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An Analysis of Stress Pattern in the Coracoclavicular Ligaments with Scapular Movements: A Cadaveric Study Using Finite Element Model

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Background: Acromioclavicular (AC) stability is maintained through a complex combination of soft-tissue restraints that include coracoclavicular (CC), AC ligament and overlying muscles. Among these structures, the role of the CC ligament has continued to be studied because of its importance on shoulder kinematics, especially after AC injury. This study was designed to determine the geometric change of conoid and trapezoid ligaments and resulting stresses on these ligaments according to various scapular motions.
Methods: The scapuloclavicular (SC) complex was isolated from a fresh-frozen cadaver by removing all soft tissues except the AC and CC ligaments. The anatomically aligned SC complex was then scanned with a high-resolution computed tomography scanner into 0.6-mm slices. The Finite element model of the SC complex was obtained and used for calculating the stress on different parts of the CC ligaments with simulated movements of the scapula.
Results: Average stress on the conoid ligament during anterior tilt, internal rotation, and scapular protraction was higher, whereas the stress on the trapezoid ligament was more prominent during posterior tilt, external rotation, and retraction.
Conclusions: We conclude that CC ligament plays an integral role in regulating horizontal SC motion as well as complex motions indicated by increased stress over the ligament with an incremental scapular position change. The conoid ligament is the key structure restraining scapular protraction that might occur in high-grade AC dislocation. Hence in CC ligament reconstructions involving only single bundle, every attempt must be made to reconstruct conoid part of CC ligament as anatomically as possible.
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Key Words: Acromioclavicular stability; Coraclavicular ligament; Scapuloclavicular complex; Finite element model

Introduction

Disruption of the acromioclavicular (AC) joint is one of the main causes of scapular malposition and altered scapular motion that, in turn, may induce a negative influence on rotator cuff function.[1-3)] High-grade AC joint dislocation results in rupture of the coracoclavicular (CC) ligaments. The CC ligaments provide vertical stability of the scapuloclavicular (SC) complex and additional horizontal stability, resulting in harmonious SC movement during glenohumeral motions.[4)] The CC ligaments consist of the conoid and trapezoid ligaments. Despite their similar structural properties, each ligament has a unique anatomic orientation and a unique function in providing stability to the AC joint. According to Harris et al.,[5)] the clavicular insertion of the conoid ligament was found to be approximately twice as wide (medial to lateral) and thick (anterior to posterior) as its coracoid insertion, giving rise to its inverted cone shape. The trapezoid ligament was more than three times thicker at its clavicular end than at its coracoid end, but it showed less narrowing of its width compared with the conoid ligament. In biomechanical study, the conoid served as the primary restraint against anterior and superior loading, while the trapezoid functioned as the primary restraint against posterior loading. The relative orientation of these two ligaments has been suggested to account for their different func-

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tions.[6-8] This distinctive role in functional stability has become the recent focus of surgical reconstruction.[9] However, the CC ligaments have a functional complexity that cannot be simply addressed by a traditional biomechanical experiment. Previous biomechanical analyses have been performed by selective sectioning experiments to determine the role of each ligament.[6-8,10] Although data from both selective sectioning studies of the components and tensile testing of the CC ligaments have provided a main understanding of the in situ function of these structures, additional studies are needed to determine the role of each ligament induced by realistic scapular rotational motions.

Therefore, this study was designed to determine the changing stress pattern of one or both conoid and trapezoid ligaments according to their geometrical changes with respect to various scapular motions. The overall hypothesis was that a complex stress distribution exists in the conoid and trapezoid ligaments as a result of their geometric changes.

Methods

One fresh-frozen shoulder from a cadaver aged approximately 55 years, stored at -20°C was used in this study. Gross and radiographic examination of the specimen showed no signs of degenerative joint disease or previous injury. Before the day of dissection, the shoulder specimen was thawed overnight at room temperature. The SC complex was isolated by removing all of the soft tissues sparing the CC ligaments, AC ligament, the sternoclavicular ligaments and the coracoacromial ligament to maintain the three-dimensional (3D) alignment on 0° of the SC complex. The reference position was determined by aligning the bony articulation of the distal end of the clavicle and the acromion process with equal tension throughout the soft-tissue structures. To maintain a reference position during the 3D modeling process, a K-wire was temporally used by connecting the scapula to the proximal clavicle (Fig. 1A).

