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Biomechanical analysis of latissimus dorsi tendon transfer with and without superior capsule reconstruction using dermal allograft

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Background: Irreparable rotator cuff tears (ICTs) remain a challenging treatment dilemma. Superior capsule reconstruction (SCR) acts as a static stabilizer to decrease superior humeral head migration. Latissimus dorsi tendon transfers (LDTs) dynamically decrease superior humeral head migration and improve external rotation. We hypothesized that the dynamic stabilizing effect of the latissimus transfer plus the static stabilizing effect of SCR would improve shoulder kinematics in shoulders with ICTs.
Materials and methods: Eight fresh-frozen cadaveric shoulders were tested in 5 conditions: (1) intact, (2) ICT (supraspinatus plus anterior half of infraspinatus), (3) SCR with dermal allograft, (4) SCR plus LDT, and (5) LDT alone. Rotational range of motion, superior translation, anteroposterior translation, and peak subacromial contact pressure were measured at 0°, 30°, and 60° of glenohumeral abduction in the scapular plane. Statistical analysis was performed using a repeated-measures analysis of variance test, followed by a Tukey post hoc test for pair-wise comparisons.
Results: ICTs increased total shoulder rotation, superior translation, posterior translation, and peak subacromial contact pressure. SCR plus LDT significantly decreased internal rotation only at 60° of abduction. The effect of SCR plus LDT was most evident at lower levels of abduction. At the mid range of abduction (30°), the static stabilizing effect diminished but the dynamic stabilizing effect remained, allowing SCR plus LDT to reduce superior translation more effectively than SCR with dermal allograft alone.
Conclusions: Adding SCR to LDT adds static stabilization to a dynamic stabilizer. Therefore, SCR plus LDT may provide additional stability at the low to mid ranges of abduction.

This basic science study is exempt from requiring University of Southern California Health Sciences Institutional Review Board approval.

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Irreparable rotator cuff tears (ICTs) remain a surgical challenge, especially in younger patients. A wide range of surgical techniques have been proposed, including cuff débridement, partial cuff repair, biceps tenotomy and tenodesis,[3] tendon transfer,[6-8] shoulder arthroplasty,[18,20] and more recently, superior capsule reconstruction (SCR).[15,17] In younger, more active patients, concerns about implant longevity and failure preclude the use of arthroplasty. Tendon transfers may be a more suitable option in this population because they do not carry the inherent risk of hardware failure associated with arthroplasty. Tendon transfers for irreparable posterosuperior rotator cuff tears include the latissimus dorsi tendon transfer (LDT),[8] as well as the lower trapezius tendon transfer.[4,5] The primary goals of the tendon transfer in this setting are restoration of humeral external rotation (ER) and re-establishment of the anteroposterior force couple of the glenohumeral joint. Although the LDT may improve function in cuff-deficient patients, native restoration of the anteroposterior force couple is rarely attained and results are variable. We previously showed that the LDT worsens the anteroposterior force couple.[19] This is likely due to the vertically oriented force vector of the transferred latissimus muscle, which places a nonphysiological vector across the glenohumeral joint to restore the function lost by tears involving the supraspinatus and infraspinatus.

Imaging studies have shown that in patients with rotator cuff tears, the humeral head can elevate superiorly, resulting in a decreased acromiohumeral distance.[9,11] Both the LDT and lower trapezius tendon transfer can decrease proximal migration of the humeral head; however, the anteroposterior force couple is not restored with the LDT.[19] Although the LDT improves superior stability, it worsens anteroinferior stability, which may be the reason arthritic changes develop in patients. SCR is another alternative for the treatment of ICTs and helps to center the humeral head by providing a passive stabilizing force to the glenohumeral joint. SCR has been shown to improve superior stability as well as anteroinferior stability.[10,17] Although the fascia lata is more effective at reducing superior translation of the humeral head, the procedure is commonly performed with a dermal allograft to reduce donor-site morbidity.[13] Theoretically, if SCR is performed concurrently with LDT, a dynamic stabilizer would be working along with a static stabilizer and would more closely replicate the anatomic combination of the dynamic supraspinatus and the static superior capsule. Therefore, the objective of this study was to biomechanically evaluate SCR with a dermal allograft combined with LDT. We hypothesized that adding SCR to LDT would increase the efficacy of resisting superior and posterior humeral head migration and reduce peak subacromial contact pressures by adding a static stabilizer to a dynamic stabilizer.

