Published in final edited form as:

Comput Methods Biomech Biomed Engin. 2010 June ; 13(3): 413–418. doi:
10.1080/10255840903317378.

Finite Element Modelling of the Glenohumeral Capsule Can Help Assess the Tested Region during a Clinical Exam

Benjamin J Ellis^{*}, Nicholas J. Drury^{**}, Susan M. Moore^{***}, Patrick J. McMahon^{**}, Jeffrey A. Weiss^{*}, and Richard E. Debski^{**}

^{*}Department of Bioengineering, and Scientific Computing and Imaging Institute, University of Utah, Salt Lake City, UT

^{**}Musculoskeletal Research Center, Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA

^{***}Mining Injury and Prevention Branch National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, Pittsburgh, PA

Abstract

The objective of this research was to examine the efficacy of evaluating the region of the glenohumeral capsule being tested by clinical exams for shoulder instability using finite element models of the glenohumeral joint. Specifically, the regions of high capsule strain produced by glenohumeral joint positions commonly used during a clinical exam were identified. Kinematics that simulated a simple translation test with an anterior load at three external rotation angles were applied to a validated, subject-specific finite element model of the glenohumeral joint at 60° of abduction. Maximum principal strains on the glenoid side of the IGHL were significantly higher than the maximum principal strains on the humeral side, for all three regions of the IGHL at 30° and 60° of external rotation. These regions of localized strain indicate that these joint positions might be used to test the glenoid side of the IGHL during this clinical exam, but are not useful for assessing the humeral side of the IGHL. The use of finite element models will facilitate the search for additional joint positions that isolate high strains to other IGHL regions, including the humeral side of the IGHL.

Keywords

inferior glenohumeral ligament; soft tissue mechanics; strain; finite element

Introduction

Approximately 5.6 million people will dislocate their glenohumeral joint (Hovelius, 1982, Nelson and Arciero, 2000) during their lifetime and eighty percent of these dislocations will occur in the anterior direction (Cave, 1974). Common injuries resulting from anterior dislocation are detachment of the inferior glenohumeral ligament (IGHL) from the anterior glenoid and labrum (Bankart, 1923, Bankart, 1938) and humeral avulsion of the glenohumeral ligaments (Bokor et al., 1999, Bui-Mansfield et al., 2002, Chhabra et al., 2004, Richards and Burkhart, 2004, Sailer and Imhof, 2004, Schippinger et al., 2001, Warner and Beim, 1997). Physical diagnostic exams are the most crucial step for diagnosis of the location of injury to the capsule (Brenneke et al., 2000, Mallon and Speer, 1995,

Matsen, 1991, Pollock and Bigliani, 1993), but the exams are relatively imprecise and the glenohumeral joint positions used for these exams are not standardized between physicians. Treatments for these injuries depend on the region of the capsule that is injured (Gerber and Ganz, 1984), but misdiagnosis of the injured region has been blamed for over 38% of recurring injuries (Cooper and Brems, 1992, Hawkins and Hawkins, 1985, Lusardi et al., 1993).

During these exams, clinicians apply forces to the humerus to translate the humeral head with respect to the glenoid. These forces also produce strains in the glenohumeral capsule (Malicky et al., 2002, Moore, 2008b), which is the primary passive stabilizer of the glenohumeral joint. The magnitudes of the resulting translations are then graded (Rockwood, 1998). Assessments are based on the application of a manual maximum force so that a firm end point is reached, restricting further translation (Harryman, 1992, Lippitt and Matsen, 1993, Rockwood, 1998). The orientation of the glenohumeral joint has been shown to influence both the magnitude of the translations (Moore et al., 2004) and the clinician's diagnostic reproducibility (Levy et al., 1999, Tzannes et al., 2004). Finally, as the external rotation angle is increased patients often feel a sense of apprehension and/or discomfort caused by the exam (Gerber and Ganz, 1984, Lo et al., 2004, Silliman and Hawkins, 1993). Currently, the patient's indication of apprehension and/or pain is useful for the physician to help diagnose the injury, but this method is purely subjective, depending as much on the patient's pain threshold as on the extent of the injury.

