Humeral head arthroplasty and its ability to restore original humeral head geometry

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Background: Modern prosthetic components are designed to enable restoration of proximal humeral morphology, provided that a precise osteotomy of the humeral head at the level of the anatomic neck is performed. To determine whether a simulated osteotomy and replacement arthroplasty with an idealized implant were able to restore original head geometry.

Materials and methods: A handheld digitizer and surface laser scanner were used to digitize 24 humeri. Computer models were used to simulate an osteotomy, performed at the anterior cartilage–metaphyseal interface, and reconstruct the head with a spherical prosthetic head. The head diameter, radius of curvature, and inclination and retroversion angles were calculated for each specimen and compared with the original humeral head.

Results: The simulated osteotomy resulted in a 4.8° decrease in inclination (P < .01) and 11.3° increase in retroversion (P < .001). The radius of curvature in the coronal plane was not significantly different (P = .284). However, in the axial plane, the prosthesis was significantly larger than the original head for both head diameter (P < .001) and radius of curvature (P < .05).

Discussion: The study suggests that the humeral head is not a perfect segment of a sphere and an osteotomy along the anterior cartilage–metaphyseal interface does not remove only the proximal humeral articular surface. Even with a fully adaptable prosthetic implant, replacement arthroplasty is not able to restore original head geometry.

Conclusions: Alterations to head geometry with the osteotomy described may alter the line of force through the prosthetic joint, producing eccentric loading at the glenoid, and contribute to early failure.

Level of evidence: Basic Science, Anatomic Study, Computer Model.

Keywords: Shoulder; arthroplasty; osteotomy; anatomy; humerus; geometry

Shoulder arthroplasty is the treatment of choice for fracture and a range of degenerative joint diseases, with low reported revision rates. Radnay et al28 in a systematic review reported a rate of revision of 6.5%. However, this may not be an accurate reflection of the success of the procedure. Sperling and Cofield36 in a long-term follow-up noted that almost half of patients graded their treatment as unsatisfactory or unsuccessful whereas survivorship, assessed by traditional criteria, was considerably higher. Hasan et al reported on 139 consecutive patients who were dissatisfied with their shoulder replacement; 74% described stiffness, and 35% complained of instability. Hasan et al found that
components were malpositioned in 23% of cases and, in the total shoulder group, 59% of the glenoid components were noted to be loose. Similarly, Matsen and colleagues\(^7\) reviewed the characteristics of 282 unsatisfactory shoulder arthroplasties and noted that glenoid loosening was found in 63% of the patients, with glenohumeral malalignment as the most likely cause. Other authors have also recognized that component positioning was critical to implant survival.\(^{21,23,35,39,40}\) Modern prosthetic components are designed to adapt to the highly variable anatomy of the proximal humerus\(^3,12,30\) and, therefore, enable restoration of an individual’s proximal humeral morphology, provided that a precise osteotomy of the humeral head at the level of the anatomic neck is performed.\(^37\)

The objective of this study was to determine whether a recognized osteotomy of the humeral head at the level of the anterior anatomic neck and replacement arthroplasty with an idealized implant were able to restore original head geometry in terms of orientation and size—specifically, inclination, retroversion, radius of curvature, and head diameter.

### Materials and methods

Twenty-four human cadaveric full arms, preserved in formalin and without skeletal abnormality, including degenerative changes of the glenohumeral joint, were selected for this study. There were 11 right humeri and 13 left humeri. Eighteen specimens were matched pairs from nine individuals. There were 14 female and 10 male specimens from cadavers ranging in age from 68 to 99 years (mean, 84 ± 8.4 years). None of the donors had undergone previous surgical procedures on the shoulder joint.

Each humerus was disarticulated, and all soft tissues were removed. A precision reference cube was attached to the greater tuberosity of each humerus (Fig. 1) to enable 2 independently collected data sets to be combined.\(^7\) Before data acquisition, the following points and lines were identified and marked on each specimen: (1) the circumference of the anatomic neck; (2) the most superior point of the articular surface at the insertion of the supraspinatus tendon (H) and the corresponding lowest point of the articular surface at the cartilage-metaphyseal interface (L); and (3) the medial epicondyle (ML) and lateral epicondyle (LC). Each humerus was then mounted, rigidly, on a custom-built jig. Data were collected by 2 separate instruments: a handheld digitizer and surface laser scanner. A MicroScribe 3DX handheld digitizer (Immersion, San Jose, CA, USA) was used for manual acquisition of specific points of interest that were difficult to identify clearly with the surface laser scanner data. The MicroScribe 3DX system enables measurements to be made with the manufacturer’s reported accuracy of 10 \(\mu\)m. The surface topography was scanned at a resolution of 200 \(\mu\)m for the humeral head and 500 \(\mu\)m for the remaining bone. The MicroScribe 3DX digitizer data for each humerus were imported into 3DReshaper software (Technodigit, Gleizé, France) and transformed to the same coordinate system as the surface laser scanner data by use of the precision reference cubes as a common reference. The combined data from each specimen were then imported into Rhinoceros NURBS (non-uniform rational B-spline) modeling software and graphically presented (Fig. 2).