Materials and methods

Specimen preparation

Eight fresh-frozen human cadaveric shoulders were used for this cadaveric biomechanical study. There were 6 male and 2 female specimens with 4 right and 4 left shoulders (average age, 69 years; age range, 60-76 years). Prior to testing, all specimens were thoroughly examined, and any specimens with a rotator cuff tear, glenohumeral joint contracture, or fracture of the acromion or coracoid were excluded. The specimens were stored at −20°C until the day before testing. After specimens were thawed overnight at room temperature, they were kept moist with physiological saline solution to prevent dehydration during testing. All soft tissues were removed except for the glenohumeral joint capsule and the coracoacromial and coracohumeral ligaments. The supraspinatus, infraspinatus, teres minor, subscapularis, deltoid, pectoralis major, latissimus dorsi, and teres major muscles were released from their origins, while the humeral insertions were retained. The glenohumeral joint was vented by a small incision through the rotator interval to eliminate variability between specimens regarding intra-articular pressure. Suture loops were made using Krackow stitches at the insertion of each muscle with No. 2 FiberWire (Arthrex, Naples, FL, USA). To load the muscles anatomically, each muscle was divided into subregions based on muscle fiber orientation: anterior and posterior regions for the supraspinatus; superior and inferior regions for the subscapularis; superior and inferior regions for the infraspinatus and teres minor; superior and inferior regions for the pectoralis major; superior and inferior regions for the latissimus dorsi and teres major muscles; and anterior, middle, and posterior regions for the deltoid muscle. Three reference screws were inserted in the scapula (at the coracoid, the anterior aspect of the acromion, and the posterior aspect of the acromion) and in the humerus (at the proximal aspect of the bicipital groove, the distal aspect of the bicipital groove, and the greater tuberosity) for position digitization.

An aluminum rod was inserted into the medullary canal of the humeral shaft and secured with several interlocking screws. The scapula was fixed in the anatomic resting position with 20° of anterior tilt in the sagittal plane. The aluminum rod was placed in a custom device that allowed axial rotation of the humerus and shoulder abduction. The humerus was positioned in the scapular

