MODELING THE EFFECTS OF THE IMPLANT GEOMETRY OF THE TOTAL SHOULDER REPLACEMENT ON THE JOINT KINEMATICS AND CONTACT MECHANICS

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INTRODUCTION

Total shoulder replacement involves resurfacing of the articular surface of the glenoid and the humeral head. These changes in anatomy will change lever arms of the muscles and soft tissue tension, and may result in abnormal kinematics [1, 2]. The shallow glenoid cavity does not greatly constrain the humeral head; therefore glenohumeral translations after total shoulder replacement are of particular interest [3, 4, 5]. Less conforming designs have been found to generate less translation and lower translational forces. Standard humeral prostheses do not take into account anatomical variations. The poor clinical results led to the appearance of the modular shoulder prostheses, with variation of the diameter and thickness of the humeral head and the size of the glenoid. By using this, surgeons can match the humeral head and glenoid, and also the angle of the humeral head and the neck of the shaft (inclination angle and retroversion angle).

The purpose of this study is to investigate the effects of the three dimensional geometry on kinematics and contact at the glenohumeral joint. This includes the radius, thickness, inclination and retroversion angle of the humeral head and the radius and the depth of the glenoid. A mathematical model will be used to model the glenohumeral joint. The model will observe the glenohumeral joint response to an external moment loading pattern where the humerus is abducted, extended and externally rotated, similar to reaching to comb the hair. Sensitivity of the three translations and rotations of the joint to variation of the geometry parameters will be explored, along with the response of contact force, area and stress. By understanding the sensitivity of joint kinematics and contact mechanics, identification of important design parameters for total shoulder replacement can be made. Previous modeling studies have generally been interested only in implant fixation and have not included muscle forces or soft tissues.

METHODS

To describe humeral head motion relative to the glenoid, right – handed coordinate systems were defined with three unit vectors [6]. The glenoid surface was a portion of sphere with radius, r_G, described by a partial sphere, with $\mathbf{g}$(x, y, z), for $g_x \leq 0$, as:

$$r_G^2 = \left(g_x - d\right)^2 + g_y^2 + g_z^2$$

where d is the distance from the center of the sphere to the origin of the glenoid coordinate system (center of the glenoid sphere). The depth of the glenoid is r_G-d. The humeral head surface was described as a partial sphere with radius r_H. The extent and orientation of the partial sphere was determined from four in vitro specimens by the digitization of the humeral head surface [7, 8]. The humeral surface in the glenoid coordinate system was formulated as:

$$r_H^2 = \left(c_{ix} - p_x\right)^2 + \left(c_{iy} - p_y\right)^2 + \left(c_{iz} - p_z\right)^2$$

where p is the origin of the sphere. Points, c_i, on the sphere also satisfied a description of the partial sphere:

$$r_C^2 \geq \left(c_{ix} - c_{rx}\right)^2 + \left(c_{iy} - c_{ry}\right)^2 + \left(c_{iz} - c_{rz}\right)^2$$

where $\mathbf{c_r}$ is the center of the rim and r_C is the radius of the rim. The inclination angle was the angle between the x-axis of the humeral coordinates system and the vector c_r. The retroversion angle was the angle between the frontal plane and epicondylar axis, which is the z-axis of the humeral coordinate system.

Three external 3Nm moments were applied in the humeral coordinate system to move the humerus in abduction, extension and external rotation. The resulting total contact force F_c and the total articular contact moment M_c about the origin of the glenoid coordinate system were calculated using a simple deformable contact model. The model also included representation of five glenohumeral ligaments and forces applied through four rotator cuff muscles [9, 10, 11, 12]. For a given position and orientation, the path of a ligament and muscle elements might run linearly from origin to insertion or wrap if the head surface was interposed. The method to find the path of the element assumed that it would have the shortest length [6]. The ligament tension was applied to the humerus if its length was greater than its initial length and the muscle forces were applied in relation to their cross-sectional areas [7].

Forces and moments acting on the humerus were those from articular contact, ligament elements, the muscles and those externally applied. Force and moment equilibrium resulted six equations:

$$F_{eG} + F_C + F_L + F_M = F_{SUM} \approx 0$$

$$M_{eG} + M_C + M_L + M_M = M_{SUM} \approx 0$$

The model was solved for the position (X, Y, Z) and (RZ, RY, RX) orientation. The solution was performed by a hybrid-form of Powell method for non-linear equations.