For each model (Figs. 2–4), the shaft axis of the humerus was constructed as a line through the center of a best-fit cylinder of the proximal humeral data points extending from the surgical neck to the distal insertion of the deltoid; the transepicondylar line was created as a single line between the medial and lateral epicondyles; and the articular portion of the humeral head in the constructed graphical model was divided using head height and the proximal 80% used to create an idealized sphere using a least squares method. The center of the sphere was calculated \((C_1)\), and the deviation from sphericity was calculated as a percentage of the standard error of the mean. The centroid of 80% of the articular surface was then calculated, providing an estimate of the center of the surface of the head \((C_2)\). The assumption was that the resultant line of force runs through the center with only minor deviation during movement.\(^{11,16,31,33,34,38}\) We also measured the following: a best-fit plane formed and bounded by the circumference of the anatomic neck, surface \((SA)\), with point \(O\) as the centroid of the surface \((SA)\); a coronal plane \((OL)\) passing through points \(O\) and \(L\) and normal to the surface \((SA)\); an axial plane \((AP)\) perpendicular to the plane \((OL)\) passing through \(O\) and normal to the surface \((SA)\); the coronal and axial diameters, determined as the distances between points created by the intersection of the planes \((OL\) and \(AP)\) with the digitized anatomic neck; and the head height \((OB)\), determined as the length of a line originating at \(O\), normal to the surface \((SA)\), and ending at the articular surface. We used the points digitized on the articular surface to determine the radius of curvature of the humeral head \((R_{ab})\), applying the technique of a least squares fit to a sphere.\(^11\) In addition, the coronal \((R_c)\) and axial \((R_a)\) radii of curvature of the humeral head were estimated by the same technique; the points on the line of intersection between the articular surface and the planes \(OL\) and \(AP\), respectively, were extracted for the calculation of each radius.
of curvature. Standard deviations from sphericity ($s_{Rhh}$, $s_{Rc}$, and $s_{Ra}$) were determined for $R_{hh}$, $R_c$, and $R_a$. The inclination angle ($\alpha$) and retroversion angle ($\beta$) were used to define the orientation of the humeral head relative to the humeral shaft. The inclination angle ($\alpha$) was calculated as an angle subtended between the humeral shaft axis ($s$) and the assumed resultant line of force ($C_1C_2$). The retroversion angle ($\beta$) was calculated as the angle between the transepicondylar line ($ML$) and $C_1C_2$ (Fig. 4).

The constructed graphical model was used to simulate resection of the articular surface and reconstruction with an idealized prosthetic implant. To simulate the osteotomy, a plane was constructed from the points $H$ and $L$ and the data points of the anterior portion of the digitized articular circumference between $H$ and $L$ (Fig. 2). For each specimen, an idealized fully adaptable spherical prosthetic head was constructed and placed on the simulated osteotomy plane. The lengths $HL$ and $OB$ were used to determine the diameter and head height of the prosthetic head, respectively. The inclination, retroversion, coronal and axial diameters, and radii of curvature (total, coronal, and axial) were calculated for each specimen and compared with the original humeral head parameters.

All tasks involved in data collection were completed by the same operators with the constructed graphical models, and subsequent calculations were completed by a single investigator. The precision of the experimental technique was calculated as the root-mean-square average of the precision error (standard deviation) calculated for each specimen. Linear and angular measurements were calculated for a total of 3 representative specimens that were digitized 3 times each. Power analysis was used to estimate the required sample size to ensure 90% power ($\alpha = .05$, $\beta = .1$). The distribution of all descriptors was tested for normality by use of a Shapiro-Wilk W test. Descriptive statistics were computed for all outcome variables, and paired $t$ tests were used to assess the differences between the original humeral head and prosthetic head parameters. All reported $P$ values were 2 tailed with $P < .05$ considered to be statistically significant. All statistical analysis was performed with the SPSS software package, version 14.0 (SPSS, Chicago, IL, USA).