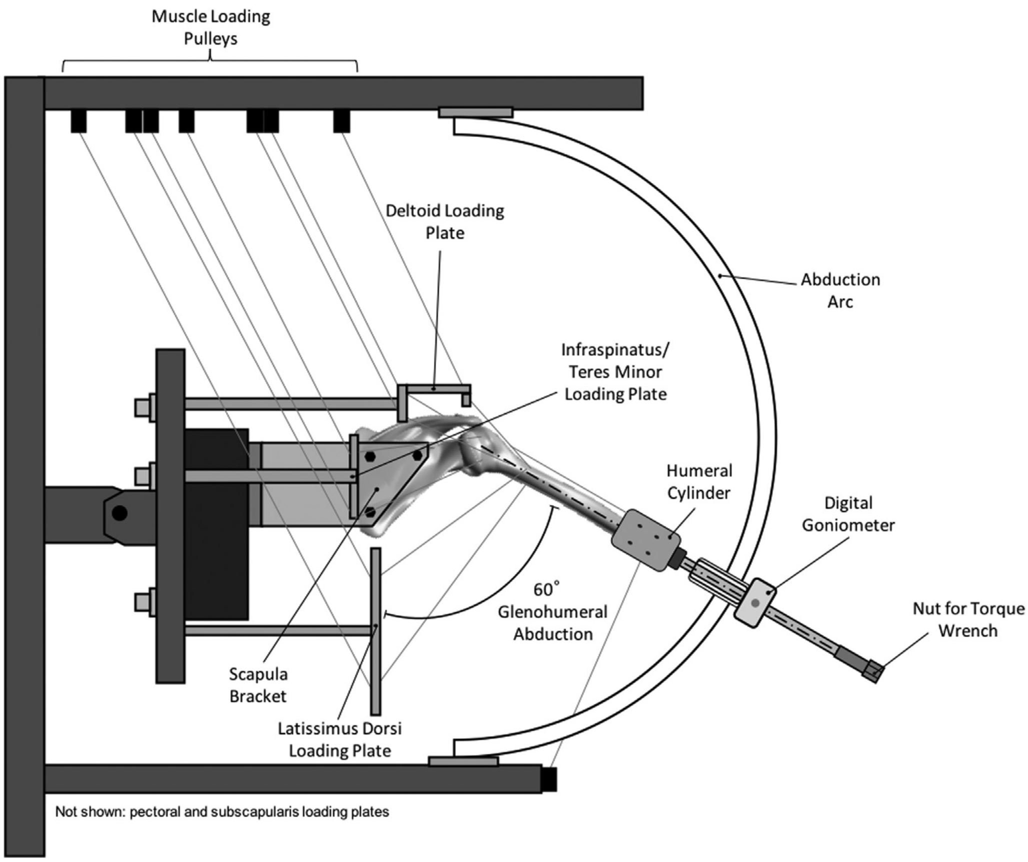

Figure 1 Biomechanical testing apparatus.

plane (30° anterior to the coronal plane). Humeral axial rotation was defined based on the anatomic relationship between the bicipital groove and the anterolateral corner of the acromion. When the bicipital groove was aligned with the anterolateral corner of the acromion at 60° of glenohumeral abduction, the humeral rotation was defined as 90° of ER.[22] Once the scapula and humerus were secured, origin plates for the rotator cuff and deltoid muscles were aligned to the scapular body. For all lines of pull, a fishing line was tied to each tendon suture and directed through the hole in the origin plate for anatomic alignment based on muscle fiber orientation. The amount of muscle loading was determined based on physiological muscle cross-sectional area ratios: 10 N for the supraspinatus, 10 N for the subscapularis, 10 N for the infraspinatus and teres minor, 39 N for the deltoid, 20 N for the pectoralis major, and 20 N for the latissimus dorsi and teres major.[1,21] To evaluate the superior stability of the glenohumeral joint, 40 N of superiorly directed load was applied through braided low-stretch fishing line (Dacron Fishing Line; Izorline, Paramount, CA, USA) wrapped around the humerus just below the humeral head using a pulley system.

Biomechanical testing

Maximum internal and external humeral rotation was measured with 2.2 newton meters of torque by a torque wrench attached to the humeral intramedullary aluminum rod (Fig. 1).[2] Prior to the measurements, the specimen was preconditioned by ranging it from the maximum internal rotation position through the maximum ER position for 5 cycles to minimize the effect of soft-tissue viscoelasticity. To evaluate the glenohumeral joint kinematics, 3 points on the scapula and 3 points on the proximal humerus were digitized with a MicroScribe 3DLX tool (Revware, Raleigh, NC, USA; accuracy within <0.3 mm).[12] Each measurement was performed from the maximum internal rotation position to the maximum ER position in 30° increments in the balanced loading condition at 0°, 30°, and 60° of abduction.

After application of the superiorly directed load, the humeral head position was measured at 0°, 30°, 60°, and 90° of ER. The differences in the location of the center of the humeral head were calculated in the superoinferior and anteroposterior directions. With the superiorly directed load, peak subacromial contact pressure was measured with a Tekscan pressure sensor (model 4000, Tekscan, South Boston, MA, USA; maximum saturation pressure, 10.3 MPa). The Tekscan sensor's sensitivity was set to 35 and calibrated with a 2-point calibration (40 N and 80 N) using an Instron 4411 load cell (Instron, Norwood, MA, USA). The mean saturation pressure after calibration was 1.42 MPa.

Five conditions were tested: (1) intact, (2) ICT (supraspinatus plus anterior half of infraspinatus), (3) SCR with dermal allograft, (4) SCR with dermal allograft plus LDT (SCR plus LDT), and (5) LDT alone. An ICT was created by resecting the joint capsule and rotator cuff medial to the glenoid. Muscle loading for the torn portions of the rotator cuff (10 N for the supraspinatus and 2.5 N for the anterior half of the infraspinatus) was no longer performed. After each testing condition, the specimens were

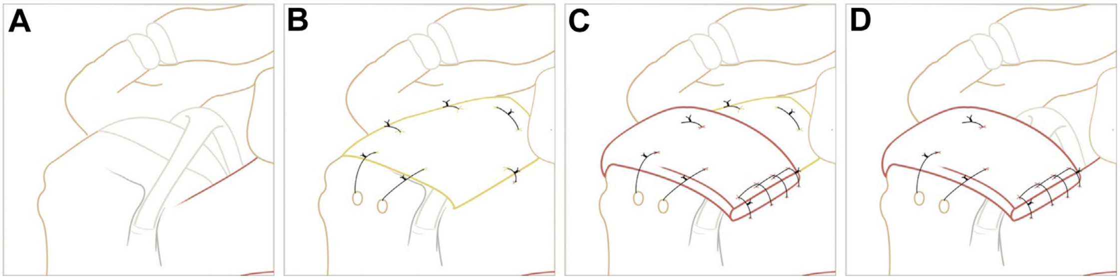

Figure 2 (**A**) Irreparable rotator cuff tear. (**B**) Superior capsule reconstruction. (**C**) Superior capsule reconstruction plus latissimus dorsi transfer. (**D**) Latissimus dorsi transfer.

