Effect of Rotator Cable Tear Size and Location in Humeral Abduction

by

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The rotator cable is described as being a mechanical structure responsible for force transmission from the rotator cuff muscles to the rotator cuff's humeral insertions. The structure is also said to be responsible for shielding the tissue lateral to it, the crescent area. Preliminary studies at our laboratory have shown contradicting results. A biomechanical, cadaveric study was implemented to determine the mechanical importance of the rotator cable by means of differing tear sizes and locations. It was hypothesized that the entire complex is essential for shoulder function based on abduction strength.

Physiological loading was applied to ten cadaveric specimens using a custom shoulder simulator to simulate abduction in the scapular plane. The specimens were tested under two cutting sequences by sectioning the lateral crescent area into quarters and releasing the quartered sections of tissue in either an anterior-to-posterior or posterior-to-anterior-direction. Both groups then underwent subsequent releases of the insertions of the rotator cable. Abduction strength and rotation torque at the distal humerus were recorded and compared to the native condition.

Abduction strength significantly decreased for the specimens that underwent an initial anterior quarter crescent area release in the anterior-to-posterior direction when three quarters of the crescent area were affected. Continuation of the tear into the posterior and anterior rotator cable insertions also resulted in a significant drop in strength. The initial posterior quarter crescent area release did not show a significance in abduction force loss, but the final release of the entire crescent area and both rotator cable insertions approached significance. The internal rotation

torque increased for the anterior group and remained stable for the posterior group. None of the changes were significant.

The results indicate that significant decreases in strength occurred when tears were isolated within the crescent area. If the rotator cable were to transmit load around the crescent area, shoulder function would not be expected to change with an intact cable. Therefore, it can be concluded that the rotator cable is not a specialized mechanical structure solely responsible for force transmission, and the entire complex is needed to support shoulder function.

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Preface

I would like to personally thank my thesis advisors, Dr. Patrick Smolinski & Dr. Mark Miller for showing me the ropes of academics and supporting me through the process of obtaining a graduate degree. In addition, a special thank you is reserved for Dr. Christopher Schmidt. Without this opportunity, I would never have been exposed to the world of medicine, and for that, I am forever grateful. To all of my friends made along the way, Anthony Davidson, Chris Spicer, Michael Smolinski, Jamie Greenwell, Dr. Luis Carrazana-Suarez, and Dr. Dimitrios Papadopoulos, I wish you nothing but continued success and cannot begin to thank you enough for going to bat for me when it mattered most.

1.0 Introduction

Rotator cuff pathology and degenerative diseases associated with muscle tissue of the shoulder are highly prevalent among adults[2,7,8,10-12,33]. While the exact percentages vary between sources, some report that up to 10% of individuals above the age of 60 have a rotator cuff tendon tear[30], which highlights the positive correlation between these tears and aging. The majority of tears develop within the supraspinatus (SS) muscle tendon[13,15]. The SS is the muscle responsible for stabilizing the shoulder joint and initiating humeral abduction[29]. Deficiencies arising within this structure can have a profound effect on an individual's ability to use their arm. Other studies have shown that a rotator cuff tear is indicative (61% probability) of pathology on the contralateral side[17].

The mechanism for rotator cuff tears is not singular, however, but rather multifaceted[34]. In addition to age related pathologies, impingement of the SS between its tendonous fibers and the bony subacromial surface of the scapula tend to compress the tissues and cause degradation. It has been shown that certain geometries of the scapula, especially the acromion, will accelerate pathological problems[21]. These geometries are not related to traumatic events, and rotator cuff pathology might be directly related to specific anatomy. Secondary impingement is also observed in individuals who are participating in overhead sports. Repetitive motions and high mechanical stresses to the joint can have an overall negative effect on tissue health. The multifaceted mechanism, in short, is comprised of age-related degeneration, anatomy, and mechanical stress due to overuse[21,30,33,34,36,37].

There have been numerous studies quantifying the relationship between symptomatic and asymptomatic rotator cuff tears[33,36,37]. Treating asymptomatic tears early on remains a clinical challenge for obvious reasons. Asymptomatic tears do not present in traditional manners; therefore, patients do not seek medical intervention, whether operative or non-operative. This creates a challenge for understanding asymptomatic tears and their mechanisms. However, the tears tend to propagate with age and continued use of the muscle[15]. Extensions of the tears could result in a transition to symptomatic[36], which creates the need to understand why certain tears do not present with a loss of shoulder function. Some authors report that 51% of individuals with an asymptomatic tear will develop symptoms within 2.8 years[36].

Patients are more likely to seek medical attention whenever there is a noticeable loss in shoulder strength or creation of pain as a result of daily living[16,35]. However, some studies have shown that the prevalence of asymptomatic rotator cuff tears is twice that of symptomatic[23]. Data from the same study also showed that 65.3% (96 out of 147 subjects) of the asymptomatic tears were full-thickness and 34.7% (51 out of 147 subjects) of the symptomatic tears were full-thickness[23]. The high values associated with full-thickness tears strengthen the case for surgical repair, even though the tears are asymptomatic, but this view is derived from a purely orthopaedic standpoint.

Smythe et al. conducted a survey to highlight the willingness of the patient population to undergo surgery for rotator cuff repairs. Both groups of previous traumatic and non-traumatic shoulder injury patients responded as being more comfortable with considering surgery if an imaging study was performed. The majority of the cohort (>60% for both groups) also responded with an unwillingness to receive surgical treatment with a lack of symptoms[31]. The relationship is not surprising when viewing the tear in the clinical setting, though, and a decrease in the ability to perform daily living tasks is the most indicative for patient willingness of repair[18].

Oh et al. performed a systematic review to determine overall indications of rotator cuff repairs. The review contained five level IV studies evaluating the relationship between rotator cuff tear size and clinical outcomes. Some of the main findings of the studies were the relationship between tear size and worse outcomes of nonoperative management[12], tears involving more than the supraspinatus had a higher chance (>50%) of requiring additional surgeries[11], patient reported excellent results following surgery decreased by 10% when the tear size increased from small/medium to large/massive[10], and the tear size is a main contributor to overall shoulder strength[6]. The combination of these findings supports the case for early intervention of surgical repair on the rotator cuff. Asymptomatic tears do not imply a continuation of unaltered shoulder strength or range of motion, and progression of the tears can result in worse clinical outcomes when compared to those managed with early intervention.

1.1 Motivation and Goals

The high prevalence of rotator cuff tears results in a need to understand the mechanical function of the structure. However, asymptotic tears indicate the possibility of a specialized structure within the complex transmitting forces and helping to compensate. The existence of such a structure could indicate an added level of complexity and consideration during surgical repair. The goal of this study was to quantify the mechanical importance of a structure known as the rotator cable, which has been described as having stress shielding properties[4], in terms of overall shoulder strength. Humeral abduction strength following simulated abduction of cadaveric specimens was measured and related to rotator cuff tears, specifically as they relate to the rotator cable. The results could aid in determining when rotator cuff surgery would be warranted based on tear size and location.

1.2 Anatomy

1.2.1 Anatomic Planes and Directions

Due to the complexity of the human body and all of the possible orientations, standardized anatomic planes and directions are used to fully define the system and its respective parts in relation to one another. The coronal plane illustrates a plane oriented through the sides of the human body, the sagittal plane from front to back, and the transverse through the mid-section (Figure 1). In a standard anatomic position (Figure 2), the term anterior describes the front of the body and posterior the back, distal describes portions further from the body whereas proximal is closer, and finally, medial is closer to the mid-line of the body and lateral is in the opposite direction (Figure 2). Superior and inferior describe relatively a higher and lower location, respectively.

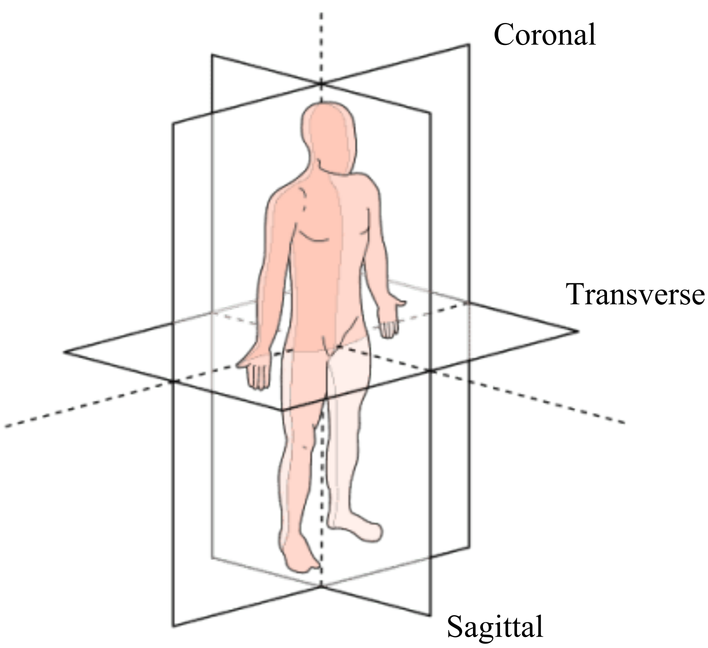

Figure 1: Anatomic planes (https://human-memory.net/anatomical-planes-of-body/)

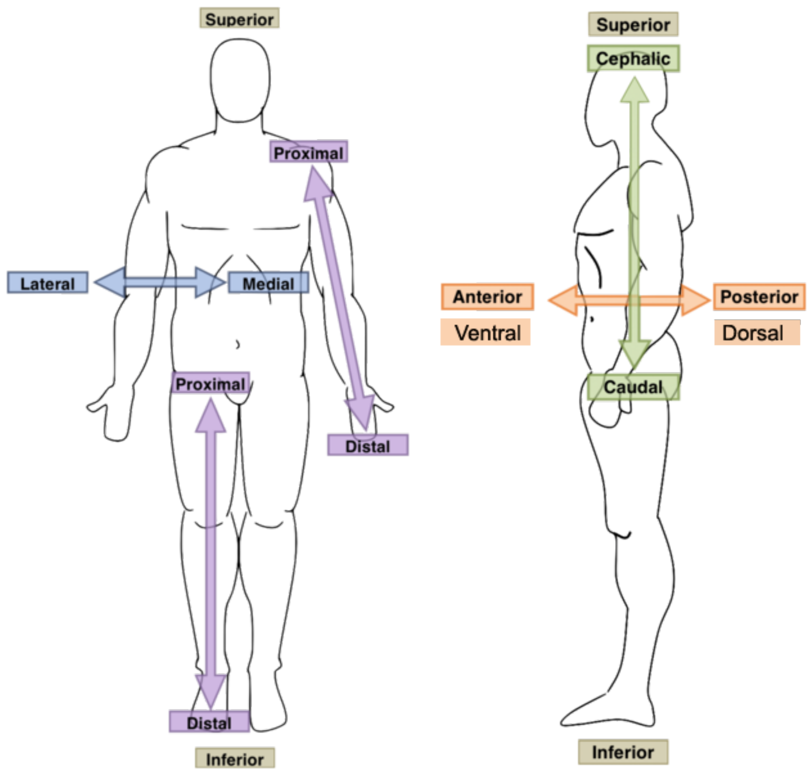

Figure 2: Anatomic directions (https://courses.lumenlearning.com/ap1x94x1/chapter/anatomical-orientation-and-directions/)

