MODELING THE EFFECTS OF ROTATOR CUFF MUSCLE ACTIVITY ON KINEMATICS, LIGAMENT TENSION AND ARTICULAR CONTACT AT THE GLENOHUMERAL JOINT

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INTRODUCTION

Various methods have been used to investigate rotator cuff muscle function including in vitro experiments, strength testing, EMG recording and muscle stimulation studies. Mathematical models could also provide the means to investigate the glenohumeral kinematics, mechanics and external loading conditions that are difficult to experimentally measure or simulate. At present, most models of the glenohumeral joint [1, 2, 3] simulate the motion of the humerus relative the torso. In general, the glenohumeral joint is described with only three degrees of freedom, and there is minimal information about how the structures within the glenohumeral joint may function in joint stability. A model [4] of the glenohumeral joint investigated glenohumeral ligament element tensions and contact forces for external loading simulating the cocked phase of throwing. Six-degree freedom motion was allowed so that the clinically important translations could be observed. Muscle forces were not modeled and the humeral head was represented as an entire spherical surface. The current study performs a more complex model of the humeral head and glenoid surfaces, the glenohumeral ligaments and the rotator cuff. The goal is to analyze the effects that the individual rotator cuff muscles have on humeral rotations and translations, joint contact forces and ligament element tensions during loading simulating the cocked phase of throwing. Sensitivity to variations in rotator cuff muscle forces are explored to describe their roles in joint stabilization during the cocked phase of throwing. Since the rotator cuff muscles have been shown to act synergistically, their effects when activated alone will be compared to their effects when varied with the other rotator cuff muscles activated at a constant level.

METHODS

To describe humeral head motion relative to the glenoid, right – handed coordinate systems were defined with three unit vectors. The glenoid surface was a portion of sphere with radius, r_G, where d was the distance from the center of the sphere to the origin of the glenoid coordinate system (center of the glenoid sphere) describing the depth of the glenoid as r_G-d. The humeral head surface was described as a partial sphere with radius r_H, with the extent and orientation of the determined from in vitro specimens [4]. The humeral head 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 center of the sphere at the origin of the humeral coordinate system. Points, c_i, of the sphere were those also satisfied:

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

where $\mathbf{c_r}$ is the center of the rim and the r_C is the radius of the rim. The resulting total contact force F_c and the total articular contact moment M_c about the humerus were calculated using a simple deformable contact model. The model also included representation of five ligaments (superior, middle and anterior, axillary pouch and posterior band of the inferior glenohumeral ligaments) and rotator cuff muscles (supraspinatus, infraspinatus (3 elements), subscapularis (3 elements) and teres minor. The origins and insertions of the muscles were obtained from the literature [1]. For a given position and orientation, the path of the ligament and muscle elements could run linearly from origin to insertion or wrap around the humeral head surface if it was interposed between the humeral insertions and scapular origins. The method to find the wrapping paths of the elements was previously described [4], and assumed that ligament or muscle would span the shortest possible path. Ligament forces were applied if the ligament element was stretched beyond its initial length [4]. Forces and moments acting on the humerus were those from articular contact, ligament element tension, the muscle forces and external forces. Forces and moments equilibrium resulted six equations, three for forces and three for moments. The model was solved for the position (X, Y, Z) and (RZ, RY, RX) orientation that minimized the summed forces and moments using a hybrid form of Powell method for non-linear equations.

The external loading pattern applied to the humerus simulated the cocked phase of throwing. Initially the rotator cuff muscles were loaded to a level defined in this study as the 100% force. These magnitudes were in proportion to their cross-section areas [5]. The magnitudes of each of the rotator cuff muscles were individually varied to 0%, 25%, 50%, 75%, 125%, 150% and 200% of the initial level both with the other muscles all at their 100% and at 0% force levels. This resulted in eight solutions for position and orientation at equilibrium for the eight loading conditions over the four cuff muscles with the other muscles activated or inactivated. Along with the kinematic parameters, the tensions in the five ligament elements and the contact force, contact area and contact stress on the glenoid joint surface were determined for each muscle loading combination.

RESULTS AND DISCUSSION

Total Rotator Cuff Activation

In the cocked phase of throwing the humeral head is abducted, extended and externally rotated, with an inferior and posterior location on the glenoid surface. Increasing to forces to the entire rotator cuff from 0%-200% resulted in centering of the humeral head as the Y and Z translations decreased, with less extension and external rotation, but more abduction. Contact force and stress initially decreased with the application of 25% total rotator cuff force compared to the 0% condition and the contact area increased. Then contact force, area and stress all increased gradually with muscle force from 25% to 200%. Ligament element tensions were only evident at 0% muscle force.

