An anthropometric study of the distal humerus

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Background: The optimal articular shape for distal humeral hemiarthroplasty has not been defined because of a paucity of data quantifying the morphology of the normal distal humerus. This study defines the osseous anatomy and anatomic variability of the distal humerus using 3-dimensional imaging techniques.

Methods: Three-dimensional surface models were created from computed tomography scans obtained from 50 unpaired human cadaveric elbows. Geometric centers of the capitellum and the trochlear groove defined the anatomic flexion-extension axis. A coordinate system was created, and the distal humerus was sectioned into 100 slices along this axis. The C line was defined as the line of best fit connecting the geometric centers of each of the slices.

Results: The anatomic flexion-extension axis of the distal humerus was found to be an average of 1° ± 1° from the C line (range, 0°-3°) in the coronal plane and 2° ± 1° (range, 0°-7°) in the transverse plane. The average trochlear width was 22 ± 3 mm, and the average trochlear height was 18 ± 2 mm. The mean width of the capitellum was 17 ± 2 mm; the height was 23 ± 2 mm (P < .001).

Conclusions: The difference in the capitellum width and height demonstrates that the capitellum is ellipsoidal, not spherical. A data bank of humeral dimensions may be used for the development of future distal humeral hemiarthroplasty implants. A more anatomic implant may optimize kinematics and maximize contact area, thus minimizing contact stresses on the native ulna and radius.

Level of evidence: Anatomic Study, Imaging.
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Keywords: Distal humerus; morphology; implant design; elbow hemiarthroplasty

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Hemiarthroplasty of the distal humerus was reported as early as 1927. It has only recently been more commonly used as devices specifically designed for this indication have become commercially available. This procedure may be ideal in situations in which only one portion of the elbow joint is affected, including distal humerus fractures not amenable to open reduction and internal fixation, avascular necrosis, and nonunions. The optimal shape of hemiarthroplasty implants has not been established because of a lack of data quantifying the morphology of the normal distal humerus.\textsuperscript{13,14} Anthropometric information is available for the shoulder\textsuperscript{1,5,9,10} and has played an important role in optimizing the design of these implants. The purpose of this study was to quantify the osseous anatomy of the distal humerus and to define anatomic variability by 3-dimensional (3D) imaging techniques. The data bank of distal humeral dimensions created may improve the designs of future distal humeral hemiarthroplasty implants.

Methods

This 3D computed tomography (CT) anatomic study of the distal humerus used 50 unpaired normal human cadaveric elbows. There were 34 male donors and 16 female donors, with an average age of 72 $\pm$ 12.5 years. CT scans were acquired with use of a 64-slice clinical scanner (GE LightSpeed Ultra; New Berlin, WI, USA) at a slice thickness of 0.625 mm. The humeri were manually segmented from the CT images by semiautomated methods and a fixed threshold of 148 Hounsfield units with Mimics software (Materialize NV, Leuven, Belgium). The 3D surface models were generated. A series of custom programs created with the Visualization ToolKit (Kitware Inc, Clifton Park, NY, USA) were used to measure each model. To simplify the measuring process, all left-sided models were mirrored before the measurements were taken.

On the 3D surface model, 9 points were manually chosen on the capitellum, 6 points on the trochlear groove, and 2 points on the posterior surface of the humerus. By use of a semiautomated algorithm, point clouds were created over the surface of the capitellum and along the trochlear groove. This algorithm ensured precision and consistency of point placement. These points were used to define the geometric center of the spherical capitellum and the circular trochlear groove (Fig. 1). A line connecting these center points defined the flexion-extension axis. A humeral coordinate system, aligned with the flexion-extension axis, was created to provide a measurement reference frame. The axial direction was determined by use of 2 points chosen on the distal aspect of the posterior humeral shaft, one located distally and one midshaft. The distally pointing axial vector was defined as the x-axis, and the laterally pointing axis was defined as the z-axis. The y-axis was determined by use of the cross-product and pointed anteriorly (Fig. 2). The process of selecting points and creation of the coordinate system was repeated by the primary author (S.J.D.) on 20 of the specimen models to ensure intraobserver reliability. The process was also repeated on 20 models by another author (A.L.) to ensure interobserver reliability. These were quantified by intraclass correlations of absolute agreement.