1.2.2 Shoulder Anatomy

The shoulder joint is composed of three bones: the scapula, humerus, and clavicle. The glenohumeral joint, which is the connection between the humeral head and the scapula, behaves as a ball and socket joint, allowing rotation in all dimensions. The scapula resides in a modified coronal plane – the scapular plane, which is at an approximate 30° anterior tilt (Figure 3) from the coronal plane. The humeral head, or ball of the glenohumeral joint, articulates against the smooth glenoid fossa, which acts as the socket (Figure 4). The shallow nature of the glenoid fossa allows for semi-unrestricted movement of the humerus, and therefore, the arm. However, movement and stabilization of a joint are inversely related, so the shallow joint yields a need for specialized muscle stabilizers.

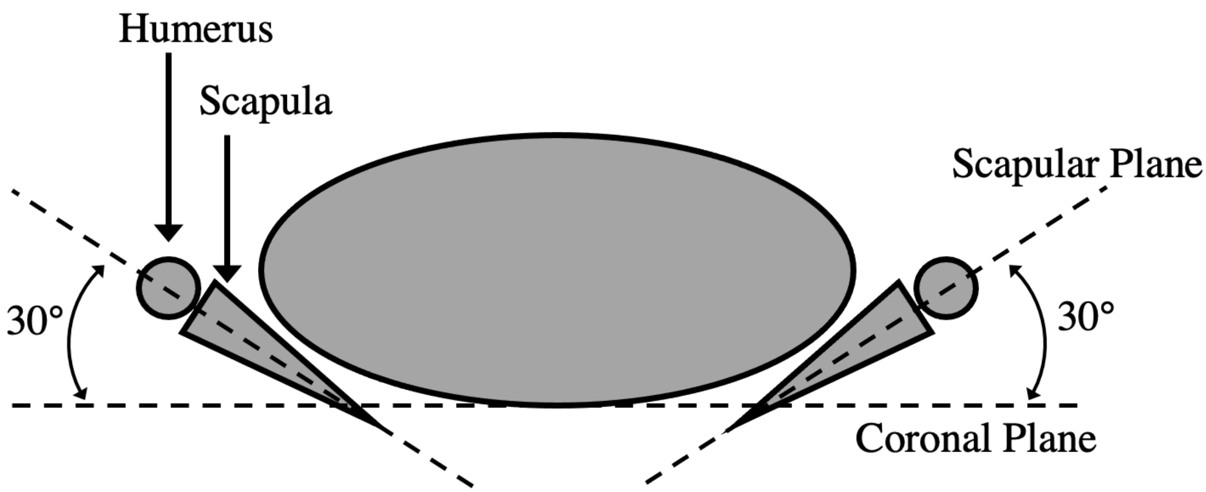

Figure 3: Transverse plane bisecting the scapulae to highlight the scapular plane's anterior tilt from the coronal plane

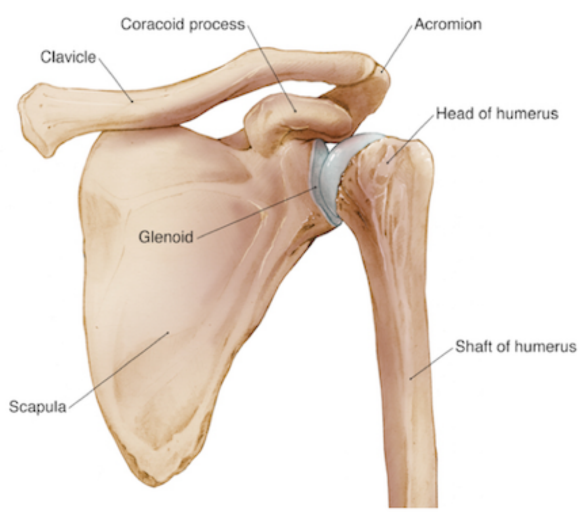

Figure 4: Bony structure of the shoulder joint (https://anatomy.lexmedicus.com.au/collection/shoulder)

The rotator cuff muscles are found deep to the muscles superficially (Figures 5 and 6) spanning the shoulder joint and provide the aforementioned stabilization. In addition, these muscles play an active role in initiating abduction and internally and externally rotating the humerus. The complex is comprised of four muscles: the supraspinatus, infraspinatus, teres minor (Figure 6), and subscapularis (Figure 7). In addition to providing stabilization and based on anatomic lines of pull, the supraspinatus acts to initiate abduction, the infraspinatus and teres minor to externally rotate, and the subscapularis to internally rotate.

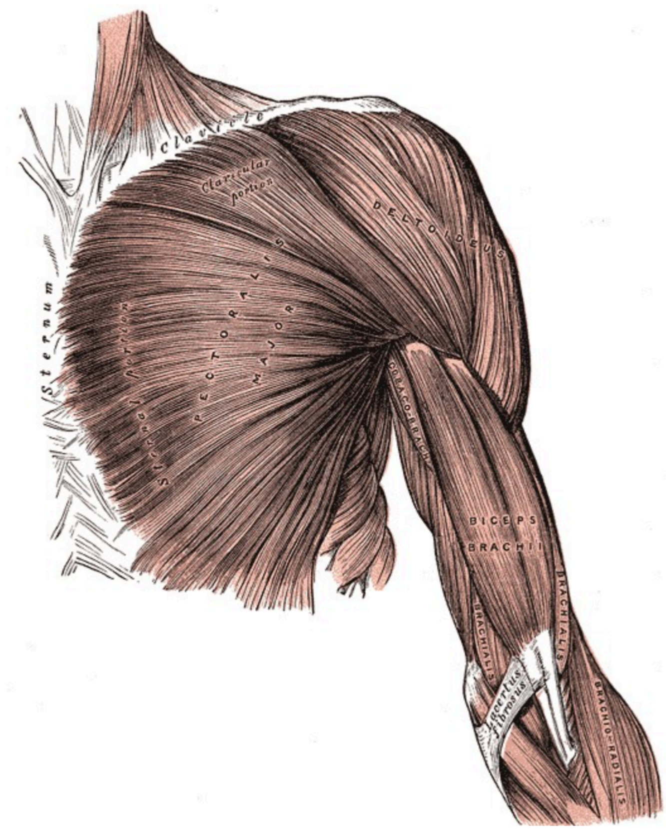

Figure 5: Superficial muscles spanning the shoulder joint[24]

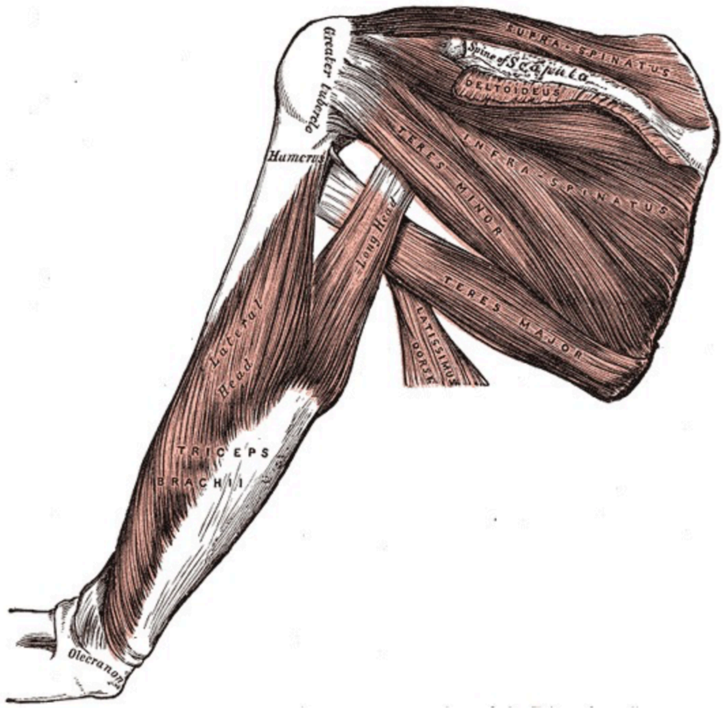

Figure 6: Posterior view of the shoulder[24]

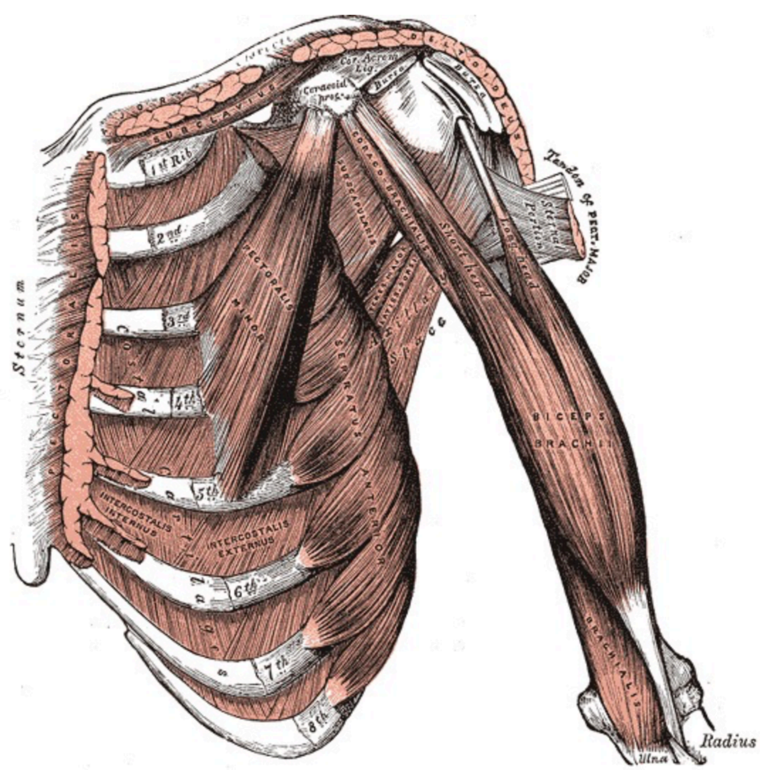

Figure 7: Anterior view of the shoulder[24]

Deep to the rotator cuff complex is the joint capsule. A joint capsule defines the ligamentous structures joining bones and acts to preserve a lubricated space for articulating surfaces and to provide additional stabilization. The muscles and capsule surrounding the shoulder joint are closely related, and their structures tend to blend near the insertions of the cuff tendons onto the humerus (Figure 8).

