



# Clavicular-Sided Tears Were the Most Frequent Mode of Failure During Biomechanical Analysis of Acromioclavicular Ligament Complex Failure During Adduction of the Scapula

Michael B. DiCosmo, B.S., Nathan Rumpf, B.S., Michael R. Mancini, B.S., Elifho Obopilwe, M.S., Robert A. Arciero, M.D., and Augustus D. Mazzocca, M.S., M.D.

**Purpose:** The purpose of this study was to describe the force and failure pattern of the acromioclavicular ligament complex (ACLC) in an adducted scapula, potentially simulating an indirect force injury of the AC joint. By using a biomechanical simulation in which the scapula is moved and the clavicle is fixed, we are able to better replicate the in vivo motion of the joint. **Methods:** Ten cadaveric shoulders (mean age of  $62.0 \pm 8.6$ ) with a bone mineral density of  $.51 \pm .18 \text{ g/cm}^2$  were used. A standard reproducible anatomic mounting system was used to secure the clavicle and move the scapula. Displacement control was used to adduct the scapula (inferior angle of the scapula moving toward the clavicle) with the clavicle fixed until specimen failure, producing torque and angle of rotation. The failure mode of the ACLC during this simulated adduction was analyzed with slow motion video analysis. Tears of the ACLC were characterized as clavicular, midline, or acromion-sided tears. **Results:** The mean torque required for load to failure was found to be 27.75 N-m (95% CI [20.85 N-m, 34.65 N-m]). The mean rotary angle at failure was  $30^\circ$  (95% CI [ $25^\circ$ ,  $35^\circ$ ]). The mean stiffness (resistance provided by the ACLC) was  $1.64 \text{ N-m/}^\circ$  (95% CI [ $1.28 \text{ N-m/}^\circ$ ,  $2.01 \text{ N-m/}^\circ$ ]). Mode of failure analysis showed there were 6 clavicle-sided tears, 1 acromion-sided tear, 2 acromion fractures, and 1 clavicle fracture. **Conclusions:** Clavicular side tears were the most frequent mode of failure compared to midline and acromion side tears. The first segment of the ACLC to fail most frequently during adduction was the posterosuperior ligament. **Clinical Relevance:** This biomechanical study simulates a potential mechanism of AC ligament injury. Additional knowledge about the mode of failure provides a better understanding of the ACLC, allowing for new information for the purpose of AC ligament reconstruction.

## Introduction

Current literature attributes the majority of acromioclavicular (AC) joint separations to injuries, in which a force acts on an adducted shoulder causing posterior rotation of the scapula and driving the acromion inferiorly.<sup>1-25</sup> Although they are the minority, indirect forces have also been known to cause AC separations.<sup>6,7</sup> Liberson et al. reported that when a force is applied to the AC joint via a pull through the upper extremity, the scapula is drawn downward and anteriorly, leading to ACLC injury.<sup>6,7</sup>

There are a plethora of studies that have investigated the biomechanics and function of the AC ligaments, in

addition to innumerable repair studies.<sup>5,8-25</sup> There are very few studies, however, on the mechanism of failure at the level of the AC ligaments. The AC capsule comprises four ligaments (anterior, posterior, superior, and inferior). These ligaments seem to function together in a way similar to the glenohumeral ligaments, which is why we believe the AC ligaments can be considered a complex or capsule. This has been defined as the acromioclavicular ligament complex (ACLC).<sup>5,24,25</sup> Since each of these ligaments can fail via a clavicle-sided, acromion-sided, or mid-line tear, there are various ways in which the ACLC can fail.<sup>1</sup> A previous investigation that used magnetic resonance imaging of

Department of Orthopaedic Surgery, University of Connecticut, Farmington, Connecticut, U.S.A.