inspected to ensure that no fixation failure had occurred. Following all testing procedures, the specimens were carefully disarticulated, and the humeral head and glenoid geometry was digitized with the MicroScribe 3DLX tool to calculate the position of the humeral head center relative to the glenoid during testing.

Surgical procedure

Superior capsule reconstruction

Two 2.3-mm anchors (Smith & Nephew, Andover, MA, USA) were inserted into the glenoid (Fig. 2, *B*). The anterior anchor was inserted in the glenoid 5 mm posterior to the tear edge, and the posterior anchor was inserted 5 mm anterior to the posterior edge of the defect. For the lateral side, 2 bone tunnels in the greater tuberosity were created with a 1.8-mm drill to perform a transosseous technique for repair. The anterior bone tunnel at the articular margin was created 5 mm posterior to the tear edge, and the posterior tunnel was created 5 mm anterior to the posterior edge of the defect. SCR was performed at 20° of glenohumeral abduction (30° of shoulder abduction) using human dermal allograft (JRF Ortho, Centennial, CO, USA). The graft dimension was calculated based on the defect size. The width in the anteroposterior direction was the same size as the defect, and the length in the mediolateral direction was the defect size plus 10 mm. For the glenoid-side fixation, 2 horizontal mattress sutures were placed. For the transosseous fixation, 2 simple sutures and a horizontal mattress suture were placed. Two posterior side-to-side sutures were placed to attach the graft to the residual infraspinatus. A single anterior side-to-side suture was placed to attach the graft to the subscapularis to create capsular continuity without over-tightening the rotator interval. The average dermal allograft thickness was 2.07 mm (standard deviation, 0.06 mm).

SCR plus LDT

A muscle transfer consisting of the latissimus dorsi and teres major was performed in conjunction with the SCR (Fig. 2, *C*). The latissimus dorsi and teres major tendons, which were often confluent, were sharply dissected together from the humeral insertion. Each corner of the harvested graft was sutured together in a simple fashion with No. 2 FiberWire. Next, the harvested graft was repositioned over the superior portion of the greater tuberosity and secured to the entire footprint with a transosseous technique at 20° of abduction. A continuous locking suture with 3 throws was placed to close the interval between the transferred tendon and subscapularis tendon. A stay suture was placed, attaching the transferred tendon to the residual infraspinatus at the top of the humeral head. The average latissimus dorsi tendon thickness was 3.3 mm anteriorly (standard deviation, 0.34 mm) and 5.2 mm posteriorly (standard deviation, 1.31 mm). Loading of the latissimus dorsi was maintained at 20 N.

Latissimus dorsi transfer

To evaluate the effect of LDT alone, the transferred latissimus dorsi tendon was removed first, followed by removal of the SCR (Fig. 2, *D*). The LDT was then replaced using the same transosseous tunnels, continuous locking sutures, and stay sutures as previously used.

Data analysis and statistics

All measurements were performed twice, checking the repeatability of maximum rotation ± 1°, digitized markers ± 1 mm, and subacromial contact force ± 5 N, and the mean values were used for data analysis. A 2-way repeated-measures analysis of variance with a Tukey post hoc test (SigmaPlot; Systat Software, San Jose, CA, USA) was used to determine significant differences between tear stages and muscle-loading conditions. The level of significance was set at $P < .05$.

