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Coracoacromial ligament integrity influences scapular spine strain after reverse shoulder arthroplasty

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A R T I C L E I N F O

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Scapular spine strain
Acromial fracture
Cuff tear arthropathy
Plane of elevation

Level of evidence: Basic Science Study; Biomechanics

Background: The purpose of this biomechanical study was to examine the effect of coracoacromial (CA) ligament state (intact vs. released) and arm position on acromial and scapular spine strain following reverse total shoulder arthroplasty (rTSA).
Methods: Eight cadaveric shoulders were implanted with a custom rTSA system and tested using an in-vitro shoulder simulator. The specimens were cycled through static range of motion in both abduction and forward elevation; first with the CA ligament in the "intact" state followed by the "released" state. Scapular spine strain was quantified via 4 strain gauges placed along anatomic locations on the acromion and scapular spine.
Results: Increases in strain were observed across all 4 strain gauge locations upon release of the CA ligament in both 0° of abduction and forward elevation. Increases in the mean strain were observed to be as great as 14% in abduction and 31% in forward elevation. The increases in strain at 0° elevation approached but did not reach statistical significance ($P \geq .072$). At 90° of abduction and forward elevation, no increases in the mean strain were observed. The greatest strain was consistently observed with the arm positioned in 0° of forward elevation ($P < .001$).
Discussion: CA ligament release in the setting of rTSA resulted in increased scapular spine and acromial strain with the arm adducted, although these increases in strain were not statistically significant. Caution should be taken intraoperatively as the release of the CA ligament may alter scapular spine and acromion stresses from deltoid loading, which may increase the risk for postoperative scapular spine fracture.

The utilization of reverse total shoulder arthroplasty (rTSA) has increased significantly over the past decade.[9,34] The indications for this procedure have expanded beyond the original indication of cuff tear arthropathy[18,19] and is now used for treating patients with glenohumeral arthritis, proximal humeral fractures, revision arthroplasty, and massive irreparable rotator cuff tears.[4,6,12,14,15,36,39,51,53] The design of this prothesis serves to fully constrain the glenohumeral joint, while increasing the moment arm of the deltoid muscle by moving the glenohumeral joint center of rotation medially and distally.[5] While rTSA can be effective at restoring function and relieving pain, complications can arise.[3,37,46,48]

Perhaps one of the most concerning complications in rTSA is fracture of the acromion or scapular spine. The incidence of scapular spine fractures has been reported to vary between 1% and 10%,[2,13,20,30,42,55] with recent multicenter studies reporting an incidence rate of approximately 4%.[32,33] These fractures have previously been classified according to the amount of deltoid origin involved in the fracture as described by Levy et al.[30] Type I fractures involve a portion of the middle deltoid origin and type II fractures involve the entire middle deltoid origin and a portion of the posterior deltoid origin, while type III fractures envelope the entire middle and posterior deltoid origins. These types of fractures can cause significant pain and lead to poor postoperative outcomes, especially in cases of type II and III fractures.[7,30] Furthermore, while several risk factors have previously been identified including gender, osteoporosis, glenoid component lateralization, and cuff tear arthropathy,[32,33] the precise etiology of this complication remains unknown.

Institutional review board approval was not applicable to this study.

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It has been suggested in recent literature that the release of the coracoacromial (CA) ligament, which connects the anterior acromion to the lateral coracoid to complete the CA arch, may increase the risk of scapular spine and acromial fractures in rTSA patients. Two cadaveric studies from Taylor et al[50] and Haislup et al[21] investigated the effect of a CA ligament release on strain in the scapular spine and acromion. Increases in scapular spine strain upon the excision of the CA ligament were reported in both studies, suggesting this to be a potential risk factor for post-operative fracture. However, each study reported significant strain increases in conflicting regions of the scapular spine. Additionally, both studies only used 2 strain gauges to measure strain, which prevented strain from being analyzed along the tensile dorsal surface of the scapular spine, a region of bone which is exerted to increased tensile stress and may be susceptible to the initiation of a fracture.[54] Forward elevation was also not considered in these studies, which may change the stress distribution across the acromion and scapular spine due to altered deltoid loading. Therefore, it was the objective of this study to determine the influence of CA ligament release on strain across the dorsal surface of the acromion and scapular spine for both abduction and forward elevation in the setting of an rTSA. It was hypothesized that release of the CA ligament would result in greater strain during forward elevation as compared to abduction. Furthermore, it was hypothesized that strain in the Levy II region of the scapular spine would be greater than that in both Levy regions I and III after the release of the CA ligament.

