FUNCTIONAL EVALUATION OF THE INTACT, INJURED AND RECONSTRUCTED
ACROMIOCLAVICULAR JOINT

by

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ABSTRACT

FUNCTIONAL EVALUATION OF THE INTACT, INJURED AND RECONSTRUCTED
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Injuries to the acromioclavicular joint usually result in pain and instability. However, few biomechanical studies have investigated the mechanism of injury and treatment. Consequently, current rehabilitation protocols and surgical techniques have similar outcomes with no "gold standard" for treatment. Therefore, the thesis objective was to evaluate the function of the intact and injured acromioclavicular joint during combined loading to provide guidelines for the development of rehabilitation protocols and reconstructions for complete dislocations.

A robotic/universal force-moment sensor testing system was utilized to apply an external load in combination with joint compression to intact and injured joint. Joint compression caused significantly decreases in primary (in the direction of loading) translations and joint contact forces while increasing coupled (orthogonal to the direction of loading) translations for the injured joint (p<0.05). These findings suggest common surgical techniques such as distal clavicle resection, which remove painful joint contact, may cause loads to be supported by other

structures and be transmitted over a smaller area due to the increased coupled motion and joint contact. Both findings reinforce the importance of restoring each component of the acromioclavicular joint after injury.

Next, the cyclic behavior and structural properties of an anatomic reconstruction of the coracoclavicular ligaments were determined during uni-axial tensile testing and compared to the intact coracoclavicular ligaments. After complete dislocation of the acromioclavicular joint, the anatomic reconstruction complex was found to have significantly lower stiffness and ultimate load compared to the intact ligaments ($p < 0.05$). However, the bending stiffness of the clavicle significantly decreased after dislocation. Consequently, the individual properties of the tendon graft used during reconstruction had more comparable results to the intact coracoclavicular ligaments than current surgical techniques.

The evaluation of the intact and injured joint during a combination of loading conditions provided guidelines for the development of an anatomic reconstruction. The experimental methodology used to evaluate the anatomic reconstruction incorporated a more realistic mechanism of failure during testing. Both studies provide insight on functional changes of the intact acromioclavicular joint following injury and reconstruction. Future investigations should quantify the loads transmitted across the joint during daily activities. Computational models could use this information in addition to data collected with the methodology developed in this thesis to optimize the proposed anatomic reconstruction.

FOREWARD

The journey in completing my masters thesis started two years ago and each person that I had contact with changed me as a person not only professionally but personally. I would not be the person I am today without the guidance and support of my friends and family.

I first like to thank Dr. Lars Gilbertson who was my mentor during my undergraduate days and introduced me to the Musculoskeletal Research Center. I was overwhelmed by facilities, the productivity and the amazing environment to conduct great research. Dr. Savio Woo, the director of the MSRC has perfected a method of conducting great research and the necessary steps to pass this knowledge on to up and coming researchers. Dr. Woo instilled a great sense of family which provides a great atmosphere to develop as a person and researcher.

I would like to thank Dr. Gina Bertocci, who brought new insight into the formation of my thesis. Also, Dr. Mark Rodosky who was the main clinician on all of my research I have performed so far. He always merges the gap between bioengineer and clinicians, provided valuable input and took an active role in the formation of my thesis.

My biggest influence in my growth professionally is due to the great guidance of my mentor and advisor, Dr. Rich Debski. He took a chance on me and pushed me to reach my potential. He also served as a great role model in his approach to research; being productive yet still producing quality. I look forward to more collaborative efforts with him in the future.

Finally, I would like to thank my friends and family, who have supported me in every challenge that I face. To my immediate family; Mom, Dad, Jamie and Becky and their respective others and to all my friends. They keep me going when things fall apart and celebrate

when things are going good. Every person has influenced me to be the person I am today and I couldn't have achieved this goal without each of them.

Although one journey has ended another is beginning. I don't know the path of my new journey but I am excited to find new challenges to conquer.

Ryan Costic

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1.0 MOTIVATION

The shoulder is a complex union of four joints that function together to allow the shoulder to have large and complex range of motion. Individually, each joint is unique in not only structure but function. The acromioclavicular (AC) joint is composed of several sets of ligaments which provide suspension of the upper extremity. Damage to the soft tissues of the AC joint frequently occurs and can disrupt the overall function of the shoulder.

Injuries to the AC joint can be both atraumatic and traumatic and usually result from repetitive loading or a direct blow to the shoulder, respectively. Atraumatic injuries are thought to be a complex repetitive loading of the joint usually resulting in degeneration of disc in men in their third to fourth decade[1]; however, treatment of atraumatic injuries usually results in resection of the degenerative tissue which can compromise stability [2]. Dislocations of AC joint can result in both degenerative changes and most of all functional changes. Minor dislocations are usually treated conservatively; but the treatment for more severe AC joint dislocations has led to a great controversy.

More severe AC joint dislocations occur during athletic participation with an incidence of 3-4 per 100,000 [3, 4]. In men, AC dislocation usually occurs in their 3rd or 4th decade and affects the dominant side in 60 to 75% of cases. Clinical follow-up studies with both conservative and surgical treatment have both shown good to excellent results; however, residual problems still remain [5-11]. With surgical treatment, over sixty new techniques or adaptations of existing techniques have been reported in the literature with no well defined "gold standard" for treatment [2, 5, 7-10, 12-28].

Although both atraumatic and traumatic injuries have thoroughly been reported in the literature; current biomechanical studies have looked at the structure and function of the AC joint during simple loading conditions[29-35]. Due the complexity of the anatomic features, their complex interactions during simple loading conditions and various mechanisms of injury, the effect of combined loading protocols on the structure and function of the AC joint should be evaluated. The determination of the response of the intact and injured joint to combined loading can provide several pieces of feedback to clinicians in prescribing treatments for AC joint injuries. For atraumatic, the complex interaction between the unique structures of the AC joint may help to explain why degeneration of joint occurs so early in life. For minor dislocations and after surgical repairs, rehabilitation protocols can be structured to improve healing of the soft tissue structures. And for surgical repairs and reconstructions, biomechanical information can lay the groundwork to provide insight into the selection of materials, construct design and surgical techniques.

2.0   BACKGROUND

This section is an overview of the relevant past research on the AC joint and its soft tissue structures. The first step in understanding the AC joint is to examine its anatomy. The function of the AC joint, along with how it is injured and repaired/reconstructed, will then be described. Finally, a review of the various biomechanical studies on the tensile properties, viscoelastic properties, and force measurements of the AC joint and its soft tissue structures is given.

2.1 Anatomy of the AC Joint

Examining AC joint anatomy is necessary when attempting to study AC joint biomechanics. The AC joint is a diarthrodial joint and consists of the clavicle and the scapula. The scapula has two bony processes, the coracoid and the acromion (**Figure 1**).   There are three main soft tissue structures in the AC joint which all help to suspend the upper extremity.   The coracoacromial (CA) ligament originates on the coracoid process and inserts on to the acromion process. The AC capsule (ligament) supports a meniscus-like disc that provides articulation of the acromion process and distal end of the clavicle [36]. The CC ligaments originate on the coracoid process and insert on the distal two-third portion of the clavicle. The CC ligaments consist of the trapezoid and conoid both named for the relative shape of each ligament. Each ligament's morphology, including dimensions and orientation, have previously been determined and resulted in anatomic variance between the two ligaments [29, 37, 38]. AC joints have two opposing functions to allow desired motion and restrict undesirable motion. The stability of the

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AC joint consists of bony congruity and stability, stability of the ligaments, and dynamic stability obtained from adjacent muscles.
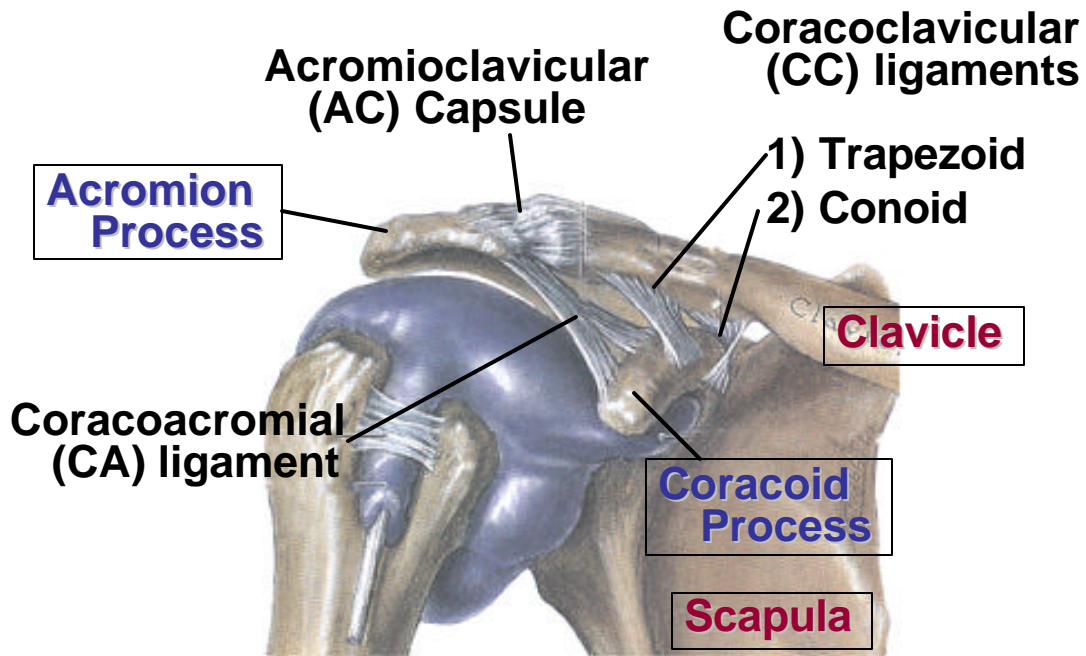
Figure 1. Soft tissue structures of the AC joint.

2.2 Function of the Intact AC Joint

The soft tissues structures of the AC joint have each been found to have different roles in proving stability and motion to the joint. The function of the CA ligament is the thought to provide structural stability to the scapula during loading and provide a guide for the humeral head during elevation[39].

Early studies of the AC joint found the AC capsule to be responsible for controlling posterior translation of the clavicle on the acromion[40]. Later, the AC capsule was found to be responsible for 90% of A-P stability while distraction of the AC joint was limited by the AC capsule (91%)[33]. These studies also found 77% of stability for superior translation of the

clavicle was attributed to the conoid and trapezoid with compression of the joint being limited by the trapezoid (75%). However, these studies restricted motion only in the direction of loading, thus not allowing for the true kinematic response of the joint.

Therefore, studies allowed for a full three degree-of-freedom motion and found that both the AC capsule and CC ligaments act synergistically to guide motion and provide stability to the joint. A materials testing machine applied an anterior and superior force of 70N and record the primary displacement and the *in situ* forces in the various soft tissue structures [38]. During loading, the *in situ* forces the AC capsule, trapezoid and conoid were evenly distributed; however, during posterior loading the trapezoid was responsible for 55.8% the applied load.

Although these studies did not restrict the motion of the AC joint, they were not a able to quantify the motion in the orthogonal axis of the loading applied. New technologic advances have allowed researchers to quantify the *in situ* forces and primary translations along with the coupled translations and provide clearer picture of the three degree-of-freedom motion of the AC joint using a robotic manipulator [30-32]. They confirmed the complex interaction of the soft tissue structures along with quantifying the coupled motion of the joint during external loading. They also determined the magnitude and direction of the in situ force in the trapezoid and conoid were found to be in opposing quadrants of the posterior axis of the scapula. To date, all biomechanical studies of the AC joint have accrued data after applying single external loads to the joint; however, combined loading is thought to contribute to various injuries to the joint.

2.3 Injuries to the AC Joint

Injuries to the AC joint are among the most commonly occurring problems in the athletic population [3, 4] and may be atraumatic or traumatic. Atraumatic injuries result from repetitive micro-trauma to the AC joint over time and lead to early degeneration of the intra-articular disc of the AC joint which could result in the development of arthritis. Such early degenerative changes suggest repetitive activities such as weightlifting, swimming or chronic overhead activity causes high compressive loads to be transmitted across the joint [41, 42].