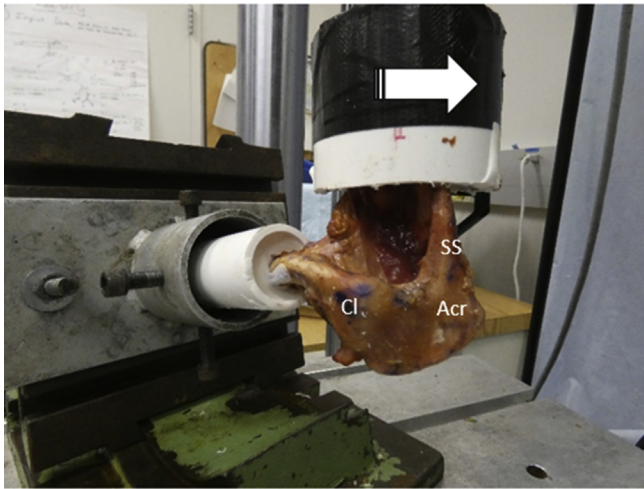
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Address correspondence to Michael B. DiCosmo, B.S., 1 Talcott Forest Rd, Unit 1N, Farmington, CT, 06032, U.S.A. E-mail: [mdicosmo@uchc.edu](mailto:mdicosmo@uchc.edu)

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**Fig 1.** Left shoulder specimen in test setup. The medial border of the potted scapula is secured to the servohydraulic actuator. The potted clavicle is secured and directly centered in the mount. Arrow indicating direction of motion. Cl, clavicle; Acr, acromion; SS, scapular spine.

AC joint injuries revealed that clavicle-sided tears were the most common.<sup>26</sup>

Previous biomechanical studies have used a fixed-scapula model to simulate acromioclavicular joint movement and evaluate postreconstruction joint stability.<sup>5,8-10,18-22</sup> However, *in vivo*, the scapula moves while the clavicle remains relatively rigidly attached at the sternoclavicular joint. Debski et al. used a robotic universal force-moment sensor system to evaluate the effects of transecting the AC ligament, while allowing the scapula to translate across its three axes.<sup>5</sup>

This study attempted to simulate a possible mechanism of ACLC injury by adducting the scapula with a fixed-clavicle. We believe that strictly adducting the scapula simulates the scapula being drawn anteriorly, which is seen with a pull through the upper extremity.<sup>6,7</sup> The purpose of this study was to describe the force and failure pattern of the ACLC in an adducted scapula, potentially simulating an indirect force injury of the AC joint. By using a biomechanical simulation in which the scapula is moved and the clavicle is fixed, we are able to better replicate the *in vivo* motion of the joint. We hypothesized that the most common mode of failure would be a clavicle-sided tear. Additionally, we hypothesized that the posterosuperior segment would be the first to fail, as previous literature suggests it is a major contributor to rotational stability.<sup>18,27</sup>

## Methods

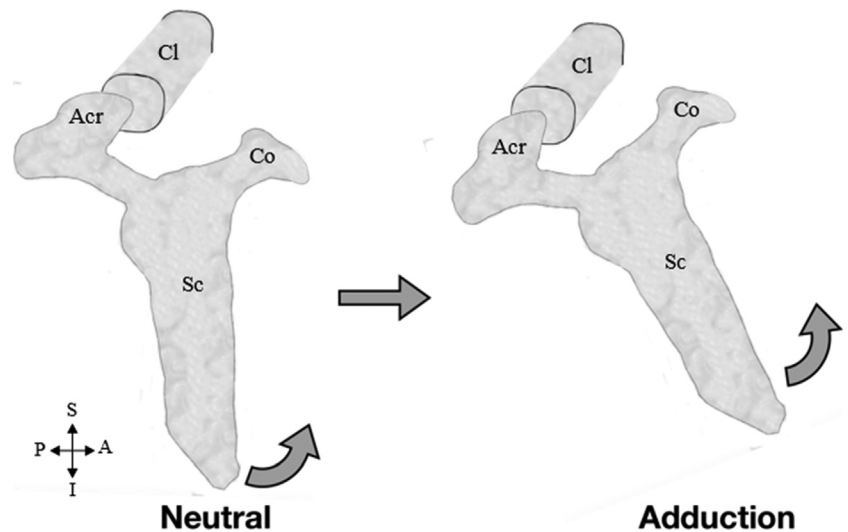
### Specimen Preparation

Ten fresh-frozen cadaveric shoulders were used in this study (mean age of  $62.0 \pm 8.6$ ). Specimen preparation was done in accordance with previously