After achievement of a solid SC complex, the AC ligament was disrupted by cutting the capsule circumferentially to eliminate complimentary function in SC stability. This anatomically aligned scapulothoracic complex was then scanned with a high-resolution computed tomography (CT) scanner (Somatom Sensation; Siemens, Erlangen, Germany) with 0.6-mm slices. Digital Imaging and Communications in Medicine files were obtained and imported into visualization software (Amira R 4.0; Mercury Computer Systems, Chelmsford, MA, USA) for construction of a virtual 3D model of the scapula, clavicle, and CC ligaments, respectively (Fig. 1B). These 3D images were imported to validated customized software (Rapidform XOR; INUS Technology, Seoul, Korea) to first be assembled as a surface model and then made into a solid model, an essential precursor, for conversion to the finite element model (FEM) mesh. The solid model of the CC ligaments, along with the scapula and clavicle, was then imported into a finite element pre-process (Abacus 6.10.3; Dassault Systèmes, Waltham, MA, USA). This enables structures to be modeled by the use of various types of geometric elements. The clavicle and scapula were assumed to be rigid since bone deformation was not considered. A tetrahedral finite element mesh was created for the conoid and trapezoid ligaments using solid geometry, while a quadrilateral mesh was obtained for the

Table 1. Geometry of the CC Ligaments

Variable	Clavicle side of CC ligament	Scapular side of CC ligament
Cross-sectional area (mm^2)	451.742	315.9312
Long axis (mm)	41.0091	29.8283
Angle (°)	119.5405	
Length (mm)	16.2314	
Volume (mm^3)	3,157.83377	
No. of node	5,624	
Element	23795 (C3D4)	

CC: coracoclavicular.

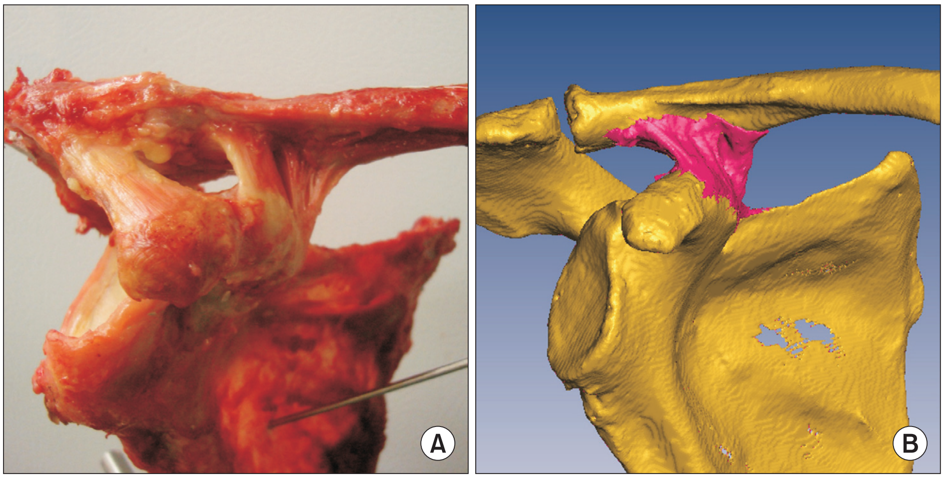

Fig. 1. Three-dimensional (3D) modeling. (A) The cadaveric coracoclavicular ligaments in reference position. (B) 3D modeling of coracoclavicular ligaments.

bones.[11] The shape and dimensions of the CC ligaments are summarized in Table 1.

The mechanical behavior of the ligaments was taken to be an isotropic, linear, elastic, and homogeneous material. The Young's modulus and Poisson's ratio were defined as shown in Table 2. The constants were obtained from the experimental measurements described in.[12] In this code, all elements use numeric integration to allow complete generality in material behavior and are interactive with each other to enable the assessment of mechanical parameters such as stress within the ligament.

The FEM of the CC ligaments was attached to the scapula and clavicle using the tie method. The tie method was imposed on the contact surface between the bone and the ligament where the CC ligaments were attached. The reciprocal motion (translation and rotation on the x-, y-, and z-axes) between each node on the mesh was constrained kinematically by the tie method.