Most traumatic injuries result from an acute event or as a late sequalae of a prior traumatic event [4]. Various studies have estimated that 25 to 52% of AC joint injuries occur during sports activities and over 75% of these injuries are caused by a contact [1, 43, 44]. The mechanism of injury usually involves a direct blow to the lateral aspect of the shoulder with the arm in an adducted position leading to downward displacement of the scapula opposed by impaction of the clavicle onto the first rib [1, 44, 45] (**Figure 2**). The force can cause three grades of injuries: a strain of the AC capsule (Type I), complete disruption of the AC capsule and strained CC ligaments (Type II), and complete disruption of the AC capsule and CC ligaments (Type III) [1, 44, 45] (**Figure 3**). With soft tissue injury, the mechanism for transmission of compressive loads across the AC joint is altered, possibly resulting in long term clinical sequalae and a number of residual symptoms including chronic pain, joint stiffness and a significantly decreased range and strength of horizontal abduction [42, 45].
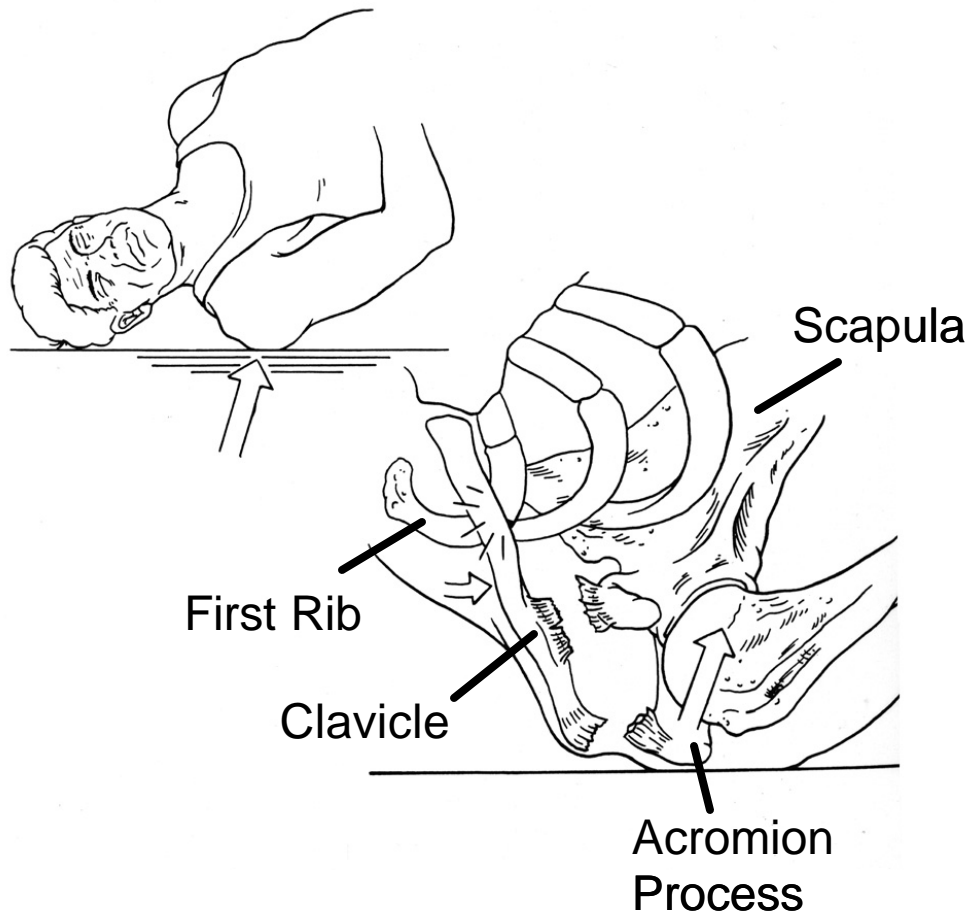
Figure 2. Mechanism of injury for AC joint dislocation
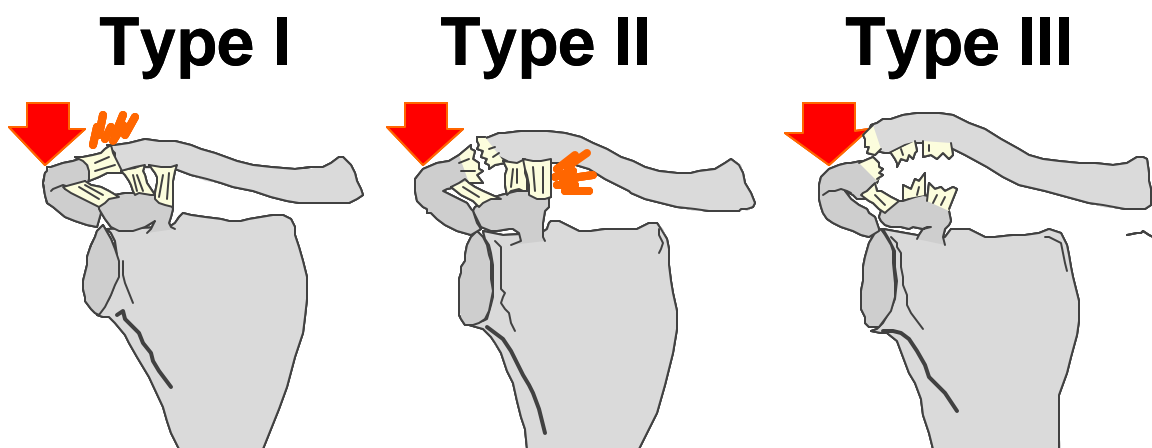
Figure 3. Injury classification for AC joint injuries.

Patients with degenerative changes or a Type I, II or III injury often present with symptoms of pain and discomfort while lying on the affected shoulder. 23 to 35% of patients have nuisance symptoms and 35 to 42% of patients reported symptoms are caused by arthritis or residual pain from six months to five years after injury [41, 42, 45]. Additionally, individuals who are involved in frequent overhead activity are prone to an increased risk of sequalae. This suggests that high compressive forces are transmitted across the AC joint which could lead to early arthritis, stiffness and pain [4, 11, 24]. After diagnosis of the type of injury, the next step is the treatment of the injured joint.

2.4 Function of the Injured AC Joint

Recent studies utilizing a robotic\universal force-moment testing system have evaluated the kinematics and forces of the injured joint. They have shown that after injury to the AC capsule (Type II Injury) there is an increase anterior and posterior loading with during their respective loading direction and these kinematic changes increase the forces in the CC ligaments [31]. Abnormal joint kinematics and load transmission could predispose individuals to post injury pain, instability and early degenerative joint disease [46].

2.5 Treatment of AC Joint Injuries

As early as 1917, treatment of AC injuries depended on whether a complete or incomplete dislocation occurred [47]. Type I and II injuries are treated conservatively, by limiting motion to allow scarring over of the AC capsule and providing subsequent stability to joint. The treatment of complete dislocations or Type III injuries revolves around the rupture of the CC ligaments which are thought to be the main suspensory ligaments of the shoulder [33].

Treatment of complete dislocation consists of both conservative management and surgical repair/reconstruction of the CC ligaments [5-10]. Initially, both conservative and surgical approaches attempt to reduce the CC space with an external sling or a surgical replacement to provide temporary fixation and allow joint scarring, with both having good to excellent initial outcomes [11]. However, these temporary solutions are associated with long term problems such as osteoarthritis, subluxation, loosening of surgical constructs and bone breakage [8, 10, 42, 48-50]. Although over 60 surgical techniques have been reported, there is no "gold standard" for treatment of AC joint dislocation [1]. Recent reports document the use of tendon grafts for surgical repair of the CC ligaments, not only providing a temporary fixation but a possible permanent biologic replacement [51]. However, all of these techniques replace or reconstruct the CC ligaments with one unidirectional structure and do not account for the anatomic variance of each ligament in the design.

Biomechanical studies have utilized tensile testing and found that current surgical repairs/reconstructions of the CC ligaments have structural properties that are significantly different than the properties of the intact ligament [34, 35]. These studies performed repairs/reconstructions on uninjured joints and did not account for damage to the clavicle and

coracoid that may accompany injury. Therefore, these studies may over-estimate the structural properties of the repairs/reconstructions and may report results that are not clinically achievable. Additional studies utilizing a robotic/UFS testing system have shown that current temporary fixation techniques fail to restore the initial stability of the AC joint to a level considered to be clinically stable [10, 52]. Both experimental testing systems, tensile and robotic/UFS, have found these differences which may explain clinical complications associated with surgical treatments of AC joint dislocation.

2.6 Robotic/UFS Testing – Functional Evaluation of Soft Tissues at AC Joint

In order to better understand AC joint function, it is necessary to know the *in situ* forces in the AC capsule and the CC ligaments, joint contact forces along with the kinematics of the joint. The ability to elucidate as much information about the intact AC joint allows not only for better diagnosis of injury, but also improved surgical techniques and rehabilitation protocols.

The robotic/UFS testing system can directly determine the *in situ* force in soft tissue structures without contacting the tissue or dissection of joint [53-55] (**Figure 4**). Any diarthrodial cadaveric be rigidly mounted with one bone fixed the robotic manipulator through a UFS and the other bone fixed the testing base. A reference position is found for the specified joint and every loading sequence is started from this position. The robotic manipulator moves the joint to reach specified force targets in a repeatable fashion. The motion of the joint is then recorded by the robot controller. Using the principle of superposition, a structure can be dissected out of the joint, the recorded kinematics can be repeated and new forces can be recorded by the UFS. The change in force after the soft tissue structure is removed is determined to be the *in situ* force in

the structure. Additionally, the robotic/UFS testing system allows researchers to apply multiple and combined loading conditions to the same specimen, and thus eliminate or reduce inter-specimen variability.

Figure 4. Robotic/UFS Testing System

For functional testing of the AC joint, each shoulder was disarticulated at the glenohumeral joint, and the clavicle and scapula were dissected free of all soft tissue except for the AC joint capsule, CC ligaments and the CA ligament. After fixing the scapula and clavicle in epoxy putty, custom-built clamps were used to mount the scapula to the end effector of a

robotic manipulator through a universal force-moment sensor (UFS, JR-Woodland, CA Model 4015) while the clavicle was rigidly fixed to the base of the robotic/UFS testing system (Unimate-Dunbar, Connecticut, Puma Model 762) (**Figure 5**). The clavicle and scapula were each potted in the maximum amount of epoxy putty possible to prevent deformation of these bodies during joint motion.
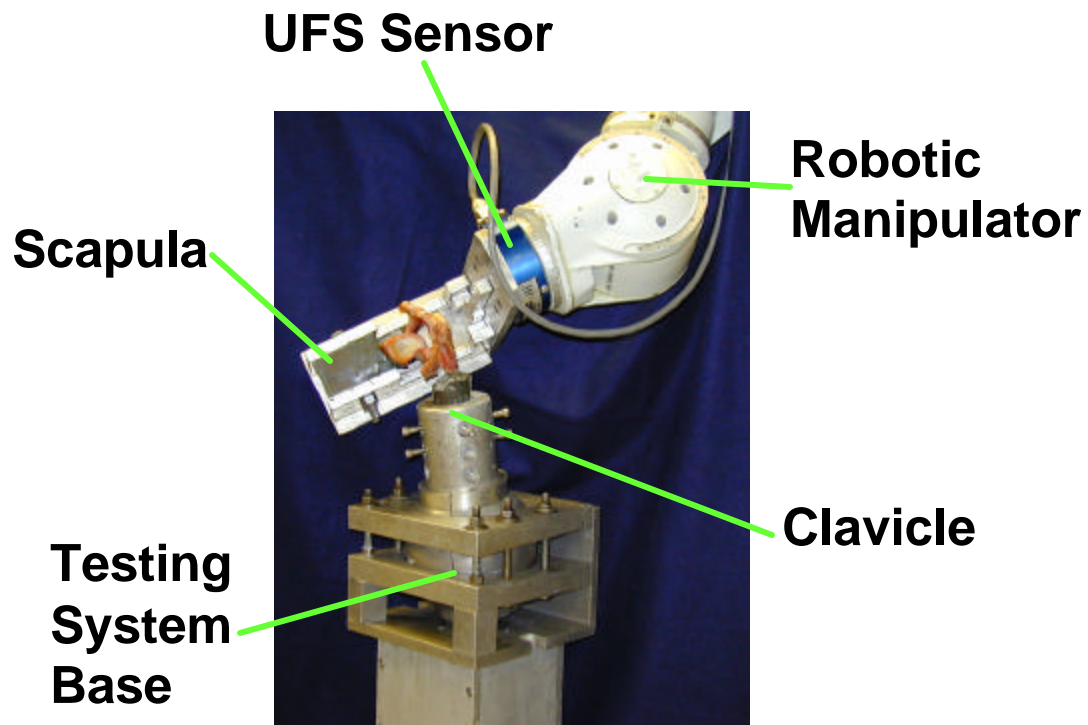
Figure 5. AC joint mounted on the Robotic/UFS Testing System.