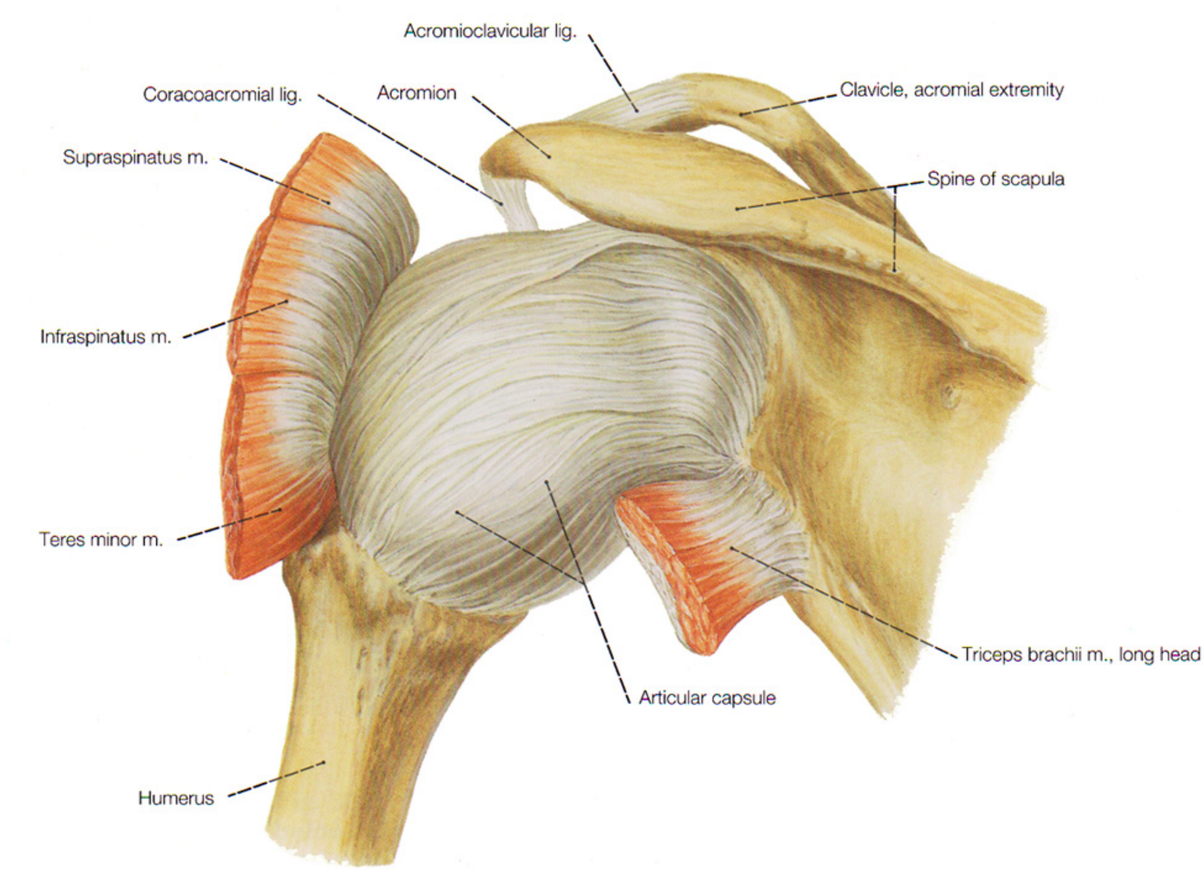

Figure 8: Rotator cuff and capsule complex (http://www.arrowptseattle.com/news/sleeperstretch)

1.3 Rotator Cable

1.3.1 Rotator Cable Anatomy

First described by Burkhart and coworkers, the rotator cable (RCa) has been defined as a thickened structure within the rotator cuff tendons that protects the crescent area (CA). The fibers of the RCa are reported to be thicker than the CA, running perpendicular to rotator cuff tendonous fibers, and originating at the coracohumeral ligament (CHL) at the anterior most border of the SS. These fibers direct load around the CA to the humeral insertions of the rotator cuff tendons. The arching band of fibers extends through the SS and IS tendons and concludes at the superior border of the teres minor (TM) muscle tendon[4] (Figure 9).

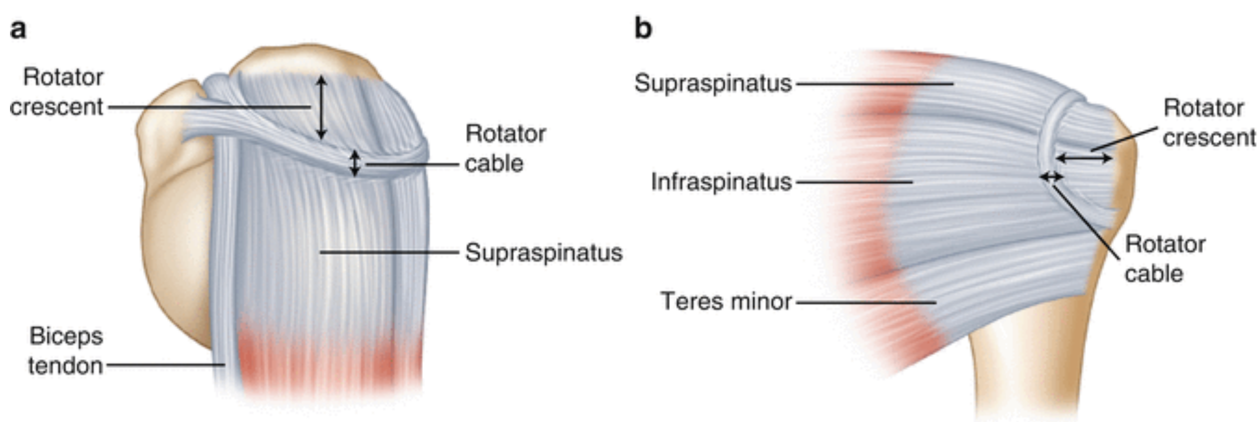

Figure 9: Anatomic decription of the RCa (https://musculoskeletalkey.com/rotator-cuff-disorders/)

The underlying anatomy of the RCa is in response to the layering of the rotator cuff and capsule complex. The CHL is a part of the ligamentous structure of the joint capsule connecting the coracoid process of the scapula to the humeral head. The ligament marks the anterior border of the RCa and the first layer (1) of the complex. The SS and IS tendon fibers are found directly beneath the ligament fibers of the CHL that run perpendicular to the tendinous tissue (2). The tendon fibers tend to spread out as they move deeper into the complex, which is noted by layer 3 (Figure 10). The CHL has a second (4) and deep layer extension that marks the anatomic start of the joint capsule (5). The RCa is an extension of the CHL as its perpendicularly oriented fibers span the tendons of the SS and IS and finally disperse at the superior junction of the TM.

The CA is the portion of SS and IS tendon located lateral to the extension of the CHL (RCa). This area is avascular and prone to tears[2,34]. Current literature has shown that the majority of the rotator cuff pathologies initiate 15cm posteriorly to the biceps groove, which is consistent with the avascular region of the CA[2,15]. However, other authors have argued a relationship between RCa existence, CA prevalence, and age[2,3]. Rotator cuff complexes have been categorized based on their respective dominance of either the RCa or CA. Ultrasound has been used to illustrate thicker CA tissue in younger patients and thicker RCa tissue in older patients[3]. The thickened nature of the RCa in older patients could explain why tears, which are also more common with age, are initiating in an area that has comparatively less tissue substance[7].

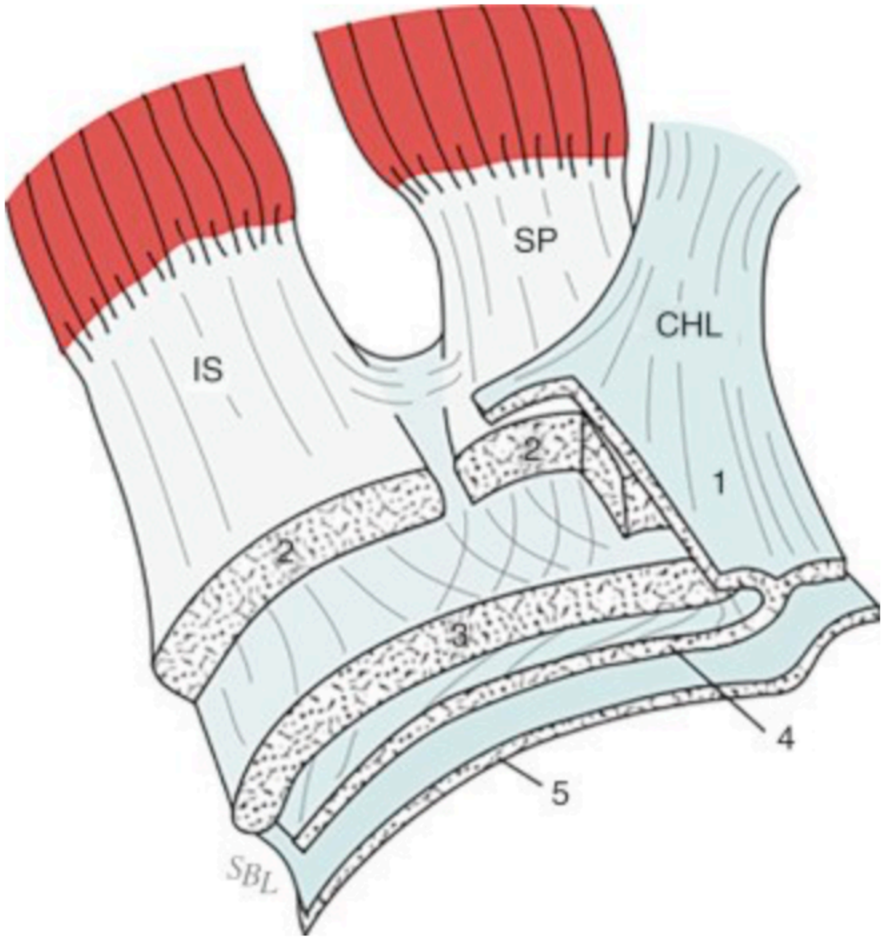

Figure 10: Tendinous and ligamentous layers of the rotator cuff[5]

1.3.2 Biomechanics of the Rotator Cable

In addition to the anatomic description of the structure, it is also said to be of mechanical importance for overall shoulder function[4,9,22,28], which could explain why tendon tears isolated to the CA might present as asymptomatic. The RCa is hypothesized to transfer muscle loads from the rotator cuff to the humeral insertions of the tendons around the CA. Current literature has investigated tendon strain, abduction strength, and joint kinematics to quantify the role of the RCa. The anterior RCa is said to be the most important for shoulder function due to its location relative to the SS and its ability to abduct[9,22,28]. Disruption of the posterior insertion affects only the inferior portions of the IS and superior portions of the TM. These muscles are responsible for externally rotating the arm, and compensations can be made. However, the rotator cuff may have difficulty compensating for abduction if the sole abductor is not functioning.