**Results**

Data collection was determined to be repeatable to within 0.5° for angular data and 0.4 mm for linear data. For both the angular and linear data, the precision of the experimental design represents an error of less than 1%.
The number of specimens analyzed enabled differences to be detected between means at the 5% significance level with greater than 90% power for all except one of the parameters being compared. Inferences about differences between the mean radii of curvature data in the axial plane and coronal plane at the 5% significance level could only be made with $\beta = .82$. The data were found to be normally distributed for all parameters. The critical value for the Shapiro-Wilk W test at the .05 level for 24 specimens was 0.916.26

**Inclination and retroversion**

The simulated osteotomy resulted in changes to both the inclination and retroversion of prosthetic implant when compared with the original humeral head (Tables I-III). There was a mean decrease of 3.8° in the inclination angle of the prosthetic head (mean, 132.1° ± 5.0°) for the simulated osteotomy when compared with the inclination of the original humeral head (mean, 136.9° ± 4.7°), a difference that was found to be statistically significant ($P < .001$). Furthermore, the simulated osteotomy significantly ($P < .001$) increased the retroversion of the prosthetic head by a mean of $11.3° ± 8.0°$, from $18.5° ± 9.0°$ to $29.5° ± 10.7°$.

**Axial and coronal diameters**

By definition, the coronal diameter of the original head equaled the coronal diameter of the prosthetic head. However, a marked difference of $3.1 ± 1.8$ mm was found between the mean axial diameter of the original head (mean, $42.3 ± 3.4$ mm) and that of the simulated head (mean, $46.7 ± 4.3$ mm) ($P < .001$). A statistically significant difference was also noted between the axial and coronal diameters of the osteotomized surface, at $2.1 ± 2.6$ mm, with a range within the 95th percentile between $1.0$ and $3.2$ mm ($P < .01$).

**Head height**

The mean head height of the resected segment was significantly larger than that of the original humeral head ($P < .01$). The prosthetic head measured a mean of $19.5 ± 2.5$ mm compared with a mean of $16.9 ± 1.5$ mm, with a mean difference of $2.5 ± 1.9$ mm.

**Radius of curvature**

The radii of curvature of the original head (mean, $24.0 ± 1.2$ mm) and simulated head (mean, $25.0 ± 1.3$ mm) were statistically different ($P < .001$) (Tables I-III). In the coronal plane, the difference between the idealized prosthetic radius of curvature and the resected segment was $0.4 ± 0.4$ mm and, again, was significantly different ($P < .01$). Furthermore, in the axial plane, a significant difference of $2.0 ± 0.9$ mm was noted between the prosthesis and original head (mean, $23.0 ± 1.1$ mm) ($P < .001$).

**Discussion**

An osteotomy of the articular surface of the proximal humerus for shoulder arthroplasty assumes that the cut surface is oriented, identically, to the articular surface geometry. This study suggests that a commonly used osteotomy approach, along the anterior margin of the cartilage-metaphyseal interface, does not remove only the proximal humeral articular surface. Furthermore, replacement of the osteotomized segment with an idealized prosthesis does not recover the original humeral head geometry.

**Original humeral geometry**

The novel technique used to collect and analyze the data has provided results that appear to concur with previous anatomic studies of the proximal humerus. This study concurs with the observations noted in other studies on head geometry that the humeral head is not spherical but is elliptical in shape.1,3,20,22 The value for the mean radius of curvature of the total humeral head was found to be similar to that reported by other investigators.12,32 Examination of the radius of curvature in the axial and coronal planes showed that the values in each plane were significantly different and closely matched the results found by Iannotti et al.12 There was also variation in the degree of sphericity between the two axes. Deviation from the mean radius of curvature was most prominent in the axial plane (1.2% of the radius of curvature), whereas in the coronal plane, the head was more spherical. Examination of the coronal and axial diameters further supports the view that the head is elliptical in shape with a long diameter (coronal plane) to short diameter (axial plane), with a high degree of correlation between the two diameters ($R = 0.90$). The variation noted in the two planes supports the results of other authors.12,15
relative to the transepicondylar line and inclination of the humeral head relative to the shaft axis were found to concur with results from other investigators. 3,12,14,18,19,25,29,33

**Recovery of original humeral head geometry**

Although the osteotomy resulted in a statistically significant reduction in the inclination of the head relative to the humeral shaft axis, the clinical relevance of this change is difficult to assess. Previous work has suggested that an increase in the inclination of the head in the coronal plane may be associated with impingement on the greater tuberosity, or lead to proximal displacement of the center of rotation and a resultant alteration in the kinematics of the joint. 3,24 With a 4.8° change in inclination, the average displacement in the center of rotation would be 2.1 mm for a 25-mm head thickness. This value falls within the normal range of translations of the joint center during active motion and, therefore, may have little or no bearing on joint kinematics.

