J Shoulder Elbow Surg (2016) 25, 1532–1541

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

An anthropometric analysis to derive formulae for calculating the dimensions of anatomically shaped humeral heads

C. Scott Humphrey, MD[a,*], Benjamin W. Sears, MD[b], Michael J. Curtin, MD[c]

[a]*Humphrey Shoulder Clinic, Eagle, ID, USA*
[b]*Western Orthopaedics, Denver, CO, USA*
[c]*St. Luke's Orthopaedics, Boise, ID, USA*

Background: The elliptical shape of the humeral head has been vaguely described, but a more detailed mathematical description is lacking. The primary goal of this study was to create formulae to describe the mathematical relationships between the various dimensions of anatomically shaped humeral heads.
Methods: Three-dimensional computer models of 79 proximal humeri derived from computed tomography scans (white subjects, 47 male and 32 female; ages, 17-87 years) were studied. Linear regression analysis of the obtained humeral measurements was performed, and Pearson correlation coefficient (*R*) values were calculated. To substantiate the results of the linear regression analysis, Welch *t*-test was used to compare various parameters of small, medium, and large humeral heads.
Results: Formulae for calculating humeral head height, diameters of the base of the humeral head in the frontal and sagittal planes, and radii of curvature in the frontal and sagittal planes were derived from the linear regression plots that were found to have strong ($1 \geq R \geq 0.50$) correlations. By Welch *t*-test, differences between the 3 head sizes were statistically significant in each case ($P \leq .022$). The elliptical shape of the base of the humeral head was found to elongate with increasing humeral head size.
Conclusions: Mathematical formulae relating various humeral head dimensional measurements are presented. The formulae derived in this study may be useful for the design of future prosthetic shoulder systems in which the goal is to replicate normal anatomy. This is the first study to describe that the elliptical shape of the base of the humeral head elongates as head size increases.
Level of evidence: Basic Science Study; Anatomy Study; Imaging

Keywords: Humeral head; shape; size; dimensions; elliptical; formula; anthropometry; gender

Most presently available shoulder prosthesis systems use humeral heads that are spherically shaped, yet several previous anatomic studies have documented that the humeral head is ovoid rather than spherical.[2,4,5,7,8,13,14,18] Two recent studies suggest that rotational range of motion and glenohumeral joint

No Institutional Review Board approval was needed for this basic science study using de-identified material.

*Reprint requests: C. Scott Humphrey, MD, Humphrey Shoulder Clinic, 3381 W Bavaria St, Eagle, ID 83616, USA.

E-mail address: humphrey@boiseshoulderclinic.net (C.S. Humphrey).

1058-2746/$ - see front matter © 2016 Journal of Shoulder and Elbow Surgery Board of Trustees. All rights reserved.
http://dx.doi.org/10.1016/j.jse.2016.01.032

kinematics might be improved by employing a prosthetic humeral head that accurately replicates normal human anatomy during shoulder arthroplasty surgery.[5,10] Although the elliptical shape of the humeral head has been vaguely described, a more detailed mathematical description of the shape of the humeral head is lacking and would be useful for the purpose of creating anatomically shaped prosthetic humeral heads.

The primary goal of this study was to create formulae that may be used to mathematically calculate the dimensions of anatomically shaped humeral heads of varying size. A secondary goal was to add to the currently available anthropometry data pertaining to the proximal humerus bone.

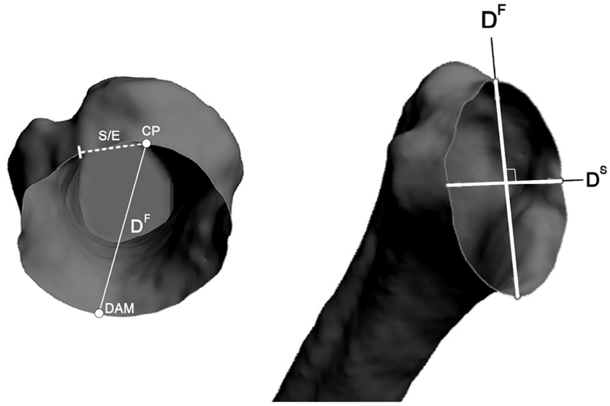

Figure 1 The critical point (*CP*) and the distal articular midpoint (*DAM*) were identified before the virtual head resection while determining the head equator as described by Hertel et al.[7] After head resection, the length of the diameter of the base of the humeral head in the frontal plane (D^F) was measured as the shortest distance between CP and DAM. D^S (the length of the diameter of the base of the humeral head in the sagittal plane) bisects and is perpendicular to D^F. D^F, D^S, and the distance between the bicipital sulcus and critical point (*S/E*) were identified and measured directly on 3D computer models of humeri.

