Reverse total shoulder arthroplasty component center of rotation affects muscle function

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Background: Medialization of the glenohumeral center of rotation alters the moment arm of the deltoid, can affect muscle function, and increases the risk for scapular notching due to impingement. The objective of this study was to determine the effect of position of the glenosphere on deltoid efficiency and the range of glenohumeral adduction.

Methods: Scapulohumeral bone models were reconstructed from computed tomography scans and virtually implanted with primary or reverse total shoulder arthroplasty implants. The placement of the glenosphere was varied to simulate differing degrees of “medialization” and inferior placement relative to the glenoid. Muscle and joint forces were computed during shoulder abduction in OpenSim musculoskeletal modeling software.

Results: The average glenohumeral joint reaction forces for the primary total shoulder arthroplasty were within 5% of those previously reported in vivo. Superior placement or full lateralization of the glenosphere increased glenohumeral joint reaction forces by 10% and 18%, respectively, relative to the recommended reverse total shoulder arthroplasty position. The moment arm of the deltoid muscle was the highest at the recommended baseline surgical position. The baseline glenosphere position resulted in a glenohumeral adduction deficit averaging more than 10° that increased to more than 25° when the glenosphere was placed superiorly. Only with full lateralization was glenohumeral adduction unaffected by superoinferior placement.

Discussion/Conclusion: Selecting optimum placement of the glenosphere involves tradeoffs in bending moment at the implant-bone interface, risk for impingement, and deltoid efficiency. A viable option is partially medializing the glenosphere, which retains most of the benefits of deltoid efficiency and reduces the risk for scapular notching.


Keywords: Shoulder arthroplasty; reverse shoulder arthroplasty; glenosphere; deltoid function; glenohumeral forces; shoulder biomechanics

Severe shoulder arthropathy is often associated with poor rotator cuff function, which complicates the outcomes of shoulder arthroplasty. In the 1970s, constrained shoulder arthroplasty prosthetic designs were investigated to compensate for the loss of function of the rotator cuff muscles. In reverse total shoulder arthroplasty (RTSA), the glenohumeral joint is converted into a ball-and-socket articulation by implantation of a metallic glenosphere on the glenoid and a stem with a concave polyethylene articulation in the humerus. This design increases the stability of the shoulder, thus allowing the deltoid to actively abduct...
the shoulder in the absence of supraspinatus function. RTSA is therefore indicated for the treatment of end-stage shoulder arthropathy associated with significant rotator cuff deficiency.\textsuperscript{7,8,18}

One of the important failure mechanisms of the early RTSA designs was aseptic loosening of the glenosphere.\textsuperscript{3,17} Prostheses often loosened secondary to large bending and shear forces on the glenoid component. These forces were attributed to the constrained design and the lateral center of rotation relative to the implant-bone interface. In 1985, Paul Grammont designed a large, medially placed prosthesis with no neck that placed the center of rotation at the glenoid prosthesis-bone interface on the basis of the theory that the constrained design and lateral center of rotation increase rotational moment arm loosening of the glenoid component. This medialization of the center of rotation reduces the bending and tensile forces at the implant-bone interface.\textsuperscript{20} Unfortunately, medialization also introduces laxity in the deltoid muscle and increases the potential for impingement, particularly between the humeral prosthesis and scapular margin below the glenoid. To correct for these adverse effects, the glenosphere is placed inferiorly on the glenoid. Whereas this inferior placement reduces deltoid muscle laxity, it does little to reduce the laxity in the external rotator muscles, and patients often complain of reduced strength in external rotation.\textsuperscript{20} In addition, medialization of the humeral shaft alters the normal contour of the shoulder, resulting in a poor cosmetic outcome.

