Muscle Force and Excursion Requirements and Moment Arm Analysis of a Posterior-Superior Offset Reverse Total Shoulder Prosthesis

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Abstract

Current reverse total shoulder arthroplasty prosthesis designs do not permit offset of the humerus in the sagittal plane. Posteriorly shifting the humerus has the theoretical benefit of lengthening the infraspinatus and teres minor muscles and their external rotation moment arms, thereby improving the tension and efficiency of each external rotator and subsequently requiring each muscle to produce less force to rotate the arm. A cadaveric shoulder controller was used to quantify the impact of a novel posterior-superior offset reverse shoulder prosthesis on muscle length, moment arms, and muscle forces relative to a non-offset reverse shoulder design during two different motions: scapular plane abduction and internal/external rotation. The results of this study demonstrate that both the non-offset and offset reverse shoulder designs had similar force and excursion demands of the infraspinatus and teres minor muscles during both scapular abduction and internal and external rotation. Additionally, the offset reverse shoulder design was associated with significantly less over-tensioning of the middle and posterior deltoid and significantly more anatomic tensioning of the teres minor than the non-offset design. However, the offset reverse shoulder was observed to have more impingement than the non-offset design. These findings support the feasibility of this design: by restoring a more anatomic resting length to the deltoid and teres minor, the posterior-superior offset rTSA design may provide better teres minor function and rotational strength and may decrease the incidence of acromial stress fractures relative to the non-offset design. Clinical follow-up is required to confirm these findings.

Current reverse total shoulder arthroplasty (rTSA) prosthesis designs have variable dimensions in the coronal plane and result in varying amounts of glenoid and humeral medial/lateral positioning. The glenoid center of rotation may be placed medially on the face of the glenoid bone, such as in the Grammont Delta III (Depuy, Inc), or it may be lateralized as in the RSP (DJO, Inc) by as much as 1 cm (Fig. 1). Humeral offset is also variable. Some designs medialize the humerus by a significant amount whereas others only slightly medialize the humerus relative to its anatomic location. These design elements affect the abdution moment arm of the deltoid and likewise affect the abduction torque produced by the deltoid.

Thus, rTSA prosthesis design has primarily focused on altering geometry in the coronal plane; little focus has attempted to investigate sagittal plane design variations. Dedy and coworkers reported that a posterior offset humeral rTSA implant (i.e., which causes an anterior shift of the humeral bone) decreased the total passive range of motion of one reverse total shoulder arthroplasty design.1 In much the same manner that medialization of the glenoid component improves the moment arm of the deltoid and decreases the deltoid torque requirement. Increasing the offset of the humeral component should increase the moment arm. Thus, a direct posterior offset of the humerus would be expected to increase the external rotation torque of the posterior rotator cuff. However, the consequence of a larger moment arm is that greater excursion is demanded of the muscle for the same amount of motion. Reverse shoulder prosthesis designs cause an inferior-medial shift in the humerus and the center of rotation (CoR), which increases the length of the deltoid abductor moment arm and also increases its tension. How-

Figure 1 Superior view of native and three rTSA designs showing variable coronal plane design features such as medial vs. lateral glenoid and medial vs. lateral humerus components. A, Native Shoulder; B, Delta III rTSA; C, RSP rTSA; D, Equinoxe rTSA.

Figure 2 Superior and inferior views of the offset humeral tray utilized in the posterior-superior offset Equinoxe rTSA. At the time of publication, the posterior-superior offset humeral tray had not been cleared by the FDA for sale in the USA.

Figure 3 External rotation moment arm comparison for native (left), non-offset Equinoxe rTSA (middle), and posterior/superior offset Equinoxe rTSA (right).
ever, the resulting humeral medialization can also shorten the anterior and posterior rotator cuff muscles. Shortening of these muscles is one explanation for postsurgical external rotator cuff weakness in patients with a functioning deltoid.2-4

An offset rTSA prosthesis was developed to facilitate greater improvements in external rotation with rTSA (Fig. 2). This offset prosthesis shifts the humerus posteriorly to better tension the posterior rotator cuff and increase the external rotation moment arms of the infraspinatus and teres minor; this prosthesis also shifts the humerus superiorly (e.g., shifts humerus less inferiorly relative to a non-offset reverse shoulder prosthesis) to reduce over-tensioning of the deltoid and to recruit more of the subscapularis and infraspinatus for abduction (Fig. 3). While the theoretical benefits of this offset rTSA prosthesis have been demonstrated previously,5,6 that analytical analysis is limited by it being a computer simulation using only one glenohumeral bone model. It was hypothesized that for the Equinoxe rTSA prosthesis, this offset would not significantly alter the excursion and force demands on the infraspinatus and teres minor compared to the non-offset prosthesis.