published methods.<sup>21,23</sup> Before the day of testing, each specimen was thawed overnight at room temperature. Specimens were disarticulated at the glenohumeral joint, and the clavicle and scapula were dissected free of all soft tissue except the AC, CC, and coracoacromial ligament. The scapula was then potted using polymethyl methacrylate (PMMA) bone cement (Keystone Industries, Gibbstown, NJ). The scapula was trimmed such that, when potted in a 7.6 cm (diameter)  $\times$  7.0 cm (length) section of polyvinyl chloride (PVC) pipe, the glenoid face was parallel to the floor when the PVC pipe was standing upright (Fig 1).<sup>8,11,19-21</sup> The clavicle was potted with PMMA bone cement in a 3.5 cm (diameter)  $\times$  7.0 cm (length) section of PVC pipe such that its long axis was centered and ran parallel within the PVC pipe.<sup>8,11,19-21</sup> This enabled clavicular fixation to a mount clamped to the table of the MTS machine (MTS System Corp., Prairie, MN). The potted clavicle was then centered into the cylindrical mount, which allowed for a consistent set up for each specimen.<sup>18,19</sup>

### Biomechanical Test Setup

The natural position and motion of the cadaver was assessed to account for anatomic variations (i.e., the shape and curvature of the clavicle, varying angles of the AC joint), which guided proper placement of the specimen but was not recorded for further analysis in this study. The specimens were then potted to allow consistent and reproducible execution of the specific motion for that specific cadaver.<sup>8,11,19-21</sup> Adduction of the scapula was achieved by decreasing the angle between the scapula and the clavicle until failure. The pipe-cemented specimens were fixed to the MTS machine allowing consistent and specific motion that could be reproduced multiple times. The cylindrical shape of the PVC pipe modeled the shape of the clavicle to ensure the natural motion around the AC joint was recreated. The potted clavicle was then fixed to a mount to recreate the effect of the sternoclavicular joint. The scapula was secured to the actuator of the MTS machine and the clavicle was secured to a mount such that it ran parallel to the X-Y table and acted as the axis of rotation. The angle of the clavicular mount was adjusted to account for the unique anatomy of the clavicle and AC joint of each specimen and to ensure the joint was not inappropriately tensioned. This consistent and reproducible setup unique to the cadaver allowed the same motion to be reproduced across all specimens. Before testing was initiated, the specimen was adjusted until the axial and rotational force on the joint measured by the MTS machine was less than 5 N. The MTS machine was zeroed, and the specimen was thoroughly sprayed with saline. To ensure the specimens were not stiff before testing, they were each preconditioned by having the MTS machine cyclically load the joint 30 times through 12° of anterior rotation



**Fig 2.** Diagram showing the adduction movement achieved by biomechanical set up. A, anterior; Acr, acromion; Cl, clavicle; Co, coracoid; I, inferior; P, posterior; Sc, scapula; S, superior.

to 12° of posterior rotation as was done in a previous study.<sup>9</sup> After preconditioning, the specimen was returned to its neutral anatomic position. The MTS machine was then considered calibrated, and the forces were zeroed before load to failure testing.

### Biomechanical Testing

Displacement control was used to apply an increasing rotational force at 5° per second until specimen failure.<sup>20,28</sup> By fixing the medial border of the scapula to the actuator, torque, generated by the actuator, simulated adduction. Adduction was designated as the inferior angle of the scapula moving toward the proximal clavicle, which simulated the motion seen in Fig 2. The system was calibrated and zeroed before each test. To ensure consistent torque measurement, the clavicle was potted directly in the center of the PVC pipe, and the potted clavicle then was centered within the mount before testing. For each trial, the MTS machine recorded the angle of rotation and torque applied to the specimen. Using displacement control allowed the stiffness to be determined during load to failure testing. Stiffness was calculated as the resistance to adduction measured as a moment by the output of the hydraulic testing machine. Descriptive statistics were calculated using mean and standard deviation for the force required for failure (mean torque), rotary angle at failure, and stiffness provided by the ACLC.