To address the issues with medialization, some glenosphere designs (such as the Reverse Shoulder Prosthesis; Encore Medical, Austin, TX, USA) lateralize the center of rotation. To counter the greater bending moment at the glenoid baseplate-bone interface, these designs enhance baseplate fixation, resulting in stability to cyclic loading equivalent to that of medialized designs (Delta III).\textsuperscript{13} Bone grafting under the glenosphere is another alternative to neutralize the effects of medialization. The implant-bone graft interface is protected from deleterious stresses, which are transferred to the interface between graft and host bone. After healing of the bone graft, these stresses are no longer significant for implant fixation. Proposed advantages of lateralizing the center of rotation include reduced laxity of the external rotators, reduced potential for prosthesis-bone impingement, and improved appearance of the shoulder contour.\textsuperscript{4}

The effects of surgical placement of components and implant design on range of motion have been previously studied. One study using a computer model found that lateralizing the center of rotation resulted in the greatest increase in shoulder abduction, followed by tilt of the glenosphere, the angle between the humeral neck and humeral shaft, and the size of the glenosphere.\textsuperscript{9} Reduced humeral neck-shaft angle and inferior placement of the glenoid reduced adduction deficit. Mechanical studies have also shown that center of rotation, glenosphere position, and neck-shaft angle had a major impact on range of motion before impingement.\textsuperscript{10}

Patients with severe rotator cuff deficiency and shoulder arthritis often have compromised deltoid function.\textsuperscript{20} Medializing the components alters the moment arm of the deltoid and can affect muscle function. However, the precise contribution of medial placement to deltoid muscle strength is not known. Further, the quantitative effect of medial placement on glenohumeral range of motion and the potential for impingement has not been fully studied. We therefore analyzed the mechanical advantage of prosthetic position on deltoid function to identify the optimum placement that would maximize muscle function as well as range of motion. Our primary objective was to determine the effect of position of the glenosphere on the force generated by the deltoid during shoulder abduction. The secondary objective was to determine the effect of glenosphere placement on impingement during shoulder adduction.

\section*{Methods}

\subsection*{Construction of bone geometry}

In a previous study, computed tomography (CT) scans were obtained from cadaveric shoulder specimens (N = 40) and segmented by the commercially available software Mimics (Materialise, Leuven, Belgium).\textsuperscript{12} The 3-dimensional CT reconstructions were validated by physical measurements and surgical reconstruction. Differences between physical measurements made on cadaveric specimens and virtual measurement on 3-dimensional CT reconstructions ranged from 0.7 to 2.7 mm. In addition, cadaveric implantation was performed on 7 specimens to assess peg perforation; the same scapulae that perforated during cadaveric surgery (3 of 7) also perforated during the virtual surgery. From that database, we selected 3 scapulohumeral models that corresponded to small, medium, and large humeral head sizes. All 3 specimens were healthy and had no visible signs of significant deformity, degenerative disease, or wear. Each of the 3 specimens was then virtually implanted with primary shoulder implants and reverse shoulder implants with varying centers of rotation relative to the anatomic glenoid articular surface (Fig. 1).

\subsection*{Primary shoulder reconstruction}

The humeral head was virtually osteotomized at an anatomic humerus neck-shaft angle of 135° and was replaced with an appropriately sized humeral head component (Fig. 1, B). We replicated the templating procedure used at our institution to select the size of the humeral head component. A sphere was fit to the native humeral head, and the head size with a radius closest to the radius of the anatomic head was selected for each CT model. The small humerus was implanted with a humeral head with radius of curvature of 20.5 mm; the medium with radius of curvature of 24 mm; and the large with radius of curvature of 26 mm.

The glenoid bone subchondral surface was fitted with a computer-aided design model representing the geometry of a
generic glenoid implant based on measurements of commercially available primary shoulder arthroplasty devices used at our institution.12 A reversed total shoulder implant. (C) Reverse total shoulder arthroplasty in the recommended surgical placement. (D) Glenosphere placed 6 mm superior. (E) Glenosphere placed 6 mm lateral. (F) Glenosphere placed 6 mm superior and 6 mm lateral. (G) Glenosphere placed 13 mm lateral. (H) Glenosphere placed 13 mm superior and 13 mm lateral.