The osteotomy resulted in a 38% relative increase in the mean retroversion angle of the prosthetic head when

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**Table I**  Geometry of original humeral head (N = 24)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination (°)</td>
<td>135.0 ± 4.4</td>
<td>127.6-141.4</td>
<td>133.1-136.9</td>
</tr>
<tr>
<td>Retroversion (°)</td>
<td>18.5 ± 9.0</td>
<td>2.7-37.4</td>
<td>14.7-22.3</td>
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<tr>
<td>Coronal diameter (mm)</td>
<td>48.8 ± 3.2</td>
<td>42.7-55.1</td>
<td>47.4-50.1</td>
</tr>
<tr>
<td>Axial diameter (mm)</td>
<td>43.6 ± 2.5</td>
<td>38.9-49.0</td>
<td>42.5-44.6</td>
</tr>
<tr>
<td>Head height (mm)</td>
<td>16.9 ± 1.5</td>
<td>14.4-20.1</td>
<td>16.2-17.5</td>
</tr>
<tr>
<td>Total</td>
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<tr>
<td>Radius of curvature (mm)</td>
<td>24.0 ± 1.2</td>
<td>22.1-26.8</td>
<td>23.5-24.6</td>
</tr>
<tr>
<td>Sphericity (mm)</td>
<td>0.20 ± 0.06</td>
<td>0.11-0.30</td>
<td>0.17-0.22</td>
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<tr>
<td>Coronal</td>
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<tr>
<td>Radius of curvature (mm)</td>
<td>24.6 ± 1.3</td>
<td>22.2-27.6</td>
<td>24.1-25.2</td>
</tr>
<tr>
<td>Sphericity (mm)</td>
<td>0.13 ± 0.06</td>
<td>0.05-0.29</td>
<td>0.10-0.15</td>
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<tr>
<td>Axial</td>
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</tr>
<tr>
<td>Radius of curvature (mm)</td>
<td>23.0 ± 1.1</td>
<td>21.3-25.2</td>
<td>22.6-23.5</td>
</tr>
<tr>
<td>Sphericity (mm)</td>
<td>0.24 ± 0.06</td>
<td>0.14-0.38</td>
<td>0.21-0.27</td>
</tr>
</tbody>
</table>

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**Table II**  Geometry of osteotomized humeral head and idealized prosthetic implant (N = 24)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination (°)</td>
<td>131.2 ± 5.8</td>
<td>115.8-139.5</td>
<td>128.8-133.7</td>
</tr>
<tr>
<td>Retroversion (°)</td>
<td>29.5 ± 10.7</td>
<td>14.0-58.7</td>
<td>25.0-34.0</td>
</tr>
<tr>
<td>Coronal diameter (mm)</td>
<td>48.6 ± 2.8</td>
<td>44.3-55.8</td>
<td>47.4-49.8</td>
</tr>
<tr>
<td>Axial diameter (mm)</td>
<td>46.6 ± 3.8</td>
<td>42.3-57.2</td>
<td>44.9-48.2</td>
</tr>
<tr>
<td>Head height (mm)</td>
<td>19.5 ± 2.5</td>
<td>15.4-24.6</td>
<td>18.5-20.6</td>
</tr>
<tr>
<td>Radius of curvature (mm)</td>
<td>25.0 ± 1.3</td>
<td>22.6-28.2</td>
<td>24.5-25.6</td>
</tr>
</tbody>
</table>

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**Table III**  Differences between geometry of osteotomized head and original geometry