The robotic/UFS testing system was utilized to determine the motion of the joint in response to externally applied loads [55]. The robot is a six axis serial-articulated manipulator with a repeatability of 0.2 millimeters and 0.2 degrees for position and orientation, respectively. Force-moment data collection was achieved using a UFS with repeatability better than 0.2 N and 0.1 N-m for forces and moments, respectively.

This testing system was operated in two modes to determine the resulting joint kinematics and *in situ* forces in ligaments. In force control mode, the testing system determined joint kinematics in response to a combination of loading conditions that included joint compression, while individual degrees of freedom were restricted to allow joint motion only in specified planes. Using the same loading conditions, the kinematic changes resulting from transection of the AC joint capsule were studied. The paths of motion determined for both the intact and AC capsule-transected conditions were saved and reproduced using the testing system in position control. The position control mode allowed application of the principle of superposition to determine the magnitude and the direction of the *in situ* force for portions of the AC capsule and the CC ligaments. Using this principle, the difference in force measured by the UFS before and after transection represented the force in that soft tissue structure. This methodology also required the clavicle and scapula to be effectively rigid compared to the soft tissue around the AC joint. This assumption was found to be reasonable for loads of up to 70 N during preliminary experiments using specimens that possessed good cortical bone and were free from any observable disease [38].

A coordinate system associated with the scapula was used to describe motion of the clavicle with respect to the scapula [4, 31] (**Figure 6**). The x-axis was perpendicular to the scapular plane and directed anteriorly. The y-axis was parallel the scapular plane and directed superiorly. The z-axis was directed laterally and obtained from the cross product of the x- and y-axes. The origin of the coordinate system was located at the center of the articular surface on the medial aspect of the acromion. An Euler angle system was used to describe the motion of the clavicle with respect to the scapula. The first rotation was about the z-axis while the second

rotation, about the y-axis, corresponded to protraction-retraction, and the final rotation, about the x-axis, corresponded to elevation.
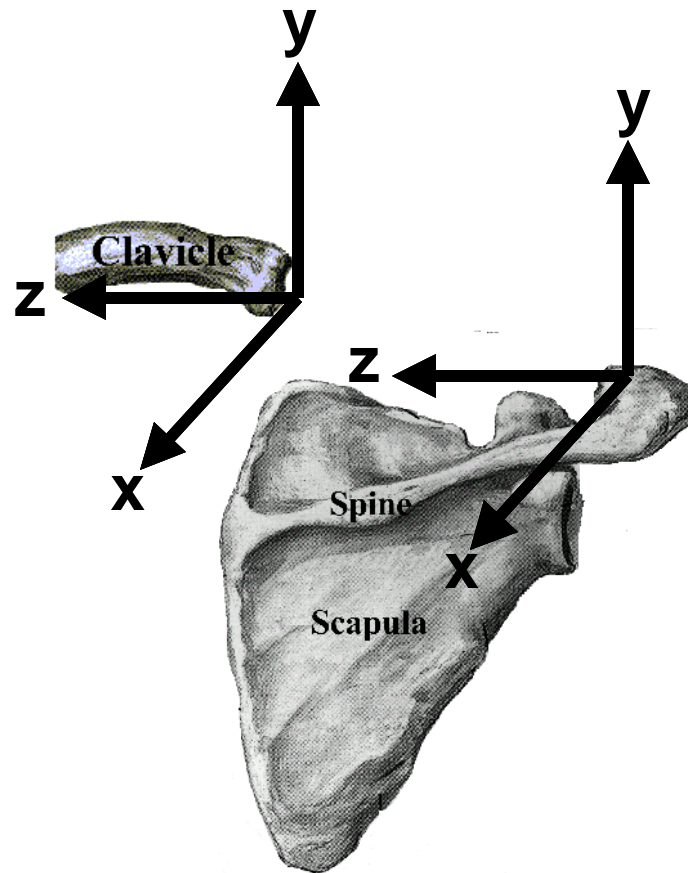
Figure 6. Coordinate system associated with the scapula.

A standard protocol, which has been reported in previous publications, was used to achieve a standard reference position for the application of each loading condition [30-32, 56]. This experimental protocol was developed to obtain an axial rotation position of the clavicle that served as a standard reference position for all loading tests. The joint was initially positioned in the testing system at 0° of elevation and 0° protraction-retraction. The scapula was free to translate along all three axes in order to maintain contact between the distal end of the clavicle

and the acromion. Force control was then used to apply a 10 N compressive load (proximally directed) to the clavicle while the forces in the two orthogonal directions were minimized. While the previously described force conditions were maintained, the clavicle was axially rotated in the positive and negative directions (in 1° increments) until the angle of rotation that minimized the moment about the longitudinal axis of the clavicle was achieved. The testing system determined and then recorded the position of the joint at this rotational angle. This reference position is used as the starting point for each loading condition that is prescribed in the loading protocol.

2.7 Tensile Testing – Properties & Behavior of Soft Tissues at AC Joint

The tensile testing of soft tissue structures is one of the most elementary biomechanical test performed, but it provides some of the most important information about the soft tissue structure. Because of the structure and complex orientation of soft tissues, the tissue usually only takes up load in tension. Therefore, it is important to see the response of the soft tissue structure during cyclic loading as well loading to failure.

Past studies have examined the structural and viscoelastic properties of the CC ligaments and the individual conoid and trapezoid in human cadavers during a uni-axial tensile test. The relationship between the load and elongation of the bone-ligament-bone complex are called the structural properties and represented by a load-elongation curve (**Figure 7**). The initial non-linear region is referred to as the "toe" region and possesses a low stiffness due to the collagen fibers aligning to take up the load applied. As larger loads are applied, the stiffness increases and the slope of the load-elongation curves becomes linear. Several parameters such as stiffness

(linear slope), ultimate load, elongation and energy absorbed to failure represent the structural properties of the bone-ligament-bone complex.
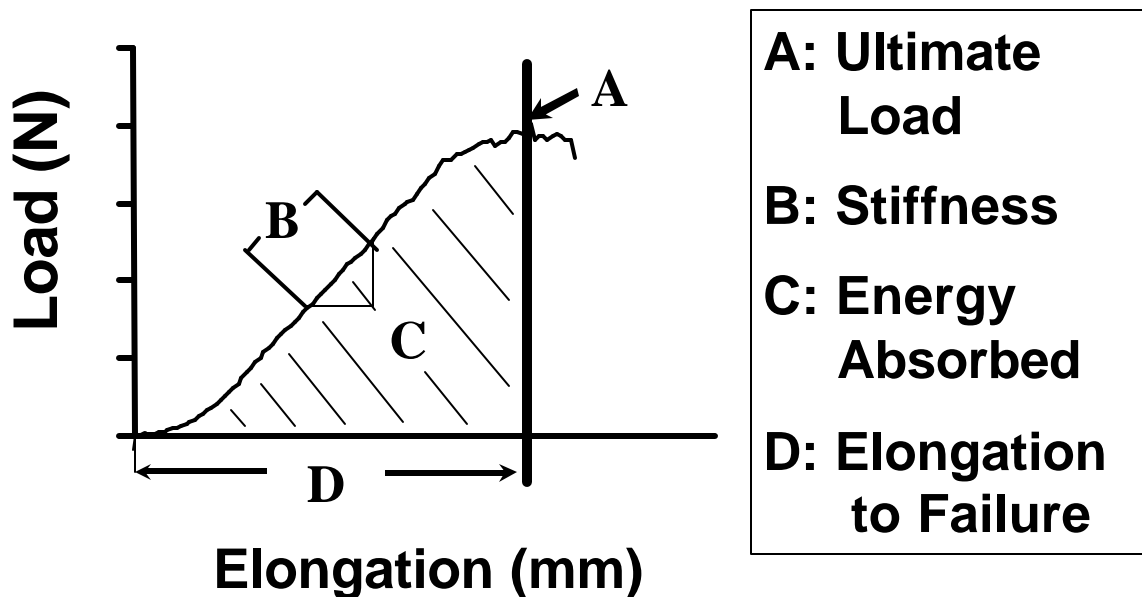
Figure 7. Schematic drawing of a load-elongation curve.

A few studies have examined the structural properties of the CC ligament complex by performing uni-axial tensile testing tests. Preliminary studies rigidly held the bone complexes and failed the intact CC ligaments, and the individual trapezoid and conoid, all in their natural configuration [34, 35]. These studies found that each ligament had similar properties to failure and reconfirmed the CC ligaments as the main suspensory ligaments of the shoulder. However, due the anatomic variance of the two ligaments, other researchers reorientated the individual ligaments to allow for uniform loading of the ligament fibers [29]. This study confirmed the results of other studies, but also examined the viscoelastic properties of the CC ligaments.

Biological soft tissues, such ligaments and tendons, possess time- and history-dependent viscoelastic behavior. During a cycle of loading and unloading between the limits of elongation, a different path for each testing cycle is followed, forming a hysteresis loop representing energy

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lost. Both ligaments and tendons display this viscoelastic behavior which is assumed to be a complex interaction. Two other important viscoelastic behaviors of ligaments are the stress-relaxation and creep behavior. Stress-relaxation is the decrease in load when a ligament is subjected to constant elongation and creep is the increase in elongation when a ligament is subjected to a constant load. These behaviors are not only important in the intact ligaments, but must also be taken into account when a replacement graft is used for reconstruction. During rehabilitation protocols, the time, amount of movement or load applied to both the injured or repaired/reconstructed ligaments are crucial pieces in maintaining stability. These behaviors provide a similar response of the ligaments or reconstruction to such movements or loads exhibited during rehabilitation.

Several repair/reconstruction complexes have been tested to compare their structural properties to the intact CC ligaments [34, 35]. They found great differences in properties compared to the intact CC ligaments which could account for clinical complications such as loosening, bone failure and loss of operative reduction. Although these studies provide vital information about current surgical repairs, the testing setup used in all previous studies have not allowed for changes in the surrounding structures during injury, mainly the clavicle and coracoid. The changes to the clavicle and coracoid after injury affect the environment which could lead to changes in the choice of materials and time of repair/reconstruction. In order to understand how current repairs/reconstructions compare to intact ligament, the environment of the replacement/reconstruction should mimic the clinical setting.

3.0   OBJECTIVES

3.1 Broad Goal

The broad goal of this research project was to better understand the biomechanical function of the soft tissues and their replacements around the AC joint in the intact, injured and repaired/reconstructed state. Specifically, an experimental methodology will be utilized to determine the kinematics and forces of the intact and injured AC joint. Knowledge of the forces and motion of the intact and injured joint is important for the understanding of treatment selection and rehabilitation after injury. The deviations in forces and motion that result from injury will provide guidelines for the design and testing of an anatomic reconstruction of the CC ligaments which may lead to an improved replacement for the injured ligaments.