The origin of the local coordinate system was set at the center of the articular surface of the medial aspect of the acromion. An Euler angle system was used to describe the motion of the scapula with respect to the scapula. The x-axis was perpendicular to the scapular plane and directed antero-posteriorly. The y-axis was parallel to the external border of the scapula and directed superiorly. The z-axis was directed externally and obtained by the cross product of the x- and y-axes (Fig. 2). The scapular plane was defined by three anatomic landmarks on the scapula: the inferior tip of the scapula body, center of the glenoid surface, and external pole of the scapula where the scapular spine intersects the body. The orientation of the scapula with respect to the clavicle was determined by rotating the scapular axes. The first rotation corresponded to the scapular external/internal rotation based on the y-axis of the scapula. The second rotation was performed on the anterior/posterior tilt based on the z-axis. The final rotation defined protraction, which was thought to be coupled to internal rotation and anterior tilt, and was about the y-axis, followed by the z-axis of the scapula. Its counterpart retraction was defined by external rotation coupled with posterior tilt along the same axes.

They were simulated up to 10° in 2-degree increments and von Misses stresses were calculated at every incremental stage. The stresses were identified at the predetermined points on the anterior, posterior, medial, and lateral aspects (such as tilt and rotation) of the conoid and trapezoid ligament, respectively. The average stresses were also obtained from the trapezoid and conoid ligaments for each movement. The average stress of four points on trapezoid and conoid ligament was used for analysis of the stress distribution with regard to each ligament. The measured value of the four points tends to concentrate stress in one direction according to the scapula motion. Therefore, we used the average stress for analysis of the stress distribution of CC ligaments on various motions.

Finite element analysis was performed using Abacus 6.10.3, which can provide an approximate solution for the stress and strain of each element and node. The peak stress was obtained from the selected points with variable scapular movements.

The CC ligaments have a heavily curved surface, and even

Table 2. Material Properties of 286 of the Finite Element Models

Mechanical behavior	Body part	Density (kg/L)	Young's modulus (MPa)	Poisson's coefficient
Elastic-plastic	Clavicle	1.8	11,000	0.3
Elastic-plastic	Scapula	2	16,000	0.3
Elastic-plastic	Coracoclavicular ligament	1	9.6	0.3

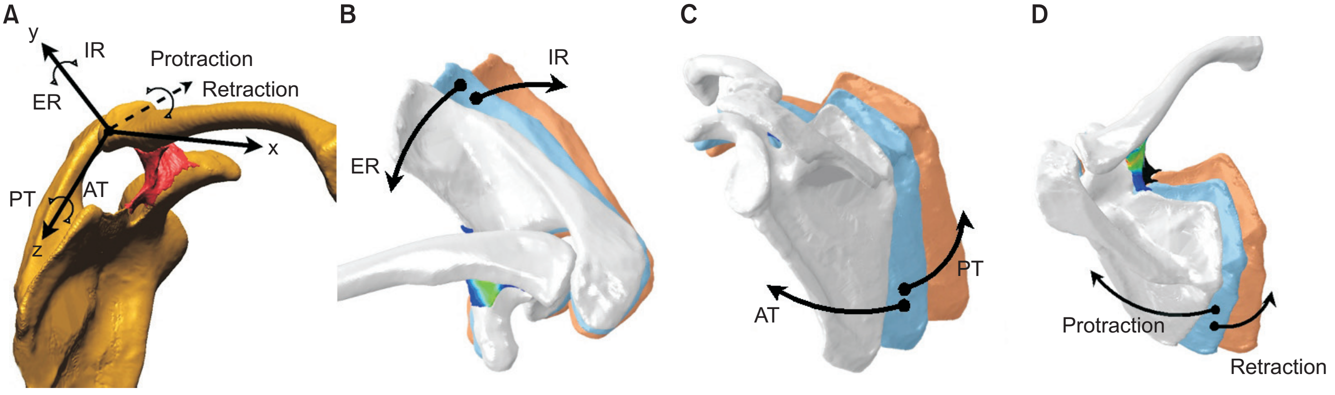

Fig. 2. (A) Coordinate system associated with scapular movement: ER/IR (B), AT/PT (C), protraction/retraction (D).
ER: external rotation, IR: internal rotation, AT: anterior tilt, PT: posterior tilt.