Materials and methods

Specimen preparation

Eight freshly frozen right male cadaveric shoulders (mean age: 73 years, range: 61-88 years) were thawed for 24 hours prior to dissection. A rotator cuff–deficient shoulder was created with a full-thickness supraspinatus and upper infraspinatus tears. The remaining rotator cuff tendons were then sutured and tagged with a heavy #5 nonabsorbable braided suture (Ethibond; Ethicon, Raritan, NJ, USA). In addition, the deltoid muscle was secured with suture. Nylon mesh was used to strengthen the attachment of the suture to the deltoid at its tendinous origin along the acromion and scapular spine (Fig. 1). The deltoid was divided into 3 segments based on the anatomic description by Sakoma et al.[43]

A custom rTSA system[16] was then implanted into each specimen using a modified technique from the Stryker–Tornier Aequalis surgical technique (Stryker, Kalamazoo, MI, USA). The glenoid baseplate was inserted with screws in neutral inclination and the humeral component was cemented in anatomic version. The humerus was resected midshaft to be mounted onto the shoulder simulator with a cemented intramedullary rod.

To quantify strain, 4 uniaxial strain gauges were placed on the acromion and scapular spine during testing (Strain gauge model # KFH-06-120-C1-11L3M3R; OMEGA Engineering, Laval, QC, Canada). Meticulous preparation of the bony surface of the acromion and scapular spine was undertaken for the strain gauge placement prior to testing, including dissection of soft tissue and periosteum, followed by the use of a cyanoacrylate adhesive. All strain gauges were placed along the acromion and dorsal border of the scapular spine based on specific anatomic landmarks within the Levy scapular spine fracture regions[7,30] (Fig. 2). The first strain gauge was placed in the Levy I region, the second in the Levy IIB region, and the remaining strain gauges placed in the Levy III region. All strain gauge leads were then connected to a central computer through a portable data acquisition unit (Model # NI USB-9237; National Instruments, Austin, TX, USA).

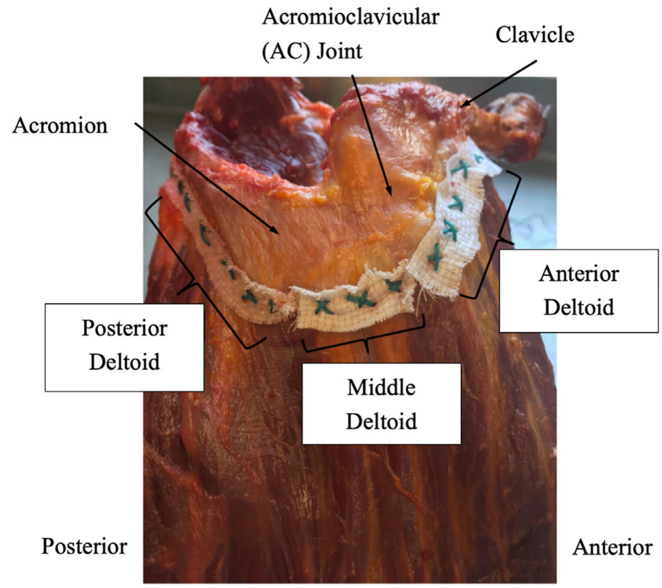

Figure 1 All 3 heads of the deltoid muscle were tagged at their origins along the distal clavicle, acromion, and scapular spine using heavy #5 Ethibond suture and supported by nylon mesh.