1.3.2.1 Strain Tracking

Mazzocca et al. investigated partial, articular sided tears of the SS tendon and its effect on tendon strain[19]. The experimental setup involved sectioning the SS into thirds in an anteroposterior direction. Partial thickness tears of varying degrees were introduced to the tendon and loads were cyclically applied. Statistically significant increases in tendon strain were observed with 50% and 75% partial thickness tears when compared to the native tendon. The study findings indicated the development of asymmetric strain patterns with disruption of the rotator cuff tendons. However, the experiment did not isolate the role of the RCa, but it created a foundation for understanding how tendon strain deviates when rotator cuff insufficiencies are present.

Mesiha et al. also used optical strain tracking to measure the strain patterns across the bursal side of the CA and RCa following simulated tears in both of these regions. Full thickness tears were randomized into two groups based on location: anterior RCa or CA. All tears began as a small tear and were advanced to a larger tear, which were based on relative dimensions of the CA and RCa. The terms small and large differ from the clinical terms used to describe a rotator cuff tear and were unique to the study[25]. Experimental measurements showed asymmetric strain patterns consistent with tears isolated to the anterior insertion of the RCa. Strains increased in the CA, RCa, and tendons located medial to the border of the RCa following RCa disruption (Figure 11). Tears isolated to the CA did not cause a significant change in strain patterns across the tendon surface.

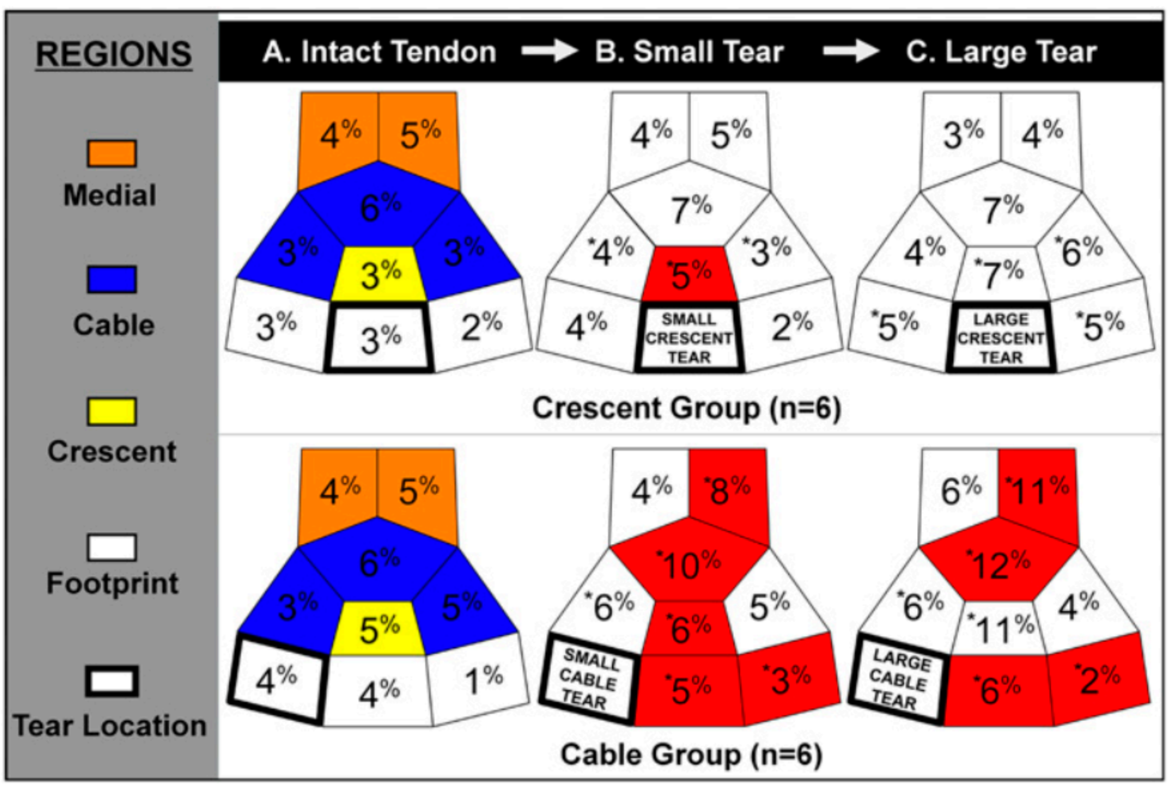

Figure 11: Surface strain following RCa and CA tears

Preliminary, unpublished results from our laboratory have shown results in contradiction with Mesiha et al. while using a similar experimental setup[32]. Strain tracking was used to test the effect of a single release of a RCa insertion, either anterior or posterior, and a full release of both RCa insertions. The change in strain was analyzed within the CA and two points medial to the RCa on the SS and IS tendon at different abduction angles. The strain did not change significantly after transection of a single RCa insertion release or a full release of both insertions.

1.3.2.2 Abduction Strength

Abduction strength and its connection to rotator cuff tear size has been used because it resembles the clinical situation[9]. Abduction force output has been measured for multiple conditions of rotator cuff tendon condition. Halder et al. performed an experiment to quantify the effect of tear propagation through the CA. The SS was sectioned into thirds in the anteroposterior dimension, and force generation at the distal humerus was measured when muscles were loaded to physiological values at each cut sequence. The sequence involved released a third of the tendon moving from anterior to posterior and eventual continuation into 5mm and 10mm of the IS tendon. Significant drops in output force were measured when the entire SS had been affected (11% decrease in abduction force) and during 5mm (27% decrease) and 10mm (47% decrease) extension into the IS. These results highlight a critical value in which shoulder function becomes affected.

1.3.2.3 Joint Kinematics

Pinkowsky et al. also investigated the importance of the RCa. The authors were concerned with joint kinematics and the ability of the RCa in stabilizing the joint in overhead throwing athletes. Cadaveric specimens were loaded to initiate a throwing motion at different angles of external rotation. Movement of the humeral head, specifically anterior translation, relative to the glenoid was measured and reported (Figure 12). Tears involving the RCa increased glenohumeral translation and changed the final position of the apex of the humeral head.

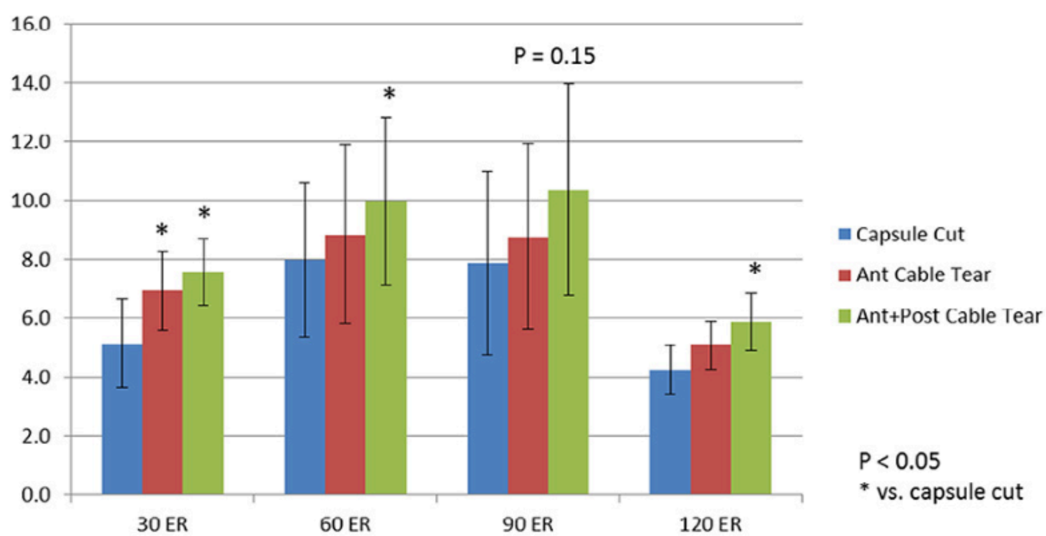

Figure 12: Anterior translation as a function of external rotation and RCa condition

2.0 Methods

2.1 Overview

Ten fresh-frozen cadaveric specimens were employed for this biomechanical study. The specimens were full arms from scapula-to-fingertip with an average age of 63.8±9.9 years. Exclusion criteria included any partial or full thickness tears of the rotator cuff or the presence of glenohumeral joint arthritis. All specimens were loaded with physiological forces to imitate abduction of the arm. The resulting abduction strength and internal/external rotation torque were analyzed at the distal humerus as the experimental outputs. Following the native condition, a sequence of cuts was introduced to the rotator cuff. First, the CA was divided into four identical sections along the insertion of the muscle tendons to the humeral head. Specimens were then randomized into two groups where either the anterior (anterior-start) or posterior (posterior-start) quarter of the CA was released. Propagation of the tear continued throughout the remaining three quarters of the CA and finished with extensions into both insertions of the RCa. Mechanical testing was performed at each stage of the sequence to quantify the effect of tear location on the experimental outputs.