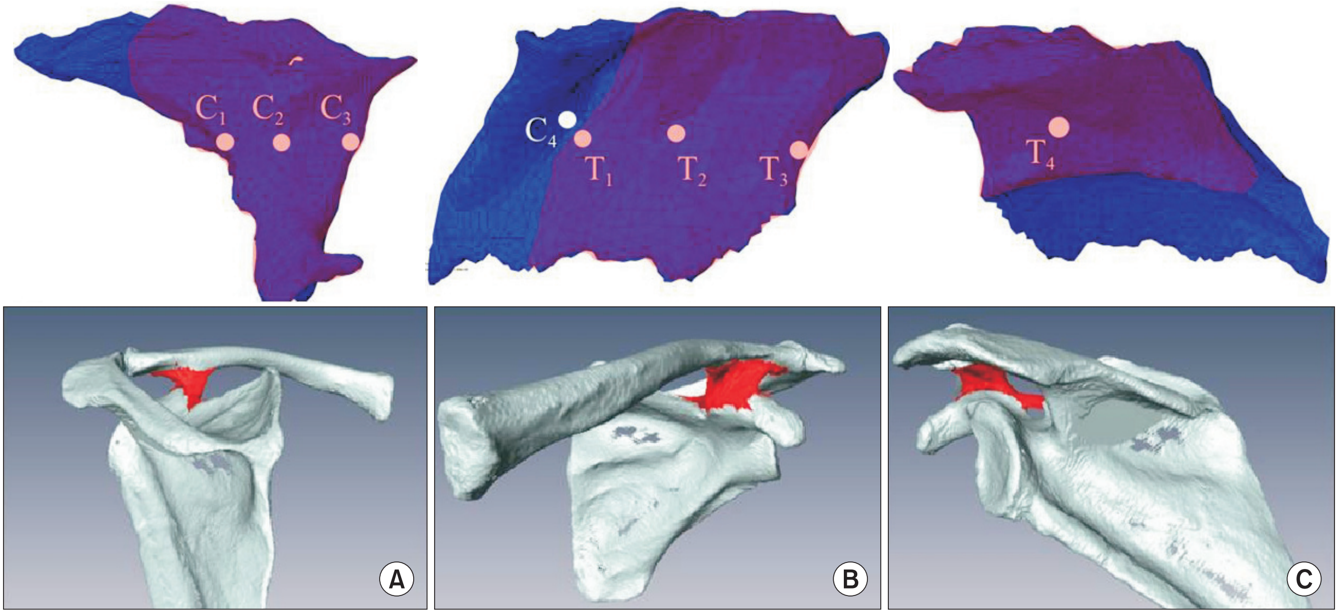

Fig. 3. Predetermined points on conoid (C) and trapezoid (T) ligaments. Lateral (C_1), Posterior (C_2), Medial (C_3), and Anterior (C_4). Posterior (T_1), Medial (T_2), Anterior (T_3), and Lateral (T_4). (A) Posterior view of the conoid ligament. (B) Lateral view of the trapezoid and conoid ligaments. (C) Medial view of the trapezoid ligament.

twisted geometry at the initial position. We adjusted the joint position to minimize bending of the CC ligaments at CT image shooting, but which could not be completely resolved. It was presumed that the curved surfaces reconstructed at the initial joint position generated the distorted stresses. For this reason, in our study, we defined the measurement points out of regions excluding the distorted stresses caused by the curved surface at the initial position. The measuring points on the conoid ligament were lateral (C_1), posterior (C_2), medial (C_3), and anterior (C_4), while those corresponding points on the trapezoid ligament were posterior (T_1), medial (T_2), anterior (T_3), and lateral (T_4). These points of the conoid and trapezoid ligaments are described in Fig. 3. The clavicle was intentionally 1 mm translated superiorly and inferiorly back along the y-axes before the main simulation process. This process is helpful in identifying time zero stress on certain areas that enable us to determine as measuring points.

