Modeling of Rotator Cuff in Shoulder Dynamics

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Introduction
The glenohumeral joint has a large range of motion, yet it is still stable. The joint consists of the intercalated joint surfaces of the humeral head and glenoid, along with the surrounding capsuloligamentous structures. Interaction between the capsuloligamentous structures and the articulating surfaces provides the basic static constraint of the joint. On the contrary, coordinated muscle contraction provides the dynamic balance and stability of the joint. All muscle force vectors can be resolved into compressive and shear components. The compressive force component by the muscle stabilizes the glenohumeral joint by the mechanism referred to as concavity-compression. The shear force component stabilizes the joint by direct pull. Static constraint would influence the recruitment of muscle in maintaining the equilibrium condition. The interactions between joint concavity-compression and the dynamic muscle loading are demonstrated by examining the potential abduction strength.

Methods
The mechanism of concavity-compression was studied and measured using a computer controlled x-y-stage which translated the load cell with the glenoids underneath the humeral head in eight different directions (Halder et al., 2001). The Glenoid was clamped onto a six-component load cell which was mounted on a motorized x-y-stage (Figure 1). The aluminum sleeve containing the proximal humerus was clamped above the glenoid on a vertically unconstrained low friction slide. The movement of the slide was measured using a linear variable displacement transducer. Axial loads were applied through the center of the articulation by adding weights to the slide to which the clamped humerus was attached (Figure 1). Stability ratios were calculated as the peak translational force divided by the peak compressive force. The components of muscle force vector had been directly assessed using a universal positioner and a six-component load-cell, which permitted precise measurement of the forces transmitted to the humeral head when a known force was individually applied to each muscle (Lee et al., 2001).

A three-dimensional model of the glenohumeral joint and upper arm was then developed by including these two important aspects of information collected experimentally. This model was then used for the prediction of shoulder functional strength and muscle force distribution associated with traumatic joint injury where the static constraints are compromised. In this model the typical free-body analysis was considered for establishing the equilibrium equations,

$$\sum f_i U_{xi} + R_x = 0 \quad (1)$$
$$\sum f_i U_{yi} + R_y + P = 0 \quad (2)$$
$$\sum f_i U_{zi} + R_z = 0 \quad (3)$$
$$\sum f_i \cdot r_{xi} = 0 \quad (4)$$
$$\sum f_i \cdot r_{yi} = 0 \quad (5)$$
$$\sum f_i \cdot r_{zi} + P \cdot t = 0 \quad (6)$$

Where $f_i$ and $P$ are muscle force and applied force, $(U_{xi}, U_{yi}, U_{zi})$, are unit force vectors. $R_x, R_y, R_z$ are joint constraint forces in compressive, superior-inferior, and anterior-posterior directions, $(r_{xi}, r_{yi}, r_{zi})$ are
moment arms of individual muscle, and $t$ is the moment arm of applied force. Constraints of muscle forces were posed to the upper limits, $f_{\text{max}}$, based on the distribution of physiological cross-sectional area

$$0 \leq f_i \leq f_{\text{max}_i}$$  \hspace{0.5cm} (7)

The joint forces in the tangential or shear directions were further constrained due to the concavity-compression related to the compressive force, based on the stability ratio

$$R_y \leq aR_x$$  \hspace{0.5cm} (8)

$$R_z \leq bR_x$$  \hspace{0.5cm} (9)

where $a$, and $b$ are stability ratio in superior-inferior and anterior-posterior directions, respectively.

The muscle force distribution to accomplish maximum applied force $P$ was obtained by

$$\text{minimizing } \text{obj} = -P$$  \hspace{0.5cm} (10)

**Results and Discussion**

For concavity-compression mechanism, the results indicated that stability ratios were 56%, 60%, 32% and 37% in the superior, inferior, anterior, and posterior directions individually (Halder, et al., 2001). Resection of the glenoid labrum resulted in an average decrease in stability ratio of 9.6 percent. Anterior shoulder dislocation may be facilitated by the lower degree of stability in the glenohumeral abduction in the anterior direction. On the other hand, even moderate compressive forces generated by the rotator cuff are sufficient to provide stability through concavity compression

The compressive force generated by each rotator cuff muscle changed significantly as the humerus was rotated from neutral to 90° ER. In neutral rotation, the compressive force averaged 90%, 85%, 98%, and 96% of the applied force to the teres minor, infraspinatus, subscapularis, and supraspinatus, respectively (Table I). Direction and magnitude of the shear force in anterior/posterior and superior/inferior direction generated by each RC muscle changed significantly with humeral rotation. Anterior shear forces by the teres minor (19%) and infraspinatus (16%) in neutral rotation changed to posterior shear forces (5% and 8%) in 90° ER. The supraspinatus generated destabilizing anterior shear force as high as 31% of the applied force to the muscle in 90° ER, which was significantly different from the other muscles in this position.

Based on the model, the maximum abduction force resisted at the distal humerus was obtained using optimization. Effects of the reduction in stability ratio in anterior direction were shown in Figure 3. With small amount of defect of the glenoid surface, i.e. small reduction of the stability ratio from normal intact, the potential abduction strengths were not much affected. However, with further decrease of the stability ratio, proportional changes of the strengths were observed where surgical restoration needs to be considered in order to regain this normal strength. The model also indicated that the potential muscle forces in rotator cuff muscles, especially the posterior ones, were the limiting factors for functional strength. Strengthening of those muscles could potentially improve the abduction strength even under slightly reduced joint static constraint.

In summary, the mathematical models could be useful tools in analyzing the surgical modalities as well as in planning of the rehabilitation program. However, to have a reliable and useful model, the specific mechanism for joint constraint and muscle functions need to be considered.
Table I: Percent force vectors generated by the rotator cuff muscles with the arm in a 90 degree abducted/neutral rotation position.

<table>
<thead>
<tr>
<th>Force Vector</th>
<th>Teres Minor</th>
<th>Infraspinatus</th>
<th>Supraspinatus</th>
<th>Subscapularis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>90 ± 5</td>
<td>85 ± 7</td>
<td>98 ± 3</td>
<td>96 ± 5</td>
</tr>
<tr>
<td>Anterior Shear</td>
<td>19 ± 8</td>
<td>16 ± 8</td>
<td>-12 ± 7</td>
<td>-26 ± 17</td>
</tr>
<tr>
<td>Superior Shear</td>
<td>-40 ± 18</td>
<td>-50 ± 12</td>
<td>-16 ± 16</td>
<td>-12 ± 10</td>
</tr>
</tbody>
</table>

Figure 1. Setup for measurement of stability ratio in concavity-compression.

Figure 2. Stability ratios (percent) in the eight tested directions with and without labrum. Values represent mean (standard deviation).

Figure 3. Potential abduction strength decreased with decreasing stability ratio in anterior direction.

References