2.2 Specimen Preparation

The humeral shafts were transected along the deltoid tuberosity, and soft tissue from the proximal portion of the specimens was removed to reveal the rotator cuff and capsule complex. Five loading sutures were placed into each muscle, which included two separate sutures for the upper and lower subscapularis and one for each remaining rotator cuff muscle. The acromion was osteotomized at its connection with the scapular spine to better visualize muscle insertions on the humeral head and the rotator cuff. The inferior portion of the shoulder capsule was sharply dissected in order to expose the inferior anatomic neck of the humerus. The humeral head was osteotomized along the anatomic neck to expose the articular surface of the capsule. Special care was taken not to disturb the muscular insertions or the long head of the biceps proximal tendon. This exposure from the articular side highlighted the thickening bands of the RCa, and a running silk suture was passed from the articular to bursal surface along both the medial and lateral borders of the structure. The humeral head was then reattached to the anatomic neck and secured with screws. The inner and outer base of the CA were measured, and the inner base was sectioned into four equal portions with a surgical marker (Figure 13).

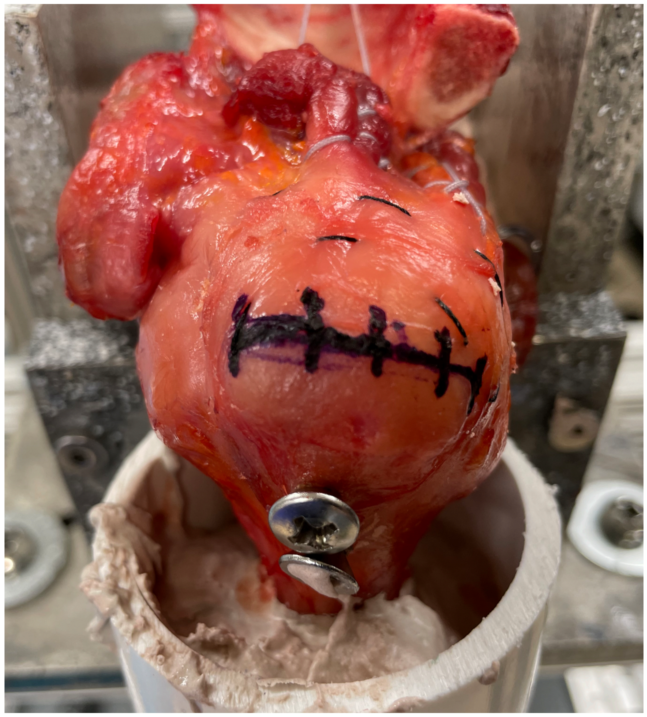

Figure 13: Prepared specimen with the CA sectioned into four equal parts

Eyelet screws were placed on the supraspinatus fossa, infraspinatus fossa, subscapularis fossa, and medial border of the scapula to simulate lines of actions for the supraspinatus, infraspinatus, subscapularis, and teres minor, respectively during loading. The transected, distal humerus was potted into a PVC sleeve using hardening, non-shrink resin (Bondo, 3M), and the scapula was potted into a custom scapular box following an identical resin procedure. The scapula was positioned in the box to ensure there was adequate contact between the humerus and glenoid fossa.

2.3 Shoulder Simulator

A custom shoulder simulator was used to apply physiological forces to the loading sutures mentioned previously (Figure 14). The simulator included five servo actuators (Parker Hannifin Corp., Cleveland, OH), each connected to a respective rotator cuff muscle by a cable and pulley system internal to the system. The actuators were connected to single-DOF load cells (MLP-100, Transducer Techniques, Inc., Temecula, CA) (Accuracy ±0.25% RO, Nonrepeatability ±0.05% RO) that provided feedback to the overall control system. The scapular box was securely mounted to the simulator while allowing the humeral head to be anatomically positioned against the glenoid. The abduction arc permitted varying range of motion while ensuring the contact was constant. A 6-DOF load cell (Bertec Corp., Columbus, OH) fixture served as the rigid connection between the distal humerus and the abduction arc, restricting any translation or rotation.

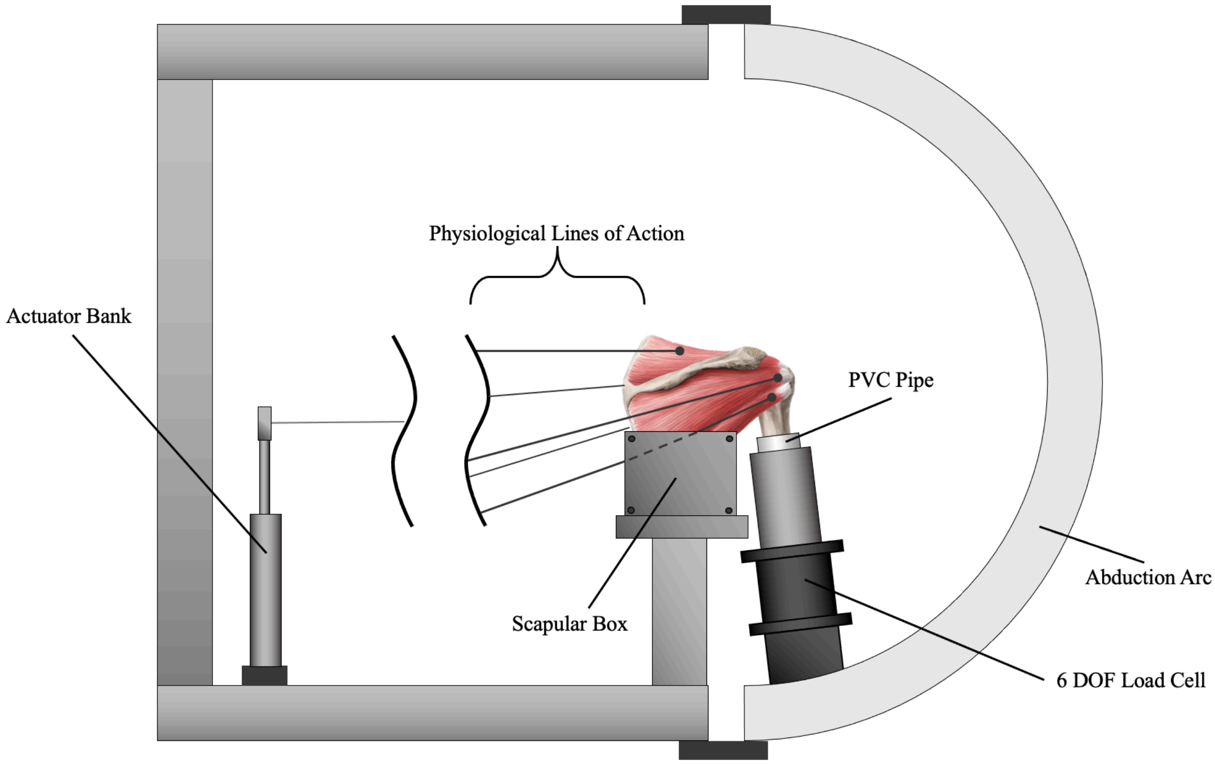

Figure 14: Shoulder simulator schematic

2.4 Testing Protocol

All muscles were preloaded to 10N once the specimen was securely fixed into the simulator to provide stabilization of the glenohumeral joint. A trained orthopaedic fellow confirmed position of the humeral head against the glenoid after stabilization. A screw was then tightened against the humerus and PVC complex to eliminate movement and provide accurate readout from the 6 DOF load cell. Actuator (muscle) forces were determined from previously published works using physiological cross-sectional area (PCSA) and electromyographic activity[14,27] (Table 1).

Table 1 Physiological load pattern for the rotator cuff muscles imitating abduction

Muscle	Supraspinatus	Infraspinatus	Teres Minor	Upper Subscapularis	Lower Subscapularis
Actuator Load	80 N	90 N	97 N	127 N	108 N

All tests were performed at 0° of scapular plane abduction. The simulator ramped up the actuators to their predetermined values within a second once the test was initiated and held constant tension for the entirety of the mechanical test. A reference line was also placed on the PVC sleeve to monitor its movement with respect to the metallic sleeve it was fitted into to ensure there was no superior translation of the humerus during loading. The native specimen was loaded and allowed to equilibrate for five minutes. A simulated CA tear was created at either the anterior or posterior quarter of the CA following the five minutes. A custom MATLAB code (MathWorks, Natick, MA) was employed to randomize the initial tear between either anterior or posterior quarter of the CA (Appendix B). The system remained loaded and the cut condition was tested for an additional five minutes. The sequence continued with propagation of the tear into the neighboring quarter of the CA until the entire base was released, and each condition was tested for five minutes. The final two conditions were extensions into the RCa. The anterior-start group extended the last CA cut into the posterior RCa, which was followed by release of the anterior RCa (Figure 15). The procedure was opposite for the group with an initial posterior CA release (Figure 16).

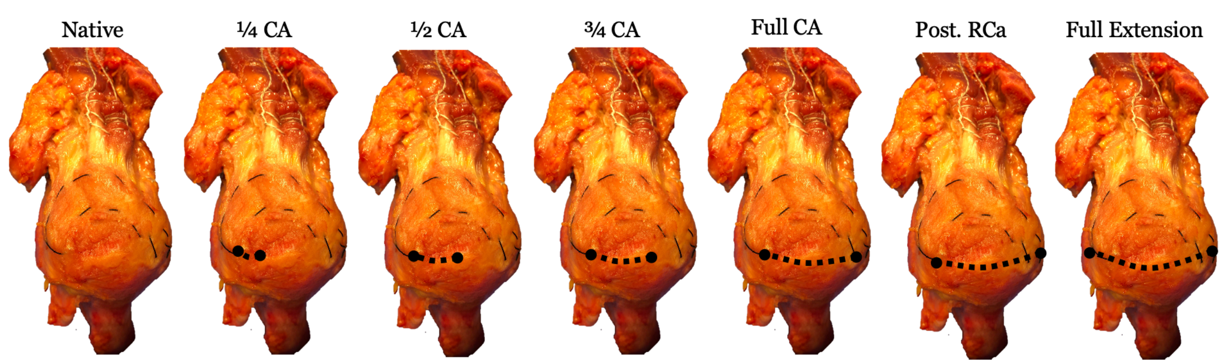

Figure 15: Sequence of tears starting at the anterior ¼ of the CA

Figure 16: Sequence of tears starting at the posterior ¼ of the CA

2.5 Humeral Abduction Force and Internal/External Rotation Torque

The midshaft of the humerus was potted and rigidly attached, after stabilization of the joint, to the 6-DOF load cell and the abduction arc. The resultant force acting perpendicular to the humerus in the scapular plane was defined as the humeral abduction strength. A positive value (orange) denoted a force initiating abduction in the scapular plane, whereas a negative value corresponded to adduction (Figure 17). The axial torque generated at the end of the humerus with respect to the long axis was measured by the load cell. Internal and external torque generation (red) was then defined as positive and negative, respectively. Data was collected at a sampling rate of 10 Hz from the load cell, and the values reported for each condition were an average over the final two minutes of each sequence.