Materials and methods

The specimens consisted of de-identified, 3-dimensional (3D) computer models derived from computed tomography scans of 79 proximal humeri from white subjects from the United States and Australia (47 male and 32 female; ages, 17-87 years, with an average age of 56 years). The models were obtained from a second party (Materialise, Leuven, Belgium) and were prescreened to exclude specimens with osteophytes or other obvious degenerative changes.

Bone landmark identification methods and measurement techniques were adapted from a previously published study.[7] Three-dimensional imaging software (Adobe Acrobat 9 Pro; Adobe Systems Incorporated, New York, NY, USA) was used to manipulate and to measure the 3D models. By use of the software, the humeral head of each specimen was virtually resected to mimic the ideal surgical head resection along the anatomic neck as would be done during shoulder arthroplasty surgery. Specifically, the cutting plane for head resection for each humerus model was derived using methodology for the identification of the head equator and other bone landmarks as described by Hertel et al.[7] Measurements of the diameter of the cross section of the base of the humeral head in the frontal plane (D^F) and sagittal plane (D^S) and the distance between the biceps sulcus and the humeral head equator were measured by software directly on the virtual models (Fig. 1). These measurements were recorded to the nearest tenth of a millimeter.

To simulate the radiographic views that had been used to make 2-dimensional measurements in the study by Hertel et al,[7] the 3D models were each rotated on the computer screen to the ideal position, and the image was then printed onto paper (Fig. 2). The scale of the printed images was adjusted to a 1:1 scale based on measurements that were made with the software directly on the virtual models. To obtain the ideal view for frontal plane measurements, each humerus model was oriented such that the head equator was parallel to the computer screen (D^F is coplanar with the head equator), and the plane of the osteotomy for the head cut was oriented perpendicular to the screen. To obtain the ideal view for sagittal plane measurements, the head equator was oriented perpendicular to the computer screen, and the plane of the osteotomy for the head cut was oriented perpendicular to the screen. This method of orientation was used to create and to print simulated radiographic images that were then marked for the purpose of measuring medial offset, posterior offset, head height, surface arc, radius of curvature in the frontal plane, radius of curvature in the sagittal plane, and critical distance (Figs. 2 and 3). Digital calipers were used for measurements on the simulated radiographs, and the measurements were recorded to the nearest tenth of a millimeter.

Radii of curvature and the center of rotation of each humeral head in both the frontal and sagittal planes were determined by use of custom-made circular templates that increased in size in 1-mm increments (Fig. 2, *C* and *G*). The long axis of the humeral diaphysis was determined through use of a custom-made, 12-mm by 150-mm rectangular ruler with a cutout slot in the middle for drawing the axis line. The ruler was centered over the humeral image so that the outer border of the ruler was contained symmetrically within the diaphysis in a manner that was meant to simulate insertion of a straight-stemmed prosthesis (Fig. 2, *B* and *F*).

Linear regression analysis was performed, and Pearson correlation coefficient (R) values were calculated to explore correlations between various humeral measurements. The strength of association for the measurement relationships was defined as follows using the absolute value of R: strong ($1 \geq R \geq 0.50$), medium ($0.49 \geq R \geq 0.30$), and weak/negligible ($0.29 \geq R \geq 0$). Positive R values implied a positive correlation, and negative R values implied a negative correlation. Mathematical equations defining the dimensional relationships between humeral head measurement variables were derived from linear regression plot trend lines (Microsoft Excel 2008 for Mac, version 12.3.6; Microsoft, Redmond, WA, USA) that were found to have strong correlations.