3.2 Specific Aims and Hypothesis

SPECIFIC AIM #1: Evaluate the effects of combined loading (joint compression combined with an anterior, posterior or superior load) on the *in situ* forces in the AC capsule and CC ligaments as well as the joint kinematics in an intact and injured joint.

HYPOTHESIS #1: Joint compression would increase the force in the CC ligaments as well as increase the coupled joint motions.

SPECIFIC AIM #2: Evaluate an anatomic reconstruction for the CC ligaments by determining the cyclic behavior and structural properties of the intact CC ligament and anatomic reconstruction complexes.

To meet these aims:

1) A robotic universal force-moment sensor testing system (UFS, JR3, Woodland, CA, Model 4015; Unimate, Dunbar, Connecticut, Puma Model 762) was used to apply external loads with or without compression to an intact and injured joint. The resulting forces and kinematics of each joint state were then determined.

2) A materials testing machine (Instron, Model 4502, Canton, MA) was used to study the cyclic behavior and structural properties of the CC ligament and anatomic reconstruction complexes.

4.0 RESPONSE OF INTACT AND INJURED AC JOINT TO COMBINED LOADING CONDITIONS

4.1 Materials and Methods

Twelve fresh-frozen cadaveric shoulders were wrapped in saline soaked gauze and stored in plastic bags at –20 degrees Celsius. Specimens that showed any signs of degenerative joint disease or previous injury upon gross and radiographic examination were eliminated from the study. A standard protocol described in Section 2.6 was then used to dissect, mount the specimen and find a starting reference position from which to apply loads.

Each loading test then applied a constant joint compressive load of either 10 N or 70 N in conjunction with a maximum of 70 N in the anterior, posterior, or superior direction to the scapula with use of the previously obtained axial rotation position as the starting position for all tests. During the loading protocol, the testing system attempted to satisfy two force targets: 1) 10 N ("No Joint Compression", maintain contact between the distal end of the clavicle and the acromion) or 70 N ("Joint Compression", simulate transfer of load across the joint) of joint compression; and 2) 10% increments of the maximum load of 70 N in the anterior, posterior, or superior direction (**Figure 8**). The scapula was allowed to translate along each of the three axes to meet the required force targets while the rotational degrees of freedom were held constant. The kinematic constraints placed on joint motion might be similar to those found during injury and were used to obtain repeatable results (due the high laxity in two rotational degrees of freedom). The testing system recorded the anterior-posterior, superior-inferior, and distal-proximal translations of the intact shoulder resulting from the application of 10 N or 70 N of

joint compression, while the resultant forces and moments at each loading position were recorded by the UFS.
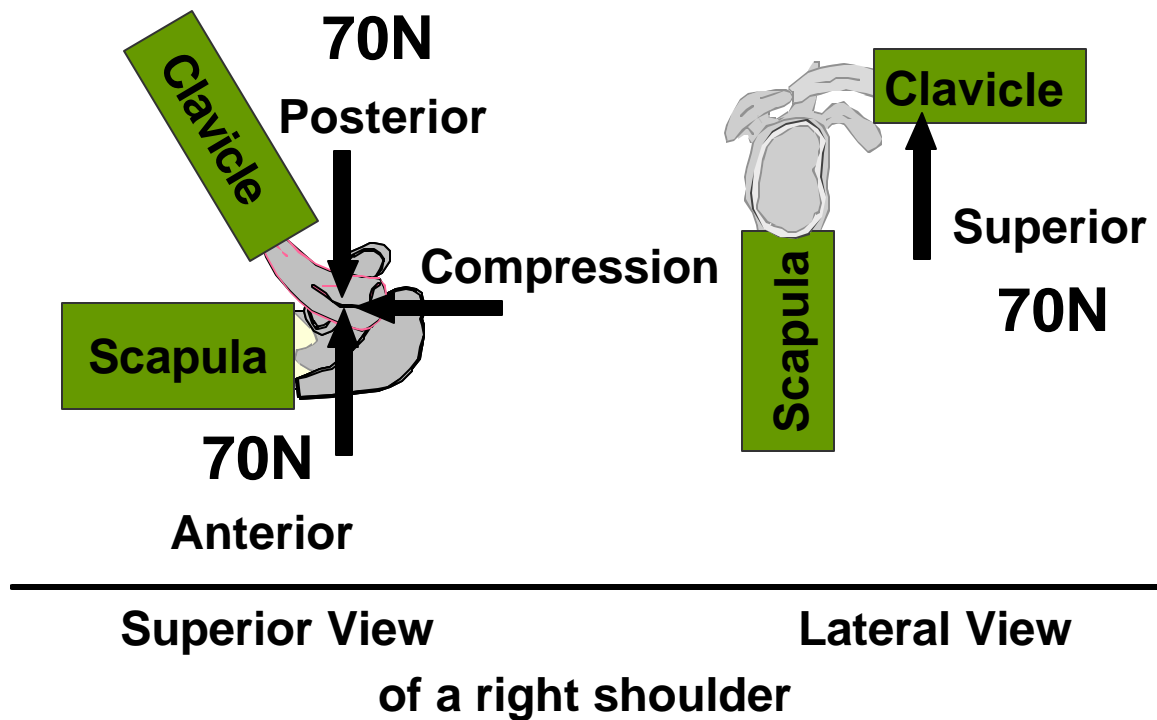
Figure 8. External loads applied to the AC joint.

To assess possible interaction between the superior and inferior portions of the AC capsule, the capsule was initially separated horizontally along the anterior and posterior aspects of the joint. "Separation" of the AC capsule included perforating it along the borders of the two regions (inferior and superior) but not removing any soft tissue. The previously determined paths of motion of the intact AC joint were repeated by the testing system while operating in position-control mode. A new set of forces and moments was measured by the universal force-moment sensor for each increment of loading in each of the three directions. The difference in forces before and after "separation" of the AC capsule quantified the amount of interaction

between the two portions of the capsule, corresponding to the load transmitted transversely throughout the capsule.

The superior and inferior portions of the AC capsule were then sequentially transected by a scalpel in random order. The previously determined paths of motion for the intact AC joint were repeated by the testing system and a new set of forces and moments was measured by the UFS for each loading condition. The difference in force between theses two tests represented the *in situ* forces in each portion of the AC capsule.

Externally applied loads of 70 N in the anterior, posterior, and superior directions were then applied with joint compressive loads of either 10 N or 70 N to each shoulder with the AC capsule-transected and the resulting kinematics were recorded for each loading condition. The conoid and trapezoid ligaments were sectioned in random order. After each structure was cut, the previously determined kinematics of both the intact and the AC capsule-transected condition were repeated by the robot for each loading condition with 10 N or 70 N of joint compression. For each increment of joint motion, the UFS measured a new set of force and moment data. Once again, the decrease in force observed by the UFS sensor between these two tests with identical shoulder positions represented the *in situ* force in each of the CC ligaments.

The data obtained from the entire protocol included the AC joint kinematics and the magnitude of the *in situ* force vector in the conoid and trapezoid for each loading condition with 10 N or 70 N of joint compression for each shoulder in the intact and AC capsule-transected states **(Table 1)**. The magnitude of the *in situ* force vector in the superior and inferior AC capsule were also determined during the three loading conditions with 10 N or 70 N of joint compression for the intact shoulder. Statistical analysis was performed with a two-factor repeated-measures analysis of variance to assess the effects of joint compression (10 N or 70 N),

loading condition (anterior, posterior or superior load of 70 N) and the joint condition (intact or AC capsule-transected) on the amount of translation in the direction of loading and coupled motion. A two-factor repeated-measures analysis of variance was also utilized to assess the effects of joint compression, joint condition and ligament on the magnitude of the *in situ* force vector in the AC capsule and CC ligaments. Both of these analyses were followed by multiple contrasts, and the significance was set at $p < 0.05$.

Table 1. Outline of experimental protocol and data acquired.

Protocol	Data Acquired
I. Intact Shoulder	
Path of Passive axial rotation of the clavicle	Kinematics of Intact Shoulder
A. 70 N anterior clavicular load with 10 N compression	
B. 70 N anterior clavicular load with 70 N compression	
C. 70 N posterior clavicular load with 10 N compression	
D. 70 N posterior clavicular load with 70 N compression	
E. 70 N superior clavicular load with 10 N compression	
F. 70 N superior clavicular load with 70 N compression	
Transect Inferior AC Capsule *Repeat Kinematics (I)*	*In Situ* Forces in the Inferior AC Capsule for Intact Shoulder
Transect Superior AC Capsule *Repeat Kinematics (I)*	*In Situ* Forces in the Superior AC Capsule for Intact Shoulder
II. AC Capsule-transected Shoulder Reapply **A, B, C, D, E & F**	Kinematics of AC Capsule-transected Shoulder
Transect Trapezoid *Repeat Kinematics (I) and (II)*	*In Situ* Forces in the Trapezoid Ligament for Intact and AC Capsule-transected Shoulder
Transect Conoid *Repeat Kinematics (I) and (II)*	*In Situ* Forces in the Conoid Ligament and Joint Contact Forces for Intact and AC Capsule-transected Shoulder

4.2 Results

AC joint testing resulted in two sets of translations of the clavicle with respect to the scapula; 1) primary (translations in the direction of the loading condition) and 2) coupled (translations in the orthogonal directions of the loading condition) translations; a posterior load results in posterior (primary) motion and superior-inferior and distal-proximal (coupled) motion. For the intact shoulder, application of joint compression decreased primary translation by 50% (-6.6±2.5 mm to -3.7±1.0 mm, $p<0.05$) during posterior loading, however, no significant change in primary translations resulted in response to an anterior or superior load ($p>0.05$) **(Figure 9)**. Significant changes in coupled translation also occurred in response to joint compression during posterior and superior loading **(Table 2)**. Joint compression decreased the coupled distal-proximal translation by 73% (-2.2±2.0 mm to -0.6±0.6 mm, $p<0.05$) during posterior loading while coupled distal-proximal translation during anterior and superior loading changed less than 0.5 mm ($p>0.05$). Similarly, the coupled anterior-posterior translation (-0.5±1.2 mm vs. 0.6±0.9 mm, $p<0.05$) shifted significantly (167%) during superior loading with joint compression. During anterior and posterior loading, minimal changes in coupled superior-inferior translations (less than 1.0 mm) were also found ($p>0.05$).
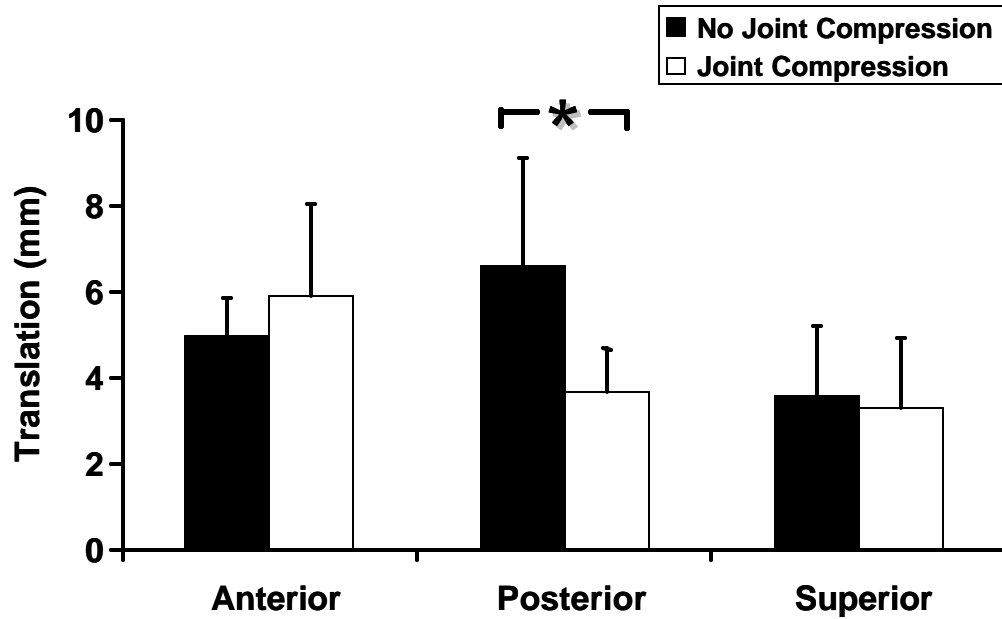
Figure 9. Primary translations in response to a 70N anterior, posterior or superior load combined with or without joint compression in an intact AC joint.