Methods

A second-generation cadaveric shoulder controller that simulates neuromuscular control was used in this study to compare muscle excursion and muscle forces associated with two different rTSA designs during two different motions that are relevant to activities of daily living (Fig. 4). This shoulder controller has been utilized in prior studies to demonstrate that releasing the subscapularis with rTSA requires less force to be generated by the deltoid and the posterior rotator cuff during abduction and results in lower overall joint reaction forces than when the subscapularis is repaired with rTSA.7,8

Stepper motors (Industrial Devices Corporation, Salem, New Hampshire) were used to actuate cables that are attached to the rotator cuff tendons and deltoid tuberosity. Force transducers measured the tension developed in each cable as active closed-loop position and orientation control algorithms controlled each motor, thereby simulating in vivo glenohumeral kinematics. Encoders attached to the stepper motors measured muscle excursion, active optical markers (Northern Digital, Inc., Waterloo, Ontario, Canada) track motion, and a six-axis load cell measures the resultant joint reaction force at the glenohumeral joint.

The shoulder controller simulated the three heads of the deltoid (anterior, middle, and posterior), infraspinatus, and teres minor. The Equinoxe posterior-superior offset and non-offset rTSA prostheses (Exactech, Inc., Gainesville, FL) were tested for two motions: 1. scapular plane abduction from 15° to 75° with the arm in neutral rotation and 2. internal/external rotation from +30° (IR) to -60° (ER) with the arm in 45° abduction and neutral flexion/extension.

The posterior-superior offset and non-offset rTSA testing was performed without the subscapularis and with each device implanted according to the manufacturer recommendation with the glenosphere implanted along the inferior glenoid rim and the humeral component in 20° of retroversion. For each test condition, 10 right cadaveric upper extremity specimens were tested. Testing of the rTSA was performed with the elbow flexed at 90° to simulate the internal rotation

![Figure 4 Shoulder controller: abduction of cadaveric shoulder with the elbow flexed](image)

![Figure 5 Joint reaction force (Newtons) for abduction in the scapular plane for native shoulder, non-offset (neutral) rTSA, and offset rTSA.](image)
torque from the mass of the extremity distal to the elbow that occurs during many activities of daily living. Neutral humeral positioning was maintained automatically by the controller by activating the stabilizing muscles during each aforementioned motion. The cadaveric shoulders were also tested in the intact (native) condition during each motion with the elbow in extension. A two-tailed unpaired Student’s t-test was used to compare differences in resting muscle length, muscle moment arms, and muscle forces between each test condition for each of the two motions, where \( p < 0.05 \) denotes significance.

**Results**

The joint reaction forces for the non-offset rTSA and the posterior-superior offset rTSA design were compared with the joint reaction force for the native shoulders (Fig. 5) and were shown to be similar or less than the native joint reaction force. Figures 6 and 7 demonstrate the similarity between the non-offset and posterior-superior offset rTSA designs in terms of the force and excursion demands of the infraspinatus and teres minor muscles for scapular plane abduction. Figures 8 and 9 demonstrate the similarity between the non-offset and posterior-superior offset rTSA designs in terms of the force and excursion demands of the infraspinatus and teres minor muscles for internal and external rotation. The average change in resting muscle length relative to the native shoulder was significantly different (\( p < 0.05 \)) for the middle deltoid, posterior deltoid, and teres minor as shown in Table 1. As described in Table 1, the offset rTSA was associated with significantly less over-tensioning of the middle and posterior deltoid and significantly more anatomic tensioning of the teres minor when compared to the non-offset rTSA.
Impingement was noted for each of the motions for the non-offset rTSA and posterior-superior offset rTSA, though generally more impingement was noted for the offset rTSA. During scapular abduction with a fixed scapula, superior impingement was noted due to greater tuberosity contact with the acromion, coracoid, or both (where the average range of motion for the non-offset rTSA and offset rTSA was observed to be 15° to 67° and 15° to 63°, respectively). During internal (+) and external (-) rotation with the arm in 45° abduction, impingement was noted in external rotation due to greater tuberosity contact with the acromion (where the average range of motion for the non-offset rTSA and offset rTSA was observed to be -60° to 30° and -33° to 30°, respectively).