Figure 17: Coordinate system defined by the 6-DOF load cell at the distal humerus: scapular plane abduction strength (orange) and axial roation torque (red)

2.6 Statistical Analysis

Descriptive statistics were used to compare the native condition to all sequences with cut condition being the independent variable. A one-way repeated measures ANOVA was used per group, and a post-hoc analysis using a Bonferroni correction was applied if significance was detected ($p<0.05$). If there was no significance calculated from the pair-wise comparisons stemming from the post-hoc analysis, a paired t-test comparing cut sequences per group was used with significance set at 0.05. Full comparison between groups for the full CA release and full extension into both RCa insertions was compared using a paired t-test. Every cut condition was also compared to all latter stages of the sequence using an identical test. A Kolmogorov-Smirnov test of normality was conducted for all groups to verify appropriate use of the parametric, paired t-test ($p<0.05$) (Appendix C).

3.0 Results

3.1 Full Comparison Among Specimens

A sample readout as a function of time from the load cell at the distal humerus is shown below in Figure 18 for an anterior-start specimen. The spikes following each sequence were a result of intervention by a trained orthopaedic fellow to make the appropriate, simulated tears. The values reported for both abduction force and rotation torque were averaged over the final two minutes of each condition, which did not include noise introduced by the fellow. All ten specimens underwent the full CA simulated tear and the final, anterior and posterior extension into the RCa insertions. The change in abduction force decreased from 6.43N at the native condition to 5.55N (14% decrease) at the full CA release and 3.77N (41% decrease) at the final extension into both RCa insertions. When compared to native, the decrease was significant for the final extension ($p=0.003$) and marginally significant for the full CA release ($p=0.067$). Due to a simulator malfunction, two specimens were excluded from the full comparison of rotation torque. The Rotation torque was 0.782Nm at the native condition, 0.785Nm when the entire CA was released, and 0.827Nm at the final extension into both insertions. None of the changes were significant and the positive values correspond to internal rotation ($p>0.681$).

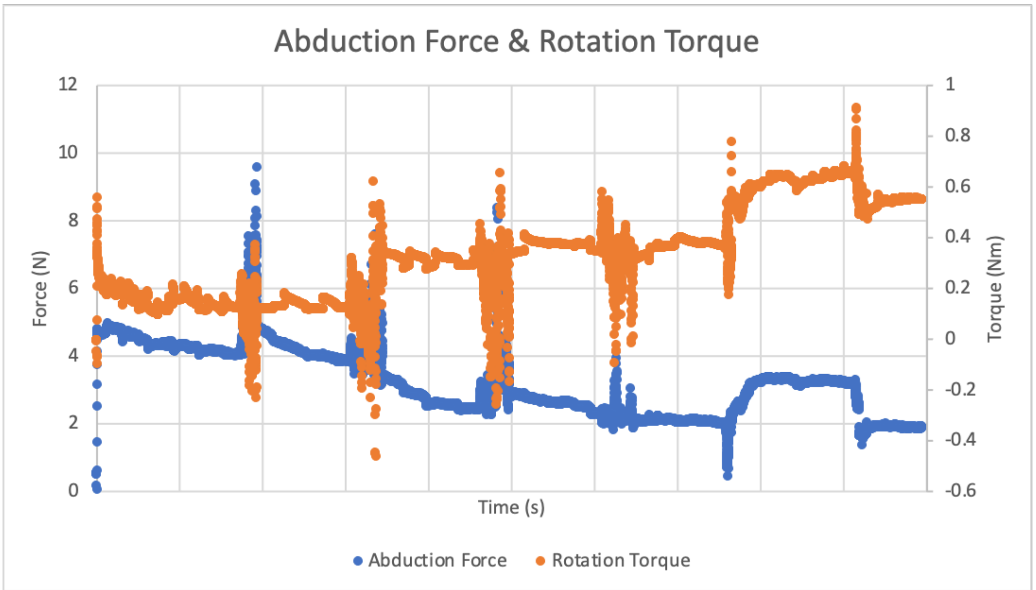

Figure 18: Sample experimental outputs as a function of time

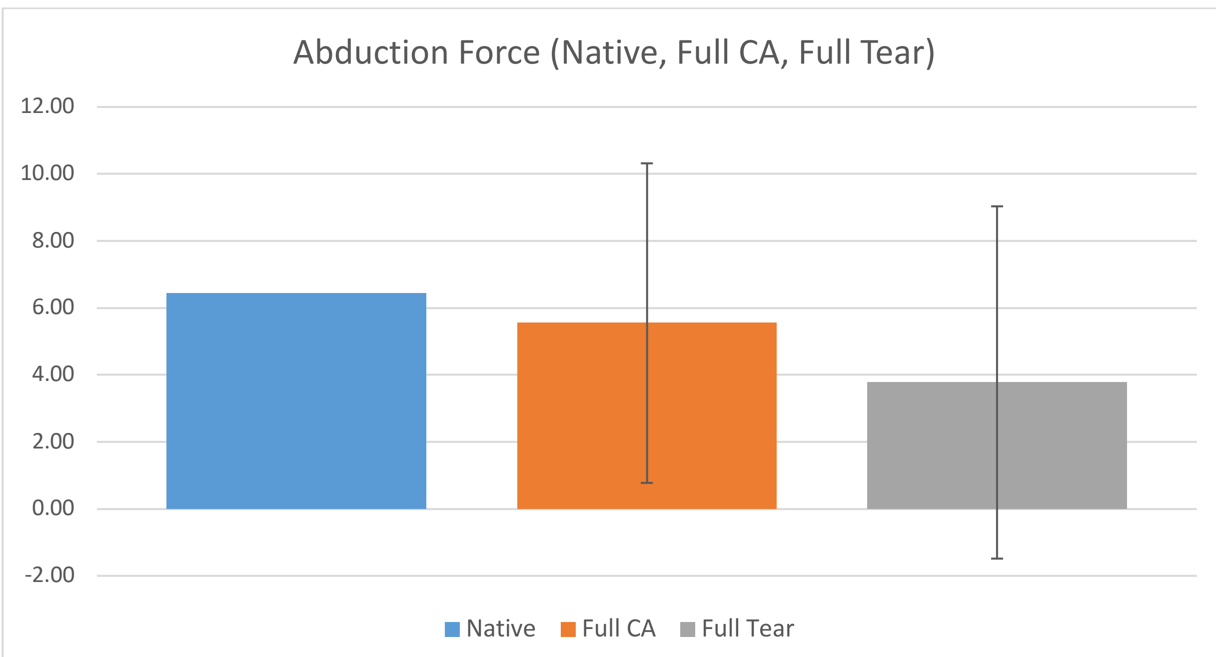

Figure 19: Abduction force for the conditions of full CA and full tear extension into both insertions of the RCa

3.2 Anterior-Start Specimen Comparison

The five anterior-start specimens had a decrease in abduction force, when compared to the native condition, of 2%, 8%, 14%, 22%, 30%, and 57% for a ¼ CA tear, ½ CA tear, ¾ CA tear, full CA tear, posterior extension into the RCa, and full extension into the remaining RCa insertion, respectively (Figure 20). The one-way repeated measured ANOVA revealed significance among all the cut conditions ($p=0.001$), but the pairwise comparison of the post-hoc analysis showed only marginal significance between the initial quarter CA release and the final release ($p>0.105$). The decreases in abduction strength for ¾ release of the CA, full CA, extension into the posterior RCa insertion, and full extension into both RCa insertions conditions were significant using a paired t-test (Table 2).

Due to a simulator malfunction during testing, rotation torque data was not obtained for two of the five anterior-start specimens. The one-way repeated measures ANOVA was not significant across cut conditions when analyzing rotation torque ($p=0.518$). Data was collected for three specimens and the internal rotation is shown (Figure 21). Statistical t-tests comparing cut sequences to the native condition are presented in Table 3.

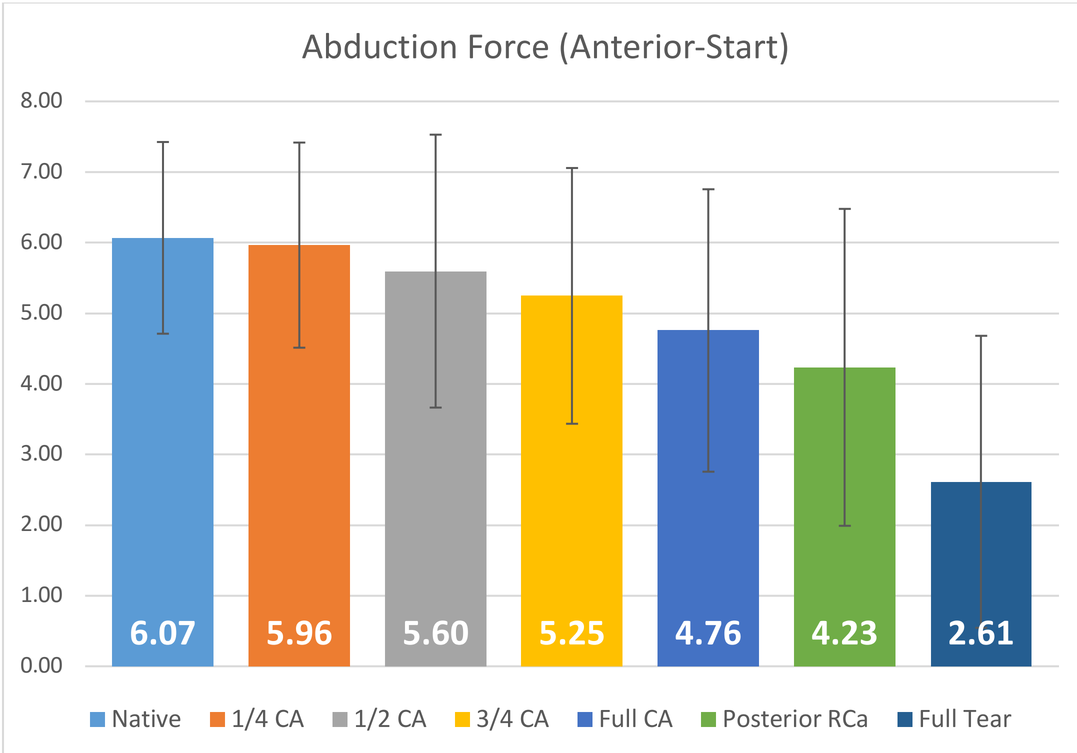

Figure 20: Abduction force for anterior-start specimens

Table 2: Statistical significance for abduction force for anterior-start specimens