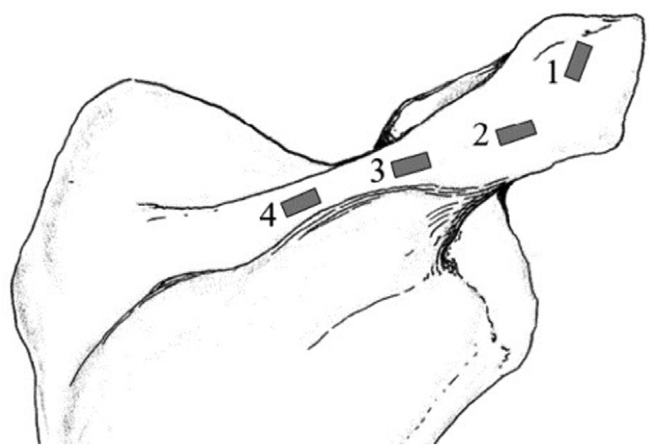

Figure 2 Illustration showing the placement of the 4 strain gauges along the dorsal surface of the acromion and scapular spine. Strain gauge (SG) #1 corresponds to the Levy type I region, SG #2 corresponds to the Levy type IIB region, and SG #3 and #4 correspond to the Levy type III region.

Shoulder simulator and testing protocol

Each shoulder was mounted to a previously validated shoulder simulator[17] through a scapular clamp and distal humeral rod (Fig. 3). The distal humeral rod was connected to the abduction arc of the simulator, which constrained humeral axial rotation but allowed for unconstrained translation of the humeral head at the joint. A 6-degree-of-freedom load cell was connected to the distal humeral rod which was used to achieve a target abduction moment. Load was applied through each muscle-tendon unit by the tagged sutures attached to computer-controlled pneumatic actuators. Based on a previous biomechanical study which reported deltoid muscle load contribution in rTSA,[1] muscle loading ratios were calculated. This included deltoid muscle loading ratios for shoulder abduction motion (15% anterior deltoid, 70% middle deltoid, and 15% posterior deltoid) and forward elevation motion

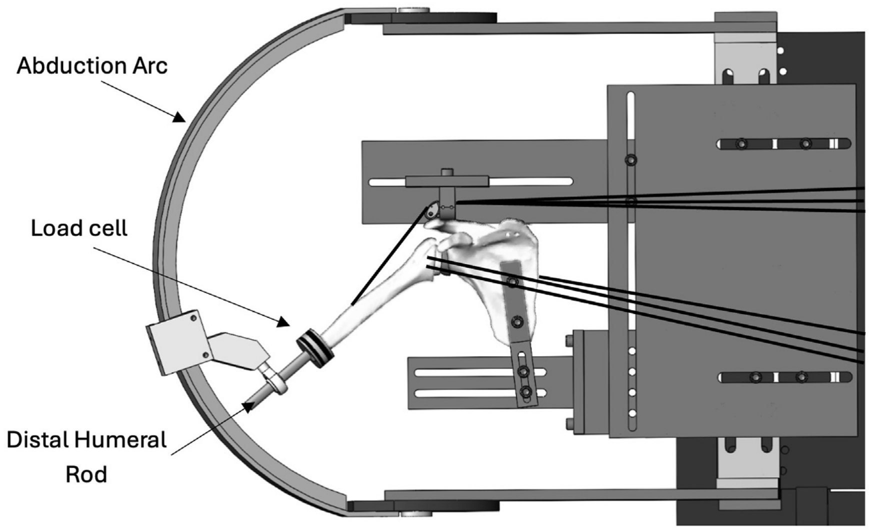

Figure 3 This illustration shows an implanted cadaveric specimen (no soft tissue shown) mounted onto a biomechanical simulator. The braided line connecting the deltoid and rotator cuff muscles to computer-controlled pneumatic actuators (not shown) is illustrated with solid black lines.