Results

Both components had a different pattern of stress distribution by geometric change with respect to the scapular movement. The shape of CC ligaments changed according to various scapular movements. The von Mises stress in the conoid and trapezoid ligaments gradually increased as the scapula was rotated. The stresses were distributed non-uniformly in the ligament with different modes of scapular movement. The highest value was observed at the anterior portion of the conoid ligament at 10° of scapular external rotation (5.3 MPa) followed by the medial portion of the trapezoid ligament at 10° of scapular external rotation (5.0 MPa). The average of each maximum value obtained for the locations on the conoid ligament reached values of 1.5 ± 1.7, 3.7 ± 0.6, 2.9 ± 1.3, 1.1 ± 0.2, 3.9 ± 0.7, and 1.7 ± 0.7 MPa with external rotation, internal rotation, anterior tilt, posterior tilt, protraction (combined anterior tilt and internal rotation), and retraction (combined posterior tilt and external rotation), respectively. In the meantime, values of trapezoid ligament were 3.7 ± 0.8, 3.2 ± 0.8, 2.3 ± 0.6, 1.7 ± 0.3, 2.1 ± 0.7, and 2.5 ± 0.6 MPa with external rotation, internal rotation, anterior tilt, posterior, protraction, and retraction, respectively (Fig. 4. 5).

In the figures, it is evident that during anterior tilt, the average stress on the conoid ligament was higher than that on the trapezoid ligament. The average stress on the conoid ligament obtained in internal rotation was higher than that obtained in the conoid ligament, whereas in external rotation, the trapezoid ligament was more stressed. During protraction, the von Mises stress in the conoid ligament remained much higher than that in the trapezoid ligament throughout the range. A higher average stress was obtained in internal rotation on the conoid ligament, whereas a higher average stress was obtained in external rotation on the trapezoid ligament.

Discussion

The data showed that both components had a different pattern of stress distribution by geometric change with respect to scapular movement. A significant amount of stress was generated from both the conoid and trapezoid ligaments as they twisted