Poor clinical outcomes, inconsistent clinical exams and complex glenohumeral capsule anatomy have motivated researchers to investigate the function of the specific regions of the glenohumeral capsule by evaluating their strain distributions (Turkel et al., 1981, Moore, 2008c, Bigliani et al., 1992, Brenneke et al., 2000, Malicky et al., 2001a). Subject-specific finite element modeling of the glenohumeral joint is a useful tool for predicting capsule strains (Debski et al., 2005, Ellis et al., 2007) (Moore, 2008a) and this method is able to predict experimentally measured strains (Ellis et al., 2006, Moore, 2008a).

Using strain to identify positions in which connective soft tissues stabilize a diarthrodial joint has been used extensively for the anterior cruciate ligament (ACL) of the knee (Butler, 1989, Henning et al., 1985, Howe et al., 1990, Renstrom et al., 1986, Woo et al., 1987). These studies led to the development of clinical exams (Katz and Fingerhuth, 1986) to diagnose knee instability and injury to the ACL. It is generally accepted that an anterior load should be applied to the tibia while the knee is at 30° of flexion to test for ACL injury. In this position, the injured knee will usually have increased translation compared to the contralateral, uninjured knee. Although, clinical exams for the ACL are standardized and commonly used, extensive research was needed for their development. The starting point was to improve the understanding of knee positions that strained the ACL. Due to the complexity of the strains in the glenohumeral capsule during joint motion (Malicky et al., 2002, Malicky et al., 2001b, Moore, 2008b), a method to correlate glenohumeral joint positions and the capsule strains produced by these positions is needed. As with the ACL, identifying the positions in which the glenohumeral capsule is strained and where those strains occur in the capsule is the first step to developing clinical exams.

The objective of this research is to conduct a feasibility study to examine the efficacy of developing clinical exams using finite element models of the glenohumeral joint by locating the regions of highly strained capsule tissue at multiple joint positions. The long-term research goal is to find joint positions for clinical exams that isolate the region of the capsule being tested, so that accurate diagnoses can be made, without subjective patient input and causing discomfort to the patient. Based on a qualitative analysis of previously reported experimental strains in the glenohumeral capsule (Moore, 2008b), it was hypothesized that

the simple translation test with an anterior load would strain the glenoid side of the IGH in the finite element model more than the humeral side at 30° and 60° of external rotation. Data addressing this hypothesis could suggest that these joint positions would be ideal for diagnosing injuries to this frequently injured region of the tissue.

Methods

The details of the construction of the subject-specific finite element model of the glenohumeral joint used in this study and its validation with experimental strain data were reported previously (Moore, 2008a); a brief description follows. The geometry of the humerus, scapula, and capsule were obtained from a computed tomography (CT) data set of a shoulder cadaver specimen (male, 45 years old, left) while the humerus and scapula were in the reference position and the capsule was in its reference configuration. For the finite element model, bones and humeral cartilage were represented with rigid bodies and the glenohumeral capsule was modeled with shell elements. Based on material testing of the capsular tissue from this shoulder, an isotropic hypoelastic constitutive model with regionally varying subject-specific elastic moduli and Poisson's ratios of 0.495 were used to represent the three regions of the IGH (anterior band (AB-IGH), axillary pouch, and posterior band (PB-IGH)) and the anterior-superior and posterior capsule regions. Model validation was performed by comparing predicted strains from the finite element model to experimentally measured strains during kinematics that simulated the simple translation test. Eight of the eleven sampling regions were found to be within two times the repeatability of the experimental strain measurements ($\pm 7\%$).

For this study, the kinematics applied to the finite element model simulated the simple translation test with an anterior load performed at three external rotation angles that are commonly used by physicians to examine anterior stability. To experimentally simulate the clinical exam, a cadaveric shoulder specimen (same as that used for the validated finite element model) was mounted in a robotic/universal force-moment sensor testing system that has been extensively used previously (Debski et al., 2005, Ellis et al., 2007, Moore, 2008a, Moore, 2008b). The humerus was secured within a thick-walled aluminum cylinder and fixed in a custom clamp mounted to the base of the system. The scapula was rigidly attached to the end-effector of the manipulator through another specially designed clamp and the universal force-moment sensor. The coordinate system of the robotic/universal force-moment sensor testing system was then defined as the anatomic coordinate system of the glenohumeral joint as previously described (Burkart and Debski, 2002, Debski et al., 1999).