(40% anterior deltoid, 50% middle deltoid, and 10% posterior deltoid). To maintain tension around the implant, a cumulative load of 10N was applied to the anterior and posterior tagged rotator cuff based on data from the same biomechanical study.

To assess the role of the CA ligament, each specimen was first tested in an "intact" ligament state, followed by a "cut" ligament state. For both states, the same implant parameters were used, which consisted of a 145° neck-shaft angle, 5 mm glenoid lateral offset with 0 mm of inferiorization, 5 mm humeral lateralization, and a 42-mm glenosphere and humeral cup size. Each shoulder was rigorously cycled prior to testing to minimize the creep response in the soft tissue. Testing was conducted at elevation angles of 0° and 90° in both the scapular plane and in forward elevation assuming a 2:1 scapulohumeral to scapulothoracic rhythm.[24,45] In each position, the deltoid load was sequentially increased until a target abduction moment of 1.5 Nm was achieved as measured by the load cell. This value was selected based on pilot studies conducted using this setup. Data were recorded once a steady state was achieved and was repeated 3 times for each arm position. This was followed by completely releasing the intact CA ligament from its coracoid attachment. The same protocol as described above was then repeated.

Outcome variables and statistical analysis

The primary outcome of this study was scapular spine and acromion strain as measured by the 4 strain gauges used in the experimental setup (reported in micro-strain; μStrain; strain × 10^{-6}). A 4-way (CA ligament state, strain gauge location, plane of elevation, and angle of elevation) repeated measures analysis of variance was used for statistical analysis (SPSS; IBM Corp., Armonk, NY, USA). Statistical significance was defined as $P \leq .05$ while using a Bonferroni adjustment to account for multiple comparisons. A sample size of 8 specimens was selected based on similar biomechanical cadaver studies previously performed.[10,16,29] The Effect size was also calculated by means of partial eta squared (η^2_p) to more clearly define the magnitude of changes in strain. Effect size was interpreted as small (0.01), moderate (0.06), and large (> 0.14).[11]

Results

The mean strain for each strain gauge is presented in Fig. 4. When averaged across all strain gauge locations, planes of elevation, and angles of elevation, the mean strain was found to increase after the release of the CA ligament (253 μStrain prior to CA ligament release vs. 281 μStrain after CA ligament release). However, this increase in strain was not found to be statistically significant ($P = .093$). Both the plane of elevation and elevation angle however were found to significantly influence scapular spine and acromial strains ($P < .001$).

The release of the CA ligament led to an increase in strain at all strain gauge locations for both 0° of abduction and 0° of forward elevation. Increases in the mean strain were as great as 14% in 0° of abduction and 31% in 0° of forward elevation, with the largest increases both occurring at strain gauge 1. Increases in strain at 0° abduction and 0° forward elevation due to CA ligament sectioning approached, but did not reach statistical significance for all strain gauges ($P \geq .072$). These changes however exhibited a moderate to large effect size (η^2_P = .080-.390). For all tests conducted at 90° of abduction and forward elevation, the mean strain decreased at all strain gauge locations upon releasing the CA ligament. These decreases in the mean strain were as large as 21% in abduction, but only 3% in forward elevation. The only statistically significant decrease in strain occurred during 90° abduction at strain gauge 3 ($P = .032$). The reduction in strain across all 4 strain gauge locations at 90° of abduction exhibited a greater effect size (η^2_P = .174-.503) compared to that during 90° of forward elevation (η^2_P = .002-.053).

Strain was observed to significantly vary across all strain gauge locations ($P = .001$). For all testing, the greatest strain was observed to occur at the location of strain gauge 2. This was significantly greater compared to the mean strain at strain gauge 4, although was not significantly greater compared to strain gauge 1 and 3 locations. Additionally, 0° of elevation exhibited significantly greater mean strain across all strain gauge locations compared to positions at 90° ($P < .001$). This was also true for the plane of elevation, with significantly greater strains observed in forward elevation compared to testing in the scapular plane ($P < .001$).

