was tested in this study because of concerns of overconstraint and limiting ROM with both anterior and posterior suturing. With only posterior side-to-side suturing, we found an increase in rotational ROM of the humerus compared with the intact state. It is unclear whether including additional anterior side-to-side suturing would have restricted rotational ROM, but on the basis of the results of Mihata et al,[12] it would have likely increased the superior stability of the PT-SCR and should be tested in future studies. This study used the same glenoid fixation as in previous studies using this model[12,15,16] and did not assess all the various anchor types available for glenoid fixation. However, in this time-zero model in which the glenoid-sided anchors remained securely fixed, it is likely that any anchor types that maintain fixation would result in similar outcomes. Our study compared PT-SCR with the intact rotator cuff state, which is the ‘‘gold standard,’’ but did not include direct comparisons to fascia lata allograft or HDA SCR. Given the prior biomechanical cadaveric study that examined fascia lata allograft and HDA SCRs using a similar cadaveric model and testing conditions, we can draw some conclusions about the trends of the biomechanical properties between these grafts and PT-SCR, but comparisons of the magnitude of the results is limited, given the different cadaveric specimens. Our study tested the biomechanical properties of PT-SCR but did not include load to failure testing of the graft.

Conclusions

PT-SCR was able to restore superior stability and subacromial contact pressures without restricting ROM. Furthermore, there was no significant graft deformation during testing. PTA demonstrates favorable biomechanical properties and is a viable source of graft material for SCR.

Disclaimer

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