**Table I** Glenosphere location for the reverse total shoulder

<table>
<thead>
<tr>
<th>Implant placement</th>
<th>Lateral (mm)</th>
<th>Superior (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (recommended placement)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Superior 6 mm</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Lateral 6 mm</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Superior 6 mm + lateral 6 mm</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Lateral 13 mm</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Superior 6 mm + lateral 13 mm</td>
<td>13</td>
<td>6</td>
</tr>
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**Reverse shoulder reconstruction**

The humeral head was removed to simulate an osteotomy with a neck-shaft angle of 155°.2,15 A humeral cup conforming to the glenosphere and covering a third of the glenosphere, corresponding to a standard depth, was then placed at 155° to the shaft axis. The glenoid subchondral surface was virtually reamed to a flat surface tilted 10° inferior relative to the plane of the glenoid face.2,15 A 36-mm-diameter hemispherical glenosphere was then positioned with its center in the anteroposterior midline of the glenoid, the inferior edge of the glenoid baseplate or metaglene (diameter = 29 mm) in line with the inferior rim of the glenoid, and the glenosphere overhanging the inferior rim of the glenoid.2,15

This placement of the glenosphere was used as the recommended “baseline” (Fig. 1, C). Four more models per specimen were generated by varying the position of the glenosphere relative to the glenoid in the lateral and superior direction to simulate differing degrees of “medialization” and inferior placement, respectively (Table I). We selected a lateralization of 13 mm that represented the average medialization of the humeral shaft when the glenosphere was placed in the baseline position; 6 mm was chosen to represent the approximate halfway point between full medialization and lateralization and represents the nominal thickness of the bone graft used at our institution. Lateral placement of the glenosphere was simulated by adding a bone graft of the same diameter as the metaglene. The humerus implanted with the humeral cup was adjusted to match the change in placement of the glenosphere.

**Muscle models**

The senior author (H.R.H.) marked the origins and insertions of the deltoid and rotator cuff on the basis of published anatomic landmarks.3 Virtual muscles were constructed in OpenSim, an open-source platform for modeling, simulating, and analyzing the neuromusculoskeletal system (https://simtk.org/home/opensim; Stanford University, Stanford, CA, USA).6 Five muscle strands were used to represent the deltoid muscles and one strand each for the rotator cuff muscles: supraspinatus, infraspinatus, subscapularis, and teres minor (Fig. 2). The supraspinatus muscle was removed in the reverse shoulder models to simulate rotator cuff insufficiency, a common indication for reverse shoulder implants.2 Wrapping of these muscles around the proximal humerus was simulated to reflect the changing direction of muscle force. The muscles were modeled with a version of the Hill muscle model19 and were assigned a maximum isometric force according to physiologic cross-sectional area, optimal fiber length, pennation angle, and tendon slack length.

**Kinematics**

The medial border of the scapular blade was used to define scapulothoracic abduction, and the axis of the humeral shaft
was used to define glenohumeral abduction. We chose the medial border of the scapula because the face of the glenoid is often affected by arthritis. In our specimens, the average difference in the angle between the medial border of the scapula and the face of the glenoid was small (1.6°). The shoulder was abducted 90° in the scapular plane with the humerus in neutral internal-external rotation, at a rate of 90° per second. A ratio of 1:2 was used to prescribe scapulothoracic abduction relative to glenohumeral abduction.16 Vertical alignment of the humeral shaft was selected as the neutral alignment, similar to previous studies involving mechanical and computer models of range of motion after RTSA.9,10 Our definition of neutral abduction could overestimate the adduction deficit because the humerus is naturally abducted 1.5° relative to the scapula at resting position.14

External force

The net weight of the upper extremity acting on the shoulder joint was represented by a force with a magnitude of 5% of body weight directed toward gravity. The location of the force on the humerus was scaled for the specimens of different sizes.21

Dynamic simulation

To solve for the distribution of muscle forces required to balance external forces, we used a static minimization of the sum of the squares of muscle activation.6 From each simulation, we were able to gather glenohumeral joint reaction forces and muscle forces. For the reverse shoulder models, bending moment at the glenosphere-glenoid bone interface (generated by the glenohumeral joint reaction forces) was computed throughout the range of abduction.