Native vs.	¼ CA	½ CA	¾ CA	Full CA	Posterior RCa Extension	Full Extension
p-value	0.336	0.196	**0.022**	**0.013**	**0.047**	**0.005**

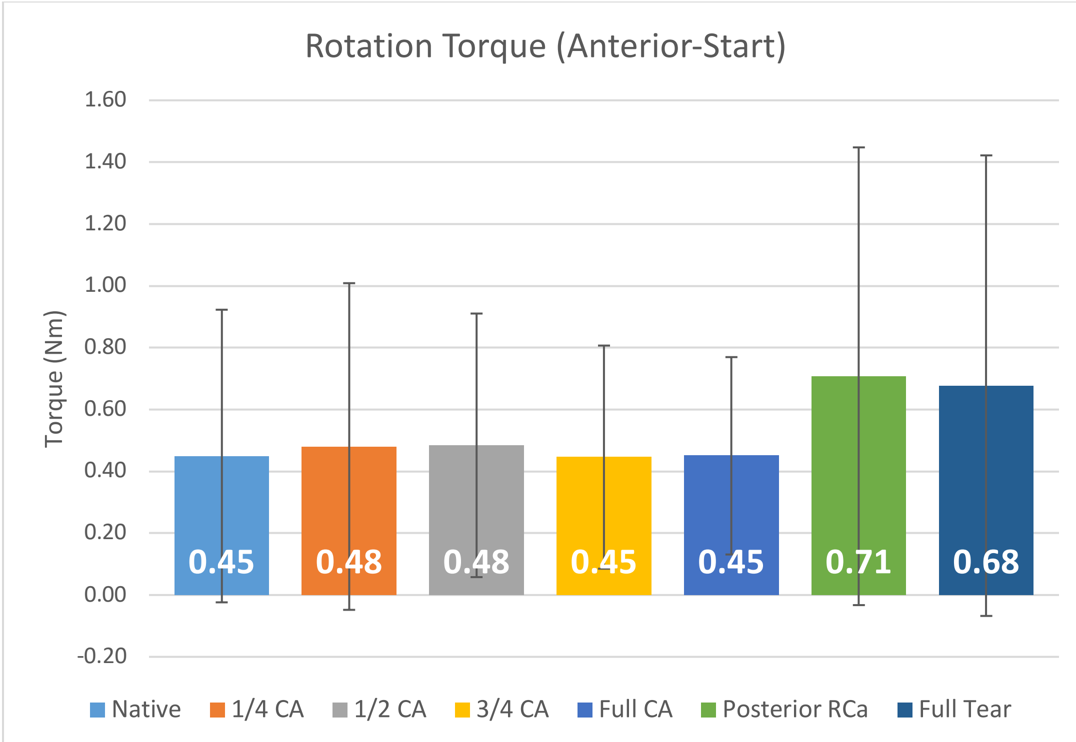

Figure 21: Rotation torque for anterior-first specimens

Table 3: Statistical significance for rotation torque for anterior-start specimens

Native vs.	¼ CA	½ CA	¾ CA	Full CA	Posterior RCa Extension	Full Extension
p-value	0.438	0.642	0.978	0.996	0.385	0.406

3.3 Posterior-Start Specimen Comparison

The posterior-start specimens showed minimal decrease in abduction among the specimens and their cut conditions (Figure 22). The one-way ANOVA was significant ($p=0.020$), and the post-hoc analysis using pairwise comparisons did not detect any significance ($p>0.356$). No decreases were significant using a paired t-test (Table 4), but the final condition of full extension into both RCa insertions approached significance ($p=0.160$). The lack of significance could be explained by the wide variability found within the posterior-start group. Specimen #3 showed such a decrease in abduction that the system began to adduct, and specimen #10 had a larger force generation compared to the others (Appendix A.1).

Internal rotation values compared to native stayed relatively consistent throughout the entirety of the test (Figure 23) and no changes were significant using a t-test (Table 5). The ANOVA did not reveal significance across the cut sequences ($p>0.926$).

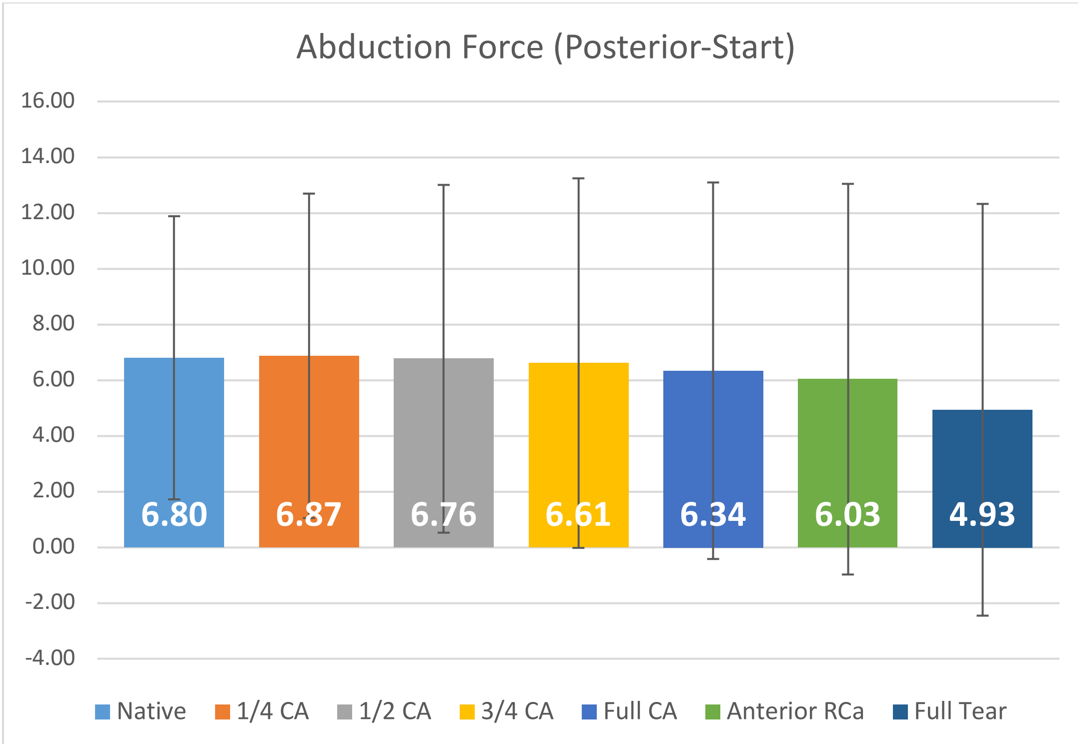

Figure 22: Abduction force for posterior-start specimens

Table 4: Statistical significance for abduction force for posterior-start specimens

Native vs.	¼ CA	½ CA	¾ CA	Full CA	Anterior RCa Extension	Full Extension
p-value	0.849	0.950	0.806	0.592	0.452	0.160

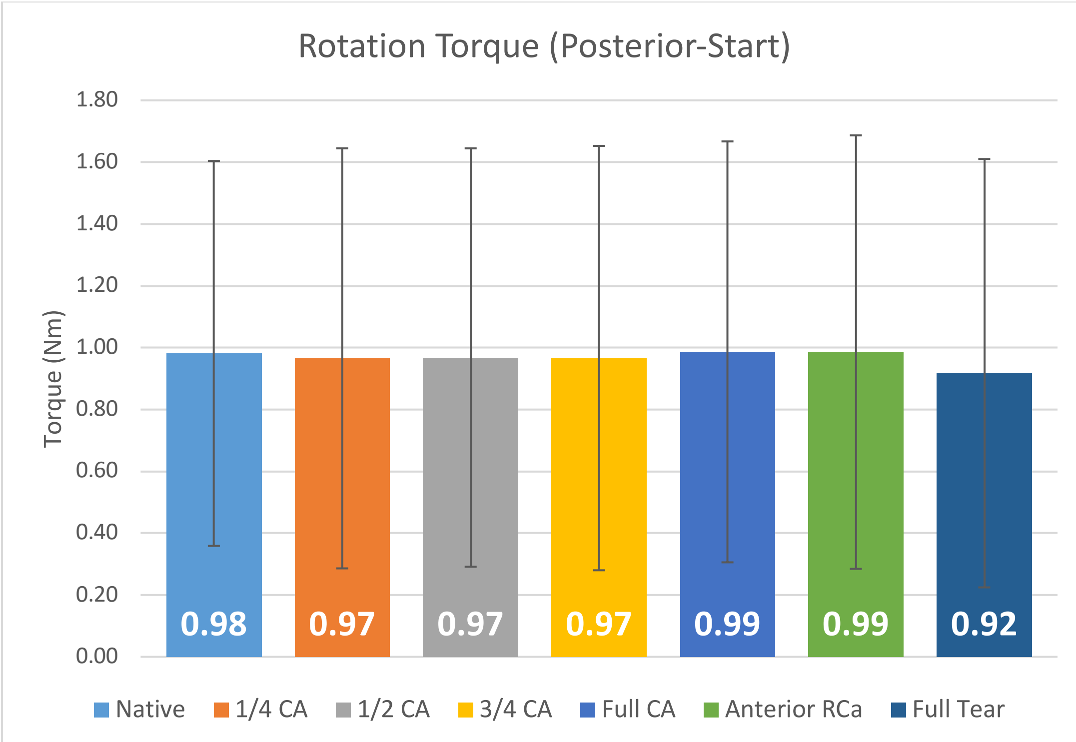

Figure 23: Rotation torque for posterior-start specimens

Table 5: Statistical significance for rotation torque for posterior-start specimens

Native vs.	¼ CA	½ CA	¾ CA	Full CA	Anterior RCa Extension	Full Extension
p-value	0.579	0.746	0.858	0.951	0.958	0.538

3.4 Statistical Comparison Between Cut Conditions

Each respective condition was compared relatively to the latter stages of the cutting sequence. Comparisons were made for each abduction force group of anterior- and posterior-start and are found below in Tables 6 and 7.

