Original Article

Lower Trapezius Tendon Transfer Restores Deltoid Function and Shoulder Stability More Effectively Than Superior Capsular Reconstruction in Massive Rotator Cuff Tears

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Purpose: To compare the biomechanical effectiveness of superior capsular reconstruction (SCR) and lower trapezius tendon transfer (LTT) to restore the native shoulder kinematics in managing massive rotator cuff tears (MRCTs) using a dynamic shoulder testing system in a cadaver model. **Methods:** Eight fresh-frozen cadaveric hemithoraces were tested using a custom-made dynamic shoulder testing system. The conditions tested are intact, supraspinatus tear, MRCT (supraspinatus and infraspinatus tear), LTT with Achilles allograft, SCR combined with LTT, and SCR alone. Measurements included cumulative deltoid force, humeral head translation (HHT), and subacromial peak pressure during humeral abduction at various angles. **Results:** Significant reductions in cumulative deltoid force were observed from intact to MRCT conditions ($P = .023$). LTT alone significantly improved deltoid force compared to its combination with SCR ($P = .017$) and outperformed SCR alone ($P = .023$). The intact condition showed increasing subacromial peak pressure with higher abduction angles, peaking at 541 kPa at 90°. MRCT exhibited the highest HHT and peak pressure, indicating significant instability. LTT reduced HHT and peak pressure compared to MRCT, indicating partial restoration of stability. The combined LTT + SCR condition demonstrated HHT values close to the intact condition and lower peak pressures, indicating substantial restoration of glenohumeral stability. **Conclusions:** Simulated active unconstrained humeral abduction in the scapular plane using an entire hemithorax model suggests that LTT can restore dynamic stability and deltoid function in MRCTs, while SCR offers static stability without restoring deltoid function. Combining LTT and SCR may result in lower subacromial peak pressures on the undersurface of the acromion than either procedure alone. **Clinical Relevance:** This study will contribute to understanding shoulder kinetics concerning current surgical techniques and suggest a dynamic concept of shoulder biomechanics testing.

Irreparable massive rotator cuff tears (MRCTs) pose a major challenge for reconstructive shoulder surgeons, particularly in debilitating patients with severe pain and functional impairment.[1] Although various surgical treatments are available for these irreparable tears, each option is supported by limited clinical and biomechanical evidence, particularly for younger, nonarthritic patients and older individuals with high functional demands. While reverse total shoulder arthroplasty might not suit these individuals,[2] joint-preserving strategies are often considered more appropriate.[3] These treatment options are partial repairs,[4] interposition bridge grafting,[5] biceps rerouting,[6] subacromial balloon spacers,[7] superior capsular

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reconstruction (SCR),[8] and tendon transfers such as those involving the latissimus dorsi[9] or lower trapezius,[10] anterior cable reconstruction,[11] and biologic tuberoplasty.[12]

Among all these techniques, SCR addresses young, active individuals with irreparable MRCTs.[13,14] Reports have shown favorable outcomes with SCR, noting enhanced range of motion and diminished pain, acting as a static stabilizer.[15,16] Nonetheless, studies have shown variable outcomes with severe fatty degeneration of the infraspinatus tendon, posing doubts about SCR's ability to replicate the dynamic stability intrinsic to the rotator cuff muscles.[17-19]

The lower trapezius tendon transfer (LTT) was introduced as one of the tendon transfer techniques for irreparable MRCTs. Studies have shown good clinical outcomes with LTT.[20-24] It can act as a dynamic stabilizer of the humeral head and gives significant biomechanical advantages in glenohumeral kinematics compared to other options of tendon transfer.[9] LTT aligns closely with the natural biomechanics of the infraspinatus tendon as the force vector of both is similar.[22] Hence, in irreparable MRCT, LTT can help to prevent superior migration of the humeral head during shoulder abduction provided the subscapularis tendon is intact.[25] Comparative studies of LTT and latissimus dorsi transfers show that LTT offers superior outcomes in shoulder mobility, functional recovery, and delay of arthritis onset.[26,27] Additionally, when SCR and LTT are compared, both are found to be effective in improving function, increasing patient satisfaction, and slowing arthritis.[28,29] However, one notable theoretical challenge of LTT is its inability to match the static stability offered by the superior glenohumeral capsule.[30]

Previous biomechanical studies[31-34] utilized a static model, limiting their outcomes to range-of-motion measurements. In contrast, we employed a dynamic shoulder testing model that more accurately reflects normal shoulder kinematics and provides a more physiologically relevant assessment compared to static testing. Through this approach, we not only validate the previous findings but also introduce the capability of measuring deltoid forces, representing a major contribution to the existing literature on this topic. The purpose of this study was to compare the biomechanical effectiveness of SCR and LTT to restore the native shoulder kinematics in managing MRCTs using a dynamic shoulder testing system in a cadaver model. We hypothesized that both LTT and SCR would restore the biomechanical parameters disrupted by MRCTs.

Methods

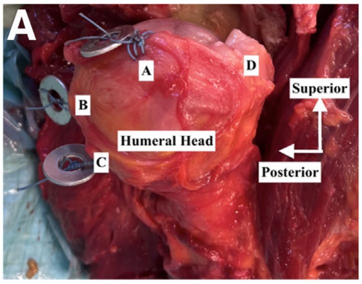
Specimen Preparation

Eight fresh-frozen human shoulder specimens, sourced from individual donors, were procured from Science Care. The cohort consisted of an equal sex distribution, with 4 females and 4 males, presenting an average age of 63.75 years (range, 55 to 75 years) and a mean weight of 219.5 pounds (range, 198 to 273 pounds). For preservation, specimens were stored at −22°C until required for experimentation. All specimens were thawed at room temperature for 24 hours before use.