With use of the flexion-extension axis as an initial reference direction vector, transverse cross sections of the articular surface were automatically segmented at 0.1-mm increments and then fitted by a least squares method. A best-fit line through these centers of all the cross sections was generated per the method of Shiba et al,\textsuperscript{13} who defined this as the C line. Cross sections with fewer than 30 points were automatically ignored to ensure a sufficient number of points at each slice to obtain an accurate circle fit. This process was iterated again, using the C line as the reference vector, thus refining the final C line by ensuring that it was defined solely by the articular surface cross sections. The reference coordinate system was aligned with the refined C line, and its origin was defined as the center of the most medial slice. The distance between the most medial and lateral slices defined the width of the articulation. The purpose of the algorithm was to determine the C line, articular width, and coordinate system. The final cross sections were obtained between the medial and lateral slices at increments of 1% of the measured articular width. The 3D location and radius of the fitted circle were recorded for each of these 100 cross sections (Fig. 3). The data were transferred into Microsoft Excel Spreadsheet (Microsoft, Redmond, WA, USA), where predefined anatomic measurements were calculated (Fig. 4).

Results

The results of all measurements, including various ratios, are presented in Table I. Intraobserver reliability for the
The anatomic flexion-extension axis of the distal humerus was $1^\circ \pm 1^\circ$ from the C line (range, $0^\circ$-$3^\circ$) in the coronal plane and $2^\circ \pm 1^\circ$ (range, $0^\circ$-$7^\circ$) in the axial plane ($P < .0001$).

The mean width of the capitellum (CW) was $17 \pm 2$ mm; the height (CH) was $23 \pm 2$ mm. A paired t test revealed that the width and height were significantly different ($P < .001$). The Pearson correlation coefficient between CW and CH was 0.772, representing a significant correlation ($P < .001$) (Fig. 5). The average trochlear width proper (TW) was $22 \pm 3$ mm, and the correlation with CW was 0.676, also representing a significant correlation ($P < .001$) (Fig. 6). The average trochlear height (TH) was $18 \pm 2$ mm. TW and TH were significantly correlated with a Pearson correlation coefficient of 0.454 ($P < .001$) (Fig. 7).

The mean lateral trochlear height (LTH) was $22 \pm 2$ mm; the mean medial trochlear height (MTH) was significantly larger at $30 \pm 4$ mm ($P < .001$). Likewise, the lateral trochlear depth (LTD) was $22 \pm 2$ mm; the average medial trochlear depth (MTD) was significantly larger at $30 \pm 4$ mm ($P < .001$).

In comparing men and women, the capitellar width (CW), capitellar height (CH), trochlear width (TW), trochlear width proper (TWP), lateral trochlear height (LTH), trochlear height (TH), medial trochlear height (MTH), capitellar depth (CD), lateral trochlear depth (LTD), medial trochlear depth (MTD), and articular width (W) were significantly larger in men ($P < .001$). The morphologic ratios (CW/CH, TW/CW, MTH/LTH, and W/TH) were not significantly different between men and women ($P > .05$).

Discussion

Implants used for elbow hemiarthroplasty aim to recreate the normal distal humeral articular anatomy. A thorough knowledge of the distal humerus morphology is necessary to create anatomic implants that will help optimize elbow kinematics and maximize contact area with the proximal radius and ulna.

Shiba et al$^{13}$ were the first to thoroughly quantify the anatomy of the ulnohumeral joint. Four human cadaveric elbows were used in their study. The humeri were cut in 0.76-mm-thick slices perpendicular to the transepicondylar line (line joining the medial and lateral epicondyles). The geometry was examined with surface analysis by creating circle fits of each slice and determining a center and radius of each circle. The centers of each circle generally were on a straight line they referred to as the C line.$^{13}$ They performed...
similar measurements on the trochlea and reported ranges of sagittal radii of the lateral trochlear flange, trochlear groove, and mediotal trochlear flange of 9.6 to 11.6 mm, 8.4 to 9.0 mm, and 11.8 to 14.7 mm, respectively. This is similar to the results of the present study, which found sagittal diameter of the lateral trochlear height, trochlear height, and mediotal trochlear height to be $22 \pm 2$ mm, $18 \pm 2$ mm, and $30 \pm 4$ mm, respectively.