The initial joint orientation in the testing system was 60° of glenohumeral abduction, 0° of horizontal abduction, and 0° of external rotation. The horizontal abduction angle was held constant throughout the entire experimental protocol. Force control was then used to apply a 22 Newton (N) compressive load (medially directed) to the humerus while the forces in the two orthogonal directions were minimized (~ 0 N). This centered the humeral head within the glenoid cavity and determined the joint position at 60° of glenohumeral abduction and 0° of external rotation. At this joint position, a 25 N anterior load was applied to the humerus, while maintaining the 22 N compressive force, and the resulting kinematics were recorded by recording the locations of registration blocks attached to the humerus and scapula with an external digitizer (Microscribe 3DX, Immersion Corporation, San Jose, CA). Preliminary testing indicated that, with the skin and musculature removed, an anterior load of 25N, while maintaining a compressive load of 22 N, would translate the humeral head to the edge of the glenoid without resulting in dislocation or subluxation.

To simulate the clinical exam at 30° and 60° external rotation, an increasing moment with a maximum of 3 Newton-meters (Nm) was applied to the humerus about its longitudinal axis

while maintaining the 22 N joint compressive force until the joint positions corresponding to 30° and ~60° external rotation, respectively, were reached. At these joint positions, the 25 N anterior load was applied to the humerus, while maintaining the 22 N compressive force, and the resulting kinematics were recorded.

The kinematics at each external rotation angle, recorded by the external digitizer during testing, were input into the finite element code as previously described (Debski et al., 2005, Ellis et al., 2007, Moore, 2008a). The coordinates of the registration blocks in both the CT and kinematic datasets allowed for correlation of the two datasets. Motion was described during the finite element simulations using incremental translations and rotations (Maker, 1995) from the reference position to the positions during the simple translation test, based on the experimental measurements of the locations of the registration blocks on the humerus and scapula in each position. The nonlinear finite element code NIKE3D was used for all analyses (Maker, 1995). LSPOST (Livermore Software Technology Corporation, Livermore, CA, USA) was used to visualize and process the predicted strains.

To compare strains within regions of the IGHL, the AB-IGHL, axillary pouch, and PB-IGHL were divided midway between their glenoid and humeral insertion sites, yielding a total of six IGHL sub-regions for analysis (Figure 1). The nodal maximum principal strains in each sub-region were averaged for each external rotation angle. An unbalanced GLM 2-way ANOVA procedure in SPSS (SPSS Inc., Chicago, IL) was used to compare regional strains at each rotation angle. Post-hoc comparisons were performed using the Tukey test. Statistical comparisons were only considered to be significant if the differences were statistically significant ($p < 0.05$) and the average strain difference was greater than the repeatability of the experimental strain measurements ($\pm 3.5\%$).

Results

While IGHL strains were relatively small and more evenly dispersed between the glenoid and humeral sides of the IGHL during finite element simulations of the simple translation test at 0° of external rotation, more tissue was strained with much higher peak strains on the glenoid side of the IGHL when the simple translation test was simulated at 30° and 60° of external rotation (Figure 1). The end result of these loading conditions was highly strained tissue on the glenoid side of the IGHL, especially the AB-IGHL, with slack, essentially non-strained tissue on the humeral side of the IGHL, especially the PB-IGHL.

Quantitative comparisons between the glenoid and humeral sides of the IGHL support the qualitative evaluations. Maximum principal strains on the glenoid side of the IGHL were significantly higher than the maximum principal strains on the humeral side when the simple translation test was simulated at 30° and 60° of external rotation ($p < 0.05$ for all three regions at both rotation angles), but not at 0° of external rotation (Figure 2). Maximum principal strains on the glenoid side of the AB-IGHL were more than 1.5 times higher and nearly four times higher than on the humeral side at 30° and 60° of external rotation, respectively. The maximum principal strains in the axillary pouch on the glenoid side were more than two times higher than the humeral side at both 30° and 60° of external rotation. Maximum principal strains on the glenoid side of the PB-IGHL were over three times higher than on the humeral side at 30° and over four times higher at 60° of external rotation. There were no significant differences in the maximum principal strains between the humeral and glenoid sides of all three sub-regions of the IGHL when the simple translation test was conducted at 0° of external rotation. Finally, the strains in the AB-IGHL were significantly higher than the other regions on both the glenoid and humeral sides of the IGHL ($p < 0.05$ for all comparisons) with the glenoid side of the AB-IGHL consistently having the highest strains

compared to all the other regions at every external rotation angle ($p < 0.05$ for all comparisons).