To substantiate the results of the linear regression analysis, the specimens were divided into 3 groups based on the head size: small ($D^F < 45.3$ mm), medium (45.3 mm $\leq D^F <$ 50.9 mm), and large (50.9 mm $\leq D^F$). The cutoff points delineating small vs. medium vs. large heads were determined by splitting the range of D^F measurements into equal thirds between the smallest D^F value (39.7 mm) and the largest D^F value (56.5 mm). Welch *t*-test was then used to compare the mean values of humeral head height (HHH), D^S, radius of curvature in the frontal plane (ROC^F), and radius of curvature in the sagittal plane (ROC^S) between the different head sizes. Unequal variance and 2-tailed distribution were assumed, and statistical significance was set at P value $\leq .05$ whenever the Welch *t*-test was used in this study.

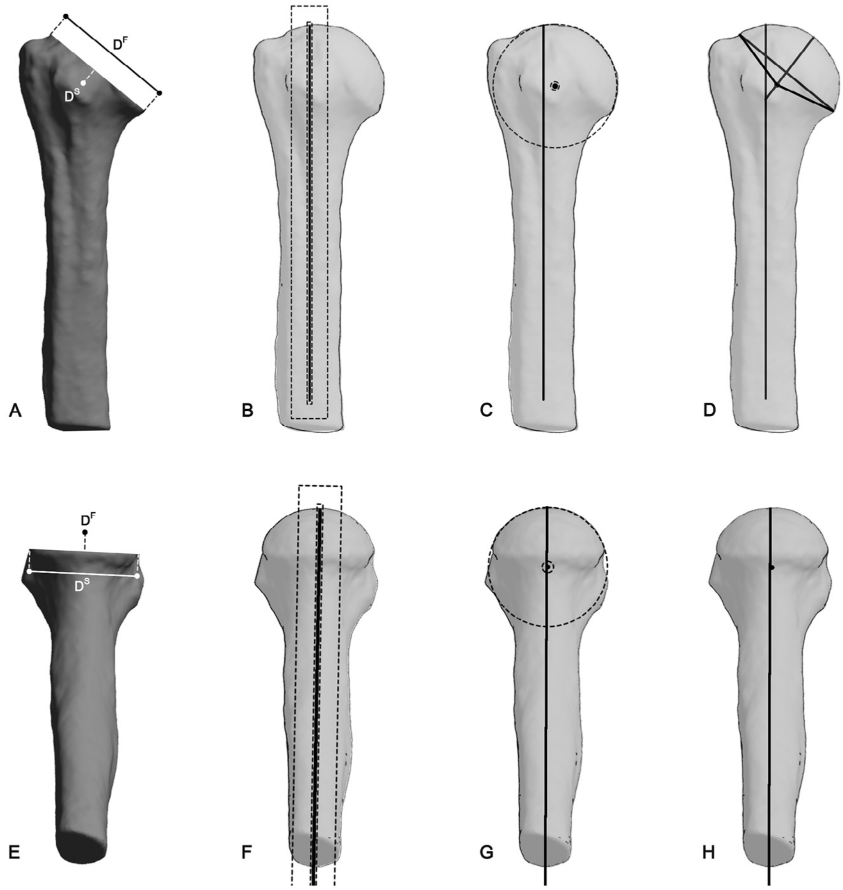

Figure 2 The method of marking simulated radiographs for anthropometric measurement is demonstrated. (**A**) To obtain the ideal view for the simulated anterior-posterior radiographs, the humeral model is oriented so that D^F is parallel to while D^S is perpendicular to the computer screen. (**B**) A custom-made ruler with a center slot is used to mark the long axis of the humerus in the frontal plane. (**C**) Custom-made circular templates that increase in size in 1-mm increments are used to identify the center of rotation and to size the radius of curvature in the frontal plane. (**D**) Additional lines are added as shown. (**E**) To obtain the ideal view for the simulated medial-lateral radiographs, the humeral model is oriented so that D^S is parallel to while D^F is perpendicular to the computer screen. (**F**) A custom-made ruler with a center slot is used to mark the long axis of the humerus in the sagittal plane. (**G**) Custom-made circular templates that increase in size in 1-mm increments are used to identify the center of rotation and to size the radius of curvature in the sagittal plane. (**H**) Final markup for the simulated medial-lateral radiographs.