Results

Range of motion

ICTs resulted in a significant increase in internal rotation at 60° of abduction ($P < .001$) (Fig. 3). SCR alone did not result in any limitation to internal rotation. SCR plus LDT and LDT alone resulted in decreased internal rotation only at 60° of abduction ($P \leq .030$). For ER, all conditions demonstrated a significant increase at 0° of abduction ($P < .001$). At 30° of abduction, all constructs showed a significant increase in ER compared with the intact condition ($P \leq .009$), and at 60° of abduction, SCR plus LDT ($P = .001$) and LDT alone ($P < .001$) continued to show an increase in ER. Total range of motion was significantly

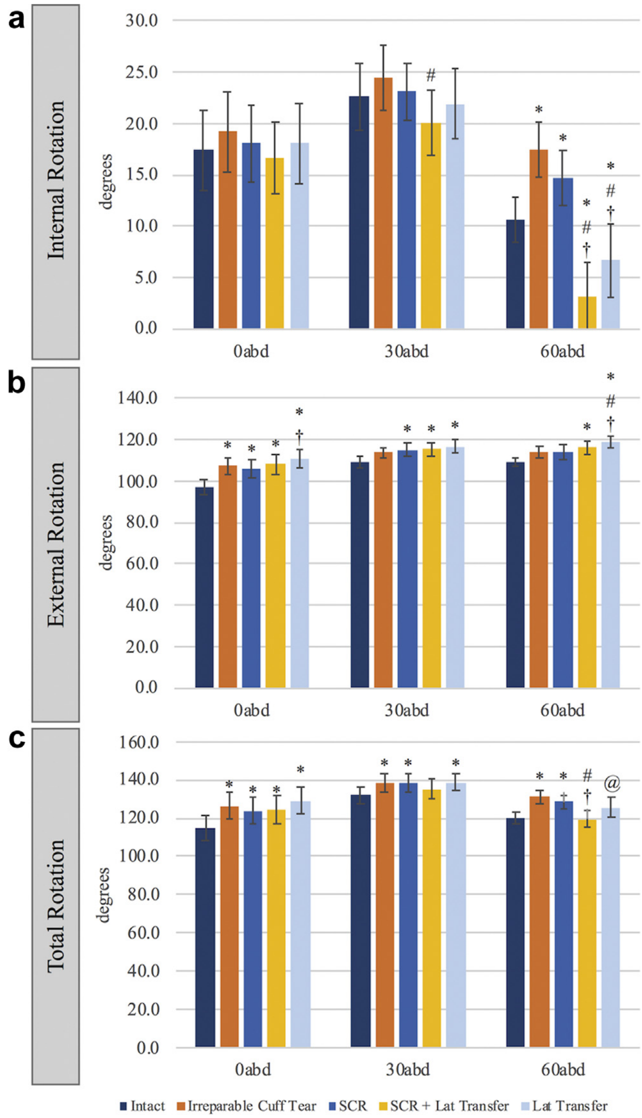

Figure 3 Glenohumeral range of motion: internal rotation (**a**), external rotation (**b**), and total rotation (**c**). Superior capsule reconstruction (*SCR*) was performed with dermal allograft. *$P < .05$ vs. intact. #$P < .05$ vs. irreparable rotator cuff tear. †$P < .05$ vs. SCR. @$P < .05$ vs. SCR plus latissimus dorsi tendon (*Lat*) transfer. *abd*, abduction.

greater for all conditions at 0° of abduction compared with the intact condition ($P < .001$). No conditions showed ranges of motion significantly lower than those of the intact condition at 30° and 60° of abduction.

Superoinferior translation with superiorly directed force

At 0° of abduction, ICTs significantly increased superior translation compared with the intact condition at all degrees of ER ($P < .001$) (Fig. 4). SCR reduced superior translation back to that of the intact condition at 0°, 30°, and 90° of ER at 0° of abduction. At 30° of abduction, SCR was less effective.