Discussion

In this study the maximum principal strain throughout the IGHL was determined during a simple translation test at three external rotation angles using a validated subject-specific finite element model of the glenohumeral joint. The strains on the glenoid side of each IGHL region were significantly higher than on the humeral side at 30° and 60° of external rotation, but not at 0°, which supported the hypothesis of this study. Further, the strain predictions from the subject-specific finite element model compared well with experimental data from a sample of five shoulders subjected to the simple translation test that was reported previously (Moore, 2008b). Both studies indicate that the simple translation test with an anterior load performed at 30° and 60° of external rotation localizes tissue strains to the glenoid side of the IGHL. This agreement further validates the results in the previous finite element study (Moore, 2008a).

The similar strain magnitudes between 30° and 60° of external rotation for most sub-regions of the IGHL imply that clinicians are testing the glenoid side of the IGHL when this exam is performed anywhere from 30° to 60° of external rotation. The data also suggest that different regions of the IGHL, particularly the AB-IGHL, may be strained significantly more than other areas of the IGHL during the simple translation test, potentially allowing clinicians to further isolate the area being tested.

The glenoid side of the AB-IGHL also had the greatest amount of strain at all external rotation angles, supporting the general concept that the AB-IGHL is frequently injured at its glenoid insertion (Bankart, 1923, Bankart, 1938). In the context of the simple translation test with an anterior load, it appears that when this test is administered at 60° of external rotation, the area around the glenoid side of the AB-IGHL is isolated. It can also be inferred that the apprehension test, a clinical exam that determines the patient's apprehension to external rotation, is probably isolating the same area, with some bias to the glenoid side of the IGHL.

Both this study and the previous experimental study (Moore, 2008b) clearly show that the humeral side of the IGHL is not loaded when the simple translation test is administered at external rotation angles equal to or exceeding 30°. Further, when the results of these studies are taken together, it appears that the strains on the humeral side are fairly inconsistent between specimens when the simple translation test with an anterior load is performed at 0° of external rotation. For these reasons, the simple translation test with an anterior load may not be appropriate for testing the humeral side of the IGHL. Injuries such as humeral avulsion of the glenohumeral capsule (Bokor et al., 1999, Bui-Mansfield et al., 2002, Chhabra et al., 2004, Richards and Burkhart, 2004, Sailer and Imhof, 2004, Schippinger et al., 2001, Warner and Beim, 1997) would probably be missed using this simple translation test.

This computational analysis had three primary weaknesses: sample size ($n=1$); the exclusion of the labrum; and the use of a hypoelastic constitutive equation in the finite element model. Previous studies have shown that there are variations in the strain patterns between specimens (Moore, 2008a), but this study used only a single validated FE model based on a single specimen (Moore, 2008b). In the future, a population of finite element models will be constructed and validated to predict the variation in the population on a subject-specific basis and assess the current trends predicted in the current study. Furthermore, the finite element model used for this study does not include the labrum. The lack of a labrum will

increase strains at the glenoid insertion (where the labrum would be), but will slightly decrease strains in the mid-substance tissue adjacent to the glenoid for every region of the IGHL (Drury, 2009). In this study, strains were averaged over large areas to compare the strain distribution between regions and joint position. Therefore, the IGHL sub-region (i.e. glenoid side of the AB-IGHL) that is tested by this clinical exam can be distinguished, but the location of the peak strain values might not be correct (i.e. mid-tissue vs. labrum vs. labrum-capsule interface). Finally, a hypoelastic material model was used to represent the glenohumeral capsule material. Hypoelasticity is objective for finite deformations (i.e., large strains and rotations) (Simo and Hughes, 1998) and the limitations of using this material model for the IGHL have previously been discussed (Ellis et al., 2007). In the context of the current study, use of a hypoelastic material might change the magnitudes of the strains, but will have very little effect on their distribution. Even though a few weaknesses exist, our results are strongly supported by previous experimental data that examined five cadaveric shoulders (Moore, 2008a).