Model output and data analysis

Glenohumeral joint reaction force, muscle forces, and muscle moment arms were computed with OpenSim during active shoulder abduction. The model of primary shoulder reconstruction was used to validate our assumptions and the use of OpenSim because in vivo experimental glenohumeral forces have been published. In addition, the primary shoulder reconstruction was used for comparison with the reverse shoulder reconstruction conditions because of the substantial difference in glenohumeral center of rotation. For the RTSA conditions without a bone graft, the bending moment at the interface of the glenosphere and glenoid bone was computed; for the RTSA conditions with a bone graft, the bending moment at the interface of the glenosphere and bone graft was computed. Glenohumeral range of motion in adduction was measured by rotating the humerus in the plane of the scapular body about the center of rotation of the glenosphere until contact was detected between the inner rim of the humeral component and the lateral border of the scapula.

Each of these measurements was normalized to the results for the baseline RTSA placement for each specimen. These normalized data were then averaged over the 3 specimens to yield an average for each glenosphere placement condition. The normalization served to reduce the variance due to differences in size, muscle attachments, and inertial properties among specimens.

Results

The glenohumeral joint reaction force for the primary total shoulder arthroplasty condition at 90° of abduction was 66% body weight and was within 5% of the force reported in vivo with use of an instrumented shoulder prosthesis (Fig. 3, A).1 This result supported the validity of our rigid-body dynamics approach for predicting shoulder forces. Simulating the RTSA condition, using recommended placement to medialize the center of rotation, and placing the glenosphere at the inferior margin of the glenoid reduced glenohumeral joint reaction force by 37% (Fig. 3, B). Superior placement of the glenosphere and full lateralization (13 mm) of the glenosphere to restore the humeral shaft to the position reflecting that of the primary total shoulder arthroplasty condition increased glenohumeral joint reaction force by 10% and 18%, respectively. Combined superior placement and full lateralization had an additive effect and increased joint reaction force by 30% relative to the baseline RTSA. On the other hand, partial lateralization (by 6 mm) increased glenohumeral joint reaction force only by 8% relative to baseline. These results indicate that each millimeter of inferior placement contributes almost equally to the reduced joint reaction force as the medialization of the center of rotation.
The summed muscle forces at 90° of shoulder abduction reflected the overall trend of glenohumeral joint reaction force (Fig. 4). The moment arm of the deltoid muscle was substantially increased in all RTSA conditions and was the highest at the recommended baseline surgical position (Fig. 5). This increase in the moment arm increased the mechanical efficiency of the deltoid muscle, providing rationale for the overall shift in deltoid activation.

The peak bending moment at the glenoid bone cut was also substantially affected by the relative lateral position of the glenosphere (Fig. 6). The recommended surgical placement generated the least bending moment at the implant-bone interface, whereas full lateralization of 13 mm generated the highest bending moment at the host-bone graft interface. The bending moment at the implant-graft interface for the grafted condition was similar to that generated in the implant-bone interface for the fully medialized condition.

Adduction range of motion was dramatically different among the groups (Fig. 7). Impingement of the humerus before the arm could return to full neutral was recorded as an adduction deficit. Placing the glenosphere at the recommended surgical position generated a residual glenohumeral adduction deficit averaging more than 10° that increased to more than 25° when the glenosphere was placed superiorly. Only with full lateralization was glenohumeral adduction unaffected by superoinferior placement.

Discussion

The rationale for the RTSA design is to convert the glenohumeral joint into a more stable ball-and-socket joint. This design facilitates shoulder abduction without requiring a functioning rotator cuff. However, surgical recommendations for glenosphere placement are conflicting. Medializing the center of rotation is recommended to reduce the bending moment at the implant-bone interface. On the other hand, lateralizing the center of rotation is proposed to reduce laxity of the external rotators, to reduce potential for prosthesis-bone impingement, and to improve appearance of shoulder contour. Patients requiring RTSA often have compromised muscle function. Because of the complex biomechanics of the shoulder, the net effect of the alteration of the center of
rotation on muscle moment arms over a given range of motion is not clear. Further, glenoid placement can have conflicting effects on range of motion and adverse bending moment at the implant-bone interface. We used a computer model to determine the effect of the position of the glenosphere on several important factors, including joint reaction force, muscle forces, implant-bone interface forces, muscle moment arms, and glenohumeral range of motion.

