MORPHOLOGICAL, VISCOELASTIC AND STRUCTURAL PROPERTIES OF THE CORACOCLAVICULAR LIGAMENTS

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INTRODUCTION: During contact sports such as football and hockey, the coracoclavicular (CC) ligaments are commonly ruptured when a blunt force drives the scapula inferiorly, with respect to the clavicle. These ligaments (trapezoid and conoid) are thought to be the primary suspensory ligaments of the shoulder. Each is thought to play a significant, but different role, providing acromioclavicular (AC) joint stability [1, 2]. However, only limited information is available on the biomechanical properties of the CC ligaments, and consequently over 30 AC joint reconstruction techniques have been proposed without knowing what "gold standard" should be used as the endpoint for CC ligament reconstruction. The objective of this study was to describe the gross morphology, and quantify the viscoelastic and structural properties for each ligament, trapezoid and conoid. This data will serve as a baseline for biomechanical evaluation of the intact shoulder and the development of improved surgical techniques for AC joint reconstruction.

MATERIALS AND METHODS: Eleven fresh-frozen, cadaveric shoulders (mean age = 59±7 years, range 50-77) were disarticulated at the glenohumeral joint and dissected free of all soft tissue, except for the CC ligaments. The coracoid process was carefully removed from the scapula and the clavicle was sectioned such that 5mm of bone remained proximal and distal to the ligament insertion sites. The CC ligaments were then bluntly separated and the clavicle bone-block split between each ligament. The bone-blocks of each ligament were then potted in custom aluminum fixtures using PMMA. Due to their limited length and common insertion point on the coracoid process, only one ligament was potted at a time and the testing order was randomized.

The thickness and width of each ligament were then measured with dial calipers (Mitutuyo, Osaka, Japan) at the mid-substance and its' cross-sectional area was calculated assuming a rectangular shape. After potting, each complex was mounted in a materials testing machine (Instron Corporation, Canton, MA) with adjustable fixturing to allow proper longitudinal alignment and loading of the ligament fibers. The entire complex was submerged in a saline bath maintained at 37°C throughout the entire protocol and all tests were performed with a crosshead speed of 50mm/min. Initially, a small tare load of 5N was applied followed by measurement of the ligament gage length using a 6" machinist scale (Fowler Company, Newton, MA). Each ligament was then preconditioned with ten cycles of elongation between 0mm and 1mm. Viscoelastic properties were evaluated with static and cyclic stress relaxation protocols. Static stress relaxation was carried out by elongating each complex to 1mm and maintaining that extension for 25 minutes. The load was then removed for one hour of recovery. Subsequently, ten cycles of elongation between 1mm and 2mm were performed for cyclic stress relaxation test. Following another recovery period, a load-to-failure protocol was executed. The structural properties of the bone-ligament-bone complex were derived from the load-elongation curve for each ligament. After failure, the first complex was removed from the machine and the remaining ligament was potted and tested using the same protocol. A paired student's t-test was used to compare the trapezoid and the conoid for all viscoelastic and structural properties, with statistical significance set at $p<0.05$.

RESULTS: Following dissection, the predominant fibers of the conoid ligament were rotated and realigned from its anatomic orientation during testing and the ligament was observed to be 15% longer ($p<0.05$) than the trapezoid ligament. On the other hand, the trapezoid was found to have a significantly greater ($p<0.05$) cross-sectional area than the conoid ligament (Table 1). The conoid ligament also relaxed 16% more than the trapezoid during the static stress relaxation test, however, no significant differences could be demonstrated ($p>0.05$). During the cyclic stress relaxation test, the conoid exhibited a significantly greater ($p<0.05$) amount of relaxation (44%) than the trapezoid. No statistically significant differences were demonstrated for all structural properties (Figure 2). Seventy-three percent of the trapezoid ligaments and 40% of the conoid ligaments failed at the insertion site on the coracoid process. Eighteen percent of the trapezoid ligaments and 50% of the conoid ligaments failed in the mid-substance, while bone avulsions from the clavicle occurred in 10% of all ligaments tested.

DISCUSSION: The morphology as well as viscoelastic and structural properties of the CC ligaments were characterized in this study. When compared to other ligaments at the shoulder, the CC ligaments were approximately 300-400% stiffer than the coracohumeral (CHL) and superior glenohumeral ligaments [3]. Furthermore, each CC ligament was approximately 100% more stiff than the lateral band of the coracoacromial (CA) ligament [4]. These differences in structural properties support the functional role of the CC ligaments as the prime suspensory ligaments of the upper extremity. The predominant failure mode of the trapezoid and conoid ligaments also correlates well with previous findings [5]. These data increase our understanding of the CC ligaments and provide basic knowledge to improve reconstruction techniques for these ligaments, as well as to create computational models to study complex loading conditions.

Table 1. The morphological, viscoelastic and structural properties of the CC ligaments (mean ±SD / *$p<0.05$).

	Trapezoid	Conoid
X-sectional area (mm^2)	*103 ±43	69 ±51
Length (mm)	*9.6 ±4.4	11.2 ±4.1
% Stress Relaxation: Static	36 ±8	31 ±7
% Stress Relaxation: Cyclic	*23 ±12	16 ±6
Linear Stiffness (N/mm)	100 ±48	80 ±25
Ultimate Load (N)	312 ±133	266 ±108
Elongation at Failure (mm)	5.8 ±2.2	6.1 ±1.6
Energy Absorbed to Failure (N-mm)	820 ±576	752 ±410
% Elongation	74 ±47	62 ±22

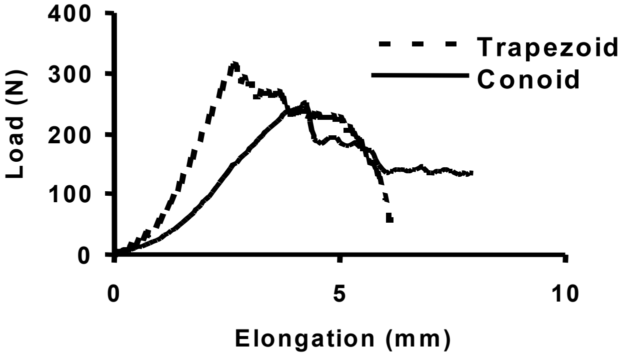

Figure 2. Typical load vs. elongation curve for the trapezoid and conoid ligament.

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