Table 2. Primary (Bold) and coupled (Italics) translations in response to a 70N anterior, posterior or superior load combined with or without joint compression in an intact AC joint.

	Loading Conditions		Translations		
	Direction	Compression	Ant-Post	Sup-Inf	Prox-Dist
Intact AC Joint	Anterior	10 N	**5.0 ± 0.9**	*-0.5 ± 1.2*	*2.1 ± 0.9*
		70 N	**5.9 ± 2.1**	*0.4 ± 0.9*	*2.2 ± 1.4*
	Posterior	10 N	**-6.6 ± 2.5** ⌐	*-0.6 ± 1.1*	*-2.2 ± 2.0* ⌐
			*		*
		70 N	**-3.7 ± 1.0** ⌐	*-0.5 ± 0.9*	*-0.6 ± 0.6* ⌐
	Superior	10 N	*-0.5 ± 1.2* ⌐	**3.6 ± 1.6**	*0.6 ± 0.8*
			*		
		70 N	*0.6 ± 0.9* ⌐	**3.3 ± 1.6**	*1.0 ± 0.8*

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The magnitude of the difference between force vectors measured before and after separation of the AC capsule into superior and inferior components was found to be negligible (<5 N) in response to all loading conditions with 10 N or 70 N of joint compression. However, joint compression significantly decreased the *in situ* force in the superior AC capsule by 10 N ($p<0.05$) during all loading conditions while the force in the inferior AC capsule remained constant ($p>0.05$) **(Figure 10)**. The force in the CC ligaments also did not change with joint compression ($p>0.05$) except in response to a posterior load of 70 N. During this loading condition, the *in situ* force in the conoid significantly increased from 16 ± 12 N to 27 ± 17 N ($p<0.05$). The conoid also had the highest *in situ* force during application of a posterior and superior load while the trapezoid had the highest *in situ* force during application of an anterior load. Joint compression also significantly increased the joint contact force by 20 N ($p<0.05$) in response to all loading conditions.
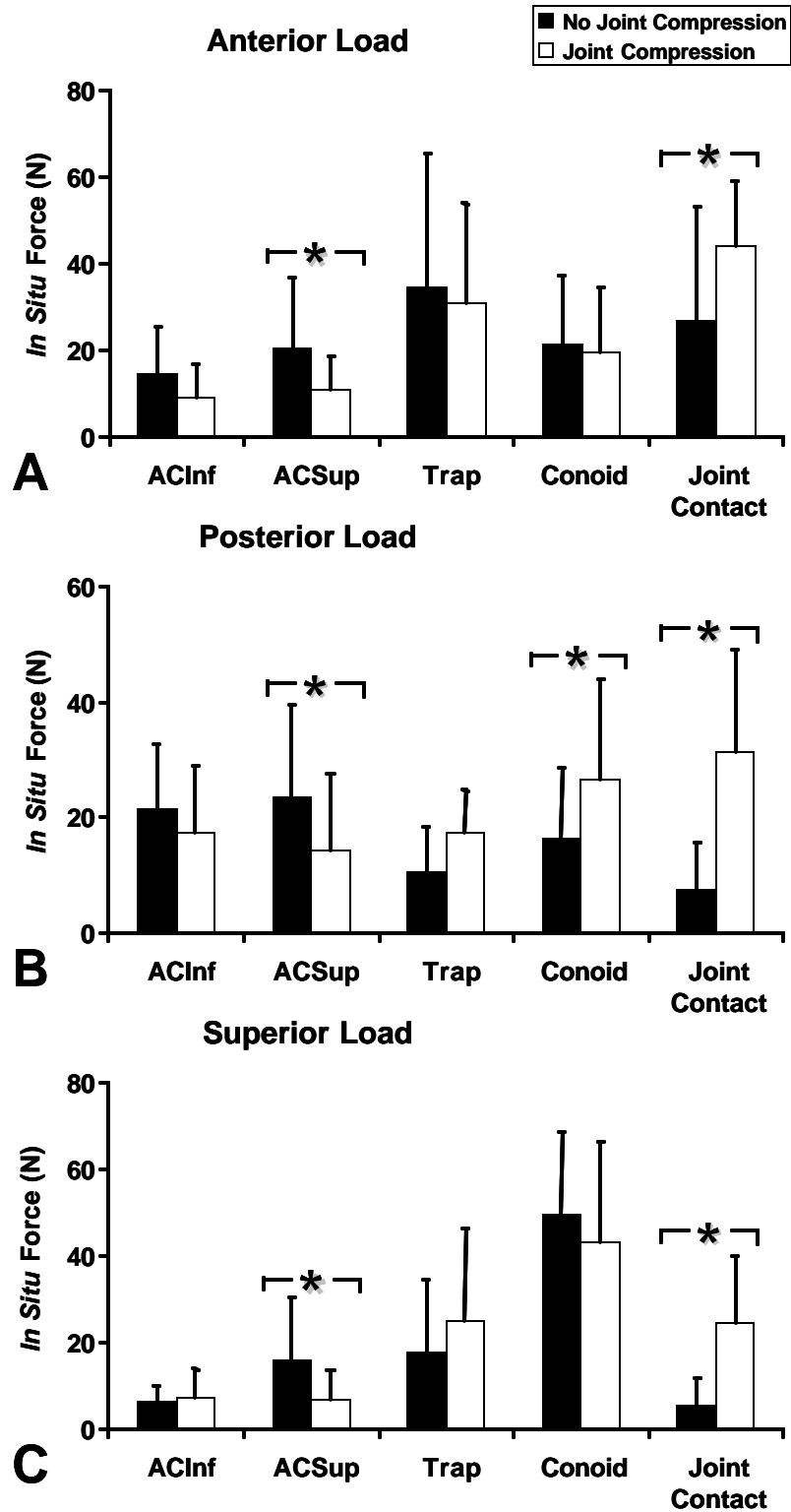
Figure 10. *In situ* forces during an applied 70N A) anterior, B) posterior or C) superior load in an intact AC joint.

Transection of the AC capsule resulted in similar kinematic changes compared to the intact shoulder for all primary motions. However, significant differences were found for the coupled motions during all loading conditions with joint compression. A posterior or superior load of 70 N significantly decreased primary translation from -12.7 ± 6.1 mm to -5.5 ± 3.2 mm and from 5.3 ± 2.9 mm to 4.2 ± 2.3 mm, respectively ($p<0.05$), while no differences could be found during anterior loading ($p>0.05$) **(Figure 11)**. Coupled motion during all loading conditions with joint compression significantly changed except for coupled distal-proximal translation during superior loading ($p>0.05$) **(Table 3)**. An anterior or posterior load of 70 N significantly decreased coupled distal-proximal translation from 6.1 ± 2.4 mm to 3.2 ± 2.0 mm and from -1.9 ± 2.8 mm to -0.1 ± 0.5 mm, respectively ($p<0.05$). Significant changes in coupled motion in the other orthogonal directions were also found during all loading conditions with joint compression. In response to an anterior load of 70 N, the coupled superior-inferior translation significantly shifted from -2.7 ± 3.0 mm to 0.6 ± 1.4 mm ($p<0.05$), while the coupled inferior translation significantly decreased from -2.4 ± 2.8 mm to -1.2 ± 1.0 mm ($p<0.05$) during application of a posterior load of 70 N. Similarly, during application of a superior load of 70 N, the coupled anterior-posterior translation significantly shifted from -1.5 ± 3.3 mm to 1.0 ± 1.2 mm with joint compression ($p<0.05$).
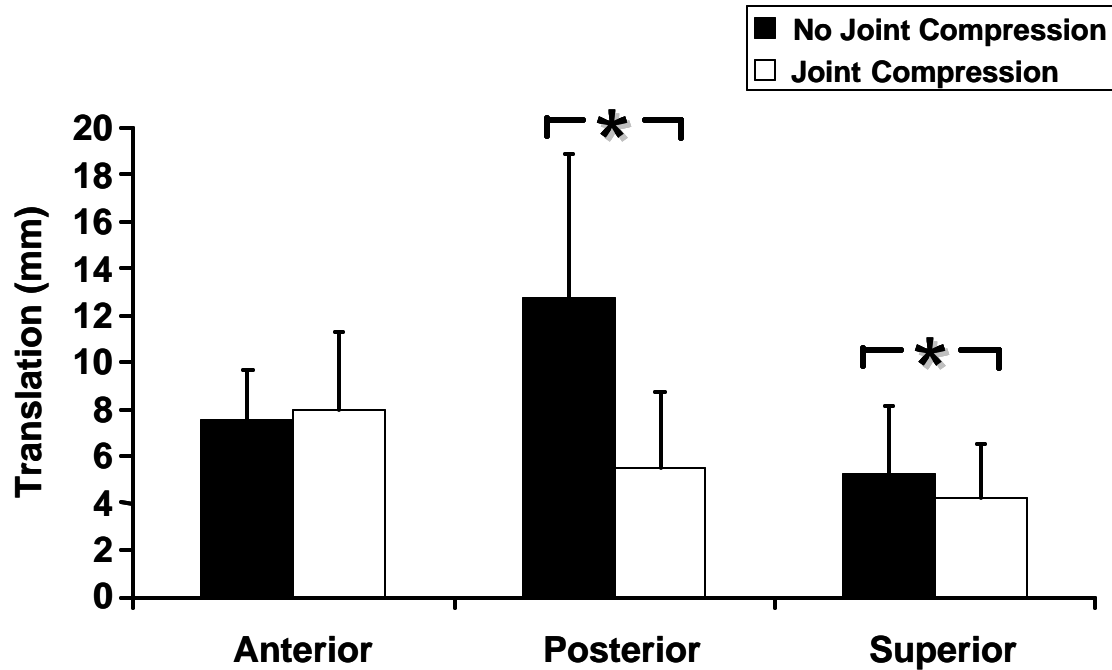
Figure 11. Primary translations in response to a 70N anterior, posterior or superior load combined with or without joint compression in an AC capsule-transected joint.

Table 3. Primary (Bold) and coupled (Italics) translations in response to a 70N anterior, posterior or superior load combined with or without joint compression in an AC capsule-transected AC joint.