Each specimen underwent meticulous examination to exclude any pre-existing conditions of the rotator cuff, other injuries about the shoulder girdle, and any signs of previous orthopaedic interventions. The dissection involved removing all tissues surrounding the shoulder girdle, retaining only the shoulder capsule, coracoacromial ligaments, rotator cuff, and deltoid tendinous insertion for further analysis. The humerus was sectioned 5 cm below the distal insertion of the deltoid, specifically at the junction of the lower third to the mid-third of the humerus. A research fellow conducted all dissections and specimen preparations under the guidance of fellowship-trained orthopaedic surgeons.

To secure the tendinous muscle insertions of the supraspinatus, infraspinatus, teres minor, subscapularis, and the deltoid muscle's 3 heads, No. 2 FiberWire (Arthrex) was utilized. Each muscle's tendinous portion was sutured using the Krakow method. Tendon sutures were placed based on the orientation of the muscle fibers for anatomic muscle loading. This FiberWire was used to affix a washer, which was then connected to a polyfilament fishing line (0.50 mm diameter; 120 lbs. strength) at the opposing end, facilitating loading for biomechanical assessment. Tendon sutures were placed in the following locations: central insertion of each rotator cuff muscle at the humeral head and anterior, middle, and posterior sutures for each head of the deltoid. The direction of the pull was set based on muscle fiber orientation.[33-35] Figure 1 shows the affixed deltoid and four rotator cuff insertions, attached with washers and fishing lines.

The cadaveric preparation involved mounting it on a transparent polycarbonate glass panel (90 × 50 cm) that contains 2,226 holes spaced 2.5 cm apart, tracking each muscle's pathway. These holes were drilled through the glass to accommodate wood screws (5 mm diameter, 7-8 cm in length), which were then inserted from the glass into the cadaver's vertebrae. The selection of vertebrae for screwing through the glass was arbitrary and random, aimed solely at mounting the hemithorax on the glass. Approximately 9 to 10 screws, spanning from the cervical to the sacral vertebrae, were placed through the glass. This configuration ensured that the specimen was maintained in an upright and stable orientation. Figure 2 depicts this arrangement. This setup enabled the accurate quantification of the dynamic forces encountered by the rotator cuff and deltoid muscles under various loading conditions, thus supporting a thorough dynamic biomechanical analysis.



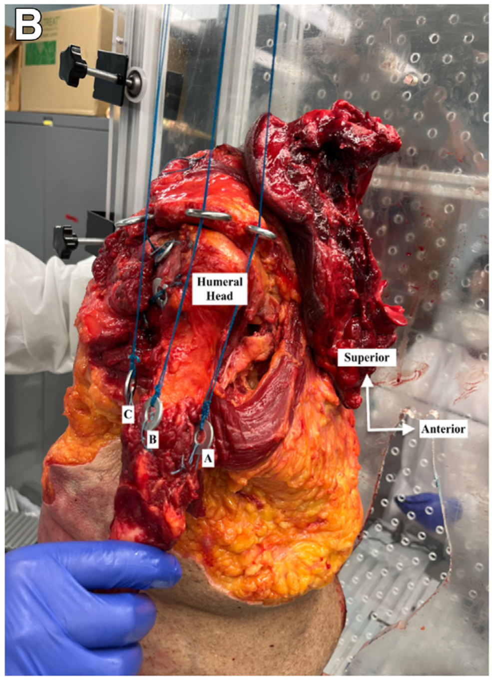


Fig 1. Attachments of musculotendinous insertions. (A) Krackow sutures attaching rotator cuff tendons around the humeral head. (B) Deltoid muscle insertions attached to washers and fishing lines, representing muscle fiber orientation.

Figure 3 is the computer-aided design model of our dynamic shoulder testing rigs used in this experiment.

Our dynamic shoulder testing system offers several advantages over traditional earlier methods. By allowing natural, unrestricted humeral abduction in the scapular plane, it provides a more realistic simulation of shoulder kinematics compared to models that use rigid frames or aluminum rods to constrain movement. The system enables dynamic muscle loading by preloading the rotator cuff muscles and permitting movement throughout the range of motion, which allows us to measure the forces exerted by each muscle. This offers insights into the dynamic stabilizing roles of these muscles—information that static models cannot provide. Additionally, by mimicking the natural interplay between muscles and joint movement, our system enhances the physiological relevance of the findings and improves their translational potential in clinical settings. The ability to capture real-time force measurements during dynamic movement also enables a comprehensive analysis of muscle function not possible with static or constrained models. Video 1 shows smooth, unrestricted humeral abduction on our testing rig.

Experimental Conditions

Six testing conditions were used for each cadaveric shoulder in the below strict chronological order (Fig 4):

(1) Intact rotator cuff served as control.
(2) Supraspinatus and superior capsule were sharply incised off from its footprint at the greater tuberosity (Fig 4A).
(3) Infraspinatus and the capsule beneath were sharply incised, the same as the supraspinatus (Fig 4B).
(4) An LTT was performed using Achilles allograft (Fig 4C).
(5) SCR was performed using a human dermal allograft (ArthroFLEX; Arthrex) (Fig 4D).
(6) Lower trapezius tendon was incised from the humeral head.

Our protocol was meticulously designed to facilitate comparisons between rotator cuff tear conditions and a normal intact state, with the subsequent addition of 2 distinct procedures. Therefore, experimental condition 3 involved superimposing an infraspinatus tear on a supraspinatus tear, representing an MRCT.[35,36] In condition 5, the addition of SCR on LTT allowed for evaluating both procedures' combined effects in addressing the compromised shoulder biomechanics associated with an MRCT. Lastly, condition 6, by removing LTT and isolating SCR, enabled us to examine its sole efficacy in correcting the altered biomechanics of an MRCT.