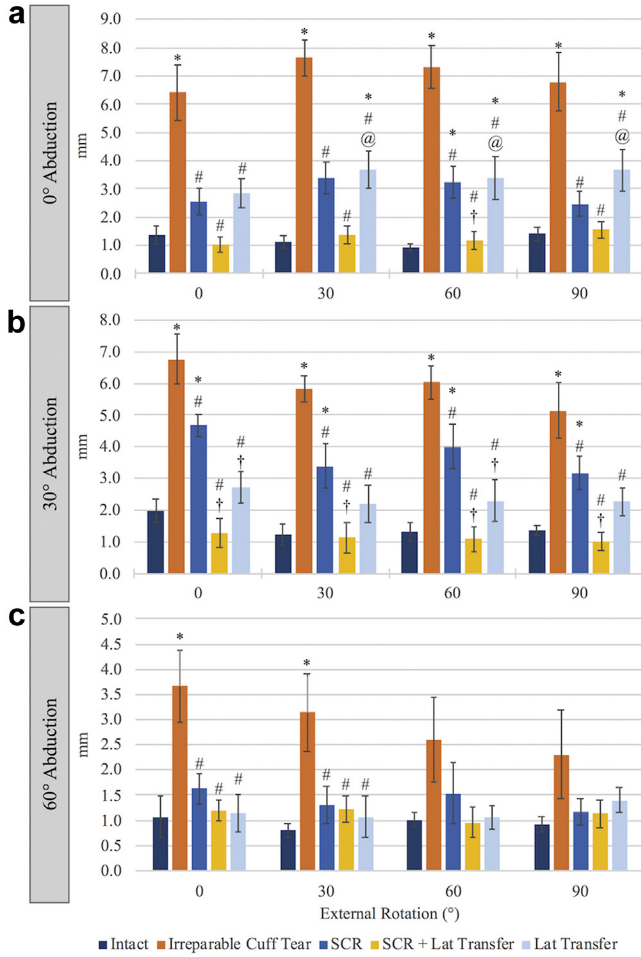

Figure 4 Superoinferior translation with superiorly directed force: 0° of abduction (**a**), 30° of abduction (**b**), and 60° of abduction (**c**). Superior capsule reconstruction (*SCR*) was performed with dermal allograft. *$P < .05$ vs. intact. #$P < .05$ vs. irreparable rotator cuff tear. †$P < .05$ vs. SCR. @$P < .05$ vs. SCR plus latissimus dorsi tendon (*Lat*) transfer.

Although superior translation was significantly less than that of ICTs, it was still significantly greater than that of the intact condition ($P \leq .030$). SCR plus LDT reduced superior translation back to that of the intact condition at all degrees of abduction and all degrees of ER ($P \geq .777$). LDT alone was able to significantly reduce superior translation from that of ICTs at all degrees of ER at 0° and 30° of abduction ($P \leq .012$). However, superior translation remained significantly greater than that of the intact condition at 30°, 60°, and 90° of ER at 0° of abduction ($P \leq .016$).

Anteroposterior translation with superiorly directed force

ICTs resulted in significantly increased posterior translation compared with the intact condition at 30°, 60°, and 90° of ER ($P < .017$) at 0° of abduction, as well as at 0°, 30°, and 60° of ER at 30° of abduction ($P \leq .034$) (Fig. 5). SCR

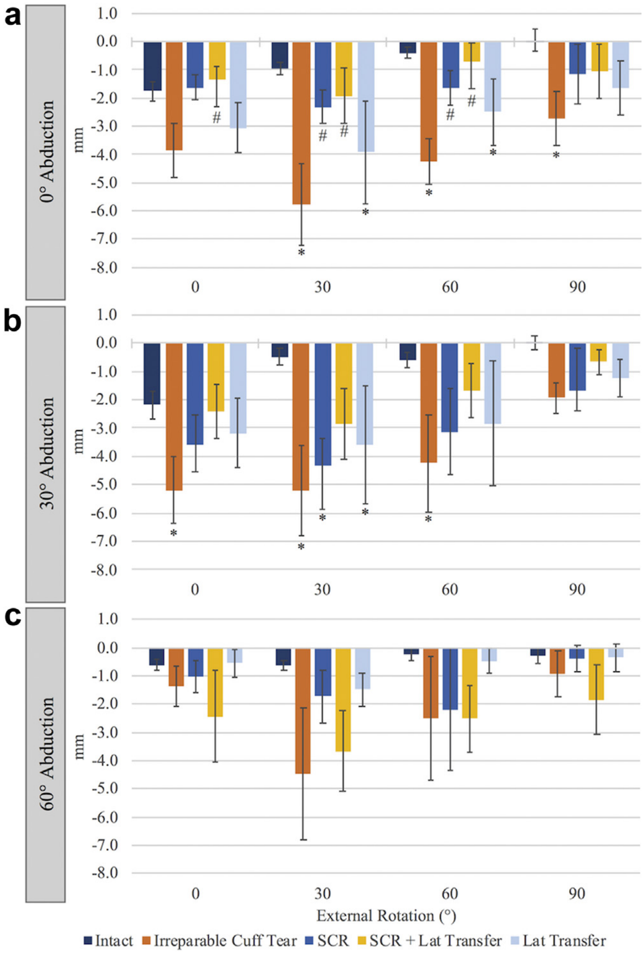

Figure 5 Anteroposterior translation with superiorly directed force: 0° of abduction (**a**), 30° of abduction (**b**), and 60° of abduction (**c**). Superior capsule reconstruction (*SCR*) was performed with dermal allograft. *$P < .05$ vs. intact. #$P < .05$ vs. irreparable rotator cuff tear. *Lat*, latissimus dorsi tendon.

