Design Rationale for a Posterior/Superior Offset Reverse Shoulder Prosthesis


Abstract

Introduction: A computer model quantified and compared muscle lengths and moment arms of two different reverse shoulder arthroplasty humeral tray designs during two different motions.

Methods: The computer model simulated internal/external rotation and abduction in the scapular plane for the normal shoulder, the 38 mm non-offset, and the 38 mm posterior-superior offset reverse shoulders. Muscle lengths were directly measured for seven muscles during each motion. External rotation moment arms were calculated for five muscles during each motion.

Results: The offset tray shifted the humerus posteriorly and superiorly relative to the non-offset tray. The more superior humeral position with the offset tray elongated the deltoid 1.0% to 3.8% less and caused each muscle to convert from an adductor to abductor earlier in abduction. The more posterior humeral position with the offset tray better restored the anatomic muscle tension, decreased the internal rotation capability (e.g., moment arm) of the subscapularis and teres major by 7.1 mm and 9.5 mm, and increased the external rotation capability of the posterior deltoid, infraspinatus, and teres minor by 1.3 mm, 8.6 mm, and 7.8 mm.

Discussion and Conclusions: The offset humeral tray better restored the anatomic muscle tensioning and increased the external rotation moment arms relative to the non-offset humeral tray, which has positive implications on strength, stability, and motion.

Reverse shoulder arthroplasty (rTSA) increases the deltoid abductor moment arm length to improve the efficiency of the deltoid as it elevates the arm and is often reported to be effective at restoring active abduction and forward flexion. However, the inferior/medial shift in the center of rotation (CoR) associated with rTSA shortens the anterior and posterior shoulder muscles; shortening of these muscles is one explanation for why rTSA often fails to restore active internal/external rotation in patients with a deficient rotator cuff and a functioning deltoid.

Loss of external rotation impairs the patient’s ability to maintain their arm in neutral rotation during elevation (e.g., positive hornblower’s sign), preventing numerous activities of daily living, including shaking of hands, drinking and eating, and washing of hair. Given the natural predominance of internal rotator muscles in a normally functioning shoulder—four internal rotators (subscapularis, teres major, pectoralis major, and latissimus dorsi) vs. two external rotators (infraspinatus and teres minor)—external rotation deficiency is more debilitating to a patient’s activities of daily living than internal rotation deficiency, particularly when the arm is elevated (Fig. 1).

Muscle transfers are often recommended in reverse shoulder patients with external rotation deficiency because the posterior deltoid alone is insufficient to restore active external rotation. While muscle transfers have been demonstrated to successfully restore active external rotation, they should not be performed if the teres minor is functional. Additionally, it should be recognized that such procedures are technically difficult, limit active internal rotation, and further alter the relationship of each shoulder muscle to its normal physiologic function.

An alternative, prosthetic-based solution to restore...
external rotation is the offset rTSA humeral tray (Fig. 2). This offset rTSA prosthesis shifts the humeral head and tuberosities posteriorly to better tension the posterior rotator cuff while increasing the external rotation moment arms of the infraspinatus and teres minor (Fig. 3). The offset rTSA prosthesis also translates the humeral head and tuberosities superiorly to reduce over-tensioning of the deltoid and to recruit more of the subscapularis and infraspinatus for abduction, relative to the non-offset reverse shoulder. The goal of this comparative computer analysis is two-fold:
1. To quantify the muscle lengths associated with the offset and non-offset humeral tray/liner designs during two motions, abduction and internal/external rotation, in order to evaluate the first null hypothesis that offsetting the humerus in the posterior/superior directions will not impact muscle length with rTSA, and
2. To quantify the muscle moment arms associated with offset and non-offset humeral tray/liner designs during two motions, abduction in the scapular plane and internal/external rotation, in order to evaluate the second null hypothesis that offsetting the humerus in the posterior/superior directions will not impact muscle moment arms with rTSA.

Methods
Similar to the methodologies presented previously, 6-8 a 3-D computer model was developed in Unigraphics (Siemens PLM; Plano, TX, USA) and used to simulate abduction in the scapular plane and internal/external rotation for the normal shoulder, the non-offset reverse shoulder, and the posterior/superior offset reverse shoulder. Both the offset and non-offset 38 mm reverse shoulders (Equinoxe; Exactech, Inc; Gainesville, FL) were geometrically modeled and implanted in a 3-D digitized scapula and humerus; a 3-D digital clavicle and ribcage were also included (Pacific Research Laboratories, Inc; Vashon Island, WA). The

Figure 1 Loss of external rotation from external rotation deficiency.