Individual Muscle Activation with Other Muscles Inactive

At the 0% level, the MGHL and IGHL resisted external loading.

Infraspinatus. The increase in infraspinatus muscle force from 0% to 200% resulted in greater extension and external rotation. For translations, an initial increase in inferior and posterior translation of the humeral head occurred with the application of 25% and 50% force. Contact stress was increased.

Subscapularis. Since the subscapularis is the only rotator cuff muscle located anterior to the humeral head the increase in its activation strongly moved the arm into flexion. Also, increasing subscapularis activation raised the humerus into greater abduction and internally rotated it. The subscapularis also acted to center the humeral head. This motion resulted in a gradual decrease in the contact force necessary for equilibrium with increasing subscapularis force. The contact area, though, decreased and thus the contact stress was noted to increase. No ligament element tensions were necessary after subscapularis activation.

Supraspinatus. Increasing supraspinatus force resulted in less extension and more external rotation. Anterior and superior translation also occurred. Contact stress decreased and contact area increased with greater supraspinatus force. Ligament tension was noted in the anterior band of the IGHL only at the 25% loading condition.

Teres Minor. There is no significant change with the muscle force increase. Contact force, area and stress were also relatively constant with increasing teres minor force. Tensions in MGHL and IGHL were noted and they decreased with increasing teres minor force.

Individual Muscle Activation with Other Muscles Active

Infraspinatus. The infraspinatus had a strong effect on joint rotation when increasing its force from 100% to 200%, with the humerus moved into greater flexion, adduction and external rotation. The coupled flexion and external rotation acted to further cock the arm. More inferior and posterior translation was also evident. Contact force and stress were increased with a corresponding decrease in contact area. Decreasing the infraspinatus force from 100% to 0% did not strongly affect kinematics or contact mechanics. No ligament tensions were present.

Subscapularis. Increasing subscapularis force from 0% to 200% resulted in increased humeral flexion, internal rotation, and more anterior and superior translation. No large changes in contact mechanics were evident with increasing subscapularis load from 100% to 200%. The contact stress was increased and the contact area decreased as the subscapularis force was lowered from 100% to 0%. No ligament tensions were noted.

Supraspinatus. Increasing supraspinatus loading from 0% to 200% caused increased external rotation from 3.6 degrees to 14.9 degrees coupled with forward flexion. No changes in translation were noted. Only when the supraspinatus force decreased to 0% did a notable posterior translation occur. Contact mechanics were not significantly altered by variation in supraspinatus force except when it reached the 0% level, when a decrease in contact area and increase in contact stress occurred. No ligament forces were present.

Teres Minor. Teres minor slightly flexed and externally rotated the humerus with its increase from 0% to 200%. Contact force, area and stress were insensitive to changes in teres minor forces. Ligament tensions were not noted.

Overall. The subscapularis and supraspinatus both played roles in centering the humeral head by moving it anteriorly and superiorly. Subscapularis alone was primary in resisting both extension and external rotations. Infraspinatus further aided the cocking motion when activated and pulled the humeral head inferiorly and posteriorly. More posterior-inferior translations resulted in higher contact stress with smaller contact area. Balance between infraspinatus and subscapularis is significant in limiting rotational motion, while supraspinatus joins them in balancing translations by centering the humeral head on the glenoid.

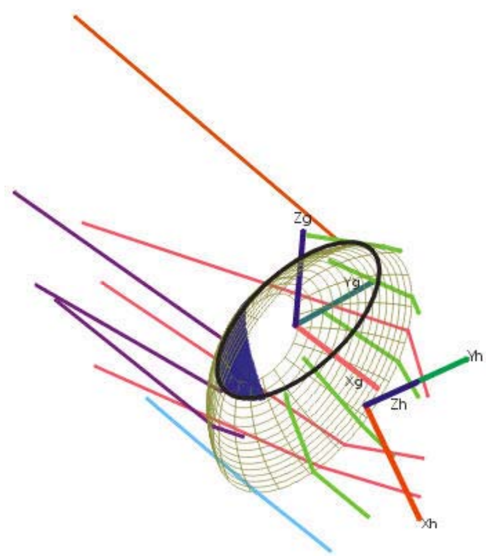

FIGURE 1: Graphical representation of the model looking from a superior-posterior vantage point. The dark circle is glenoid rim. The gridded partial sphere is the humeral head. Muscles and ligament paths are shown. The shaded region is the contact area. Glenoid and humeral coordinate systems are labeled as Xg, Yg, Zg, and Xh, Yh, Zh. Xh is the long axis of the humerus.

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