Surgical Procedures

LTT. The LTT was identified and harvested from its anatomic insertion site, specifically the most medial of the scapular spine's inferior border.[37] It was subsequently tied with No. 2 nonabsorbable braided polyester sutures (Ethibond Excel; Ethicon) using a Krackow stitching technique to facilitate manipulation. An Achilles tendon allograft, procured from a tissue bank, was used for the

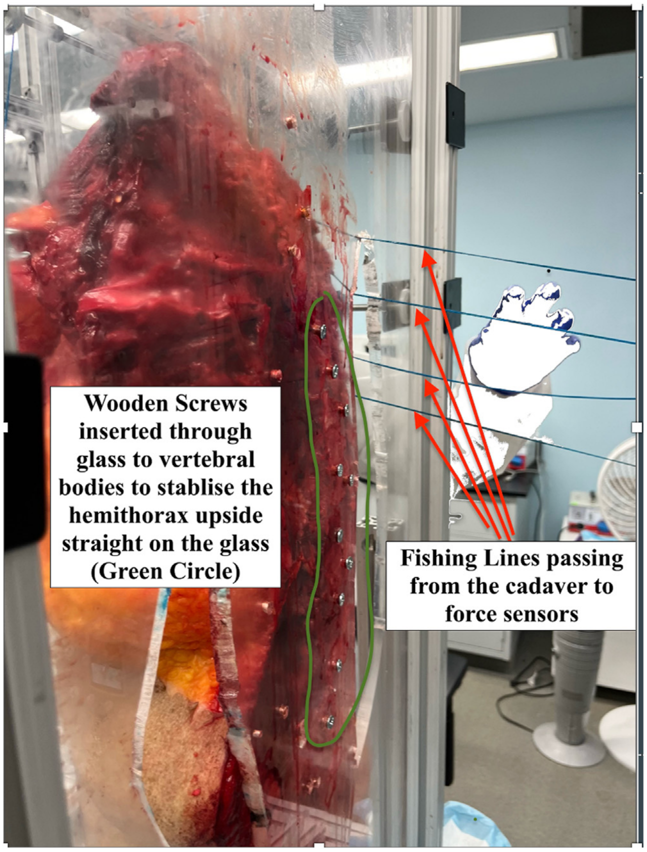


Fig 2. Cadaver mounting setup on polycarbonate glass panel. Hemithorax mounted on a transparent polycarbonate panel (90 × 50 cm) using fishing lines and wooden screws for upright, stable orientation. This setup allows precise measurement of dynamic muscle forces during humeral abduction.

LTT. The calcaneal bone block was removed before utilization. The mean total length of the Achilles tendon was 10.30 ± 0.21 cm, and the mean thickness of its distal tendinous portion was 5.24 ± 1.56 mm. The distal tendinous part was sutured using a No. 2 high-strength suture (FiberWire Suture; Arthrex) with multiple Krackow stitches. The distal tendinous part of the harvested Achilles graft was fixed onto the greater tuberosity at a 90° humeral abduction. Two bone tunnels were created in the greater tuberosity and fixed using 2 SwiveLock (4.75 × 19.1 mm; Arthrex). Subsequently, the proximal part of the Achilles tendon was sutured to the harvested lower trapezius. As per the earlier study, we have attached the graft at the footprint of infraspinatus insertion at the humeral head.[35]

SCR. We utilized a dermal allograft (AFLX301 Decellularized Dermis; LifeNet Health) for this procedure. The thickness of the graph was 5 mm. The graft was prepared by punching 6 holes on the medial side and 4 holes on the humeral side. The holes on the medial side were arranged in 3 pairs, with each pair spaced 4 mm apart and each hole within a pair spaced 1 mm apart. This arrangement matched the superior glenoid at 10-, 12-, and 2-o'clock positions. On the lateral side, there were 4 holes, with 2 holes used by each SwiveLock anterior to the Achilles tendon allograft attachment on the humerus. Three Arthrex Knotless SutureTak Anchors (2.9 mm; Arthrex) were inserted along the superior margin of the glenoid at the 10-, 12-, and 2-o'clock positions. For humeral fixation, 2 bone tunnels were created to perform a transosseous repair in the greater tuberosity, fixed in a crisscross manner using 2 Arthrex SwiveLock (4.75 × 19.1 mm; Arthrex) at 30° of humeral abduction. The distal part of the Achilles tendon was not covered on the lateral edge of the SCR graft, as shown in Figure 4E. We fixed the SCR on the supraspinatus footprint at the humeral head.

Measurements

Deltoid Forces. Our customized shoulder testing apparatus is designed to measure the force exerted by the deltoid. The system's core is a servo-hydraulic connected to a PVC pipe. In our setup, 1 full rotation of the motor results in 1° of shoulder abduction. Operating at 100 rpm, the motor produces a shoulder abduction rate of 100° per minute, or approximately 1.67° per second. This standardized rate of abduction was maintained consistently across all specimens, ensuring uniformity in our measurements despite variations in arm length. This pipe is securely attached to the motor shaft using a screwdriver mechanism to eliminate any rotational slippage. The PVC pipe extends to connect with a stool that has a threaded mechanism. This mechanism is designed to wind and unwind a thread based on the motor's operation, allowing precise control over the tension exerted by the system. The end of this thread is then horizontally linked to a force gauge sensor, forming the critical connection point for measuring muscular force. The threads pass through pulleys before securely attaching to the deltoid muscle area. These threads are guided through hooks at the subacromial space, ensuring an accurate force transmission and measurement pathway.

Subacromial Pressure. A contact pressure sensor (FlexiForce; Tekscan) film (2 × 2 cm) is placed under the subacromial region to measure the contact pressure over time. When the shoulder abducts from 0° to 90°, this sensor actively records changes in subacromial pressure, displaying these variations through a contour map. Care was taken to avoid distortion of the film to maintain accuracy of the pressure measurements.

