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Changes to the mechanical properties of the glenohumeral capsule during anterior dislocation

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ABSTRACT

The glenohumeral joint is the most frequently dislocated major joint in the body, and instability due to permanent deformation of the glenohumeral capsule is a common pathology. The corresponding change in mechanical properties may have implications for the ideal location and extent of plication, which is a common clinical procedure used to repair the capsule. Therefore, the objective of this study was to quantify the mechanical properties of four regions of the glenohumeral capsule after anterior dislocation and compare the properties to the normal glenohumeral capsule. Six fresh-frozen cadaveric shoulders were dislocated in the anterior direction with the joint in the apprehension position using a robotic testing system. After dislocation, mechanical testing was performed on the injured glenohumeral capsule by loading the tissue samples in tension and shear. An inverse finite element optimization routine was used to simulate the experiments and obtain material coefficients for each tissue sample. Cauchy stress–stretch curves were then generated to represent the mechanical response of each tissue sample to theoretical loading conditions. Based on several comparisons (average of the material coefficients, average stress–stretch curve for each region, and coefficients representing the average curves) between the normal and injured tissue samples, the mechanical properties of the injured tissue samples from multiple regions were found to be lower than those of the normal tissue in tension but not in shear. This finding indicates that anterior dislocation primarily affects the tensile behavior of the glenohumeral capsule rather than the shear behavior, and this phenomenon could be caused by plastic deformation of the matrix, permanent collagen fiber rotation, and/or collagen fiber failure. These results suggest that plication and suturing may not be sufficient to return stability to the shoulder after dislocation in all individuals. Thus, surgeons may need to perform a procedure that reinforces or stiffens the tissue itself, such as reconstruction or augmentation, to improve repair procedures.

1. Introduction

The glenohumeral joint is the articulation between the humerus and the scapula. It is the most dislocated major joint in the body, and about 2% of the population dislocates the joint between the ages of 18 and 70 (Hovelius, 1982). The majority of shoulder dislocations (about 80%) occur in the anterior direction. Further, dislocations most commonly occur in the apprehension position, which is characterized by 60° of glenohumeral abduction and 60° of external rotation (Cave et al., 1974).

The glenohumeral capsule connects the glenoid of the scapula to the humeral head and functions to stabilize the glenohumeral joint at the end ranges of shoulder motion. The anteroinferior capsule is the region of the glenohumeral capsule consisting of the anterior band of the inferior glenohumeral ligament and the axillary pouch that functions to resist dislocation in abduction and external rotation and is commonly injured during dislocation (Hovelius et al., 1983; Kaltsas, 1983; Matsen III et al., 1993, 1998; Rowe et al., 1984). The glenohumeral capsule also consists of a posterior band of the inferior glenohumeral ligament, antero-superior region, and posterior region (Fig. 1).

The most common pathology associated with dislocation is instability of the glenohumeral joint due to permanent deformation of the glenohumeral capsule (Bigliani et al., 1992; Speer et al., 1994; Ticker et al., 1996). Permanent deformation can be quantified by measuring the non-recoverable strain in the tissue. Current surgical repair techniques for shoulder dislocations typically consist of plicating the capsule, or folding it over on itself to reduce redundancy, and suturing the capsular folds together to restore the original length of the tissue. However, studies examining arthroscopic plication procedures following traumatic anterior dislocation have shown recurrent dislocation in up to 18% of patients and fair to poor functional outcomes in up to 24% of patients, which may be due to

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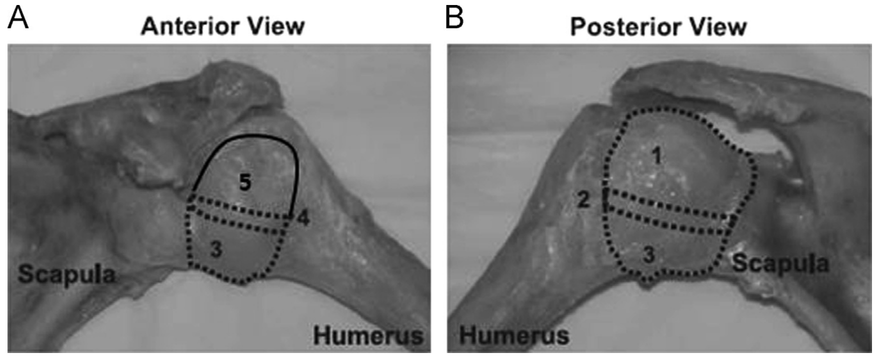