This study established a methodology to assess the capsule regions tested (strained) by clinical exams using a computational model. Once the region tested is identified, the next step, as was done for the ACL, is to look for side-to-side differences in translation between injured and uninjured shoulders in these joint positions using a repeatable methodology. Many of the discrepancies and complications with clinical exams for shoulder injuries (Levy et al., 1999, Tzannes et al., 2004) may be due to a lack of a systematic approach while developing the exams. In the future, diagnostic methods that are based on quantitative results from standardized clinical exams that do not cause discomfort to the patient or require their subjective responses would be advantageous. Our research group is currently in the process of constructing subject-specific finite element models of the glenohumeral capsule that include the labrum (Drury, 2009) and the proper constitutive model representing the capsule with a fiber-reinforced, hyperelastic material model. We hope to determine effective joint positions for clinical exams using a population of subject-specific finite element models of the glenohumeral joint.

Acknowledgments

Financial support from the National Institutes of Health (AR47369 and AR050218) is gratefully acknowledged.

References

- Bankart ASB. Recurrent or habitual dislocation of the shoulder joint. *Br Med J*. 1923; 2:1132–3. [PubMed: 20771383]
- Bankart ASB. The pathology and treatment of recurrent dislocation of the shoulder joint. *Br J Surg*. 1938; 26:23–9.
- Bigliani LU, Pollock RG, Soslowsky LJ, Flatow EL, Pawluk RJ, Mow VC. Tensile properties of the inferior glenohumeral ligament. *J Orthop Res*. 1992; 10:187–97. [PubMed: 1740736]
- Bokor DJ, Conboy VB, Olson C. Anterior instability of the glenohumeral joint with humeral avulsion of the glenohumeral ligament. A review of 41 cases. *J Bone Joint Surg Br*. 1999; 81:93–6. [PubMed: 10068012]
- Brenneke SL, Reid J, Ching RP, Wheeler DL. Glenohumeral kinematics and capsulo-ligamentous strain resulting from laxity exams. *Clin Biomech (Bristol, Avon)*. 2000; 15:735–42.
- Bui-Mansfield LT, Taylor DC, Uhorchak JM, Tenuta JJ. Humeral avulsions of the glenohumeral ligament: imaging features and a review of the literature. *AJR Am J Roentgenol*. 2002; 179:649–55. [PubMed: 12185037]
- Burkart AC, Debski RE. Anatomy and function of the glenohumeral ligaments in anterior shoulder instability. *Clin Orthop Relat Res*. 2002;32–9. [PubMed: 12072743]