To better define the elliptical shape of the base of the humeral head, regression analysis plots and Pearson correlation coefficient results were used to examine the relationship between the lengths of the axis of the ellipse in the frontal plane (D^F) and the axis of the ellipse in the sagittal plane (D^S). Welch *t*-test was also used to compare the mean values of the difference between the long and short axis ($D^F - D^S$) of the ellipse at the base of the head for small, medium, and large humeral heads.

Male and female specimens were also analyzed separately using linear regression analysis and Welch *t*-test to explore potential differences between the anthropometric results based on gender.

To ensure that specimen morphology and measurement techniques were consistent with what has been previously reported, anthropometric measurement results from this study were compared with results from other previously published studies.[1,3-5,7-9,17,19,20]

Results

In our study, when males and females were analyzed together as a group, the average angle of inclination of our specimens was 135° (range, 122°-144°). HHH averaged 17.7 mm (range, 14.0-21.9 mm). The average measurement at the base of the humeral head in the frontal plane (D^F) was 48.8 mm (range, 40.3-56.5 mm); in the sagittal plane (D^S), it measured 44.5 mm (range, 36.4-51.2 mm). The average difference between the D^F and D^S measurements at the base of the head ($D^F - D^S$) was 4.3 mm (range, −1.3 to 9.3 mm). The average D^F/D^S ratio was 0.91 (range, 0.83-1.03). The average radius of curvature in the frontal plane (ROC^F) was 25.4 mm. The average radius of curvature in the sagittal plane (ROC^S) was 23.8 mm.

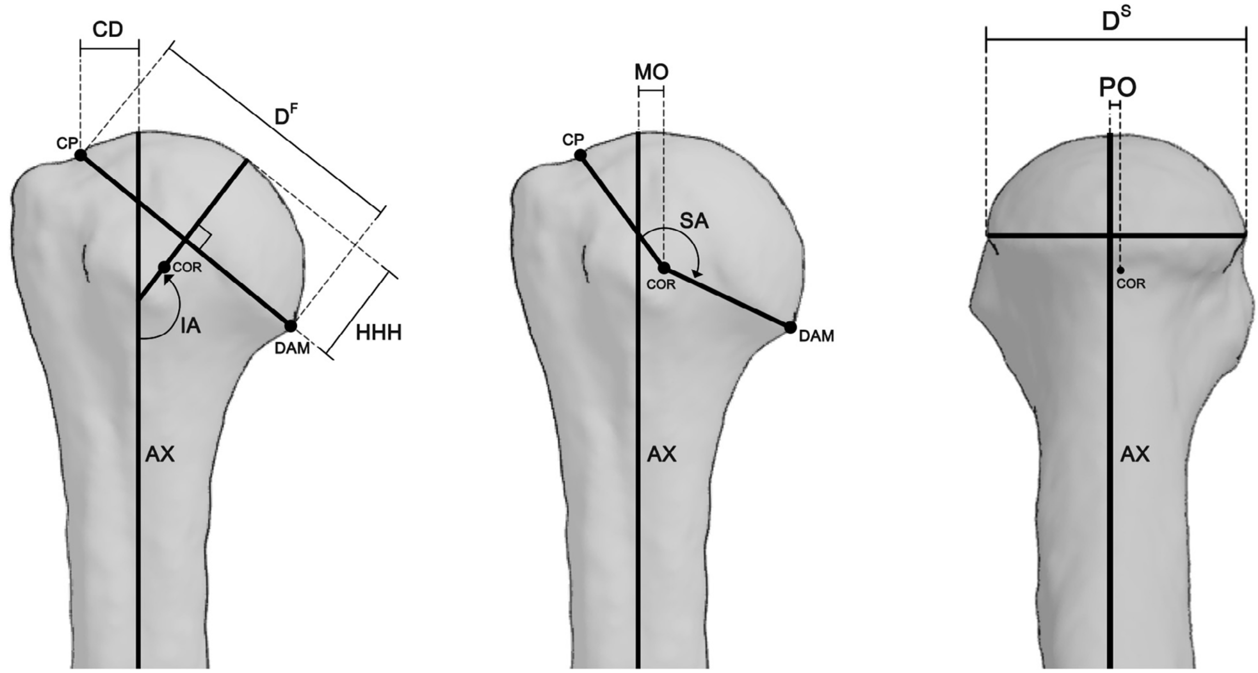

Figure 3 Anthropometric measurements: *AX,* long axis of the humerus; *CD,* critical distance; *CP,* critical point; *COR,* center of rotation; *DAM,* distal articular midpoint; *D^F,* diameter of the base of the head in the frontal plane; *D^S,* diameter of the base of the head in the sagittal plane; *HHH,* humeral head height; *IA,* inclination angle; *MO,* medial offset; *PO,* posterior offset; *SA,* surface arc.