Figure 2 Comparison of the non-offset (left) and offset (right) 38 mm Equinoxe rTSA: the offset humeral tray translates the humerus (shown transparent) posteriorly and superiorly relative to the non-offset prosthesis. At the time of publication, the posterior-superior offset humeral tray had not been cleared by the FDA for sale in the USA.
digital humerus and scapula were assembled to simulate a normal shoulder, functioning as the control in this analysis; the humeral head was centered on the glenoid and offset by 4 mm from the center of the glenoid to account for the thickness of the cartilage and labrum. Seven muscles were modeled as three lines from origin to insertion; the analyzed muscles are the: anterior deltoid, middle deltoid, posterior deltoid, subscapularis, infraspinatus, teres major, and teres minor. Both offset and non-offset reverse shoulders were implanted at the same location along the inferior glenoid rim of the scapula in 20° of humeral retroversion.

Muscle lengths were measured for all seven muscles as the average of the three lines simulating each muscle and are presented as an average length over each arc of motion (0° to 65° abduction with a fixed scapula and 0 to 40° of internal/external rotation with the humerus in 0° abduction) relative to the normal shoulder. To clarify, each average muscle length, at each degree of motion was compared as a percentage of the corresponding muscle length of the normal shoulder; where a positive percentage indicates muscle elongation and a negative percentage indicates muscle shortening, each relative to the normal shoulder. Abductor and rotation moment arms were calculated in Matlab (Mathworks, Inc.) for five muscles (posterior deltoid, subscapularis, infraspinatus, teres major, and teres minor). Abduction moment arms were calculated from 0° to 140° humeral abduction in the scapular plan using a 1.8:1 scapular rhythm. Rotation moment arms were calculated from 30° internal to 60° external rotation with the arm in 30° abduction.

Results
Both the offset and non-offset reverse shoulders shifted the CoR medially by 27.1 mm and inferiorly by 4.5 mm relative to the normal shoulder. The offset humeral tray/liner shifted the humerus posteriorly and superiorly relative to the non-offset reverse shoulder. The change in the CoR altered muscle lengths for both the offset and non-offset reverse shoulders. The inferior shift in the CoR elongated the anterior, middle, and posterior heads of the deltoid for both the offset and non-offset reverse shoulders during both types of motions (Tables 1 through 3). The more superior position of the humerus with the offset tray elongated the deltoid 1.0% to 3.8% less than did the non-offset tray. As depicted in Tables 2 and 3, the medial shift in the CoR shortened the subscapularis, infraspinatus, teres major, and teres minor for both the offset and non-offset reverse shoulders during both types of motions. However, the more
posterior position of the humerus with the offset tray better restored the anatomic muscle length of all seven muscles during both types of motion (e.g., each muscle length approached 0%, the average length of that muscle in the normal shoulder).

The change in the CoR also altered muscle moment arms for both the offset and non-offset reverse shoulders. During abduction with the normal shoulder, the subscapularis and infraspinatus act as abductors throughout the range of motion, and the posterior deltoid and teres minor convert from an adductor to abductor at 101° and 60°, respectively. In the non-offset reverse shoulder, the posterior deltoid converts from an adductor to abductor at 64°, the subscapularis converts from an adductor to abductor at 82°, the infraspinatus converts at 68°, and the teres minor converts at 135°. Because the offset tray shifts the humerus superiorly relative to the non-offset tray, each muscle converts from an adductor to abductor earlier in abduction, where the posterior deltoid converts at 59°, the subscapularis converts at 62°, the infraspinatus converts at 43°, and the teres minor converts at 110°. During rotation (Figs. 4 and 5), both the offset and non-offset reverse shoulders decrease the internal rotation capability (e.g., moment arm) of the subscapularis and teres major but increase the external rotation capability of the infraspinatus and teres minor relative to the normal shoulder. Because the offset tray shifts the humerus posteriorly, the internal rotation moment arm of the subscapularis and teres major is decreased on average by 7.1 mm and 9.5 mm while the external rotation moment arm of the posterior deltoid, infraspinatus, and teres minor is increased on average by 1.3 mm, 8.6 mm, and 7.8 mm, respectively.

**Discussion**

Inverting the anatomic concavities with rTSA fundamentally changes the position of the CoR relative to the normal shoulder and shifts the humerus in the medial/inferior direction, which has implications on muscle tension and moment arms. The results of this study demonstrate that offsetting the humerus in the posterior/superior direction using the offset humeral tray/liner further altered muscle lengths, moment arms, and modified the function of each muscle during both types of motion analyzed relative to the non-offset reverse shoulder.

