SENSITIVITY OF CARTILAGE PRESSURE TO LIGAMENT STIFFNESS DURING SHOULDER ABDUCTION

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INTRODUCTION

Rotator cuff tears are considered one of the primary causes of shoulder pain and dysfunction in adults [1]. Statistics show that more than 50% of patients over the age of 60 and 80% of patients over the age of 80 have a cuff tear [2]. Unfortunately, the success rate of rotator cuff repair is variable with many resulting in a re-tear. The chance of persistent tears or re-tears has been documented to be 35% for small tears and 94% for larger multi-tendon tears [3-5]. Similarly, revision surgeries can be as high as 30% for isolated supraspinatus tendon tears [6].

The aim of our research is to provide orthopedic surgeons with specific recommendations that will improve the outcome of rotator cuff surgeries. It is therefore important to understand the biomechanical properties of the ligaments, capsule, and dynamic properties of the muscles of the shoulder joint. Of note from the literature is the variation in the measured stiffness of shoulder joint ligaments [7-8]. It is essential to know how the variation of ligament stiffness affects the cartilage pressure in the glenohumeral joint. To investigate this, we developed a three-dimensional finite element (FE) model of the shoulder joint that includes the major ligaments and glenohumeral cartilage.

METHODS

The geometries of the humerus and scapula were created from computed tomography (CT) data of the shoulder (voxel size: 0.34 x 0.34 0.49 mm). The CT files were imported into Amira (v5.6, Visualization Sciences Group, France, and Zuse Institue Berlin, Germany) for segmentation of the bones using a semi-automated method. After segmentation, surfaces were generated and exported as an STL file and then imported into Geomagic Studio (v2014, Geomagic Inc., USA). The bone surfaces were smoothed, refined and noise was reduced. Finally, a solid model was created and exported as an STPAP203.

Construction of the FE model and all simulations were performed using Abaqus (v6.13, Daussalt Systems, France). Quadrilateral dominant surface meshes were used for the humerus and scapula (E=17GPa, ν=0.35) [9]. The cartilage mesh was a layer of elements offset from the surface of the proximal and distal ends of the humerus and scapula, respectively. Scapula cartilage was defined as 1 mm thick and the humerus cartilage as 0.5 mm thick (E=30MPa, ν=0.45) [10]. Frictionless contact was defined between the humerus and scapula cartilage.

The coracohumeral ligament (CHL), superior glenohumeral ligament (SGHL), middle glenohumeral ligament (MGHL), and inferior glenohumeral ligament (IGHL) were modeled as axial springs (Fig. 1).

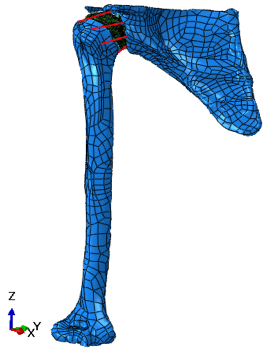

Figure 1: Finite element model of shoulder joint with ligaments (red)

The model was kinematically constrained along the scapula, and a 15 degree abduction was enforced on the humerus while translational components of the humerus were left unconstrained. The simulation was run with ligaments at three stiffness values: (1) the average value reported in the literature, (2) low: the average value minus the reported standard deviation, and (3) high: the average stiffness plus the reported standard deviation (Table 1). No stiffness values were found for the MGHL, therefore the average of the SGHL and IGHL were used. The kinematics of the humerus and cartilage contact pressure was recorded under the three stiffness levels.

Table 1: Stiffness for ligaments, K (N/mm) [7-8]

	CHL	SGHL	MGHL	IGHL
Low	30.8	15.9	15.6	15.4
Avg	36.7	17.4	21.4	25.4
High	42.6	18.9	27.1	35.4

RESULTS AND DISCUSSION

From the simulation results, it is interesting that the translational motion of the humerus remained almost the same for the first 5° of abduction. After 5° of abduction motion, the medial-lateral translation began to change for low, average and high ligament stiffness. By 15°, medial translation for average stiffness ligaments was 16.6% higher than low stiffness ligaments and 7.9% lower than high stiffness ligaments (Fig. 2). On the other hand, at 15° abduction, anterior translation for average stiffness ligaments was 1.7% higher than high stiffness ligaments and 4.3% lower than low stiffness ligaments (Fig. 3).

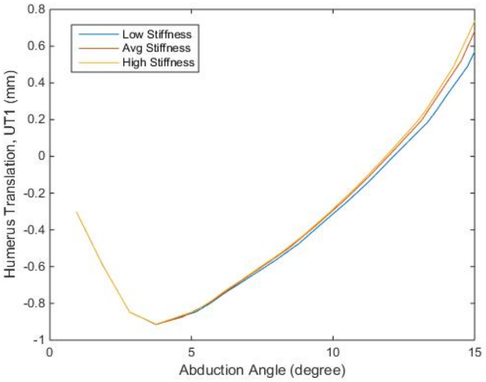

Figure 2: Humerus medial-lateral translation

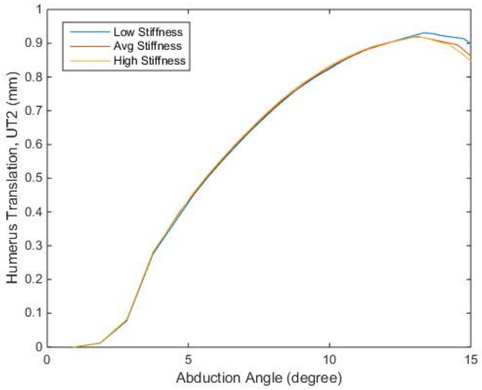

Figure 3: Humerus anterior-posterior translation

The average contact pressure of the scapula cartilage was nearly constant for all stiffness values until 5° of abduction, as expected, since there was no change in translation motion of humerus until 5° of abduction (Fig. 4). But after 5°, the changes in cartilage contact pressure was abrupt – possibly because of differences in the topology of the scapula cartilage surfaces that were in contact. After 13° of abduction, the cartilage contact pressure rose sharply and varied for all three stiffness values. The medial-lateral and anterior-posterior translation changes observed after 10° might be contributing to the cartilage contact pressure differences. A similar phenomena was also observed for the humerus cartilage contact pressure.

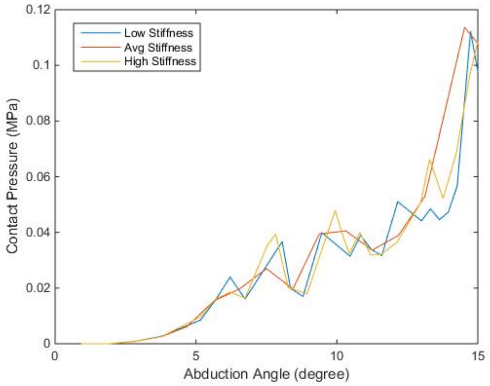

Figure 4: Scapula cartilage contact pressure during abduction

Our results suggest that the translation of humerus can be sensitive to ligament stiffness. This sensitivity of the humerus translation motion also has contributing effects on how the contact pressures are generated in cartilage. This is important for both experimental studies where care should be taken to not disturb the ligaments when measuring cartilage mechanics and modeling studies that make use of this experimental data. To date, we have not validated our model, but experimental procedures are going on to validate the simulation results.

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