Table 6: Statistical comparisons between cut conditions for the anterior-start group (abduction strength)

Condition	Native	vs. 1/4 CA	vs. 1/2 CA	vs. 3/4 CA	vs. full CA	vs. posterior RCa	vs. full tear
Native	-	0.336	0.196	0.022	0.013	0.047	0.005
vs. 1/4 CA	-	-	0.271	**0.020**	**0.008**	**0.049**	**0.005**
vs. 1/2 CA	-	-	-	0.037	**0.029**	0.167	**0.020**
vs. 3/4 CA	-	-	-	-	0.042	0.224	**0.020**
vs. full CA	-	-	-	-	-	0.418	**0.028**
vs. posterior RCa	-	-	-	-	-	-	**0.019**
vs. full tear	-	-	-	-	-	-	-

Table 7: Statistical comparisons between cut conditions for the posterior-start group (abduction strength)

Condition	Native	vs. 1/4 CA	vs. 1/2 CA	vs. 3/4 CA	vs. full CA	vs. anterior RCa	vs. full tear
Native	-	0.849	0.950	0.806	0.592	0.452	0.160
vs. 1/4 CA	-	-	0.630	0.551	0.330	0.241	0.069
vs. 1/2 CA	-	-	-	0.497	0.234	0.168	**0.041**
vs. 3/4 CA	-	-	-	-	0.090	0.087	**0.017**
vs. full CA	-	-	-	-	-	0.099	**0.018**
vs. anterior RCa	-	-	-	-	-	-	**0.028**
vs. full tear	-	-	-	-	-	-	-

4.0 Discussion

To quantify the effects of RCa disruption, Mesiha et al. investigated surface tendon strain across the rotator cuff. Cadaveric specimens underwent cut sequences involving the CA and RCa similar to the current study. The authors focused on the anterior insertion of the RCa at the CHL and not the posterior. Similar size tears were isolated to either the CA or RCa and compared. The tendon strain changed significantly whenever the anterior insertion was affected. Tears isolated to the CA did not significantly alter the tendon strain during loading. However, creating a conclusion based on tendon strain, which has no direct connection to a clinical situation, is difficult. Perhaps the results illustrate an underlying mechanism of the RCa, but there are other variables involved when determining why certain rotator cuff lesions are asymptomatic or symptomatic. The experiment addressed tear location, but it did not quantify items such as loss of function or strength. The findings of the current study encapsulated both insertions of the RCa and CA while monitoring outputs that have direct implications on patient care: abduction and rotation strength.

The RCa is located within the tendons of the SS and IS, which correspond to the primary initiator of abduction and an external rotator. Halder et al. explored tear size and functional strength outputs as a function of tear location affecting those two muscles and how it was related to the RCa. Again, the authors isolated the RCa and CA and performed a series of simulated tears to monitor the effect on humeral abduction strength, identical to the output in the current study. The anterior RCa was left intact, and a sequence of tears was extended from the anterior border of the SS and eventually concluded 10mm into the IS in the anteroposterior dimension. The results indicated a mechanical importance of the RCa. Abduction strength, when compared to native, showed a significant decrease when the entirety of the SS insertion was torn. However, recalling the anatomic definition of the RCa, this decrease corresponds to an intact posterior RCa insertion and, so, in essence, a significant drop was observed when only the CA was affected. It is important to keep in mind that a continued 5mm and 10mm extension into the IS also created a significant decrease of 27% and 47%, respectively, when compared to the native condition. These final two conditions were the only two following the SS insertion incision. It would be expected that the strength loss would be significant with the tear increase stemming from the entire SS insertion.

The findings presented by Halder can easily be related to the findings of the current study. A simple one third and two third anteroposterior tear of the SS tendon resulted in a drop of less than 1% and 2%, respectively. While these values cannot be compared directly to the results of this study based on how the affected areas were sectioned and the incision size, there is a relationship between similar size tears and the respective decreases. For instance, a release of the first quarter and half of the CA, with the RCa insertion intact, for the anterior-start group (most similar to the cut sequence direction of Halder et al.), yielded in a reduction in abduction strength of 2% and 8%, none of which were significant. Significance first appeared in the current study for the anterior-start group at a release of ¾ of the CA with the posterior insertion of the RCa left intact ($p=0.022$). The exact location of the posterior border of the SS was not explicitly noted during the cutting sequences here, so it is difficult to determine when the CA cut in the current study reached the posterior border. However, the significant decrease did happen somewhere before the posterior insertion of the RCa was disrupted, and the same can be observed from Halder et al. The statistical significance for the current study continued with the remainder of the sequence, as well. Halder et al. concluded that their study was consistent with the RCa hypothesis of transmitting force because the decrease in strength observed with full SS release (11%) corresponded to a medium sized rotator cuff tear (<3cm), which has been shown to remain asymptomatic. This study related tear sizes, asymptomatic dimensions of tear sizes, and the 11% decrease where the significance was first determined. In essence, this drop is within a region clinically where the body could compensate and present as asymptomatic even though there is a mechanical decrease with the RCa intact.

The posterior-start group did not show significance for any of the conditions when compared to native, but it was approached when the CA and both insertions of the RCa were torn ($p=0.160$). The lack of significance is not that surprising, though. For the posterior-start group, the anterior borders of the SS are left intact until the latter stages of the tear propagation. The remaining, intact SS, located most superiorly over the humerus, is able to sufficiently abduct the arm. The abduction moment arm of the muscle is preserved longer when compared to the anterior-start group. However, the magnitude of the decrease in strength when isolated to the CA only was similar between groups of anterior-start and posterior-start.

The comparisons between groups found in Table 7 do show significant decreases in abduction force for the posterior-start group. These decreases, however, are relative to a simulated tear and not a native specimen. At this point, the significance was measured when the majority of the rotator cuff had been torn. This loss in shoulder strength, again, is not surprising considering the lack of tissue connection of the supraspinatus at the final condition.

Rotation torque increased during all conditions for the anterior-start group, but the increases were based on a total of three specimens due to system malfunction. The physiological loading applied to the rotator cuff appeared to balance the agonist and antagonist muscles responsible for internal and external rotation. The output of the native condition was close to zero, so any change in torque was magnified, which could explain the high increases in internal rotation.

The posterior-group, however, remained relatively consistent compared to native through the entirety of the test. No significant differences were determined as a result of tear size or location.

The current findings, mainly as a result of abduction strength output, using the biomechanical test do not support the RCa being a specialized mechanical structure. Decreases in strength were recorded for tears isolated to the CA region with the RCa left intact. If the RCa were to function as originally proposed by Burkhart and coworkers, there would not be a significant change in strength until the RCa was affected. It can be concluded that the entirety of the rotator cuff/cable complex is important for overall shoulder strength and function.

It is also important to mention limitations of the study, especially in terms of the rotation torque data acquired. The loading pattern applied to the rotator cuff muscles was one determined based on the initiation of abduction. The output variable of abduction strength was then quantified. However, since the loading did not simulate either external or internal rotation, the values obtained were collected with high variability. In future studies, imitating rotation by means of differing muscle forces should be considered when determining the effect of rotator cable tear size in rotation strength.

Appendix A Raw Data

A.1 Humeral Abduction Raw Data (N)

Specimen	Group	Native	¼ CA	½ CA	¾ CA	Full CA	Anterior RCa Extension	Posterior RCa Extension	Full Tear
#1	Anterior	4.21	3.99	2.55	2.53	2.07	-	3.25	1.89
#2	Posterior	6.32	6.23	6.17	6.39	6.37	6.14	-	5.68
#3	Posterior	3.11	2.44	1.85	1.13	0.44	-0.34	-	-1.15
#4	Anterior	6.97	7.11	6.96	6.54	6.20	-	5.44	4.94
#5	Posterior	4.51	4.60	4.60	4.38	3.98	3.56	-	1.81
#6	Posterior	4.41	4.09	3.62	3.18	3.09	2.94	-	0.94
#7	Anterior	6.20	5.80	6.10	5.4	4.45	-	2.66	1.46
#8	Anterior	5.30	5.30	5.00	4.60	3.89	-	2.24	0.18
#9	Anterior	7.65	7.62	7.37	7.15	7.18	-	7.59	4.59
#10	Posterior	15.66	17.00	17.57	17.97	17.81	17.87	-	17.39

A.2 Rotation Torque Raw Data (Nm)

Specimen	Group	Native	¼ CA	½ CA	¾ CA	Full CA	Anterior RCa Extension	Posterior RCa Extension	Full Tear
#1	Anterior	0.144	0.132	0.306	0.370	0.382	-	0.645	0.551
#2	Posterior	0.361	0.292	0.236	0.227	0.270	0.224	-	0.179
#3	Posterior	0.468	0.386	0.520	0.656	0.652	0.648	-	0.647
#4	Anterior	0.210	0.220	0.176	0.129	0.171	-	0.000	0.004
#5	Posterior	0.980	0.974	0.938	0.860	0.914	0.894	-	0.812
#6	Posterior	1.190	1.213	1.149	1.014	1.004	1.054	-	0.896
#7	Anterior	-	-	-	-	-	-	-	-
#8	Anterior	-	-	-	-	-	-	-	-
#9	Anterior	0.995	1.088	0.971	0.839	0.798	-	1.001	1.477
#10	Posterior	1.908	1.963	1.998	2.075	2.092	2.108	-	2.053

Appendix B MATLAB Randomization Code

```
clc

clear all

syms S201936 S201997 202380 S202206 SS202031 S201936 S202091 S201879R S202099
S201879L;

X = [S201936 S201997 202380 S202206 SS202031 S201936 S202091 S201879R S202099
S201879L];

Y = X(randperm(numel(X)));


Ant = Y(1:floor(numel(X)/2));

Post = Y(1+floor(numel(X)/2):numel(X));


% Copied & pasted the output randomized groups since the randomization changes
% with every run of the code.
%
% Ant =
%
% [ S202099, S202091, S202206, S201936, S201879R]
%
%
% Post =
%
% [ S202380, S201926, S201879L, S201997, S202031]
%
```

Appendix C Kolmogorov-Smirnov Test of Normality

Group	Condition	p-value
Anterior-first	Native	0.993
Anterior-first	¼ CA	0.942
Anterior-first	½ CA	0.925
Anterior-first	¾ CA	0.980
Anterior-first	Full CA	0.978
Anterior-first	Posterior RCa	0.710
Anterior-first	Full Extension	0.821
Posterior-first	Native	0.499
Posterior-first	¼ CA	0.473
Posterior-first	½ CA	0.499
Posterior-first	¾ CA	0.606
Posterior-first	Full CA	0.672
Posterior-first	Anterior RCa	0.690
Posterior-first	Full Extension	0.735

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