Humeral Head Translation. We used motion-tracking sensors to digitize the distance between the humeral head and the acromion (Optotrak Certus; NDI). One

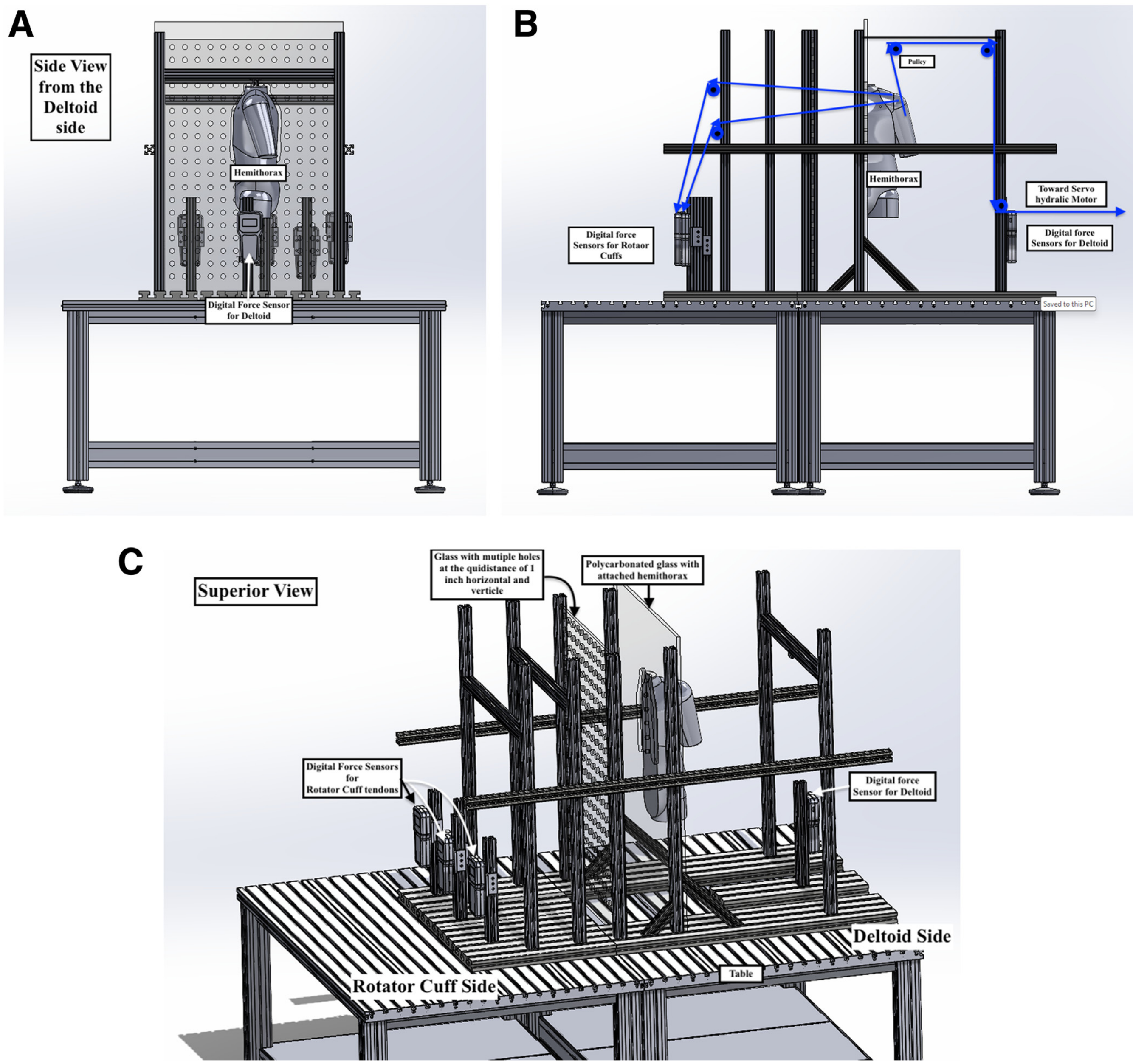


Fig 3. Dynamic shoulder testing rig. Side view (A), front view (B), and oblique view (C) of the customized rig with servo-hydraulic motors enabling unrestrained humeral abduction from 0° to 90°. The system manipulates rotator cuff muscle forces for biomechanical assessment. Computer-aided design models depict the mechanical components used.

marker was placed at the acromion (center of the anterior and posterior margin of the acromion) and another 5 cm below the superior margin of the bicipital groove for humeral head location. Each Optotrak marker displayed the x, y, and z coordinates, enabling the tracking of displacement during the shoulder's abduction to a 90° angle.

Statistical Analysis. All measurements for data acquisition were performed thrice. Continuous variables were presented as mean ± standard deviation (SD), while categorical variables were characterized using frequencies and percentages. Shapiro-Wilk test was employed to assess the normality of the data. Following the normality assessment, a 1-way analysis of variance (ANOVA) was selected to examine the potential association between cumulative deltoid force, humeral head translation (HHT), and subacromial peak pressure. Post hoc analyses were carried out using the Tukey honestly significant difference (HSD) test to investigate further the specific group differences among the 6 test conditions. The statistical significance was defined as $P < .05$. Statistical analyses were performed using