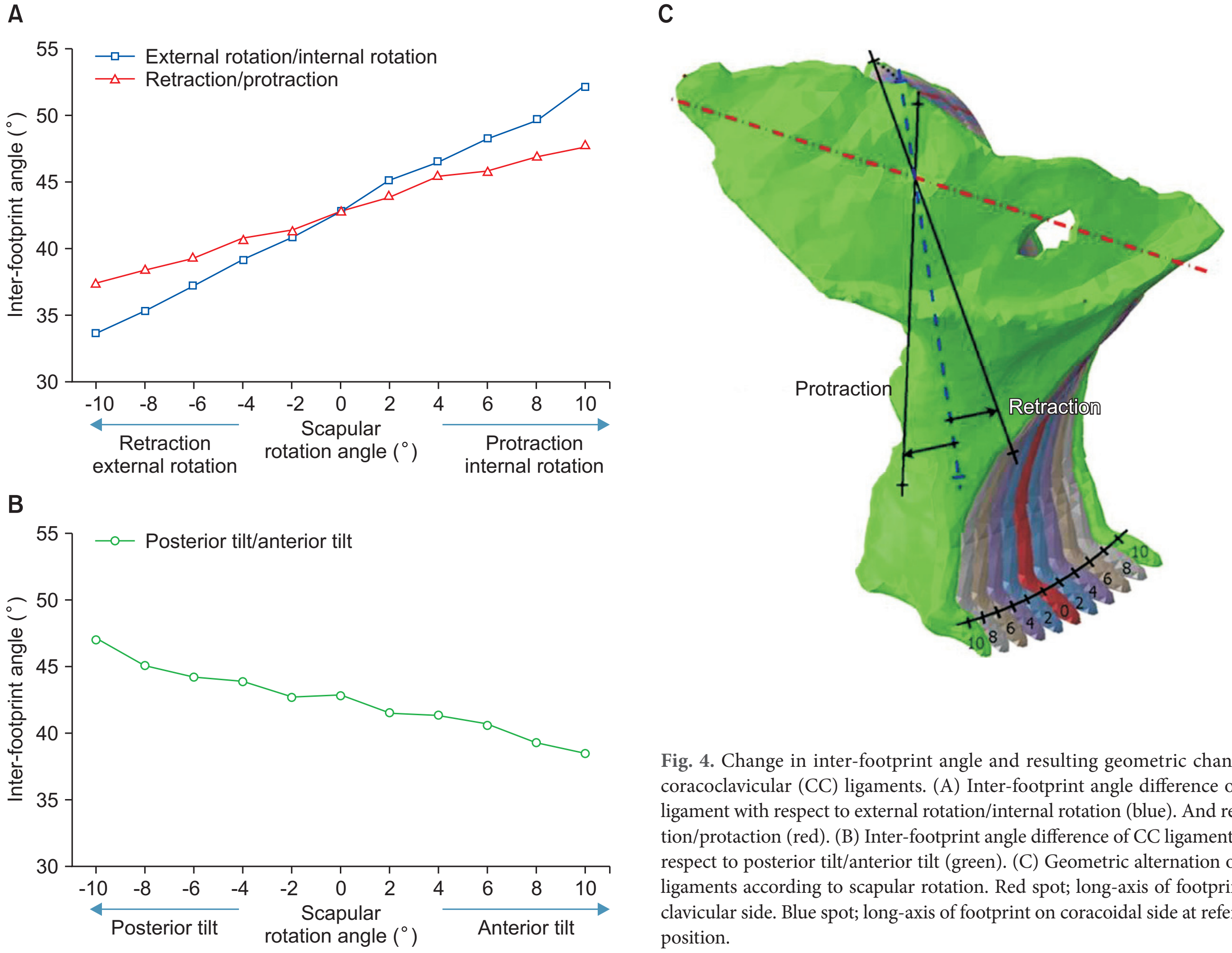

Fig. 4. Change in inter-footprint angle and resulting geometric change of coracoclavicular (CC) ligaments. (A) Inter-footprint angle difference of CC ligament with respect to external rotation/internal rotation (blue). And retraction/protaction (red). (B) Inter-footprint angle difference of CC ligament with respect to posterior tilt/anterior tilt (green). (C) Geometric alternation of CC ligaments according to scapular rotation. Red spot; long-axis of footprint on clavicular side. Blue spot; long-axis of footprint on coracoidal side at reference position.

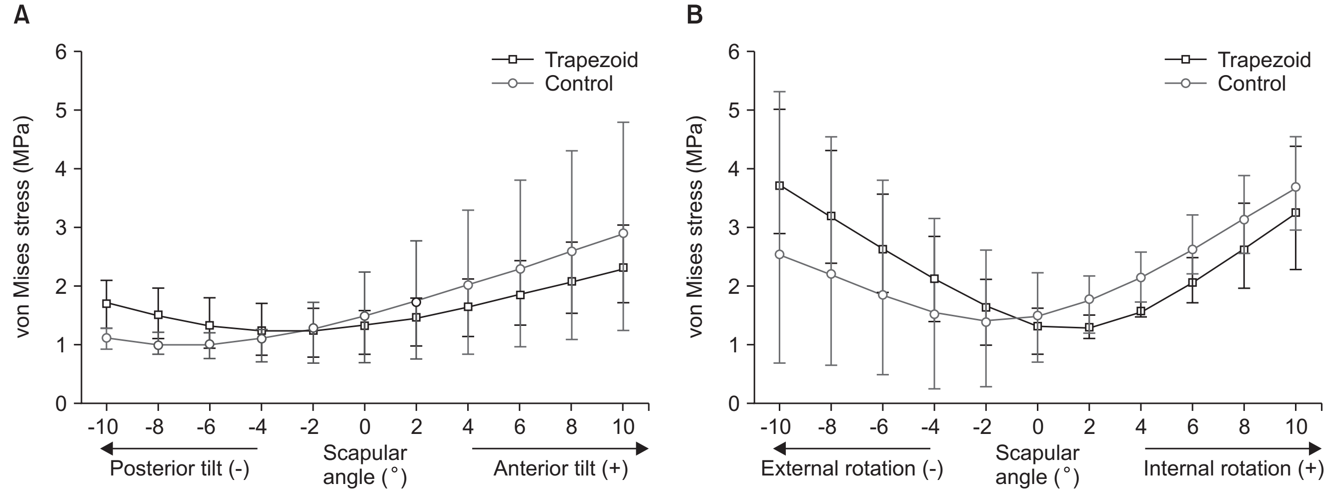

Fig. 5. Angle-stress curves. (A) Stress pattern on conoid and trapezoid ligaments according to posterior tilt/anterior tilt. (B) Stress pattern on conoid and trapezoid ligaments according to external rotation/internal rotation.

or untwisted around each other according to gradual increment of the scapular rotations.