Regarding changes in muscle lengths for each type of motion, the offset reverse shoulder resulted in more anatomic tensioning of each muscle relative to the non-offset reverse shoulder. Specifically for the deltoid, the offset reverse shoulder was associated with 1.0% to 3.8% less over-tensioning of the deltoid as compared to that with the non-offset reverse shoulder. Deltoid elongation between 10% and 20% has been suggested to improve its resting tone/tension, increase strength, and improve the overall stability of the joint with rTSA; however, increased deltoid elongation also modifies the normal deltoid contour, creates cosmetic concerns, and may play a role in long-term fatigue failure of the deltoid.1,5,9-12 Additionally, the offset reverse shoulder was associated with 1.2% to 5.4% more anatomic tensioning of the subscapularis, 0.4% to 5.4% more anatomic tensioning of the teres major, 3.3% to 6.3% more anatomic

<table>
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<tr>
<th>Table 1</th>
<th>Average Muscle Length Relative to Normal Shoulder as the Non-offset and Offset Reverse Shoulders are Abducted in the Scapular Plane from 0° to 65°</th>
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<tbody>
<tr>
<td>Abduction</td>
<td>Ant. Deltoid</td>
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<tr>
<td>38 mm non-offset</td>
<td>8.8%</td>
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<td>7.3%</td>
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<td>Average Difference</td>
<td>1.5%</td>
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<tr>
<th>Table 2</th>
<th>Average Muscle Length Relative to Normal Shoulder as the Non-offset and Offset Reverse Shoulders are Internally Rotated from 0° to 40° with the Arm at 0° Abduction</th>
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<td>Internal Rotation</td>
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<td>38 mm offset</td>
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<td>1.9%</td>
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<tr>
<th>Table 3</th>
<th>Average Muscle Length Relative to Normal Shoulder as the Non-offset and Offset Reverse Shoulders are Externally Rotated from 0° to 40° with the Arm at 0° Abduction</th>
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<tr>
<td>External Rotation</td>
<td>Ant. Deltoid</td>
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<td>38 mm non-offset</td>
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<tr>
<td>38 mm offset</td>
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tensioning of the infraspinatus, and 6.0% to 9.8% more anatomic tensioning of the teres minor as compared to that with the non-offset reverse shoulder. While the functional effect of shortening the anterior and posterior rotator cuff is unknown, these observations related to muscle shortening may describe the mechanism for why limited improve-
ments in active internal and external rotation are reported for rTSA1,5-12 and why patients with rTSA are reported to have a different scapulo-humeral rhythms and specifically, more scapular motion than in normal shoulders.13 The more anatomic muscle tensioning achieved with the offset humeral tray offers the potential for improved internal/external rotation capability and more normal scapula-humeral rhythms/kinematics relative to the non-offset reverse shoulder.

Regarding changes in muscle moment arms, during abduction, the offset tray caused the posterior deltoid, subscapularis, infraspinatus, and teres minor to convert from adductors to abductors at lower arm elevation. Improved abduction capability limits each muscle’s antagonistic behavior with the deltoid, potentially reducing the force required by the deltoid to elevate the arm. In rotation, the offset tray caused the posterior deltoid, infraspinatus, and teres minor to be more effective external rotators. Improved external rotation capability is important for patients with external rotation deficiency; as external rotation is required for many activities of daily living, increasing the rotator moment arm lengths of the only two external rotators is advantageous to restore function. Finally, as the infraspinatus and teres minor are both sometimes affected by the pathologies in which rTSA is indicated, even small improvements in the external rotation capability of the posterior deltoid is advantageous and may be sufficient to provide an alternative to a muscle transfer in order to restore function.

This study has some limitations. The computer model limited rotation of the scapula and did not simulate wrapping of each muscle around the humerus or scapula. Because muscle wrapping was not modeled, muscle lengths and moment arms (particularly at low elevation) may be slightly underestimated. Additionally, the average muscle length for each simulated motion was presented as a percentage of the normal shoulder. It is unknown if the normal shoulder is the best reference as the collapsed condition of the glenohumeral joint resulting from the pathologies in which the reverse shoulder is indicated may result in muscle remodeling, altering the origin to insertion distance of each muscle. Additionally, this computer model simulated one medium-sized glenohumeral anatomy and therefore does not account for all possible anatomical and morphological variations in which these devices are implanted. Finally, muscle lengths and moment arms can be impacted by a variety of other factors, including glenoid placement on the scapula, the size of the humeral osteotomy, the retroversion of the humeral or glenoid component, or the thickness of humeral liner/glenosphere. Future work should evaluate and confirm the clinical significance of these observed theoretical improvements in muscle length and moment arms achieved with this offset reverse shoulder.

Conclusions

The offset humeral tray better restores anatomic muscle tensioning and increases external rotation moment arms relative to the non-offset rTSA which has positive implications on strength, stability, and motion. Just as Dr. Grammont medialized the humerus and CoR with his rTSA design1 to increase the deltoid abductor moment arms and improve the efficiency of the deltoid to facilitate abduction, this offset humeral tray shifts the humerus posteriorly to better tension the shoulder muscles and increase the rotator moment arms thereby improving the efficiency of the posterior deltoid and the posterior rotator cuff muscles to facilitate external rotation. Based upon these results, we reject null hypothesis 1 and 2 and conclude that offsetting the position of the humerus in the posterior/superior direction using the offset humeral tray impacts both muscle length and moment arms with rTSA.

Disclosure Statement

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References