The goal of this study was to analyze the effects that the three-dimensional implant geometry. The radius, thickness, inclination and retroversion angle of the humeral head and the radius and the depth of the glenoid were varied. The sensitivity of the humeral translations and rotations and the contact forces and areas to these geometric variables was determined. When one parameter was changed, the others were fixed at the values of the average shoulder.

All geometric parameters were varied through a common range of values for total shoulder replacement: humeral head radius (21.9-26.3 mm); humeral head thickness (12.3-19.5 mm); inclination angle (115-145^0); and retroversion angle (0-30^0); glenoid radius (25.5-29.5 mm); glenoid depth (3.9-6.9 mm). Comparisons were made between the average geometry and the other incremental changes in total shoulder joint geometries.

RESULTS AND DISCUSSION

The radius of the humeral head. The increase in the radius of the humeral head sphere resulted in less translation, less extension and more abduction with the external rotation unchanged. On the articular surface, the contact area decreased. The magnitude of the contact force did not change, though, so the stress on the surface increased.

The radius of the glenoid. Increasing the radius of glenoid sphere allowed the humeral head to translate more, extend less and externally rotate more. The contact area and the contact stress were unchanged.

The thickness of the humeral head. More superior-inferior translation was found by increasing the humeral head thickness. Also the humerus externally rotated more and extended less. Although increasing thickness increased the overall area of the humeral head surface, the contact area did not change. A slightly increasing magnitude of the contact force did not result in greater contact stress.

The depth of the glenoid. Increasing the depth of the glenoid resulted in the less anterior-posterior and superior-inferior translation, more extension and less external rotation. Increasing the humeral head thickness did not make the contact area increase but the increasing in the depth of the glenoid did. Due to the more centered location of the humeral head in the glenoid, the magnitude of the contact force decreased. This resulted in a large decrease in the contact stress.

The retroversion angle of the humeral head. There was a pattern of increased posterior and inferior translation with increased retroversion angle. There was increasing articular contact force. Also the contact area decreased, and so the contact stress increased. The increase in the retroversion angle externally rotated the humerus more with less extension (See Figure 1).

The inclination angle of the humeral head. No significant changes in translations were found with increasing inclination angle, but there was less extension and more abduction. The contact area and the contact stress were unchanged.

In general, ligament tensions were not needed for equilibrium to be met, due to the presence of the constant rotator cuff muscle forces. Only when the thickness of the humeral head was increased do the soft tissues show tensions at equilibrium.

This sensitivity analysis using analytical modeling methods provides information about how changes in the humeral head and glenoid geometries can affect glenohumeral kinematics for a common activity of daily living. This is in contrast to other modeling efforts that have mainly been concerned with implant fixation. These results give some indication of how changes to modular implants may change the loads transmitted to the glenoid component also, and thus could be coupled with current finite element models of glenoid component fixation. Future work on soft tissue loading and more realistic joint surfaces may lend greater understanding to the relationships between implant design, kinematics and functional results.

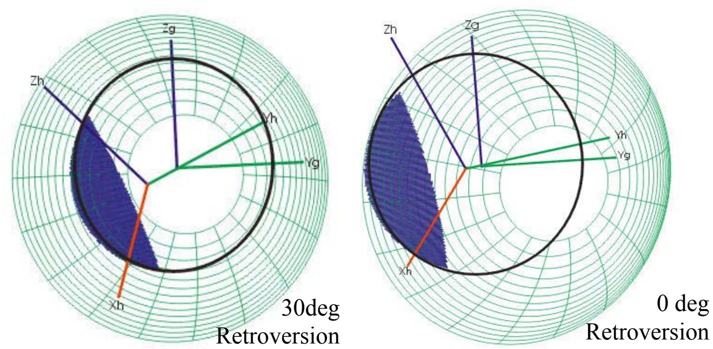

Figure1: Medially directed views onto the glenoid face of results for 0 and 30 degrees humeral retroversion angles. Glenoid rim is dark circle, with Xg, Yg, Zg coordinate system with +Yg anterior. Humeral coordinate system Xh, Yh, Zh, with Xh the long axis of the humerus and Zh the lateral to medial epicondylar line. Contact area is shaded. Humeral head is further posterior and inferior for 30 degrees and contact are is smaller.

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