### Video Analysis

Video recordings were captured for mechanism of failure analysis. Videos of load to failure tests were taken with a Canon VIXIA HF R800 HD camcorder (Canon, U.S.A., Inc., Lake Success, NY) and a standard iPhone® 11 camera (Apple Inc., Cupertino, CA). Each camera was placed 2 feet away from the specimen and

focused directly on the superior portion of the ACLC. One camera was positioned more anteriorly on the clavicular side and the other posteriorly on the acromial side. The videos were then downloaded to a personal computer and reviewed using iMovie (Version 10.1.15, Apple Inc., Cupertino, CA), which allowed playback speed of 10% of real time and frame-by-frame analysis. Three blinded reviewers (all researchers or orthopedic surgeons with expertise in biomechanics and sports medicine) independently evaluated each specimen video in real time and slow motion. Each reviewer classified the type of tear as clavicle-sided, midline, or acromion-sided, as well as the portion of the superior ACLC that failed first (anterosuperior or poster-superior).<sup>1</sup> After individual analysis the reviewers met to achieve a consensus on all items. Each video was examined as many times as needed until consensus could be reached. A clavicle-sided tear was defined as greater than 50% of the fibers of the ACLC pulling off of the clavicular insertion. Acromion-sided tears were defined in the same way at its respective insertion. Midline tears were defined as a tear in which 100% of both the acromial and clavicular fibers remained anchored to their insertion points. The segment of the superior ACLC that first failed dictated an anterior or posterior tear.

### Results

Ten specimens were included in the analysis. The mean age of the included specimens was  $62.0 \pm 8.6$  years. The cadaveric shoulders included were 10 unpaired male specimens (5 right shoulders, 5 left shoulders). The overall bone mineral density measured at the humerus using a dual-energy X-ray absorptiometric scan (Lunar DPX IQ; GE Healthcare) was  $.51 \pm .18$  g/

**Table 1.** Load-to-Failure Data

	Mean	Standard Deviation	95% Confidence Interval
Peak Rotary Torque* (N-m)	27.75	10.87	[20.85, 34.65]
Peak Rotary Angle† (°)	30	8	[25, 35]
Stiffness‡ (N-m/°)	1.64	.57	[1.28, 2.01]

\*The torque required for load to failure.

†The amount of rotation by the MTS machine required for failure.

‡The resistance provided by the acromioclavicular ligament complex.

cm<sup>2</sup>. Table 1 displays the load to failure results. The mean torque required for load to failure was found to be 27.75 ± 10.87 N-m (95% CI [20.85 N-m, 34.65 N-m]). The mean rotary angle at failure was 30 ± 8° (95% CI [25°, 35°]). The mean stiffness, which is the resistance provided by the ACLC, was 1.64 ± .57 N-m/° (95% CI [1.28 N-m/°, 2.01 N-m/°]).

Analysis of mode of failure showed 6 clavicle-sided tears, 1 acromion-sided tear, 2 acromion fractures, and 1 clavicle fracture (Fig 3). The mechanism of the clavicle-sided tears started with posterosuperior segment failure ( $n = 5$ ) or anterosuperior segment failure ( $n = 1$ ) followed by complete clavicular-sided failure ( $n = 6$ ) (Fig 3A). The mechanism of acromial-sided tears began with posterosuperior segment failure followed by complete acromial-sided failure ( $n = 1$ ) (Fig 3B).

## Discussion

We found that during load to failure via adduction of the scapula, the posterosuperior portion of the ACLC was the first to fail most often. When the posterosuperior ACLC failed, it was most often a clavicle-sided failure. Previous biomechanical studies are consistent with these findings. Kibler et al. used magnetic resonance imaging to show that in AC joint injuries the ACLC detaches from the clavicle side more frequently than the acromion.<sup>26</sup> Additionally, Morikawa et al. showed that the different segments of the superior half of the ACLC have different contributions to stability of the AC joint.<sup>18</sup> In this investigation, the anterior and posterior segments of the superior ACLC together contributed more to posterior rotational stability, while the anterior and superior segments of the superior ACLC contributed more to posterior translation.<sup>18</sup> A clinical study by Maier et al. examined the injury pattern of the ACLC in acute dislocations and found that 72% of the observed tears were clavicle sided.<sup>1</sup> This is consistent with our cadaveric study that also showed predominantly clavicle-sided failure upon scapula adduction. Understanding which segment of the ACLC is damaged and the order in which it is damaged allows for more effective and specific operative repairs. This information begins to provide more

understanding as to why some patients respond well to nonoperative treatment and others require reconstruction.

Falling with a direct blow to the lateral aspect of the shoulder is a common mechanism of AC injury. We believe this mechanism of injury is simulated by adduction of the scapula. Previous biomechanical studies have used a fixed-scapula model to simulate AC joint movement and evaluate postreconstruction joint stability.<sup>5,8-10,18-22</sup> By using a biomechanical simulation in which the scapula is moved and the clavicle is fixed, we are able to better replicate the in vivo motion of the joint. This study can help set the basis for evaluating AC joint reconstruction using a technique that may better simulate the joint biomechanics, which can potentially shed new light onto the reasons AC reconstructions tend to fail.