Fig. 1. Anterior (A) and posterior (B) view of the glenohumeral capsule. The following regions of the capsule are labeled: the posterior region (1), the posterior band of the inferior glenohumeral ligament (2), the axillary pouch (3), the anterior band of the inferior glenohumeral ligament (4), and the antero-superior region (5).

the fact that the location and extent of plication is fairly subjective (Bonnevialle et al., 2009; Chiang et al., 2010; Ozbaydar et al., 2007; Westerheide et al., 2006).

Knowing the magnitude and location of changes to the mechanical properties of the capsule may have implications for the ideal location and extent of plication as a treatment for glenohumeral dislocation. In the past, only the mechanical properties of the uninjured or normal glenohumeral capsule have been determined (Bey et al., 2005; Bigliani et al., 1992; Rainis et al., 2009; Voycheck et al., 2010), and no consensus exists on whether the mechanical properties are altered by dislocation. Therefore, the objective of this study was to quantify the mechanical properties of four regions of the glenohumeral capsule after anterior dislocation and compare the properties to the normal glenohumeral capsule.

2. Methods

A combined experimental–computational protocol was used to determine the material coefficients of four regions of the glenohumeral capsule in response to uniaxial tension and shear after anterior dislocation of the glenohumeral joint (Voycheck et al., 2010; Rainis et al., 2009; Browe et al., 2013) (Fig. 2). First, the cadaveric shoulder specimens were dislocated using a robotic/universal force–moment sensor (UFS) testing system (Fig. 2A). Then, the glenohumeral capsule was excised and the various regions of the capsule were mechanically tested in tension and shear along the longitudinal and transverse directions (Fig. 2B). Finally, the boundary conditions from the mechanical testing were used with an inverse finite element routine to determine optimized material coefficients for each region (Fig. 2C).

Six cadaveric shoulders (71 ± 24 years), consisting of three males and three females, were stored at about -20 °C and thawed for 24 h at room temperature before testing. The shoulders were dissected free of all soft tissue, leaving only the scapula, humerus, and glenohumeral capsule. The humerus and scapula were then potted in epoxy putty; the humerus was fixed in a cylinder with the same longitudinal axis of the humerus as previously described (Burkart and Debski, 2002; Burkart et al., 2003; Debski et al., 1999; Moore et al., 2008). The scapula was fixed in a rectangular prism such that the walls of the prism approximated the scapular plane, also as previously defined (Debski et al., 1999).

Each shoulder was then mounted in a robotic/UFS testing system in a position of approximately 60° of glenohumeral abduction and 0° of external rotation (Moore et al., 2008) (Fig. 2A). The robotic/UFS testing system is a six-axis, serial-articulated manipulator (PUMA model 762, Unimate, Inc., Pittsburgh, PA) with a repeatability of 0.2 mm for position, 0.2° for orientation, 0.2 N for forces, and 0.1 N m for moments (Debski et al., 1999). Custom fixtures held the scapula and humerus rigidly to the end-effector and the base of the testing system, respectively. The coordinate system utilized by the robotic/UFS testing system was then established using anatomic landmarks as previously described (Burkart and Debski, 2002; Burkart et al., 2003; Debski et al., 1999; Moore et al., 2008).