Loading Conditions		Translations		
Direction	Compression	Ant-Post	Sup-Inf	Prox-Dist
Anterior	**10 N**	**7.5 ± 2.2**	*-2.7 ± 3.0* ⌉	*6.1 ± 2.4* ⌉
			*	*
	70 N	**7.9 ± 3.3**	*0.6 ± 1.4* ⌋	*3.2 ± 2.0* ⌋
Posterior	**10 N**	**-12.7 ± 6.1** ⌉	*-2.4 ± 2.8* ⌉	*-1.9 ± 2.8* ⌉
		*	*	*
	70 N	**-5.5 ± 3.2** ⌋	*-1.2 ± 1.0* ⌋	*-0.1 ± 0.5* ⌋
Superior	**10 N**	*-1.5 ± 3.3* ⌉	**5.3 ± 2.9** ⌉	*1.9 ± 1.8*
		*	*	
	70 N	*1.0 ± 1.2* ⌋	**4.2 ± 2.3** ⌋	*1.6 ± 1.2*

(Left header spanning all data rows: "Capsule-transected AC Joint")

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The magnitude of the *in situ* force vector in the CC ligaments did not significantly change during all loading conditions with joint compression ($p > 0.05$), except during application of a superior load of 70 N when the *in situ* force in the conoid ligament significantly decreased from 65±32 N to 42±27 N ($p<0.05$) **(Figure 12)**. Similar to the intact AC joint, the conoid had the highest *in situ* force during application of a posterior and superior load while the trapezoid had the highest *in situ* force during application of an anterior load. In response to an anterior, posterior or superior load of 70 N with joint compression the joint contact force significantly increased by 20 N ($p < 0.05$).
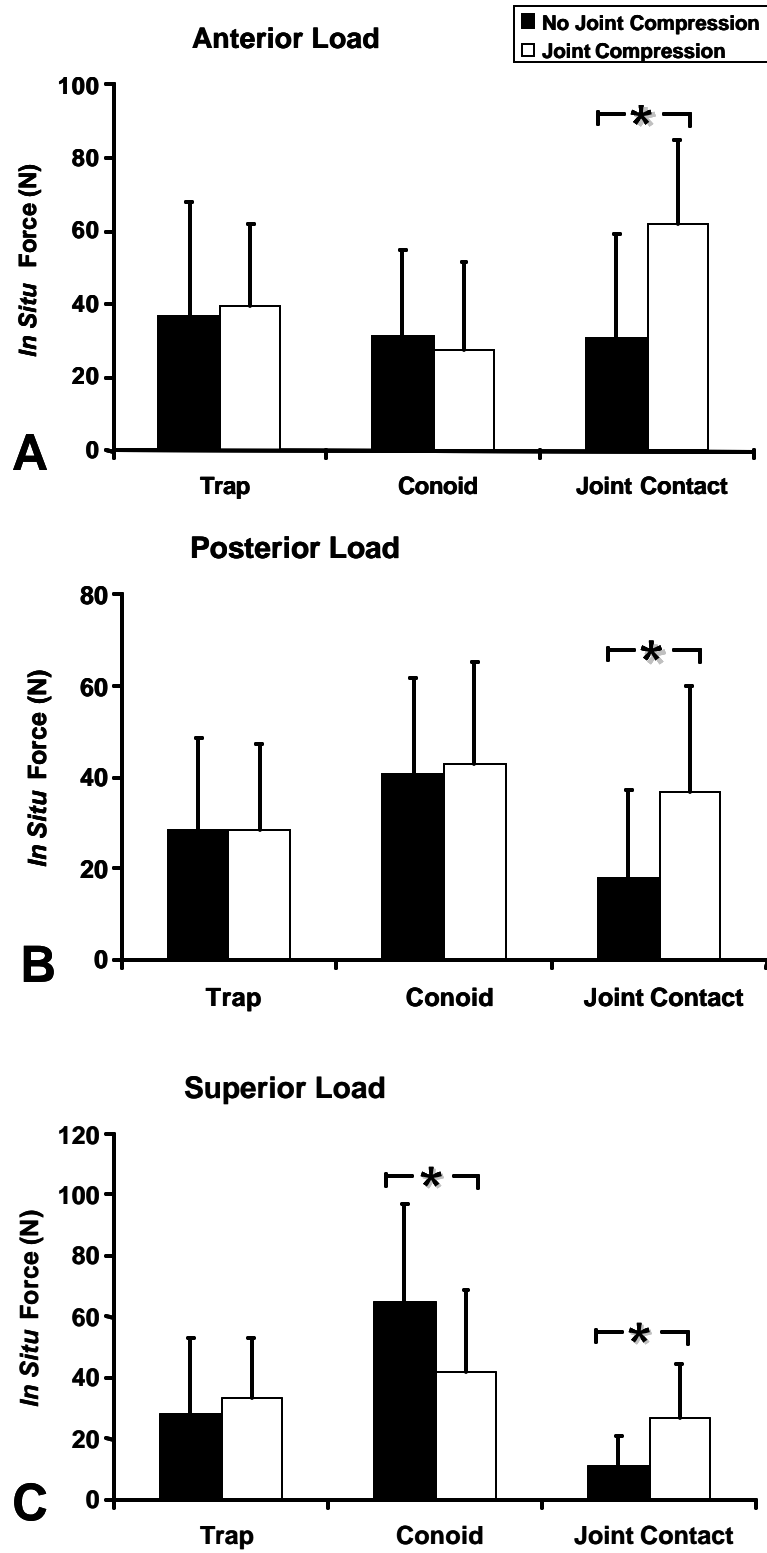
Figure 12. *In situ* forces during an applied 70N A) anterior, B) posterior or C) superior load in an AC capsule-transected joint.

4.3 Summary

The robotic/UFS testing system allowed simultaneous quantification of joint motion and *in situ* forces in the AC capsule and CC ligaments during three degree-of-freedom joint motion in response to anterior, posterior, and superior loading conditions in combination with joint compression. The results of this study do not support our hypothesis that the force in the CC ligaments would increase in response to joint compression. However, joint compression was found to significantly affect several other parameters in the intact and AC capsule-transected shoulder.

4.4 Conclusions

For the intact shoulder, joint compression during posterior loading significantly reduced posterior translation by 50% and also increased the *in situ* force in the conoid ligament. This increase of force represents the only finding that supports our hypothesis and reinforces the concept that the conoid ligament makes a significant contribution to stability during anterior-posterior translation [38]. This data also suggests that all soft tissue structures at the AC joint act synergistically to resist anterior and posterior loads [33].

Joint compression also caused a significant decrease in the *in situ* force of the superior AC capsule for the intact shoulder while dramatically increasing the force transmitted by joint contact during application of the three loading conditions examined in this study. This finding suggests that high compressive forces could be mainly transmitted through bony contact between the acromion process and the distal end of the clavicle and not by soft tissue structures of the joint. Thus, common surgical procedures such as distal clavicle resection while initially

reducing painful joint contact may resultantly cause unusually high loads to be transmitted by the soft tissues at the shoulder [32]. If transmitted to the CC ligaments, which already contribute significantly to resisting the applied loads, these forces could cause ligament injury during these loading conditions.

After the AC capsule was transected simulating a Type II injury, the effect of joint compression significantly reduced the primary translations in response to posterior and superior loading. However, the coupled translations dramatically increased in response to joint compression during anterior and posterior loading. The decrease in primary translations with the increase in coupled translations suggests that the AC capsule is responsible for maintaining normal joint contact between the acromion and the distal end of the clavicle. The application of joint compression to the AC capsule-transected shoulder also increased the joint contact force by 20 N, similar to the intact shoulder. The migration caused by the increased coupled motions and the increase in the joint contact forces suggests that the alignment between the articular surfaces of the distal clavicle and acromion are not normal and these higher forces might be transmitted over smaller areas. Therefore, high stress concentrations might develop at the AC joint and ultimately lead to degenerative changes. Since the AC joint's intra-articular disc usually starts deteriorating by the third decade, injuries to the AC capsule previously ignored during surgical procedures should be treated to prevent early degeneration of the disc and articular surfaces [57, 58].

Previous studies from our laboratory have examined the function of the intact and AC capsule-transected shoulder without joint compression in response to the same loading conditions [30-32]. Similar findings in all the studies validate our experimental methodology. Another investigation assessed the effects of axial compression on the mechanics of the AC joint [33]. The AC capsular ligaments were found to provide the greatest contribution at small

displacements while the trapezoid was the primary contributor during large displacements. Differences between the studies can be attributed to the choice of coordinate systems, axis for application of joint compression, magnitude of loading and number of degrees-of-freedom allowed during joint motion. In addition, the current study applied joint compression in combination with anterior, posterior or superior loads.

5.0   TENSILE PROPERTIES OF ANATOMIC RECONSTRUCTION

5.1 Materials and Methods

Nine fresh-frozen cadaveric shoulders (mean age 51±13, range 21-60) were stored at –20 degrees Celsius. Prior to the day of the test, each shoulder specimen was thawed overnight at room temperature. Each shoulder was disarticulated at the glenohumeral joint and the clavicle and scapula were dissected free of all soft tissue except for the AC joint capsule, CA ligament and the CC ligaments. Specimens that showed any signs of degenerative joint disease or previous injury upon gross and radiographic examination were eliminated from the study. After fixing the scapula and proximal two-thirds of the clavicle in epoxy putty, custom-built clamps were used to mount the clavicle to the crosshead of a materials testing machine (Instron, Model 4502, Canton, MA) **(Figure 13)** while the scapula was fixed to the base of the materials testing machine.
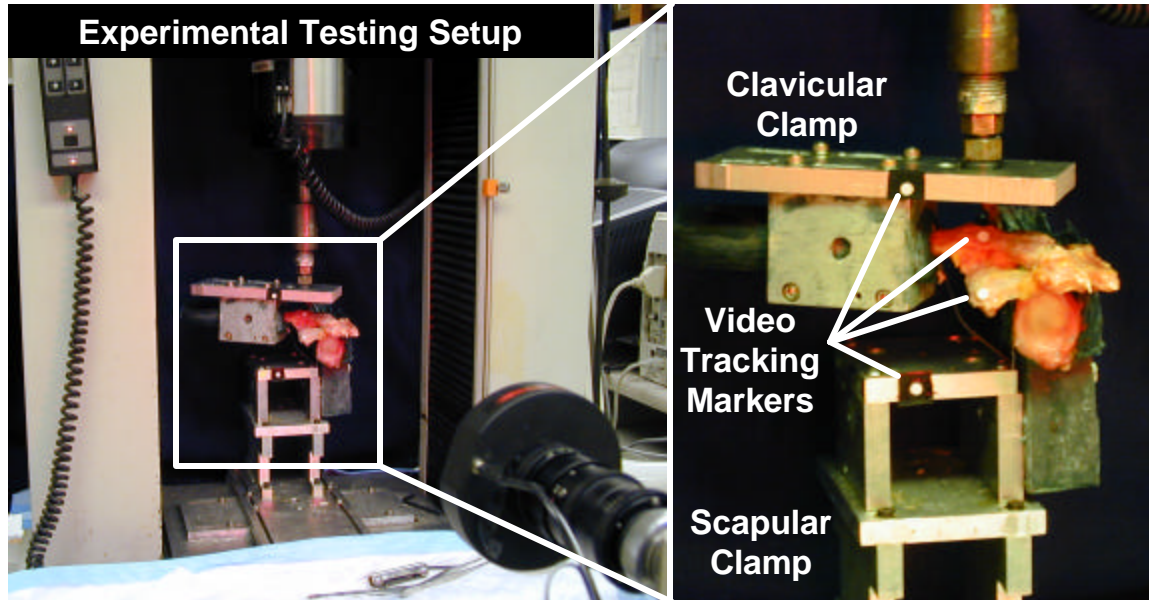
Figure 13. Tensile testing experimental setup including the video tracking markers, clavicular clamp and scapular clamp.

After mounting, each specimen was orientated in an anatomic position with the CC ligament complex centered under the crosshead of the materials testing machine to ensure proper loading of the CC ligaments. The anatomic position was defined by aligning the bony articulation of the distal end of the clavicle and the acromion process with equal tensioning throughout the soft tissue structures. The custom-built clamps were rigidly fixed and the AC capsule was transected to isolate the CC ligament complex. For video analysis, one retro-reflective marker was glued to both the coracoid process and clavicle while another two tape markers were fixed to the crosshead and the base of the testing machine **(Figure 13)**. Video analysis was utilized to determine the stiffness of the CC ligaments and semitendinosis tendon graft along with the bending stiffness of the coracoid and clavicle during complete AC joint dislocation (Motion Analysis, Santa Rosa, CA, U.S.A.) with a resolution of 0.1 mm. The three

different sections of the complex (coracoid, intact CC ligaments, and clavicle) were analyzed individually for bending stiffness or soft tissue stiffness.

The CC ligament complexes were kept moist with saline solution and tested at room temperature with a crosshead speed of 50 mm/min and an initial preload of 5N. Cyclic loading was utilized to simulate the initial loads of early rehabilitation protocols and provide information on the initial fixation of the graft during loading. Preliminary testing determined an appropriate range of loading (20N – 90N) that would allow the CC ligament complex to reach the initial linear range of load-elongation curve. Previous studies utilizing similar protocols were referenced to choose an appropriate setup configuration and speed of the crosshead [59]. The testing protocol included cyclically loading the complexes from 20N to 60N for 100 cycles followed by one hour of recovery in an unloaded state. Cyclic loading was then repeated with a maximum of 90N for 100 cycles. The cyclic behavior of the CC ligament complex was derived from the load-elongation curves. Creep was defined as the amount of elongation between the peaks of the first and last cycle of loading after preloading the complex. Permanent elongation was defined as the difference in elongation after recovery from a cyclic creep test compared to initial length of the complex. Preliminary tests included a third test of cyclic testing from 20N to 60N for 100 cycles to assess additional permanent damage to the CC ligament complex and the repeatability of the cyclic tests.