Sabo\textsuperscript{1} performed a morphologic analysis of the capitellum on 50 cadaveric elbows using CT scan images and measurements similar to those of the present study. They found an average capitellar height of $23.2 \pm 2.8$ mm (range, 18.0-29.5 mm), with a mean width of $13.9 \pm 2.3$ mm (range, 9-19 mm). Wevers\textsuperscript{14} sectioned 6 distal humeri in the sagittal plane and performed circle fits to characterize the shape of the distal humeral articulation. They found a range in capitellar width from 14.5 to 21.5 mm. They did not specifically report on capitellar height but suggested the size for the height of the capitellar portion ranging from 19.2 to 23.7 mm.\textsuperscript{14} Shiba\textsuperscript{15} also measured sagittal radius of the capitellum and reported a range from 9.8 to 12.0 mm. This study’s results are consistent with the results of these 3 previous studies. The current study found a mean capitellar width of $17 \pm 2$ mm (range, 12-21 mm) and a mean capitellar height of $23 \pm 2$ mm (range, 18-27 mm). In addition, we found that the capitellar width and height were statistically different. This indicates that the capitellum is ellipsoid, not spherical, and is consistent with a recent report on capitellar morphology.\textsuperscript{11}

The measures taken in the present study were referenced from the C line as described by Shiba et al.\textsuperscript{13} In the current study, the C line was defined as the line of best fit connecting the geometric centers of each of the 100 circle fits of the distal humerus. The flexion-extension axis of the distal humerus is defined by the geometric center of the capitellum, approximated as a sphere, and the geometric center of the trochlear groove, approximated as a circle.\textsuperscript{2-4,6,7} We found that on average, these lines differed by $1^\circ \pm 1^\circ$ (range, $0^\circ$-$3^\circ$) in the coronal plane and $2^\circ \pm 1^\circ$ (range, $0^\circ$-$7^\circ$) in the axial plane ($P < .0001$). These large standard deviations and large ranges demonstrate the variability between the C line and the flexion-extension axis. This information becomes significant in implant design, as the measurements found in this study are referenced to the C line; therefore, any implant produced from these measurements must also be referenced to the C line, not the anatomic flexion-extension axis.

The circle fit method used in this study created 100 circles in the sagittal plane. The diameter of each is presented in schematic form in both anterior-posterior and distal-proximal projections in Figure 8. This provides a detailed description of the articular shape of the distal humerus, which could prove useful in development of a distal humeral hemiarthroplasty.

The present study has limitations. First, the sample size is relatively small to define such a complex articulation that has such high variability between subjects. Second, we defined the anatomy of the distal humerus on the basis of 3D CT reconstructions. CT scans do not include articular cartilage; therefore, the measurements taken reflect only the osseous anatomy of the distal humerus. Schub et al.\textsuperscript{12} demonstrated that the thickness of cartilage was not
### Table 1: Average measurements for all specimens, men only, and women only