Complete measurement results are listed and are compared with those from other published studies in Supplementary Table SI.

Pearson correlation coefficient results were calculated to examine direct correlations between the various dimensional relationships. A complete list of correlations is shown in Supplementary Table SII.

Formulae for calculating the dimensions of anatomically shaped humeral heads were derived from the linear regression analysis plot trend lines that were used to correlate humeral head measurement variables where males and females were analyzed together as a group (Supplementary Figures S1 to S4; available on the journal's website at www.jshoulderelbow.org). Correlations between D^F and D^S, HHH, ROC^F, and ROC^S were all noted to be strong, with a minimum R value of 0.74. Using these formulae, for any given value of the length of the base of the head in the frontal plane, one may calculate the values of the other humeral head dimensions (Fig. 4).

Welch t-test results demonstrated that the mean values for HHH, D^S, ROC^F, and ROC^S were statistically different (maximum P value ≤ .0002) in every case in comparing small, medium, and large heads (Table I).

With regard to the elliptical shape of the humeral head, a strong relationship was demonstrated in comparing the difference between D^F and D^S lengths ($D^F - D^S$) to D^F lengths ($R = 0.67$; P value < .001) (Fig. 5, *A*). When the specimens were divided into 3 groups on the basis of head size, the average difference between the D^F and D^S measurements at

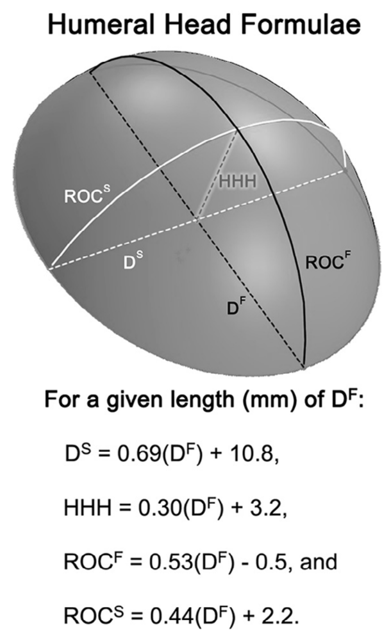

Figure 4 Image of an elliptically shaped prosthetic humeral head. Using the formulae, for any given value of D^F (*dashed black line*), one may calculate the values of the other humeral head dimensions, including D^S (*dashed white line*), HHH (*dashed gray line*), ROC^F (*black arc*), and ROC^S (*white arc*).