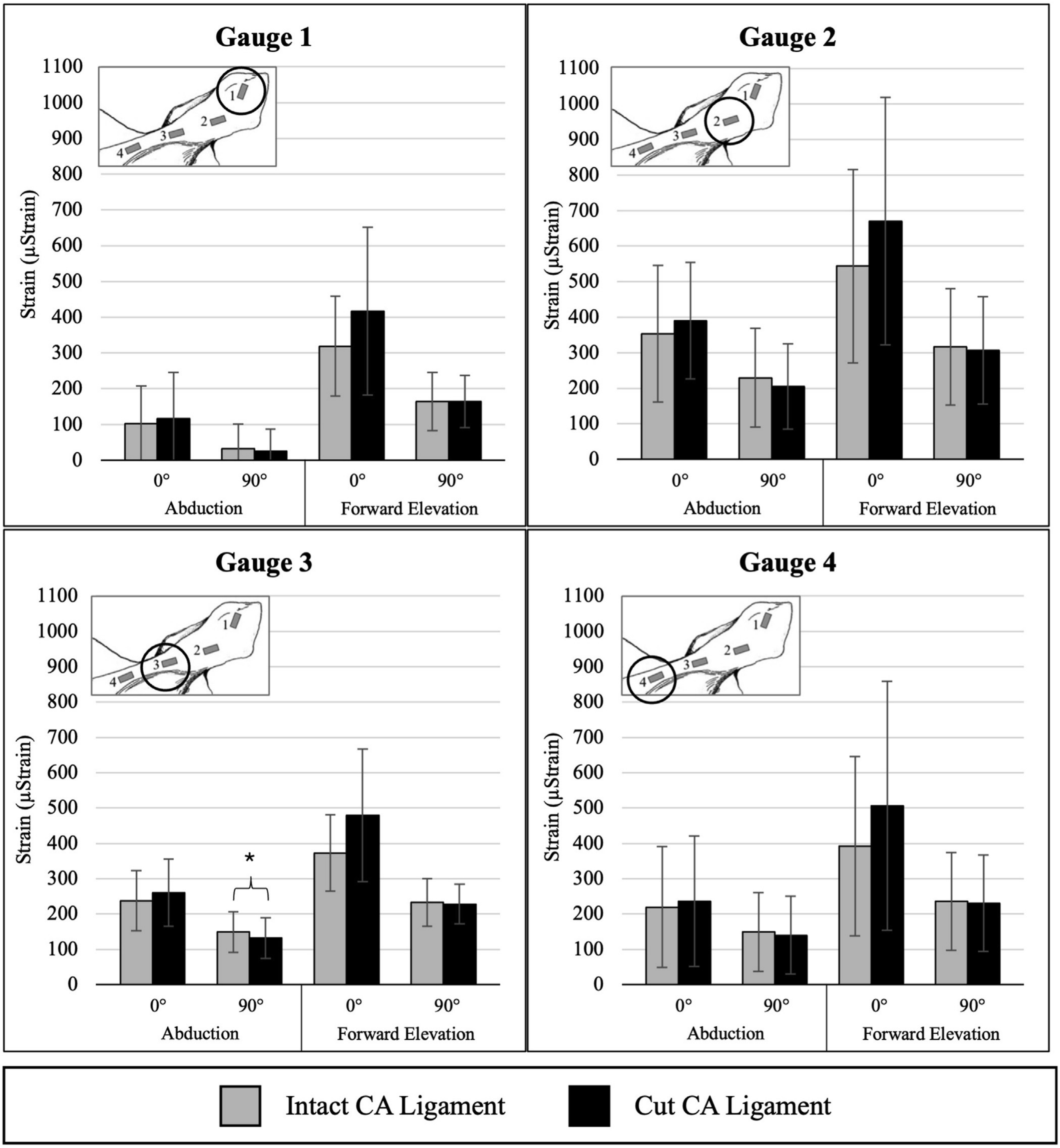

Figure 4 Mean strain magnitudes for all strain gauges at both 0° and 90° of abduction and forward elevation. '*' signifies a statistically significant difference with $P < .05$.