As evident from the stress–angle curves, the average stress on the conoid ligament was rapidly increased when anterior tilt, internal rotation, and protractions were applied. The von Mises stress on the trapezoid was rapidly increased as the scapula was moved toward the posterior tilt, external rotation, and retraction. These findings show that the two ligaments worked synergistically against various scapular movements.

According to these findings, we can speculate that CC ligaments might control the scapular motion by sequential stretching.

The current understanding of the role of conoid and trapezoid ligaments has been mainly derived from selective sectioning studies on the CC components and tensile testing predicted as horizontal and vertical load applied to the clavicle or scapula.13) Although the findings have played an integral role in improving our understanding of the role of the CC ligaments in AC joint stability, questions remain because the in situ function of these structures was mainly studied after the simulation of pure horizontal and vertical SC motions that rarely occur in real life.

In this context, little is known about the stress patterns of the pathomechanism of scapular malposition frequently observed in high-grade AC dislocation.2) The stress pattern on both conoid and trapezoid ligaments found in our study supports the results obtained by the previous study by Oki et al.14) indicating that AC and CC ligament disruption affected the in vitro shoulder girdle kinematics, and it was inferred that AC and CC ligament disruption could lead to scapular dyskinesis.

Sequential tension changes or length differences in the CC ligaments according to glenohumeral motion have been studied. Izadpanah et al.13) found that the length differences of the conoid and trapezoid ligaments occurred with shoulder abduction, wherein conoid ligament length increased significantly with increased shoulder abduction and trapezoid ligament exhibited an isometric function on shoulder abduction with insignificant length changes. Our former FEM study11) reported identical results. These studies found that the CC ligaments with glenohumeral abduction required scapular combined rotations including posterior tilt, upward rotation, and external rotation. However, stress changes in the CC ligaments with discrete scapular movements have not been studied until now, and this study would provide important data regarding CC ligament tension and scapular movements.

In light of our study results, adequate management of the conoid ligament, which shows high stresses on anterior translation, internal rotation of the scapula and protraction, is required because it is the key structure undergoing maximal stress with protraction, baseline characteristics leading to scapular dyskinesis. With average stress on each ligament at different angles, we hypothesized that variable stress changes between the conoid and trapezoid ligaments could contribute to stable scapular movement during glenohumeral motion with a reciprocal or complementary mode of action. In particular, the highest stress concentration was observed at the conoid ligament at 10^o of protraction. This finding might indicate that the conoid ligament is a key element determining scapula position during glenohumeral motion. In other words, confrontational clavicular motion with respect to scapular motion, which is regulated by the conoid and trapezoid ligaments, is critical for generating native kinematics for shoulder motion.

Anterior and posterior tipping of the scapula occurs around a coronal axis through the joint. Scapular tipping combined with external and internal rotation of the scapula maintains the contact between the scapula and the contour of the rib cage. These combined motions, called protraction and retraction, cause the scapula to slide around the thorax with maximal contact. With this biomechanical background, simulation of the scapular rotation with respect to the clavicle was determined using a rotation center set on the AC joint.

This study has several limitations. First, we assumed that both ligaments were simple elastic materials even though actual in vivo ligaments are compressible and viscoelastic.15,16) For this reason, we compared only the patterns of stress distribution at the conoid and trapezoid ligaments and did not attempt to determine the absolute values of equivalent stresses. Second, we took the stresses at 2-degree intervals, which is relatively large for an assessment. The values ideally should have been taken in a continuum with minimal increments. The last limitation of our study was that we used a computer simulation of the scapular movements. In vivo scapular movements are variable and challenging to simulate. The scapula sometimes moves along with the clavicle and at other times the clavicle is stationary and the scapula moves around it. Reproducing the scapular movements occurring in vivo is extremely difficult. Here we were able to simulate the scapular movements in the cadaveric model and measure the relative stress changes that are very difficult to obtain in living individuals.

Thus even though the FEM has been widely used for analysis of the stress distribution within various types of materials,17,18) additional structure–function studies are needed in order to more accurately determine the pattern and method of load transmission in the CC ligaments in response to realistic scapular rotational motions.

Conclusion

In conclusion, despite having a vertically oriented configuration, CC ligaments can play an integral role in regulating horizontal SC motion as well as complex motions indicated by increased stress over the ligament with incremental scapular position change. In particular, the conoid ligament might be the key restraint associated with scapular protraction, which frequently occurs in high-grade AC dislocations.

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