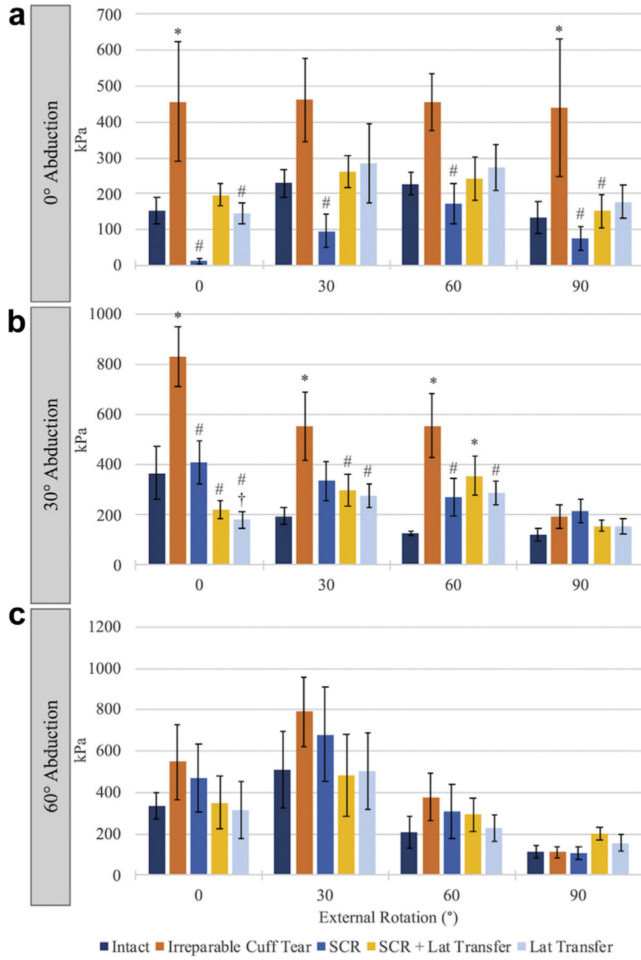

Figure 6 Subacromial peak pressure: 0° of abduction (**a**), 30° of abduction (**b**), and 60° of abduction (**c**). Superior capsule reconstruction (*SCR*) was performed with dermal allograft. *$P < .05$ vs. intact. #$P < .05$ vs. irreparable rotator cuff tear. †$P < .05$ vs. SCR. *Lat*, latissimus dorsi tendon.

alone and SCR plus LDT were able to restore posterior translation back to that of the intact condition at each of these positions ($P \geq .515$). However, LDT alone still resulted in significantly greater posterior translation compared with the intact condition at 30° of ER ($P = .003$) and 60° of ER ($P = .045$) at 0° of abduction and at 30° of ER ($P = .026$) at 30° of abduction.

Subacromial peak contact pressure

ICTs significantly increased peak contact pressure relative to the intact condition at 0° of abduction with 0° of ER ($P = .026$), 0° of abduction with 90° of ER ($P = .025$), 30° of abduction with 0° of ER ($P < .001$), 30° of abduction with 30° of ER ($P < .001$), and 30° of abduction with 60° of ER ($P < .001$) (Fig. 6). The repairs restored peak contact pressure back to that of the intact condition, except for SCR plus LDT at 30° of abduction with 60° of ER ($P = .043$). At 60° of abduction, although the same trends were generally seen, neither ICTs nor the repairs were statistically significantly different from the intact condition.

Discussion

This biomechanical study demonstrates evidence of improved centering of the humeral head when SCR with dermal allograft is combined with LDT for ICTs. Tendon transfers are still controversial, and results are highly variable. The exact role of the LDT for irreparable posterosuperior rotator cuff tears is also debated. We have previously shown the LDT's inability to restore the anteroposterior force couple in the setting of an irreparable posterosuperior rotator cuff tear.[19] In an attempt to improve the outcomes of the LDT, we theorized that by passively stabilizing the glenohumeral joint using an SCR as a static stabilizer, the dynamic stabilizing effect of the tendon transfer may better assist in shoulder function. Our results demonstrate that the combined effect of the LDT and SCR provides improved stability at low to mid abduction angles. We have not, however, proved that this combined treatment will lead to improved clinical results in comparison with either procedure performed in isolation.