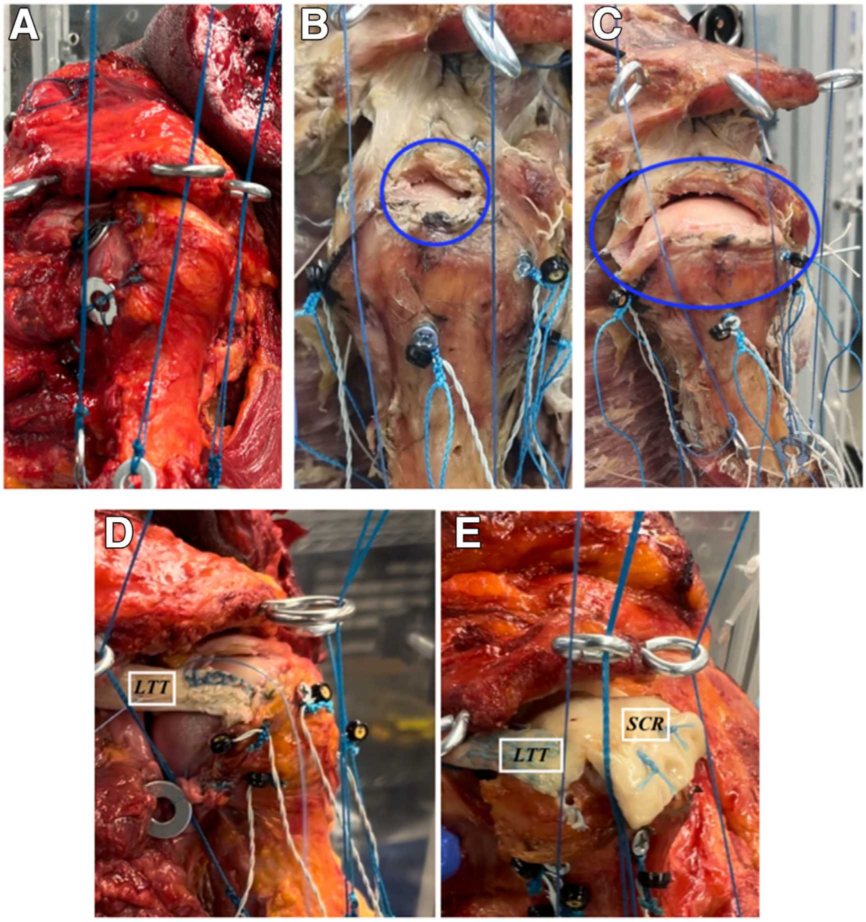


Fig 4. Various experimental conditions. Illustrations of experimental conditions: (A) Intact rotator cuff (control). (B) Supraspinatus tear—supraspinatus and superior capsule incised from greater tuberosity (blue circle). (C) Infraspinatus tear—infraspinatus and capsule incised (blue circle). (D) Lower trapezius tendon transfer using Achilles allograft attached at greater tuberosity. (E) Superior capsular reconstruction using dermal allograft fixed at the humeral head. (LTT, lower trapezius tendon transfer; SCR, superior capsular reconstruction.)

IBM SPSS Statistics for Windows, Version 29.0 (IBM Corp.).

Results

Deltoid Cumulative Forces

Statistical analysis revealed significant variances in cumulative deltoid forces across the 6 experimental conditions tested. Table 1 and Figure 5 depict cumulative deltoid force. Notably, transitioning from an intact condition to an MRCT significantly reduced cumulative deltoid force by 28% ($P = .023$). Figure 3 illustrates this result. The LTT intervention increased deltoid force by 27.25% ($P = .166$). SCR alone decreased deltoid force by 34% relative to MRCT ($P = .208$). Notably, combining LTT with SCR caused increased deltoid force by 32.57% compared to SCR alone ($P = .023$) and significantly decreased it by 13.6% compared to LTT alone ($P = .017$). The combined LTT and SCR resulted in a significant deltoid force reduction of 20.9% from the intact condition ($P = .001$).

HHT

The HHT was measured as the total displacement between the humeral head and the acromion during abduction, calculated using the Euclidean distance formula: $D = [X^2 + Y^2 + Z^2]^{1/2}$. Table 2 and Figure 6 present the mean HHT values (in millimeters) and their standard errors at various abduction angles for each experimental condition.

In the intact condition, HHT decreased with increasing abduction angles from 2.24 mm at 0° to 0.98

Table 1. Mean and Standard Error of Cumulative Deltoid Forces

	Mean (N)	SE (N)
Intact	42.44	25.9
Supraspinatus tear	33.06	20.04
Supra- + infraspinatus tear (MRCT)	30.53*	20.65
LTT	38.85	31.81
LTT + SCR	33.57**	18.27
SCR	20.14***	10.53

NOTE. This table presents the mean cumulative deltoid forces (in Newtons) and their standard error (SE) under 6 experimental conditions: intact, supraspinatus tear, MRCT (supraspinatus and infraspinatus tear), LTT, LTT combined with SCR, and SCR alone.

LTT, lower trapezius tendon transfer; MRCT, massive rotator cuff tear; SCR, superior capsular reconstruction.

*$P = .023$ comparing with intact.

**$P = .017$ comparing with LTT.

***$P = .023$ comparing with LTT + SCR.

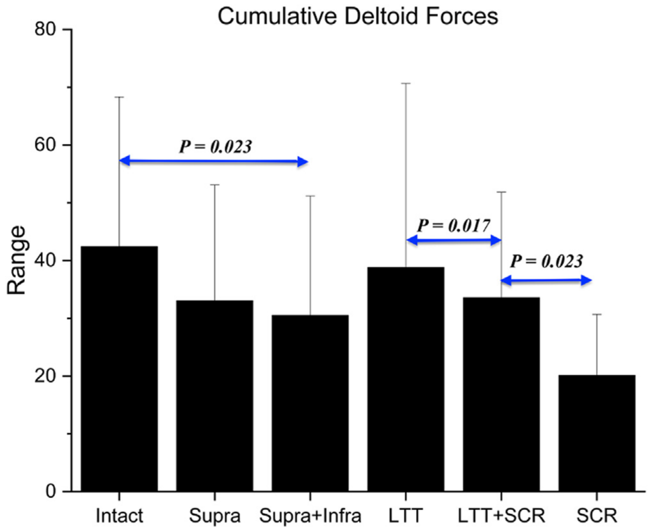


Fig 5. Cumulative deltoid forces under various conditions. This graph shows the mean cumulative deltoid forces (in Newtons) across 6 experimental conditions: intact rotator cuff, supraspinatus tear, massive rotator cuff tear (supraspinatus and infraspinatus tear), LTT, LTT combined with SCR, and SCR alone. The first double arrow represents the *P* value between intact and massive rotator cuff tear condition. (LTT, lower trapezius tendon transfer; SCR, superior capsular reconstruction.)