Inferior placement of the glenoid had the biggest effect on the mechanical advantage of the deltoid muscle and reduced the deltoid force required to abduct the humerus. Medializing also reduced deltoid forces but to a smaller degree than inferior placement. Inferior placement in combination with medialization increased the deltoid moment arm and reduced the deltoid force by as much as 25%. This improvement in mechanical advantage could be of substantial clinical benefit to the patient population with severe rotator cuff deficiency and deltoid dysfunction in whom RTSA is most commonly indicated.

Glenohumeral joint reaction forces are important and determine prosthetic wear and implant survival. We noted reduced joint reaction forces associated with the reduced deltoid forces with medial and inferior placement of the glenosphere. Thus medial and inferior placement of the center of the rotation may have a beneficial effect on durability of the arthroplasty in addition to improving function.

The net moment generated by the joint reaction force on the implant-bone interface was reduced by medialization, supporting the design rationale and surgical recommendation to protect the interface to reduce potential for loosening. In the bone-grafted condition, the net moment at the graft-host interface was greater than in the fully medialized

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**Figure 4** Average total muscle force at 90° of abduction (sum of deltoid, subscapularis, infraspinatus, and teres minor muscle forces).

**Figure 5** Reverse total shoulder arthroplasty increased the deltoid moment arm, which changed with location of the glenosphere.
condition. This moment would be clinically relevant until the graft healed adequately. On the other hand, the bending moment at the implant-bone interface for the grafted condition was similar to that generated in the fully medialized condition. Therefore, assuming graft healing, the implant-bone interface is less likely to be subject to the increased stresses generated by reduced medialization.

Range of motion after shoulder arthroplasty affects function and is an important clinical outcome. In addition, impingement in adduction can give rise to scapular “notching” and can increase the risk for prosthetic failure. Pure medialization substantially reduces the range of adduction, whereas inferior placement increases range of motion. 9

Increasing the lateralization by bone grafting combined with inferior placement significantly increases adduction range of motion and reduces the risk of scapular notching.

One limitation of our study was that we simulated a ratio of scapulothoracic abduction to glenohumeral abduction at 1:2. This ratio represents normal scapulothoracic rhythm; after RTSA, scapulothoracic rhythms of 1:1 have been reported.5 We tested the sensitivity of the model to altered scapulothoracic rhythm and found that the average percentage increase in muscle forces was between 6% and 12% when the ratio of scapulothoracic abduction to glenohumeral abduction was changed from 1:2 to 1:1. We selected 3 shoulder specimens to reflect small, medium, and large
patients on the basis of the anatomy of a normal shoulder. Variations in anatomy can cause variation in computed forces and range of motion. This study was focused on the relative position of the glenosphere. To reduce the effect of variance due to differences in size, muscle attachments, and inertial properties among specimens, we normalized the results relative to the baseline RTSA condition. This reduced the variation between specimens as reflected in the reasonable size of the error bars. There are several additional variables that affect bone-implant interface forces. We did not consider the effect of neck-shaft angle or a larger glenosphere. A lower neck-shaft angle can lateralize the humeral shaft, whereas a larger glenosphere can shift the humerus more inferiorly.\(^9,10\)

We did not simulate the effect of muscle stretch or laxity that may be produced by medialization, which can alter muscle function by affecting the relative length-tension curve. This effect on muscle is clinically relevant and is being incorporated in a future study. We also did not simulate the effect of a massive rotator cuff deficiency affecting the infraspinatus, which can alter the distribution of muscle forces and the net joint contact force. Finally, only one generic prosthetic design with a few variables was analyzed. These results may not be representative of all RTSA designs.

### Conclusion

Our study quantifies the tradeoffs in selecting optimum placement of the glenosphere in RTSA. Medialization does reduce the bending moment at the implant-bone interface but requires inferior placement to reduce the risk for impingement and scapular notching. Lateralization with a bone graft can reduce the risk for impingement but carries the risk of higher bending moment at the host-graft interface (at least until healing). One viable option is partially medializing the glenosphere in RTSA, which retains most of the benefits of lower deltoid and glenohumeral forces and reduces the risk for scapular notching.

### Disclaimer

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