- Butler DL. Kappa Delta Award paper. Anterior cruciate ligament: its normal response and replacement. *J Orthop Res.* 1989; 7:910–21. [PubMed: 2677288]
- Cave, E.; Burke, J.; Boyd, R. *Trauma Management.* Chicago, IL: Year Book Medical Publishers; 1974.
- Chhabra A, Diduch DR, Anderson M. Arthroscopic repair of a posterior humeral avulsion of the inferior glenohumeral ligament (HAGL) lesion. *Arthroscopy.* 2004; 20(Suppl 2):73–6. [PubMed: 15243431]
- Cooper RA, Brems JJ. The inferior capsular-shift procedure for multidirectional instability of the shoulder. *J Bone Joint Surg Am.* 1992; 74:1516–21. [PubMed: 1469011]
- Debski RE, Weiss JA, Newman WJ, Moore SM, McMahon PJ. Stress and strain in the anterior band of the inferior glenohumeral ligament during a simulated clinical examination. *J Shoulder Elbow Surg.* 2005; 14:S24–31.
- Debski RE, Wong EK, Woo SLY, Sakane M, Fu FH, Warner JJ. In situ force distribution in the glenohumeral joint capsule during anterior-posterior loading. *J Orthop Res.* 1999; 17:769–76. [PubMed: 10569490]
- Drury NJ, Ellis BJ, Weiss JA, McMahon PJ, Debski RE. The Impact of Glenoid Labrum Thickness and Modulus on Labrum and Glenohumeral Capsule Pathology. Submitted to *J Shoulder Elbow Surg.* 2009
- Ellis BJ, Debski RE, Moore SM, McMahon PJ, Weiss JA. Methodology and sensitivity studies for finite element modeling of the inferior glenohumeral ligament complex. *J Biomech.* 2007; 40:603–12. [PubMed: 16580002]
- Ellis BJ, Lujan TJ, Dalton MS, Weiss JA. Medial collateral ligament insertion site and contact forces in the ACL-deficient knee. *J Orthop Res.* 2006; 24:800–10. [PubMed: 16514656]
- Gerber C, Ganz R. Clinical assessment of instability of the shoulder. With special reference to anterior and posterior drawer tests. *J Bone Joint Surg Br.* 1984; 66:551–6. [PubMed: 6746691]
- Harryman DT 2nd, Sidles JA, Matsen FA 3rd. Laxity of the normal glenohumeral joint: A quantitative in vivo assessment. *J Should Elbow Surg.* 1992; 1:66–76.
- Hawkins RH, Hawkins RJ. Failed anterior reconstruction for shoulder instability. *J Bone Joint Surg Br.* 1985; 67:709–14. [PubMed: 4055865]
- Henning CE, Lynch MA, Glick KR Jr. An in vivo strain gage study of elongation of the anterior cruciate ligament. *Am J Sports Med.* 1985; 13:22–6. [PubMed: 3976977]
- Hovellius L. Incidence of shoulder dislocation in Sweden. *Clin Orthop.* 1982:127–31. [PubMed: 7083659]
- Howe JG, Wertheimer C, Johnson RJ, Nichols CE, Pope MH, Beynnon B. Arthroscopic strain gauge measurement of the normal anterior cruciate ligament. *Arthroscopy.* 1990; 6:198–204. [PubMed: 2206182]
- Katz JW, Fingerhuth RJ. The diagnostic accuracy of ruptures of the anterior cruciate ligament comparing the Lachman test, the anterior drawer sign, and the pivot shift test in acute and chronic knee injuries. *Am J Sports Med.* 1986; 14:88–91. [PubMed: 3752353]
- Levy AS, Lintner S, Kenter K, Speer KP. Intra- and interobserver reproducibility of the shoulder laxity examination. *Am J Sports Med.* 1999; 27:460–3. [PubMed: 10424215]
- Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Relat Res.* 1993:20–8. [PubMed: 8504601]
- Lo IK, Nonweiler B, Woolfrey M, Litchfield R, Kirkley A. An evaluation of the apprehension, relocation, and surprise tests for anterior shoulder instability. *Am J Sports Med.* 2004; 32:301–7. [PubMed: 14977651]
- Lusardi DA, Wirth MA, Wurtz D, Rockwood CA Jr. Loss of external rotation following anterior capsulorrhaphy of the shoulder. *J Bone Joint Surg Am.* 1993; 75:1185–92. [PubMed: 8354677]
- Maker, BN. Lawrence Livermore Lab Tech Rept. 1995. NIKE3D: A nonlinear, implicit, three-dimensional finite element code for solid and structural mechanics. UCRL-MA-105268
- Malicky DM, Kuhn JE, Frisanchio JC, Lindholm SR, Raz JA, Soslowsky LJ. Neer Award 2001: nonrecoverable strain fields of the anteroinferior glenohumeral capsule under subluxation. *J Shoulder Elbow Surg.* 2002; 11:529–40. [PubMed: 12469076]