mm at 90°, indicating enhanced stability. The supraspinatus tear condition showed slightly higher HHT than the intact across all angles, with a significant increase at 30° of abduction (2.46 mm vs 1.96 mm; $P = .0067$). The MRCT condition exhibited the highest HHT values, indicating significant instability, with significant differences from the intact condition at 30°, 45° ($P = .00012$), and 90° ($P = .00089$). Application of LTT reduced HHT compared to MRCT, showing partial restoration of stability with significant improvements at all angles (Table 2). The combination of LTT + SCR demonstrated HHT values close to the intact condition, with no significant difference at 90° (1.11 mm vs 0.98 mm) ($P = .11$). SCR alone improved stability over MRCT and LTT but had higher HHT than the intact and LTT + SCR conditions; at 90°, HHT was 1.51 mm with SCR alone, significantly higher than the MRCT condition ($P = .00076$).

Subacromial Peak Pressure

Table 3 and Figure 7 present the mean subacromial peak pressure (in kPa) at various humeral abduction angles under different experimental conditions. In the intact condition, the subacromial peak pressure increases consistently with higher abduction angles, ranging from 45.26 kPa at 0° to 541 kPa at 90°. The supraspinatus tear shows increased pressures compared to the intact condition across all angles, with the highest difference observed at 30°. The supra- and infraspinatus tear (MRCT) condition exhibits the highest pressures at all angles, indicating substantial instability. The LTT condition shows pressures higher than the intact but lower than MRCT, suggesting partial restoration of stability. The combined LTT + SCR condition demonstrates the lowest pressures at 0°, 30°, and 45° and is considerably lower than the intact and other tear conditions, indicating considerable stabilization. The SCR condition alone shows lower pressures at 0° and 30° but significantly higher pressure at 90° compared to the intact condition, possibly due to the spacer effect of the dermal allograft. Overall, the combined interventions (LTT + SCR) offer the best restoration of normal subacromial peak pressure values, closely approximating or bettering the intact condition and indicating improved shoulder joint stability.

Discussion

Our study demonstrated that combining LTT with SCR effectively restores shoulder biomechanics in

Table 2. Humeral Head Translation at Various Abduction Angles

	HHT, Mean (SE), mm				
	Humeral Abduction Angle				
Experimental Conditions	0°	30°	45°	60°	90°
Intact	2.24 (0.78)	1.96 (0.75)	1.70 (0.75)	1.34 (0.64)	0.98 (0.54)
Supraspinatus tear	2.70 (0.89)	2.46 (0.84)[*]	2.11 (0.68)	1.77 (0.68)	1.40 (0.45)
Supra- + infraspinatus tear (MRCT)	3.33 (0.95)	3.02 (0.82)[*]	2.63 (0.71)[*]	2.27 (0.59)	1.90 (0.58)[*]
LTT	2.51 (0.80)[†,‡,§]	2.23 (0.66)[†,‡,§]	1.96 (0.59)[†,‡,§]	1.59 (0.53)[†,‡,§]	1.25 (0.45)[†,‡,§]
LTT + SCR	2.24 (0.63)[†,§,‖]	1.97 (0.63)[†,§,‖]	1.67 (0.52)[†,§,‖]	1.29 (0.39)[†,§,‖]	1.11 (0.43)[†,§,‖]
SCR	2.69 (0.75)[†,‡,‖]	2.46 (0.63)[†,‡,‖]	2.15 (0.53)[†,‡,‖]	1.84 (0.60)[†,‡,‖]	1.51 (0.47)[†,‡,‖]

This table shows the mean HHT in millimeters and their standard error (SE) at different angles of humeral abduction (0°, 30°, 45°, 60°, and 90°) for the 6 experimental conditions: intact, supraspinatus tear, MRCT, LTT, LTT + SCR, and SCR alone.

HHT, humeral head translation; LTT, lower trapezius tendon transfer; MRCT, massive rotator cuff tear; SCR, superior capsular reconstruction.

*Post hoc significance versus intact ($P < .05$).

[†]Post hoc significance versus supra- and infraspinatus tear ($P < .05$).

[‡]Post hoc significance versus LTT + SCR ($P < .05$).

[§]Post hoc significance versus SCR ($P < .05$).

[‖]Post hoc significance versus LTT ($P < .05$).