Following another one-hour recovery period, a load-to-failure protocol was executed. The load-elongation curves and failure modes of the complex were recorded. For each complex, the linear stiffness was calculated by determining the slope of a line fit to the linear portion of the load-elongation curve. All curve fits resulted in an R^2 (squared correlation coefficient) greater than 0.975. Ultimate load was defined as the maximum obtained load for each test. Energy

absorbed to failure was determined by calculating the area under the curve up to the ultimate load. After failure, the remaining CC ligament soft tissue was removed, the remaining bony components were returned to the original reference position and the anatomic reconstruction was performed.

A 7mm diameter hole was drilled through the base of the coracoid process, a 6mm diameter clavicular hole was placed directly superior to the base of the coracoid process and another 6mm diameter clavicular hole was placed 1 cm distally. Each graft consisted of a semitendinosis tendon prepared at each end with Arthrex 5-0 FiberWire using the Krachow, Thomas, Jones technique. Each graft was prepared with use of a tendon preparation board (Graftmaster, Smith and Nephew, Endoscopy, Andover, MA, U.S.A.) and graft length was individualized for each specimen to ensure each end of the tendon graft would have end-to-end contact after reconstruction.

Each end of the prepared semitendinosis graft was passed inferiorly through separate clavicular holes and then passed simultaneously through the base of the coracoid process. The passage of the tendon was chosen to simulate the native geometry of the CC ligaments [37, 38]. The two ends of the tendon were then fastened end-to-end on the superior aspect of the coracoid process with an added reinforcement stitch to ensure approximation of the tendon ends (Figure 14). The same cyclic creep testing and load-to-failure protocol (Figure 15) for the intact CC ligament complex was then repeated for the anatomic reconstruction, including the same calculations to quantify the creep, permanent elongation, stiffness, ultimate load and energy absorbed at failure. The displacements of reflective markers retrieved from video analysis were used to determine the stiffness of the three individual components of the anatomic reconstruction complex (coracoid, tendon graft, and clavicle). Failure modes were also recorded.
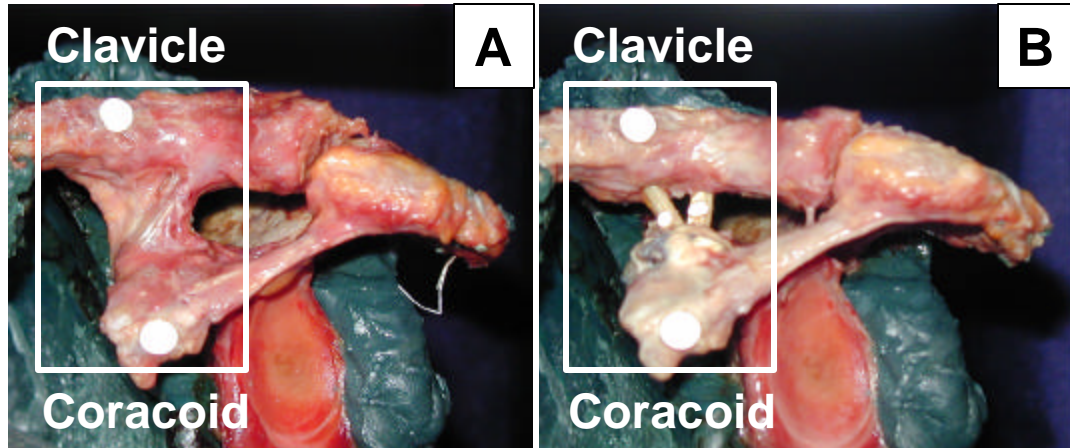
Figure 14. A) Intact AC joint including the CC ligament complex and B) after dislocation with anatomic reconstruction using a tendon graft.
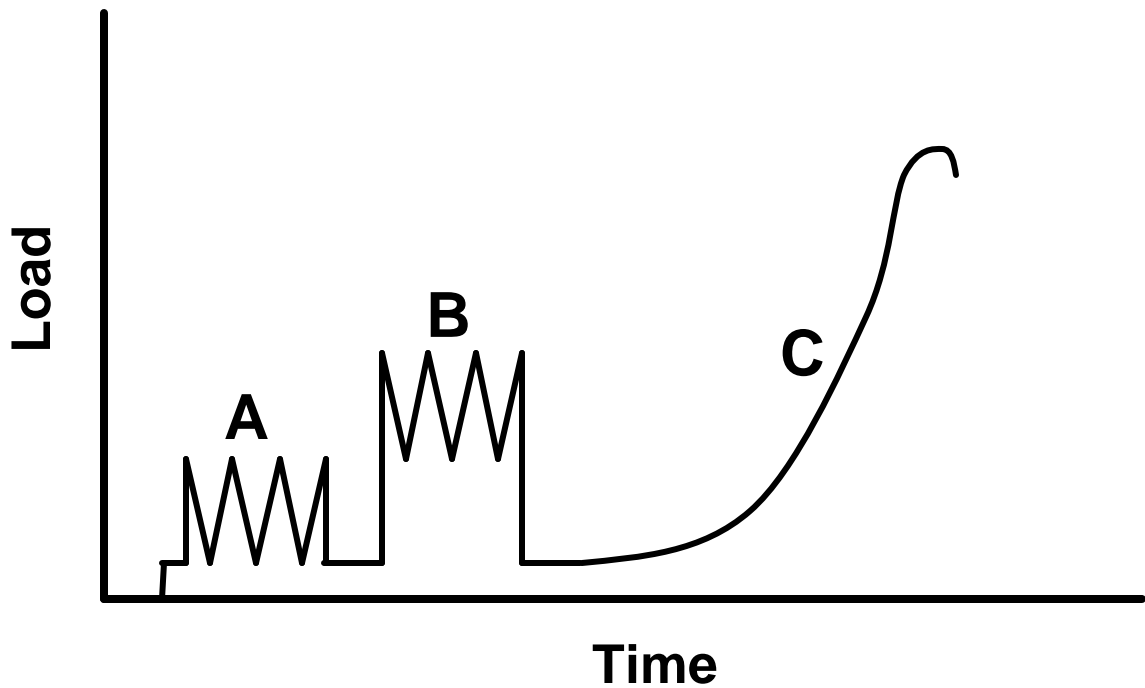

Figure 15. Load-time protocol for: A) cyclic creep test (20N-60N); B) cyclic creep test (20N-90N); C) load-to-failure.

The data obtained from the cyclic protocol for both the CC ligament and anatomic reconstruction complexes included the amount of creep and permanent elongation during cyclic loading. The structural properties including linear stiffness, ultimate load, energy absorbed to failure and percent elongation for both complexes were found following a load-to-failure test. The stiffness of the individual components of the complexes was also calculated and included the stiffness of the CC ligaments or tendon graft along with the bending stiffness of the clavicle and coracoid. Failure modes were determined by visual inspection and video analysis. Statistical analysis was performed with one-way repeated measures ANOVA to compare the CC ligament and anatomic reconstruction complexes, combined and individual components, for structural properties with significance set at $p < 0.05$.

5.2 Results

5.2.1 Cyclic Behavior

Typical elongation-time graphs for both the CC ligament and anatomic reconstruction complexes in response to cyclic loading are shown in **Figure 16**. The elongation in response to cyclic loading for the CC ligament complex increased from 0.1±0.2 mm to 0.3±0.2 mm after increasing the maximum load from 60N to 90N, respectively **(Table 4)**. After an initial elongation of 1.9±0.7 mm during cyclic loading with a maximum load of 60N, the creep of the novel anatomic reconstruction decreased to 1.5±0.4 mm with a maximum load of 90N. After recovering from cyclic creep tests with maximum loads of 60N and 90N, the permanent elongation of the CC ligament complex was 0.2±0.4 mm and 0.2±0.6 mm (Total: 0.4 mm), respectively. Similarly, the permanent elongation of the novel anatomic reconstruction complex

was 0.9±1.5 mm and 1.1±1.6 mm (Total: 2.0 mm) after recovering from cyclic creep tests with maximum loads of 60N and 90N, respectively. Preliminary tests including a third test of cyclic loading confirmed no more permanent damage to either complex and was subsequently discontinued in further testing assuming this trend to be consistent throughout all specimens.
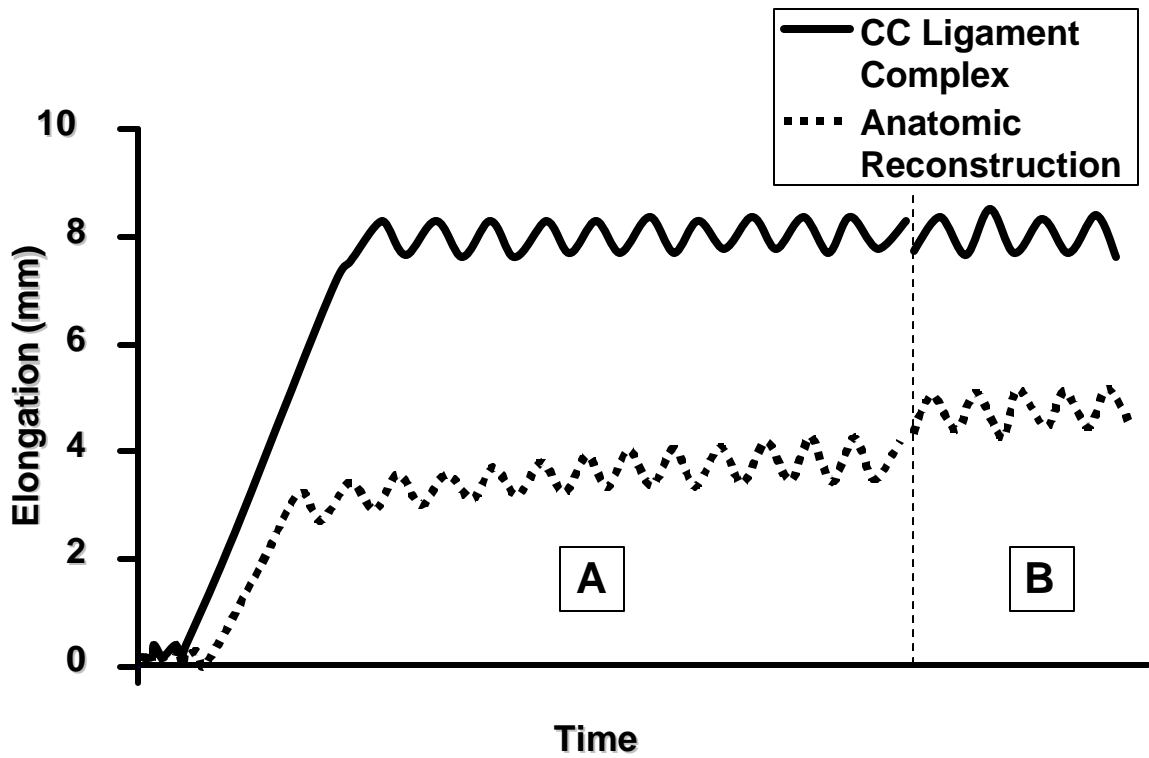
Figure 16. Typical elongation-time curve for the CC ligament and anatomic reconstruction complexes in response to cyclic loading; A) First ten cycles and B) Last five cycles of loading.