- Malicky DM, Soslowky LJ, Kuhn JE, Bey MJ, Mouro CM, Raz JA, Liu CA. Total strain fields of the antero-inferior shoulder capsule under subluxation: a stereoradiogrammetric study. *J Biomech Eng.* 2001a; 123:425–31. [PubMed: 11601727]
- Malicky DM, Soslowky LJ, Kuhn JE, Bey MJ, Mouro CM, Raz JA, Liu CA. Total strain fields of the antero-inferior shoulder capsule under subluxation: a stereoradiogrammetric study. *J Biomech Eng.* 2001b; 123:425–31. [PubMed: 11601727]
- Mallon WJ, Speer KP. Multidirectional instability: current concepts. *J Shoulder Elbow Surg.* 1995; 4:54–64. [PubMed: 7874566]
- Matsen FA 3rd. Capsulorrhaphy with a staple for recurrent posterior subluxation of the shoulder. *J Bone Joint Surg Am.* 1991; 73:950. [PubMed: 2071630]
- Moore SM, Ellis BJ, Weiss JA, McMahon PJ, Debski RE. The Glenohumeral Capsule Should be Evaluated as a Sheet of Fibrous Tissue: Validation of a Subject-specific Finite Element Model. *Annals of Biomedical Engineering.* 2008a In Review.
- Moore SM, Musahl V, McMahon PJ, Debski RE. Multidirectional kinematics of the glenohumeral joint during simulated simple translation tests: impact on clinical diagnoses. *J Orthop Res.* 2004; 22:889–94. [PubMed: 15183451]
- Moore SM, Stehle JH, Rainis EJ, McMahon PJ, Debski RE. The Current Anatomical Description of the Inferior Glenohumeral Ligament Does Not Correlate with its Functional Role in Positions of External Rotation. *J Orthop Res.* 2008b In Press.
- Nelson BJ, Arciero RA. Arthroscopic management of glenohumeral instability. *Am J Sports Med.* 2000; 28:602–14. [PubMed: 10921658]
- Pollock RG, Bigliani LU. Glenohumeral Instability: Evaluation and Treatment. *J Am Acad Orthop Surg.* 1993; 1:24–32. [PubMed: 10675853]
- Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986; 14:83–7. [PubMed: 3752352]
- Richards DP, Burkhart SS. Arthroscopic humeral avulsion of the glenohumeral ligaments (HAGL) repair. *Arthroscopy.* 2004; 20(Suppl 2):134–41. [PubMed: 15243447]
- Rockwood, CA.; Matsen, FA., 3rd; Wirth, MA.; Harryman, DT, 2nd. *The Shoulder.* 2. Vol. 1998. Philadelphia, PA: W. B. Saunders Co; 1998.
- Sailer J, Imhof H. Shoulder instability. *Radiologe.* 2004; 44:578–90. [PubMed: 15150645]
- Schippinger G, Vasiu PS, Fankhauser F, Clement HG. HAGL lesion occurring after successful arthroscopic Bankart repair. *Arthroscopy.* 2001; 17:206–8. [PubMed: 11172253]
- Silliman JF, Hawkins RJ. Classification and physical diagnosis of instability of the shoulder. *Clin Orthop Relat Res.* 1993; 7–19. [PubMed: 8504616]
- Simo, JC.; Hughes, TJR. *Computational Inelasticity.* New York: 1998.
- Turkel SJ, Panio MW, Marshall JL, Girgis FG. Stabilizing mechanisms preventing anterior dislocation of the glenohumeral joint. *J Bone Joint Surg Am.* 1981; 63:1208–17. [PubMed: 7287791]
- Tzannes A, Paxinos A, Callanan M, Murrell GA. An assessment of the interexaminer reliability of tests for shoulder instability. *J Shoulder Elbow Surg.* 2004; 13:18–23. [PubMed: 14735068]
- Warner JJ, Beim GM. Combined Bankart and HAGL lesion associated with anterior shoulder instability. *Arthroscopy.* 1997; 13:749–52. [PubMed: 9442330]
- Woo SL, Hollis JM, Roux RD, Gomez MA, Inoue M, Kleiner JB, Akeson WH. Effects of knee flexion on the structural properties of the rabbit femur-anterior cruciate ligament-tibia complex (FATC). *J Biomech.* 1987; 20:557–63. [PubMed: 3611132]

Figure 1.

Inferior view (left shoulder) of fringe plots of IGH 1st Principal strains at 60° degrees abduction and full anterior translation at 0°, 30°, and 60° of external rotation. (A) Humerus. (B) Glenoid. (C) IGH Mid-line. (D) AB-IGH. (E) Axillary Pouch. (F) PB-IGH. The glenoid side of the IGH is consistently loaded more than the humerus side at 30° and 60° of external rotation.

Figure 2.

Maximum principal strains at 0°, 30°, and 60° of external rotation on the glenoid and humeral sides of each IGHL region. Maximum principal strains were significantly higher on the glenoid side for each IGHL region at 30° and 60° of external rotation, but not at 0°. (* $p < 0.05$) (mean $\pm$ SD).