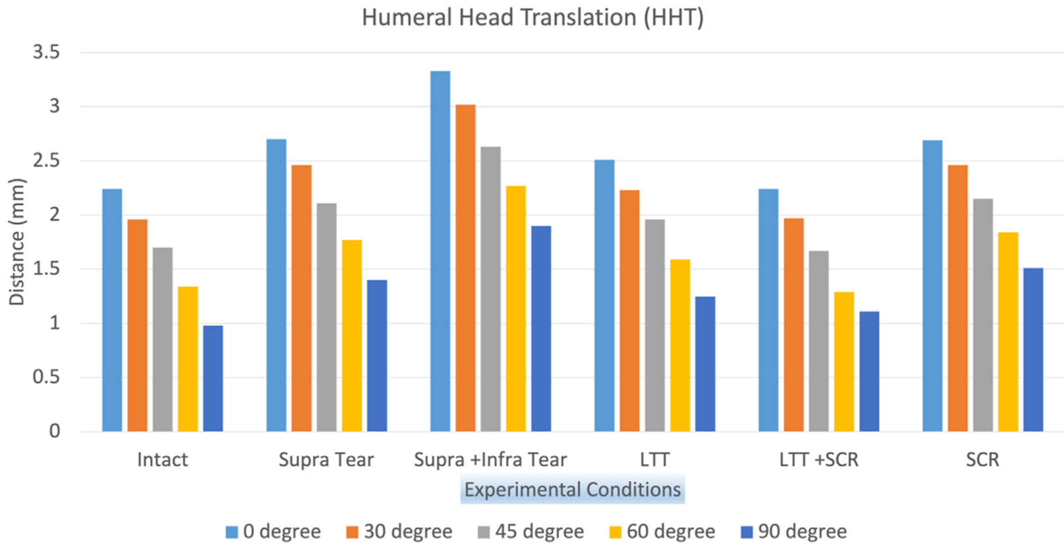


Fig 6. Humeral head translation (HHT) during abduction. The figure presents the mean HHT in millimeters at various angles of humeral abduction (0°, 30°, 45°, 60°, and 90°) across the 6 experimental conditions: intact, supraspinatus tear, massive rotator cuff tear, LTT, LTT + SCR, and SCR alone. Higher HHT values indicate greater instability. (LTT, lower trapezius tendon transfer; SCR, superior capsular reconstruction.)

MRCTs, as evidenced by significant improvements in cumulative deltoid force, HHT, and subacromial peak pressure.

We measured the cumulative deltoid forces required for abduction and observed a significant decrease in deltoid force in the MRCT condition due to altered biomechanics from the loss of stabilizing function of the supraspinatus and infraspinatus muscles. The absence of these rotator cuff tendons leads to superior migration of the humeral head, shortening the deltoid's lever arm and reducing its mechanical advantage, making the deltoid less effective at generating force. LTT alone effectively restored deltoid function by providing dynamic stability. In contrast, SCR, which offers static stability, further decreased deltoid force in our experiment. Therefore, while LTT can restore deltoid function, its effect was reduced by 13.6% when combined with SCR. These findings highlight the critical role of rotator cuff integrity in facilitating effective deltoid function during shoulder abduction and suggest that dynamic stabilization provided by LTT may be more beneficial than static stabilization alone.

Two other critical biomechanical parameters studied were subacromial peak pressure and HHT. We used a 3-dimensional marker system to provide direct distances between 2 marked points, revealing changes in HHT. Earlier studies reported humeral head migration as either superior or anterior; we incorporated both components and presented changes in HHT during humeral abductions. Muench et al.[38] established that

Table 3. Subacromial Peak Pressure at Various Humeral Abduction Angles

Experimental Condition	0° (Kpa)	30° (Kpa)	45° (Kpa)	60° (Kpa)	90° (Kpa)
Intact	45.26 (26.26)[*]	93.21 (25.72)[*]	107.47 (39.19)	242.73 (52.69)	541 (146.35)
Supraspinatus tear	69.47 (28.25)	186.47 (57.52)	206.15 (72.98)	277.15 (78.63)	607.68 (91.54)
Supra- and infraspinatus tear (MRCT)	126.85 (40.14)	221.85 (47.33)	334.35 (60.08)	412.65 (62.79)	747.8 (127.05)
LTT	40 (27.60)[*,†,‡]	74.15 (30.61)[*,†,§]	91.45 (42.27)[†,§,‖]	235.9 (71.28)[†,§]	480.9 (106.71)[*,†,§]
LTT + SCR	46.47 (12.98)[*,‡,§]	82.82 (25.32)[†,§]	97.88 (29.96)[*,§]	288 (52.13)[*,†,§]	596.05 (143.53)[*,†,‡]
SCR	50.02 (5.7)[*]	97.17 (21.23)[*,†,‖]	100.35 (21.22)[†,‖]	295.17 (47.6)[*,†,‡]	658.70 (123.79)[*,†,‡,§]

NOTE. This table provides the mean subacromial peak pressure (in kilopascals, kPa) and their standard error (SE) at different angles of humeral abduction (0°, 30°, 45°, 60°, and 90°) across the 6 experimental conditions: intact, supraspinatus tear, MRCT, LTT, LTT + SCR, and SCR alone. LTT, lower trapezius tendon transfer; MRCT, massive rotator cuff tear; SCR, superior capsular reconstruction.

*Post hoc significance versus intact ($P < .05$).

†Post hoc significance versus supra- and infraspinatus tear ($P < .05$).

‡Post hoc significance versus LTT ($P < .05$).

§Post hoc significance versus SCR ($P < .05$).

‖Post hoc significance versus LTT + SCR ($P < .05$).