Mihata et al[17] first described the SCR procedure in a biomechanical study. They found that SCR using fascia lata allograft fully restored superior glenohumeral stability. In a follow-up study, Mihata et al[13] compared acellular dermal allograft with fascia lata allograft and found that the dermal allograft was more flexible and stretched up to 15% compared with fascia lata allograft. We chose dermal allograft in our study because of its current widespread clinical use. Our dermal graft thickness was 2.07 mm (standard deviation, 0.06 mm), which could be a reason contact pressures were not completely restored in all levels of abduction.[16] Although the exact mechanism of improved function with SCR remains elusive, improved clinical results have been published.[15] Pseudoparalysis is a contraindication to perform a latissimus transfer for ICTs, and failure may be due to loss of the centering force in these rotator cuff–deficient shoulders. SCR alone has been able to reverse pseudoparalysis in some patients.[14] With SCR plus LDT, the combined effect may allow for improved centering of the humeral head and improved function with the dynamic stabilization of the latissimus in addition to the static effect of the SCR using dermal allograft. This could potentially expand the indications of the LDT for ICTs to patients who otherwise would not be ideal candidates. Clinical studies have not been performed to date, and therefore, this procedure cannot be recommended at this time.

SCR plus LDT had significantly less superior migration at the low to mid ranges of abduction compared with LDT or SCR alone. The combination of SCR and LDT may be of some benefit if additional stability is needed in these ranges of motion. This difference diminished between repair groups at high abduction angles (60°). Both the SCR and the LDT are able to function most effectively at the lower levels of abduction. The SCR is under the greatest tension at 0° of abduction and loses efficacy with increasing abduction angles. The addition of the LDT further contributes to prevention of superior translation owing to its inferiorly directed force vector component. In addition, the bulk of the tendon transfer contributes to the SCR's spacer effect, further decreasing superior translation. SCR plus LDT was also the most effective repair at normalizing posterior translation at the low to mid levels of abduction. This difference diminished at a high range of abduction (60°) as well. LDTs have been previously shown to affect the anteroposterior force coupling about the shoulder.[19] In this study, the addition of the SCR to the LDT reduced the increased posterior translation seen with LDT alone. Therefore, the addition of SCR may help the LDT more effectively restore glenohumeral kinematics by reducing the imbalance in anteroposterior force coupling.

The function of the rotator cuff is to maintain concavity compression to the glenohumeral joint, and the superior capsule provides static stabilization of the glenohumeral joint. Without a functioning rotator cuff and superior capsule, this dynamic and static stabilizing force is lost. By combining SCR with LDT, we showed improved centering of the humeral head with less anteroposterior translation and with decreased superior translation compared with SCR or LDT alone. Although SCR alone has shown functional improvement and reversal of pseudoparalysis in some patients, a subset of patients continue to have pseudoparalysis.[14] These patients may benefit from the addition of a dynamic stabilizer. Furthermore, the addition of the LDT to the SCR resulted in greater ER in this study; therefore, SCR plus LDT may be useful in irreparable cuff tear patients with ER deficits.

This study has several limitations. Dynamic stability was approximated through our rigorous design and testing apparatus; however, it cannot exactly represent in vivo muscle dynamics. Our results only considered the glenohumeral joint kinematics, and the complex effects of the scapulothoracic joint were not taken into account. Centering of the humeral head was specifically tested; however, the active pull of the latissimus in vivo may have an improved effect on forward elevation and ER. Our results are also limited to the use of dermal allograft, which has been shown to stretch. These results cannot be extrapolated to include fascia lata autograft but do give us a worst-case scenario. In addition, the combined procedure using both SCR and LDT requires a more extensive approach and dissection than SCR alone.

Conclusion

SCR with dermal allograft combined with LDT improved humeral head centering at the low to mid ranges of shoulder abduction in this cadaveric study. Improved centering of the head has implications that may allow the latissimus to improve forward flexion and active ER in a clinical setting.

Disclaimer

Reza Omid receives royalties from Medacta and Integra and has consultant agreements with Wright/Tornier, Medacta, and Integra. All the other 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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