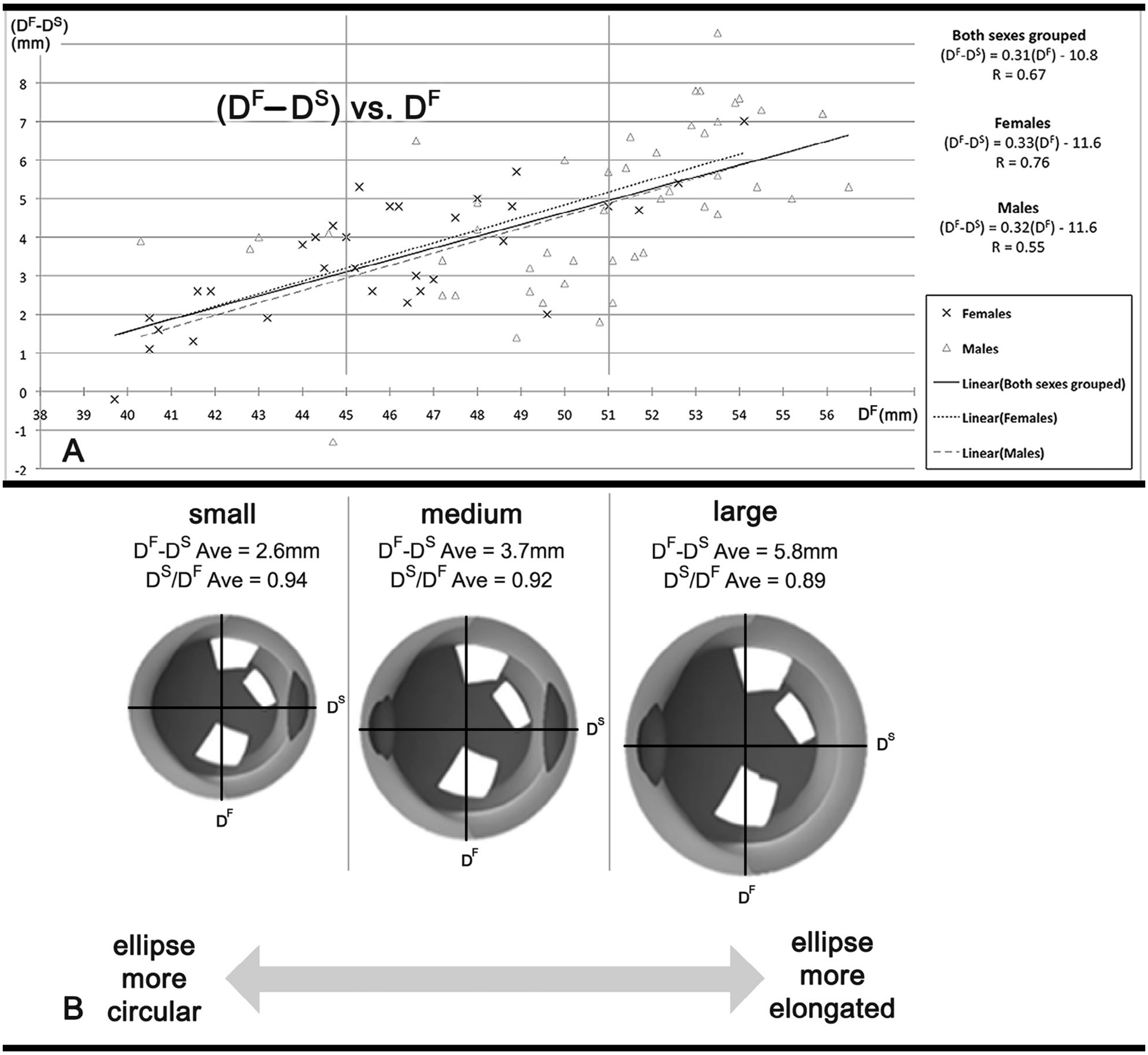

Figure 5 (**A**) Scatter plots with linear trend lines demonstrate the mathematical relationship between the length difference between the head axes in the frontal and sagittal planes ($D^F - D^S$) and the diameter of the base of the head in the frontal plane (D^F). Linear regression analysis was performed separately for all specimens grouped together, for females only, and for males only. Associated formulae and Pearson correlation coefficient values are listed. (**B**) As humeral head size increases, the length of D^F becomes longer relative to the length of D^S, indicating that the shape of the base of the humeral head changes from a more circular to a more elongated ellipse with increasing head size.

the base of the head was 2.6 mm for small heads (range, −1.3 to 4.3 mm), 3.7 mm for medium-sized heads (range, 1.4-6.5 mm), and 5.8 mm for large heads (range, 2.3-9.3 mm). When Welch *t*-test was used to compare the difference between the D^F and D^S values ($D^F - D^S$) for small, medium, and large heads (Table I), the small heads were noted to be statistically different from both medium (P value = .022) and large (P value < .001) heads. Medium-sized heads were also noted to have $D^F - D^S$ values that were statistically different from those of large heads ($P < .001$). The Welch *t*-test results substantiate the linear regression analysis findings, which show that when males and females were analyzed together as a group, the elliptical shape of the base of the humeral head elongates as the base of the humeral head in the frontal plane (D^F) increases in length (Fig. 5, *B*).