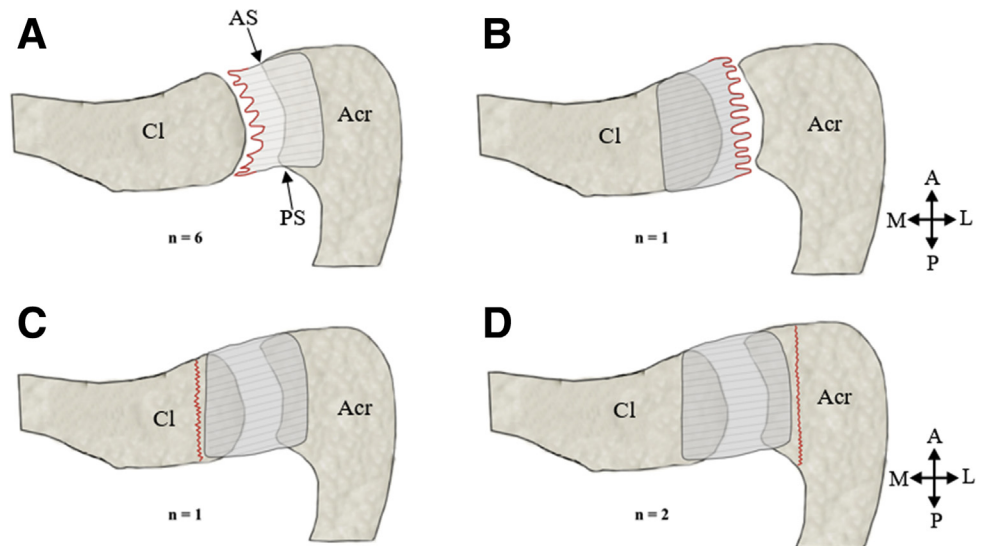
We additionally sought to characterize the maximal rotary torque and angles of rotation required to fail the native ACLC via adduction of the scapula. It is known that the ACLC offers stability in the anterior-posterior and superior-inferior direction and is considered a relatively strong structure. This investigation determined that the ACLC requires on average 27.75 N-m (95% CI [20.85 N-m, 34.65 N-m]) of force for failure during scapular adduction. These findings are much smaller when compared to similar measures found by other biomechanical studies. This is likely because of the motion used. By using only adductive motion, our results were focused on the effects of the ACLC rather than the effects of other stabilizers of the AC joint like the CC ligaments.

For those specimens that failed via fracture, we hypothesize that there were two contributing factors: 1) the specimens showed no signs of bony impingement; therefore, the ACLC was likely stronger than the bone, and 2) the advanced age of the donors (mean age of 62.0 ± 8.6 years) is older than the typical patient with an AC dislocation. It is also important to note that the CC ligaments did not fail during the load to failure study for any specimen. We believe this could be due to the fact that there is more of a rotational component to these injuries. Although evaluating injury of the CC ligaments was not the main purpose of this paper, it warrants further investigation.

## Limitations

This study has some limitations. Given that the glenohumeral joint was disarticulated, the nature of this in vitro biomechanical study is a limiting factor in the application of the findings to in vivo conditions of the ACLC. Specimens were from donors with a mean age of 62.0 ± 8.6 years, whereas patients with AC dislocation are typically younger.

**Fig 3.** Schematic showing the superior view looking down at the clavicle and acromion. Depicting various modes of failure seen during load to failure testing. (A) Clavicle-sided failure ( $n = 6$ ). (B) Acromion-sided failure ( $n = 2$ ). (C) Clavicle fracture ( $n = 1$ ). (D) Acromion fracture ( $n = 2$ ). A, anterior; Acr, acromion; AS, anterosuperior segment; Cl, clavicle; L, lateral; P, posterior; M, medial; PS, posterosuperior segment.



## Conclusion

Clavicle-sided tears were the most frequent mode of failure compared to midline and acromion-sided tears. The first segment of the ACLC to fail most frequently during adduction was the posterosuperior ligament.

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