The path of passive glenohumeral abduction and the path of external rotation were then determined similarly to the method used by Moore et al. (2008). The purpose of establishing the passive paths of abduction and external rotation was to determine the joint position required for dislocation (i.e., the apprehension position) and to precondition the soft tissues prior to dislocation. The forces applied to the humerus in the anterior/posterior and superior/inferior directions were minimized and a constant 22 N compressive force was applied in the medial direction, which ensured that the humeral head was centered within the glenoid at all abduction angles. The purpose of the 22 N compressive force was to maintain contact between the glenoid and humeral head throughout all movements. In order to achieve the force targets, the scapula was allowed to translate in three dimensions. The passive path of glenohumeral abduction was established in 1° increments from 0° to 70° of glenohumeral abduction, and served as reference positions for the application of external rotation moments to achieve the external rotation path. The joint was then oriented at 60° of glenohumeral abduction and the path of external rotation was established by incrementally applying a 3 N m rotation moment to the humerus while maintaining a 22 N joint compressive force.

The robotic/UFS testing system was then utilized to dislocate the glenohumeral joint in the anterior direction with the humerus abducted and externally rotated by applying external loads to the humerus. Dislocation was defined by the humeral head translating half the largest anterior–posterior width of the glenoid plus 3 mm in the anterior direction. The additional 3 mm was chosen to ensure that the joint was fully dislocated and accounts for the thickness of the labrum. With the joint at 60° of glenohumeral abduction and 60° of external rotation, an anterior load was applied to the joint until the definition of dislocation was achieved. The joint was returned to the position corresponding to 60° of abduction and 0° of external rotation without any external loads applied and allowed to recover for 30 min.

The glenohumeral capsule was subsequently removed from the joint and divided into the four regions: the posterior region, the axillary pouch, the anterior band, and the anterior–superior region (Fig. 1). For each region, a tensile deformation (and shear deformation for two regions) was applied to each tissue sample, while the clamp reaction force and clamp displacement were recorded (Fig. 2B). The tissue sample geometries, clamp reaction forces, and clamp displacements were then used in an inverse finite element optimization routine to simulate the experimental conditions. The material coefficients were optimized when the sum-of-squares difference between the load–deformation curves from experimental measurements and computational predictions was minimized.

The longitudinal direction of each tissue sample was defined previously (Rainis et al., 2009). A total of two nondestructive loading conditions were used in this protocol for the axillary pouch and posterior region: (1) tensile deformation applied along the longitudinal axis (tensile longitudinal) and (2) shear deformation applied along the longitudinal axis (shear longitudinal). Only loading condition (1) was applied to the anterior band and antero-superior region due to the smaller area of tissue available in these regions.

The mechanical testing assembly had one fixed clamp and one that moved with the actuator (Fig. 3). The tissue samples were kept moist with a saline solution throughout the testing protocol. Multiple adapters allowed the same clamp to be used in both tensile and shear configurations. For each tensile deformation (Fig. 3A), a preload of 0.5 N was applied to the tissue sample using a materials testing machine (Elf 3200, Enduratec, Inc., Eden Prairie, MN) and custom load cell (Honeywell, Morristown, NJ, resolution $\pm$ 0.1 N). Once the tissue sample was preloaded, the initial width, length, and thickness of the tissue samples were determined as the average of three measurements obtained using digital calipers (thickness) and a ruler (width and length). The tissue sample was preconditioned via ten cycles of cyclic elongation to 1.5 mm (roughly 10% of the width) at a rate of 10 mm/min. Immediately after preconditioning, a displacement of 2.25 mm was applied to the tissue at a rate of 10 mm/min (Voycheck et al., 2010). The tissue samples were allowed to recover between the non-destructive tests for 30 min.

Following the recovery period, the tissue sample was removed from the fixed clamp and the tissue that was previously held within the clamps was then reclamped using a shear clamp (Fig. 3B). For shear deformations, two preloads were applied to the tissue sample. One preload was parallel to the axis of loading (0.1 N) using the load cell from the tensile protocol and the other preload was perpendicular to the axis of elongation (0.03 N) using an additional load cell (Honeywell, Morristown, NJ, resolution—0.01 N) (Fig. 3B). Once the tissue was preloaded, the initial width, length, and thickness of the tissue samples were determined as the average of three measurements obtained using digital calipers (thickness) and a ruler (width and length). The tissue sample was then preconditioned via 10 cycles of cyclic elongation between 0 and 2 mm (roughly 8% of the height) at a rate of 10 mm/min.