Table 4. Comparison of the cyclic behavior of CC ligament and anatomic reconstruction complexes. (*p<0.05)

			CC Ligament Complex	Anatomic Reconstruction
Cyclic Behavior	Creep (mm)	(20-60N)	0.1 ± 0.2	1.9 ± 0.7
		(20-90N)	0.3 ± 0.2	1.5 ± 0.4
	Permanent Elongation (mm)	(20-60N)	0.2 ± 0.4	0.9 ± 1.5
		(20-90N)	0.2 ± 0.6	1.1 ± 1.6

5.2.2 Structural Properties

The shape of typical load-elongation curves (**Figure 17**) for the CC ligament and anatomic reconstruction complexes are similar to those reported for other ligaments and tendons, with an initial nonlinear, low-stiffness toe region, followed by a linear region with much higher stiffness [9, 34, 35, 60-62]. A characteristic failure of the CC ligament complex was exhibited by eight out of nine specimens and consisted of failure of the mid-substance of the conoid followed by failure of the clavicular insertion of the trapezoid. Contrarily, the anatomic reconstruction complex failed in a variety of areas including two clavicular failures, four mid-substance failures, and three coracoid process failures. Clavicle and coracoid failures were noted in four out of five female specimens.
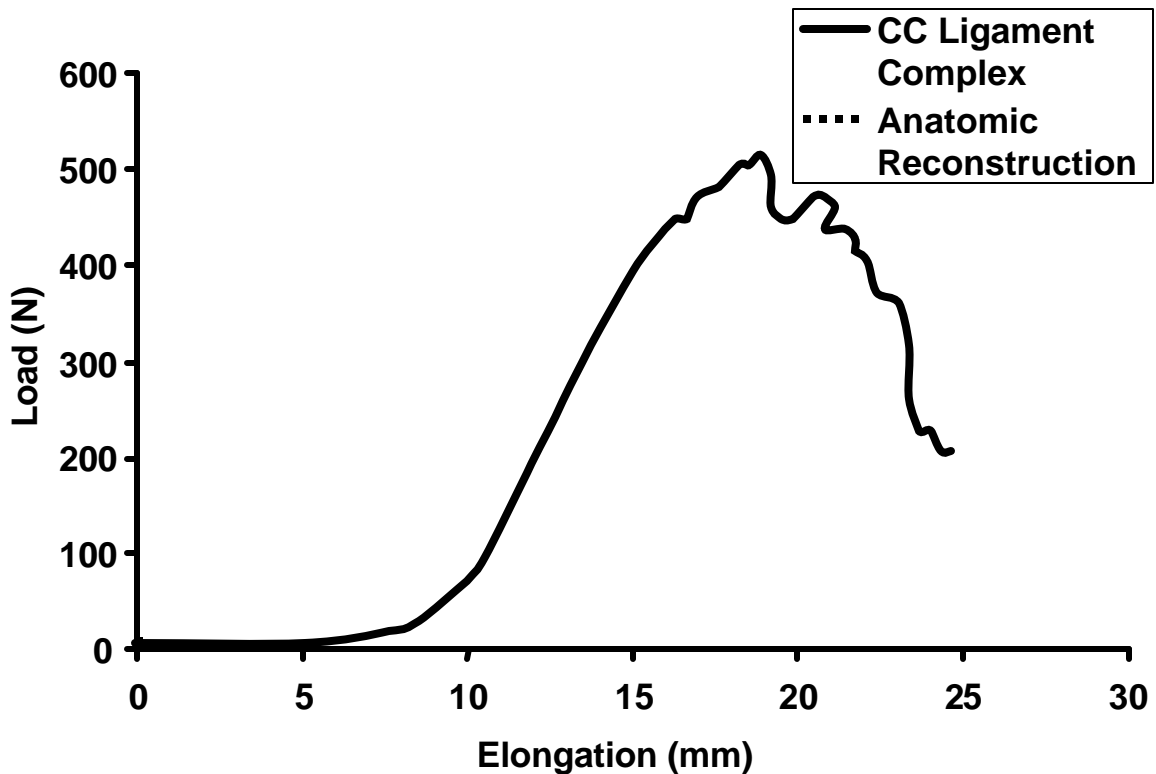
Figure 17. Typical load-elongation curve for the CC ligament and anatomic reconstruction complexes.

Statistically significant differences could be demonstrated for all structural properties **(Table 5)**. The stiffness of the anatomic reconstruction complex (23.4±5.2 N/mm) was significantly less than (60%) the stiffness of the CC ligament complex (60.8±12.2 N/mm) and the ultimate load of the anatomic reconstruction complex (406±60 N) was 25% lower than the CC ligament complex (560±206 N, p<0.05). Consequently, the elongation and energy absorbed at failure of the anatomic reconstruction complex (14.8±3.4 mm and 5569±1453 N-mm) was significantly greater than (100% and 60%) that of the CC ligaments (7.5±3.5 mm and 3516±1982 N-mm), respectively (p<0.05).

Table 5. Comparison of the structural properties of CC ligament and anatomic reconstruction complexes. (*p<0.05)

		CC Ligament Complex	Anatomic Reconstruction	
Structural Properties	Stiffness (N/mm)	60.8 ± 12.2	23.4 ± 5.2	*
	Ultimate Load (N)	560 ± 206	406 ± 60	*
	Elongation at Failure (mm)	7.5 ± 3.5	14.8 ± 3.4	*
	Energy Absorbed at Failure (N-mm)	3516 ± 1982	5569 ± 1453 *	

The individual components of each complex exhibited different properties before complete AC joint dislocation than after injury **(Table 2)**. The bending stiffness of coracoid was consistently twice as large as the bending stiffness of the clavicle, CC ligaments or the semitendinosis tendon graft. The bendng stiffness of the clavicle after injury (137.3±74.1 N/mm) significantly decreased 40% compared to the bending stiffness during dislocation of the AC joint (226.6±173.8 N/mm, p<0.05). Consequently, the stiffness of the semitendinosis tendon graft (46.7±19.2 N/mm) during failure was significantly 75% lower than the stiffness of the CC ligaments (212.1±212.1 N/mm) during failure (p<0.05).

Table 6. Comparison of the stiffness of individual components of CC ligament and anatomic reconstruction complexes. (*p<0.05)

	CC Ligament Complex		Anatomic Reconstruction Complex	
	Clavicle	*CC Ligaments*	*Clavicle*	*Tendon Graft*
Stiffness (N/mm)	226.6 ± 173.8	212.1 ± 212.1	137.3 ± 74.1 *	46.7 ± 19.2*

5.3 Summary

The experimental testing setup utilized in this study allowed for bending of the clavicle and coracoid simulating a more realistic mechanism of injury to the AC joint. Tensile testing of the CC ligament and anatomic reconstruction complexes allowed for the determination of both cyclic behavior and structural properties. Small amounts of permanent elongation were found for both complexes during cyclic loading. Significant decreases in stiffness and ultimate load along with significant increases in elongation and energy absorbed at failure were shown after anatomic reconstruction. After complete dislocation of the AC joint, the bending stiffness of the clavicle also significantly decreased.

5.4 Conclusions

The incorporation of bending of the clavicle and coracoid during testing allowed the experimental testing setup to mimic the mechanism of injury for complete AC joint dislocation. Previous studies held both the clavicle and coracoid rigid, therefore the clavicle was potted to

simulate impaction on the first rib consistent with complete dislocation. The experimental testing setup allows for the evaluation of cyclic loading and loading to failure on the overall complex along with the individual contribution of each component of both the CC ligament and anatomic reconstruction complexes. By failing the intact CC ligament complex, the design for the anatomic reconstruction can incorporate not only the effects on the intact CC ligaments but the effects on the clavicle and coracoid which are vital parts of the anatomic reconstruction complex.

The anatomic reconstruction complex, even after a large initial creep in response to cyclic loading, exhibited a small amount of permanent elongation. The large range of standard deviation for permanent elongation of the anatomic reconstruction resulted from seven specimens having no permanent elongation. Specimens with permanent elongation greater than zero were likely due to slippage of the initial fixation of the tendon graft, which may be reduced with tensioning of the graft during surgical reconstruction. Although the amount of creep and permanent elongation of the anatomic reconstruction are larger than the CC ligament complex, these measurements are below the level that is expected to produce clinical symptoms of instability [10]. These findings suggest that patients could tolerate early cyclic loading conditions during rehabilitation protocols while still maintaining stability of the initial fixation.

The structural results of this study support our hypothesis that the anatomic reconstruction more closely approximates the structural properties of intact CC ligaments than current surgical complexes. The structural properties of the anatomic reconstruction complex exhibited significant differences compared to the CC ligament complex in all properties determined during uniaxial tensile testing. Current repair/reconstruction complexes have comparable structural properties to the anatomic reconstruction complex [34, 35]. However, in this

study the structural properties of the anatomic reconstruction complex include the properties of the clavicle and coracoid, and the significant decrease (40%) in the bending stiffness of the clavicle after dislocation may largely contribute to the reduced structural properties of the anatomic reconstruction complex [63]. The stiffness of the tendon graft itself more closely approximates the stiffness of the intact ligaments. Consequently, both current repair/reconstructions and the anatomic reconstruction have diminished properties compared to intact CC ligaments [34, 35]. In addition, the incorporation of biological tissue into the reconstruction and the possibility of tendon-to-bone healing may further improve the properties of the anatomic reconstruction.

Previous researchers have evaluated the structural properties of the CC ligaments and their repairs/reconstructions with testing setups that rigidly fixed the coracoid and clavicle [34, 35]. In this study, fixation of the clavicle allowed for distal clavicular and coracoid bending and evaluation of the bending stiffness of these bony components. The proximal two thirds of the clavicle was potted and mimicked the impaction of the clavicle against the first rib, simulating the clinical mechanism of complete AC joint dislocation. This setup provided a consistent and reproducible failure mode of the CC ligaments and the structural properties determined in this study may be more accurate and clinically achievable. Future studies may utilize this testing setup to approximate the clinically injured state during the design and evaluation of novel anatomic reconstructions. The bony failures in women after anatomic reconstruction suggests these women had poorer bone quality than there male counterparts. The quality of the bone will be factored into the design of anatomic reconstructions and selection of tendon grafts to minimize clinical complications of fractures following reconstruction.

6.0   DISCUSSION/CONCLUSIONS

The Robotic/UFS and tensile testing systems provided a quantitative evaluation of intact, injured and reconstructed AC joint. Examining the intact AC joint during combined loading provided motion and forces of intact AC joint and reaffirmed the synergistic effect of the soft tissues not only in response to a single external load, but also with a combined external load including compression. The cyclic behavior and structural properties of the native CC ligaments determined during tensile testing provided new insight into the relationship between the ligaments and their surrounding bony attachments in response to cyclic loading and failure. These basic findings provide a baseline of information including forces, kinematics, properties and behavior that the normal AC joint will encounter during activities of daily living.

After injury, the function of the AC joint changes which can predispose the patient to earlier degeneration, pain and instability. The overall goal of clinicians is to restore the structure and function of the injured AC joint back to the intact state, so it is imperative to examine what structural and functional changes have occurred in the injured AC joint. Combined loading after a Type II injury revealed the importance of the articulation between the distal end of the clavicle and the acromion which provided stability during loading however the increase in joint contact force could be the cause for subsequent degeneration. Also the increase in resultant load transmitted to the CC ligaments could predispose the joint to unusually high loads and possible failure. Tensile testing of the CC ligament complex provided vast new insight on complete AC joint dislocation (Type III) including the mechanism of injury and the subsequent change in the surrounding bony structures of the AC joint. These new findings provide valuable information

in a clinician's decision on rehabilitation, repairs or reconstructions to ultimately return the joint back to the intact baseline.

These baseline findings for both intact and injured AC joints provided insight into the development and testing of an anatomic reconstruction which exhibits great potential as primary repair for severe AC joint dislocations. With improved structural properties and the initial promise of withstanding early rehabilitation protocols, the anatomic reconstruction provides promise for a permanent biologic replacement for the ruptured CC ligaments during complete AC joint dislocations. Overall, this dissertation provided a broad examination of the intact, injured and reconstructed AC joint and vital clinical input into for the future development of a computational model of the AC joint. The model can provide a quick and effective clinical tool for the development and evaluation of new surgical techniques with the ultimate goal of developing of a "gold standard" for treatment of AC joint injuries.

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