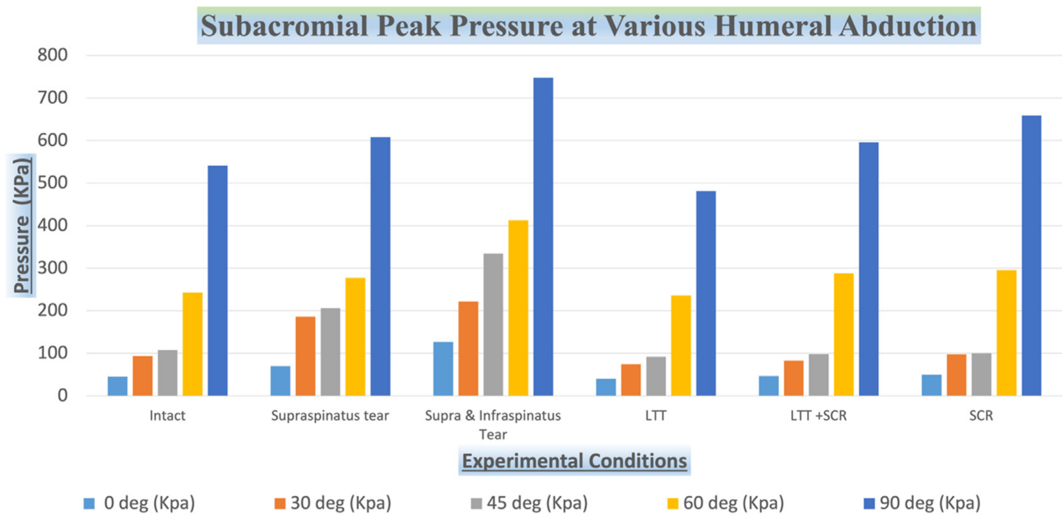


Fig 7. Subacromial peak pressure at various humeral abduction angles. This bar graph illustrates the mean subacromial peak pressure (in kilopascals, kPa) at different angles of humeral abduction (0°, 30°, 45°, 60°, and 90°) for the 6 experimental conditions: intact, supraspinatus tear, massive rotator cuff tear, LTT, LTT + SCR, and SCR alone. (LTT, lower trapezius tendon transfer; SCR, superior capsular reconstruction.)

LTT significantly corrects superior humeral head migration compared to latissimus dorsi transfer. Subsequently, Baek et al.[32] confirmed that LTT corrects HHT due to its dynamic joint-centering effects in its pull direction, countering the anterior and superior migration of the humeral head in the absence of the supraspinatus and infraspinatus. Based on previous literature[32,38] postulating that maintaining the integrity of the anteroposterior force couple reduces the occurrence of superior and anterior migration of the humeral head during glenohumeral abduction, the dynamic joint-centering effect and the restoration of anteroposterior force coupling of LTT contributed to suppressing the translation of the humeral head in the current study.

Subacromial peak pressure, measured in the subacromial space below the acromion of the scapula, surprisingly increased at 90° of humeral abduction with SCR. We believe that this increase may be due to the spacer effect of the dermal allograft causing tissue crowding in the relatively narrow subacromial space. In contrast, Baek et al.[32] reported significantly lower subacromial contact pressure with SCR at 0°, 20°, and 40° of abduction. Scheiderer et al.[39] demonstrated that thick SCR (6 mm) better restores shoulder function compared to a thin one (3 mm). Our experiment used a 5-mm-thick dermal allograft for SCR. Earlier studies by Mihata et al.[34] and Adams et al.[40] established that SCR with fascia lata allograft restores subacromial peak pressure more effectively than dermal allograft.

Kane et al.,[41] in an in vivo study using dynamic biplane radiography during scapular plane abduction, determined that SCR using dermal allograft did not effectively depress the humeral head or decrease the acromiohumeral distance during full shoulder abduction. More recently, Muench et al.,[42] in a biomechanical study of SCR using dermal allograft with a dynamic cadaveric shoulder model, revealed a loss of graft tension at 45° to 60° of glenohumeral abduction. As a result, the graft could not depress the humeral head at these higher abduction angles. In our study, after 60°, the graft lost its tension and acted as a spacer, significantly raising subacromial pressure at 90° of abduction. SCR with dermal allograft and fascia lata allograft have different moduli of elasticity and stiffness. We used the dermal allograft in our experiment, which is essential to consider when comparing the results with LTT. Our setup addressed one of the critical limitations of earlier shoulder biomechanics studies conducted in static or dynamic environments with restrained humeral abduction in a fixed external frame. By eliminating this constraint, we provided a more accurate representation of natural shoulder movement. Further clinical studies on SCR and LTT are necessary to confirm the complementary roles of each procedure.

Limitations

This study has several limitations. As a time-zero biomechanical analysis, we did not consider graft-to-bone healing, physiological adaptation, muscle retraining, or postsurgical rehabilitation. Furthermore, this testing system has not been validated. Thus, our results should be interpreted with caution. Estimating muscle loading in LTT is challenging due to the lower trapezius muscle's small size and low contraction capability. We used partial torso specimens and approximated the origins and pull lines of the lower trapezius based on each specimen's anatomy but maintained consistent muscle-loading directions using anatomic landmarks like the scapular spine and inferior scapular angle. Our biomechanical assessments were limited to the scapular plane; positions like forward flexion or extension were not evaluated. Additionally, we focused on glenohumeral joint motions without accounting for scapulothoracic movement, which may limit replication of coordinated motion between these joints in vivo. Another limitation is that we tested all shoulders in the same fixed sequence, which may have introduced order effects like tissue changes in the LTT over time, potentially affecting its state when combined with SCR. Randomizing the sequence or using paired shoulders with different starting procedures would have strengthened the study by allowing independent evaluation of each procedure and minimizing the impact of sequential testing. We acknowledge that the relatively small differences in HHT between the intact and MRCT conditions (approximately 0.9 to 1.2 mm), as well as the higher subacromial pressure observed at higher degrees of abduction with SCR, may be due to our methodology where the supraspinatus and infraspinatus tendons were incised but not completely resected. The residual tendon tissue could act as a partial spacer, limiting humeral head migration and increasing tissue volume in the subacromial space, potentially causing impingement during abduction. This might explain both the modest HHT changes and the elevated subacromial pressures in our study compared to others where tendons were fully resected. Despite their small magnitude, these differences are statistically significant and can impact shoulder biomechanics, highlighting the clinical relevance and the importance of surgical interventions to restore stability.

Conclusions

Simulated active unconstrained humeral abduction in the scapular plane using an entire hemithorax model suggests that LTT can restore dynamic stability and deltoid function in MRCTs, while SCR offers static stability without restoring deltoid function. Combining LTT and SCR may result in lower subacromial peak pressures on the undersurface of the acromion than either procedure alone.

Disclosures

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