**Discussion**

In general, the force and excursion demands placed on the posterior rotator cuff muscles for the posterior-superior offset rTSA design were very similar to the demands on the posterior cuff for the non-offset rTSA. Additionally, the joint reaction forces were also very similar, indicating that glenoid fixation should be adequate. These findings support the feasibility of this design. However, it was noted that there was reduced range-of-motion with the posterior-superior offset design due to greater tuberosity impingement.

The posterior-superior offset design resulted in less lengthening of the deltoid muscle at rest. This finding was statistically significant for the middle and posterior deltoid. All current rTSA designs lengthen the deltoid by 10% to 20% and indeed deltoid lengthening is thought to be important to function and stability of the shoulder after rTSA. However, as the clinical impact of long-term muscle elongation is unknown, designs which lengthen the deltoid by smaller amounts may be preferable. Additionally, excessive deltoid over-tensioning may contribute to acromion stress fractures, a postoperative complication associated with rTSA.

Computer modeling studies have previously shown significant shortening of the infraspinatus and teres minor at rest in various rTSA designs. The functional effect of the posterior-superior humeral offset on the teres minor was significantly less shortening of the muscle at rest as compared to the non-offset rTSA (-10.3 ± 7.6 mm vs -1.8 ± 8.0 mm). By restoring a more anatomic resting length to the teres minor, the posterior-superior offset rTSA design may provide better teres minor function compared to the non-offset design. Clinically, improved teres minor function may improve the usefulness of the upper extremity by improving external rotation strength, thereby better facilitating activities of daily living.

**Conclusions**

This cadaveric shoulder controller study confirms that the posterior-superior offset rTSA design may offer two advantages over the non-offset rTSA design. Specifically, reduced deltoid over-tensioning and improved teres minor muscle tensioning. These effects on the muscles of the shoulder may lead to better function of the reverse shoulder postoperatively, greater ability to perform activities of daily living, and reduced acromion stress fractures. Additional benefits to this design, including larger external rotation moment arms, may have been observed during rotation at lower degrees of humeral abduction. Impingement of the greater tuberosity was observed during external rotation at 45° of humeral abduction with the offset rTSA design; this impingement truncated the motion and prevented realization of the reduced force. Although the non-offset Equinoxe rTSA has been clinically successful since 2007, the results of this study indicate that it may be possible to further optimize shoulder muscle performance by alterations in the design of the prosthesis. Clinical follow-up is required to confirm these findings.

**Disclosure Statement**

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**References**


3. Lemieux PO, Hagemeister N, Tétreault P, Nuño N. Influence of the medial offset of the proximal humerus on the glenohu-

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**Table 1**

Comparison of the Differences in Average Resting Muscle Length Relative to the Native Shoulder

<table>
<thead>
<tr>
<th>Avg Diff in Resting Muscle Length (mm)</th>
<th>Anterior Deltoid</th>
<th>Middle Deltoid</th>
<th>Posterior Deltoid</th>
<th>Infraspinatus</th>
<th>Teres Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-offset rTSA</td>
<td>19.5 ± 7.0</td>
<td>22.0 ± 3.5</td>
<td>20.6 ± 6.2</td>
<td>-0.5 ± 11.9</td>
<td>-10.3 ± 7.6</td>
</tr>
<tr>
<td>Offset rTSA</td>
<td>13.5 ± 6.5</td>
<td>14.7 ± 3.4</td>
<td>13.8 ± 5.8</td>
<td>7.8 ± 11.6</td>
<td>-1.8 ± 8.0</td>
</tr>
<tr>
<td>P value</td>
<td>0.0774</td>
<td>0.0003</td>
<td>0.0278</td>
<td>0.1545</td>
<td>0.0330</td>
</tr>
</tbody>
</table>

Positive values = muscle elongation; negative values = muscle shortening.