When linear regression analysis was performed for the humeral head dimensional relationships on the basis of gender (Supplementary Figs. S1 to S4), we found that the mathematical equations comparing D^F to D^S, HHH, ROC^F, and ROC^S were very similar for males vs. females. That is, in comparing

Table I Welch *t*-test results comparing small, medium, and large heads

Measurement	Head size	Average value (mm)	Groups compared	Statistically different?	*P* value
D^S	S	40.2	S to M	Yes	.000
	M	44.5	M to L	Yes	.000
	L	47.2	S to L	Yes	.000
HHH	S	15.7	S to M	Yes	.000
	M	17.6	M to L	Yes	.000
	L	18.9	S to L	Yes	.000
ROC^F	S	22.2	S to M	Yes	.000
	M	25.0	M to L	Yes	.000
	L	27.6	S to L	Yes	.000
ROC^S	S	21.3	S to M	Yes	.000
	M	23.4	M to L	Yes	.000
	L	25.8	S to L	Yes	.000
$D^F - D^S$	S	2.6	S to M	Yes	.022
	M	3.7	M to L	Yes	.000
	L	5.8	S to L	Yes	.000

D^F, diameter of the base of the humeral head in the frontal plane; D^S, diameter of the base of the humeral head in the sagittal plane; *HHH*, humeral head height; ROC^F, radius of curvature in the frontal plane; ROC^S, radius of curvature in the sagittal plane; *S*, small heads ($D^F < 45.3$ mm); *M*, medium heads (45.3 mm $\le D^F <$ 50.9 mm); *L*, large heads (50.9 mm $\le D^F$).

each linear regression trend line by gender, only a small difference was seen for males vs. females with regard to slope and y-intercept. Correlations between D^F and D^S, HHH, ROC^F, and ROC^S were all noted to be strong when linear regression analysis was performed on the basis of gender, with a minimum *R* value of 0.66 for males and 0.70 for females. Similarly, the linear trend lines equations for each gender vs. for the group as a whole (Supplementary Figs. S1 to S4) varied only slightly with regard to slope and y-intercept.

When the elliptical shape of the humeral head was analyzed by linear regression analysis on the basis of gender, the resulting trend lines also demonstrated only small differences in slope and y-intercept, and the correlations were noted to be strong in comparing males ($R = 0.55$) vs. females ($R = 0.76$) vs. both sexes grouped together ($R = 0.67$) (Fig. 5, *A*).

Male and female specimens were also analyzed separately with regard to general anthropometric measurements. The D^F values in our study ranged from 39.7 to 56.5 mm, with a mean value of 48.7 mm. When analyzed by gender, 69% of specimens measuring below the mean were female (25/36), whereas only 16% measuring above the mean were female (7/43). Welch *t*-test was performed to compare the general anthropometric measurement values on the basis of gender (Table II), and the results show that the mean D^F, D^S, HHH, ROC^F, and ROC^S values are larger for males than for females (maximum *P* value = .0001). There was no statistically significant difference between the male and female groups in analyzing critical distance inclination angle, medial offset, posterior offset, or surface arc.

Discussion

Several previous anatomic studies have documented that the humeral head is elliptical or ovoid rather than spherical,[2,4,5,7,8,13,14,18] but in the present study, a more detailed mathematical description of the shape of the humeral head is provided. The formulae derived in this study may be used to calculate average dimensional values for an anatomically shaped humeral head of any given size based on the diameter of the base of the humeral head in the frontal plane (Fig. 4). Formulae for calculating the head height, radii of curvature in the frontal and sagittal planes, and diameters of the base of the humeral head in the frontal and sagittal planes are presented. These formulae may be useful in the design of future prosthetic shoulder systems in which the goal is to replicate normal anatomy.

This is the first study to report that the elliptical shape of the base of the humeral head seems to elongate in the frontal plane as head size increases. Prior studies have reported the average difference between the D^F and D^S measurements at the head base: Iannotti et al reported an average difference of 2 mm[8]; Hertel et al reported a difference of 2.5 mm[7]; Harrold and Wigderowitz reported a difference of 2.1 mm[5]; and Amstutz and Clarke reported a difference of 3.9 mm.[1] The authors of these prior studies did not explore whether the dimensional relationships of the shape of the elliptical head remained constant or not with increasing humeral head size.