Discussion

The primary function of the CA ligament has previously been suggested to prevent excessive anterosuperior translation of the humeral head.[40,49] However, it has recently been proposed that this structure also functions to complete the scapular ring, thereby distributing stress between the acromion and coracoid.[50] As such, disruption of this ligament may alter the stresses within the scapular spine created from the pull of the deltoid. This could be important in rTSA as the release of the CA ligament, which can occur during surgical approach using either a deltopectoral approach or anterosuperior approach, may influence scapular spine stresses and increase the risk for postoperative fracture.

Although the results from this study did not find the excision of the CA ligament to significantly increase scapular spine or acromial strains, moderate to large increases in scapular spine and acromial strain, as observed by the effect size, were observed at 0° of both abduction and forward elevation. These increases in strain, albeit not statistically significant, may increase the potential risk for postoperative scapular spine fracture, especially in patients with poor or decreasing bone quality.

Perhaps the most important finding in this study was that the release of the CA ligament resulted in the greatest increase in scapular spine and acromial strain when the arm was positioned in 0° of forward elevation. Mean increases in strain were observed to be greater than 23% across the acromion and scapular spine with the arm in this position. It is likely that as the force of the anterior deltoid increases during forward elevation, greater torsional stress is exerted onto the acromion. In the native case, the CA ligament supports the anterior acromion and possibly helps to reduce the strain in this region by distributing some of the load from the deltoid to the coracoid. However, with the CA ligament resected, the anterior acromion is unsupported and functions more similarly to a cantilevered beam. As such, the acromion may be subjected to greater deflection, and thus greater strain. Although the increase in strain during this motion was not found to be statistically significant between the 2 conditions, this trend emphasizes the importance of the CA ligament for distributing the muscle load from the deltoid in the early phases of forward elevation.

Several other important trends were also observed in this study. Strain was observed to increase in both the scapular spine and acromial regions upon excision of the CA ligament at 0° of elevation regardless of the plane of elevation. Furthermore, there was little to no change in strain upon the release of the CA ligament when the arm was elevated to 90°. These findings are likely due to the directional change of the cumulative deltoid load on the acromion and scapular spine. In 0° of elevation, the deltoid line of action is directed inferiorly, resulting in a greater bending moment on the acromion and scapular spine. As the arm is elevated, the deltoid line of action is directed more laterally then inferiorly, reducing the bending loads applied to the acromion and increasing the axial loads. This suggests the stress distribution across the CA ligament to be dependent on the direction of deltoid force, with greater stress distribution occurring at lower angles of elevation. This could be important in patients with cuff tear arthropathy who may exhibit greater deltoid activation at lower elevation due to supraspinatus deficiency.

Strains on the scapular spine corresponding to the Levy type IIB region consistently resulted in the greatest strains compared to the other regions in this study. These findings are in agreement with what has been reported clinically as type II fractures have exhibited a greater incidence rate than type I and III fractures.[7,28,30] The greater incidence of fracture in this region may be due to the difference in geometric or material properties between these regions of the acromion and scapular spine, although further investigation is needed.

Studies from Taylor et al[50] and Haislup et al[21] have previously evaluated the influence of CA ligament excision on scapular spine and acromial strain in cadaver models. However, these studies reported contradicting results, with one reporting the scapular spine and the other the acromion, to exhibit increased strain upon excision of the CA ligament. Although each study placed a single-strain gauge in Levy regions II and III, the inconsistency in these findings is likely due to lack of specification in strain gauge placement between studies. Inconsistent placement of these strain gauges medially or laterally could have influenced the measured strain. In our study, we specified the placement of each strain gauge within their respective Levy regions, improving consistency across all cadavers. We also used 4 strain gauges across the scapular spine and acromion, allowing for a more thorough analysis to be performed across the entire spine construct of the scapula. Furthermore, both studies from Taylor et al[50] and Haislup et al[21] placed the strain gauge corresponding to Levy region III near the spinoglenoid notch within the supraspinatus fossa. We believe the strains on the dorsal boarder of the scapular spine are more relevant than those in the supraspinatus fossa, as the greatest strains within the scapular spine have previously been shown to occur along the dorsal scapular spine border.[54] Finally, the studies conducted by Taylor et al[50] and Haislup et al[21] only evaluated movement in the scapular plane and did not consider motion in the plane of forward elevation, with subsequent changes in deltoid muscle activation. In our study, we showed the increases in scapular spine and acromial strain to be greater in forward elevation than in abduction after excision of the CA ligament.