<table>
<thead>
<tr>
<th>Paired differences between original and idealized</th>
<th>Mean</th>
<th>SD</th>
<th>SEM</th>
<th>95% Confidence interval</th>
<th>t</th>
<th>df</th>
<th>Significance (2 tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination (°)</td>
<td>3.8</td>
<td>2.8</td>
<td>0.58</td>
<td>2.56 4.96 6.49 23 &lt; .001</td>
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<tr>
<td>Retroversion (°)</td>
<td>−11.0</td>
<td>8.0</td>
<td>1.63</td>
<td>−14.39 −7.66 −6.77 23 &lt; .001</td>
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<tr>
<td>Coronal diameter (mm)</td>
<td>0.1</td>
<td>1.3</td>
<td>0.27</td>
<td>−0.45 0.68 0.42 23 .676</td>
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<tr>
<td>Axial diameter (mm)</td>
<td>−3.0</td>
<td>3.5</td>
<td>0.71</td>
<td>−4.46 −1.51 −4.19 23 &lt; .001</td>
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</tr>
<tr>
<td>Head height (mm)</td>
<td>−2.7</td>
<td>2.0</td>
<td>0.41</td>
<td>−3.5 −1.82 −6.56 23 &lt; .001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of curvature (mm)</td>
<td>−1.0</td>
<td>0.56</td>
<td>0.11</td>
<td>−1.2 −0.74 −8.62 23 &lt; .001</td>
<td></td>
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<tr>
<td>Axial radius of curvature (mm)</td>
<td>2.0</td>
<td>0.90</td>
<td>0.2</td>
<td>1.6 2.4 10.79 23 &lt; .001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronal radius of curvature (mm)</td>
<td>0.4</td>
<td>0.36</td>
<td>0.73</td>
<td>0.22 0.52 5.12 23 &lt; .001</td>
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<td></td>
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</tbody>
</table>
compared with the original humeral head geometry. Although a quantifiable relationship has not yet been fully established, an increase in retroversion has been implicated in secondary displacement of the greater tuberosity after arthroplasty for a 4-part fracture of the humeral head. The change in retroversion angle would alter the position of the center of rotation of the prosthesis humeral head and, by implication, impact the stability of the joint and balance of the anterior and posterior structures. Fischer et al noted that a change in the position of the rotational center by 20% of the head’s radius may alter the lever arm of the rotator cuff by 20%. The increase in retroversion found in this study would result in a change to the center of rotation of this value, approximately. Furthermore, the alteration in the line of force through the joint may produce eccentric loading on the glenoid, increasing the risk of excessive glenoid wear and glenoid loosening. Thus, following the line of the anterior portion of the anatomic neck as a guide for the osteotomy as proposed by some authors would appear to have a deleterious effect on the recovery of humeral head geometry and perhaps on the kinematics of the glenohumeral joint in the axial plane.

The osteotomy resulted in a discrepancy between the axial and coronal diameters of 3.1 mm. Correspondingly, selection of an implant with a head diameter matching the coronal diameter resulted in prosthetic overlap of the cut humeral surface in the axial plane by the same amount. Protrusion of the prosthetic head over the edge of the osteotomized humeral head may increase the tension on either the subscapularis muscle or infraspinatus muscle, or both, and could lead to tendinopathy and possible tendon rupture. Using a prosthesis to match the axial diameter may reduce the risk of a tendinopathy or rupture. However, there may be inherent risks in using what would effectively be a smaller head. Alterations to the congruency and constraint of the joint might alter loading conditions and joint kinematics. Coupled to the discrepancy in head diameter in the axial plane, the radius of curvature of the prosthesis did not replicate the radius of curvature of the humeral head in the axial plane. Small changes in diameter and radius of curvature in the coronal plane have been found to alter the kinematics of the glenohumeral joint. The effect of an increase in radius of curvature in the axial plane may be modification of the assumed fixed nature of the center of rotation of the humeral head within the glenoid fossa, either in absolute position or in its instantaneous position during shoulder motion. The result may be an alteration to the line of force through the glenohumeral joint and changes to soft-tissue tension, with a risk of rupture of the subscapularis muscle, possibly.

Iannotti et al and other authors describe the necessity to reconstruct the glenohumeral joint to within 2 or 3 mm of the anatomic radius of curvature to match the conformity of the natural glenohumeral joint. The change in radius of curvature and diameter seen in this study (using an idealized prosthetic implant) would be sufficiently small to comply with their requirements.

Conclusions

The results from this study suggest that a simulated osteotomy along the anterior border of the articular surface and replacement arthroplasty with an idealized implant were not able to restore original head geometry in terms of inclination, retroversion, radius of curvature, and head diameter. The aforementioned erroneous assumptions that the osteotomized segment is a perfect segment of a sphere and oriented identically to the normal head geometry might be corrected by considering an alternative osteotomy technique or a new implant design.

Disclaimer

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References

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