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>CW</th>
<th>CH</th>
<th>TW</th>
<th>TWP</th>
<th>LTH</th>
<th>TH</th>
<th>MTH</th>
<th>CD</th>
<th>LTD</th>
<th>TD</th>
<th>MTD</th>
<th>W</th>
<th>CW/CH</th>
<th>TW/CW</th>
<th>MTH/LTH</th>
<th>W/TH</th>
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<tr>
<td>Average (mm)</td>
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<td>17.2</td>
<td>23.3</td>
<td>25.3</td>
<td>21.0</td>
<td>21.6</td>
<td>17.8</td>
<td>29.9</td>
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<td>21.9</td>
<td>17.8</td>
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<td>1.7</td>
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<td>3.2</td>
<td>2.6</td>
<td>2.2</td>
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<td>4.1</td>
<td>1.0</td>
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<td>4.6</td>
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<td>0.1</td>
<td>0.2</td>
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<td>Max/min (mm)</td>
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<td>33.8/19.6</td>
<td>27.4/15.8</td>
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<td>25.5/17.4</td>
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<tr>
<td>Average (mm)</td>
<td>72.8</td>
<td>18.1</td>
<td>24.4</td>
<td>26.9</td>
<td>22.1</td>
<td>22.6</td>
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<td>9.4</td>
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<td>1.8</td>
<td>2.5</td>
<td>2.1</td>
<td>1.6</td>
<td>1.6</td>
<td>3.6</td>
<td>0.8</td>
<td>1.6</td>
<td>1.6</td>
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<tr>
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<td>20.7</td>
<td>23.5</td>
<td>19.3</td>
<td>19.4</td>
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<td>26.4</td>
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<td>38.9</td>
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<tr>
<td>Max/min (mm)</td>
<td>97/46</td>
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<td>36.0/23.8</td>
<td>42/33.2</td>
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</tbody>
</table>

*CW,* capitellar width; *CH,* capitellar height; *TW,* trochlear width; *TWP,* trochlear width proper; *LTH,* lateral trochlear height; *TH,* trochlear height; *MTH,* medial trochlear height; *CD,* capitellar depth; *LTD,* lateral trochlear depth; *TD,* trochlear groove depth; *MTD,* medial trochlear depth; *W,* articular width.
uniform in their magnetic resonance imaging study. They selected 8 points along the distal humeral articular surface, including 3 points on the lateral capitellum, 3 points on the medial capitellum, and 2 points along the trochlear groove. They found that the cartilage thickness of the lateral capitellum ranged from 1.06 to 1.49 mm, the medial capitellum from 0.87 to 1.63 mm, and the trochlear groove from 0.78 to 1.32 mm. These differences may affect the calculation of the flexion-extension axis and C line. In spite of this, the previously cited studies that included articular cartilage in their analysis demonstrated relatively consistent measurements with the present study. Finally, we used a circle fit algorithm to define the morphology of the capitellum and trochlea. Neither of these structures conforms to perfect geometric shapes, such as spheres or ellipses; therefore, this may result in measurement error in some cases.

The strengths of the present study are that we examined the morphology of the distal humerus with modern 3D techniques, with high intraobserver and interobserver reliability. We used similar principles to the study performed by Shiba; however, because of the technology used, we were able to analyze many more specimens and used a software program that is very accurate (≤1.0 mm measurement error). Other studies using similar software report high accuracy of ≤0.5 mm discrepancy between measurements taken on CT scan and direct measurements on the anatomic specimens. We were also able to define our circle fits on the basis of slices perpendicular to the C line, whereas Shiba initially created circle fits perpendicular to the transepicondylar axis, which has considerable variability between subjects.

Figure 5 Correlation of capitellar height with capitellar width ($R = 0.772; \ P < .001$).

Figure 6 Correlation of trochlear height with trochlear width proper ($R = 0.676; \ P < .001$).

Figure 7 Correlation of trochlear height with trochlear width proper ($R = 0.454; \ P < .001$).

Figure 8 Average diameter of each of the 100 slices in millimeters of all specimens. The x-axis represents the 100 slices; the y-axis represents diameter in millimeters. The top figure represents distal to proximal projections (coronal plane). The bottom figure represents anterior to posterior projections (axial plane).
Conclusion

This study characterizes the osseous anatomy and anatomic variability of the distal humeral articulation by accurate 3D reconstruction methods. Despite not including the articular cartilage thickness in our measurements, a data bank of distal humeral dimensions has been created and may be effective in the development of future distal humeral hemiarthroplasty implants. A more anatomic implant may optimize elbow kinematics and maximize contact on the native ulna and radius, which may ultimately increase function and improve longevity of the implant.

Disclaimer

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References