Postoperative acromial and scapular spine fractures in the setting of rTSA remain a challenging complication. The prevalence of these fractures has been reported to vary in literature, although several multicenter studies have reported incidence rates close to 4%.[20,32,33,35] The symptoms of this pathology have been shown to depend on the location of the fracture.[7] Patients with Levy type I or type IIA fractures often have milder symptoms with mild pain, while patients with type II or III fractures often have greater pain, reduced motion, and worse clinical outcomes. The management of these patients can also be challenging. Patients with type I fractures have shown to do well with conservative treatment, with their range of motion and pain often improving from their preoperative scores. However, conservative management has led to poor outcomes in patients with type II or type III fractures.[7] Some groups have started to treat these fractures surgically by using open reduction and internal fixation methods, although the optimal surgical technique remains unclear.[8,13,41,44]

The etiology of these fractures also remains unclear and is believed to be multifactorial. Several nonmodifiable risks factors have been identified including gender, bone density, cuff tear arthropathy, inflammatory arthritis, and scapular anatomy.[32,33,38,47,52,55] Modifiable risk factors, such as implant lateralization, deltoid lengthening, glenoid baseplate position, and screw orientation, have also been studied.[22,23,25-27,31,54] Greater understanding of these risk factors can help to improve preoperative planning and intraoperative methods to reduce the risk of these fractures moving forward.

This study was not without limitations. Static muscle loading was used on both anterior and posterior rotator cuff muscles across all angles of testing, which did not replicate the dynamic forces within rotator cuff throughout abduction as seen in-vivo. Furthermore, only 1 rTSA design configuration was used throughout this study. Changes in different implant design variables may lead to more prominent changes in acromial and scapular spine strain with the release of the CA ligament as the deltoid tension and direction would likely be altered. Additionally, uniaxial strain gauges were used to quantify strain instead of strain gauge rosettes. Uniaxial strain gauges measure strain in the direction in which they are placed while strain gauge rosettes consist of 3 uniaxial strain gauges, allowing these devices to quantify strain in all directions.

It must also be noted that testing was conducted on healthy male cadaver specimens. Therefore, the fracture risk associated with releasing the CA ligament in a patient population with a compromised CA arch, or those at greater risk for fracture, is unclear. For example, the preservation of the CA ligament may be important in patients with a pathologic acromial structure, possibly due to acetabularization in patients with rotator cuff tear arthropathy. The importance of preserving the CA ligament also remains unclear in patients with a previous acromioplasty or partial CA ligament release, as these operations may compromise the integrity of the CA arch. CA ligament preservation may also be more beneficial in cases where the humerus is distalized from a proximally migrated state, which would likely lead to greater deltoid tension. As such, further investigation is needed to determine the importance of preserving the CA ligament in patients at greater risk of exhibiting acromial or scapular spine fracture.

Conclusion

The release of the CA ligament in the setting of rTSA led to increases in scapular spine and acromial strains at low elevation and during forward elevation. Although these increases in strain were not found to be statistically significant, they were associated with a large effect size which indicates a moderate to large change in strain between the intact and sectioned conditions. These results suggest that the release of the CA ligament may increase the risk for postoperative scapular spine fracture. Surgeons must use caution intraoperatively when deciding whether to section or preserve this soft tissue structure.

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