Table II Anthropometric measurements compared by gender

Measurement	Female		Male		Welch's *t*-test	
	Average	Range	Average	Range	Groups different?	*P* value
CD	5.4 mm	−1.0-10.9 mm	6.3 mm	0.0-14.4 mm	No	.216
D^F	46 mm	40-54 mm	51 mm	40-57 mm	Yes	.000
($D^F - D^S$)	3.5 mm	−0.2-7.0 mm	4.7 mm	−1.3-9.3 mm	Yes	.003
Distance S/E	10.4 mm	2.4-14.3 mm	11.5 mm	6.7-15.9 mm	Yes	.020
D^S	42.4 mm	38.6-47.6 mm	44.5 mm	36.4-51.2 mm	Yes	.000
D^S/D^F	0.93	0.87-1.01	0.91	0.83-1.03	Yes	.020
HHH	16.8 mm	14-20.9 mm	18.2 mm	14.1-21.9 mm	Yes	.000
IA	135°	122-144°	135°	127-144°	No	.780
MO	5.9 mm	2.2-9.4 mm	5.8 mm	1.9-12.4 mm	No	.882
PO	1.5 mm	−0.3-4.3 mm	1.2 mm	−0.9-4.2 mm	No	.264
ROC^F	23.8 mm	20-29 mm	26.4 mm	21-30 mm	Yes	.000
ROC^S	22.5 mm	22-27 mm	24.7 mm	19-27 mm	Yes	.000
SA	147°	133-160°	145°	131-157°	No	.309

CD, critical distance; *Distance S/E*, distance from the bicipital groove to the critical point (mm); D^F, diameter of the base of the humeral head in the frontal plane (mm); (D^F-D^S), length difference between long and short ellipse axes at the base of the humeral head; D^S/D^F, the ratio of short to long ellipse axes; D^S, diameter of the base of the humeral head in the sagittal plane (mm); *HHH*, humeral head height (mm); *IA*, inclination angle (degrees); *MO*, medial offset (mm); *PO*, posterior offset (mm); ROC^F, radius of curvature in the frontal plane (mm); ROC^S, radius of curvature in the sagittal plane (mm); *SA*, surface arc (degrees).

For the 79 humeral heads used in this study, the average difference between D^F and D^S measurements at the base of the head was 4.3 mm (standard deviation, ±2 mm; range, −1.3 to 9.3 mm), but the average difference clearly increased in value as humeral head size increased.

The elongation of the elliptical shape of the head base that occurs with increasing head size may be demonstrated in a couple of ways: first, because the slope value is approximately equal to 0.7 for each of the linear regression trend lines equations in Supplementary Figure S1, it is evident that D^S lengthens at a slower rate than D^F as head size increases; and second, if the difference between D^F and D^S is plotted relative to the length of D^F (Fig. 5, *A*), results show that the value of ($D^F - D^S$) increases as the head size increases. To substantiate these linear regression analysis results, we compared ($D^F - D^S$) values between small, medium, and large head sizes (Table I). The difference was statistically significant in comparing $D^F - D^S$ values in each case (minimum *P* value = .022). We conclude that on average, small humeral heads are closer to being spherically shaped, whereas with larger humeral heads, the elliptical shape at the base of the head is typically more elongated.

We found from our gender-based analysis comparing the means of the anthropometric measurements obtained in this study that females as a group have smaller humeral heads than males do (Table II). When the linear regression trend lines for males vs. females are examined (Supplementary Figs. S1 to S4), it can be observed that mostly females populate the end of each trend line that is closest to the graph origin, whereas males predominantly populate the end of each trend line that is farthest from the origin. Interestingly, though, only subtle differences are seen in comparing the linear regression analysis trend lines for males vs. females vs. both sexes grouped together with regard to slope and y-intercept values. We conclude from this that although females in general have smaller humeral heads than males do, the dimensional changes that occur with increasing head size appear to happen predictably and proportionally for both males and females and that the dimensional relationship equations (Fig. 4) are not substantially altered when analysis is performed on the basis of gender. Based on these observations, we believe that there is no need for a prosthesis system with gender-specific prosthetic humeral heads as long as a full range of head sizes is provided.

When comparing the elongation of the elliptical shape of the head by gender, we found that in the equations for the linear regression trend lines comparing D^S to D^F (Supplementary Fig. S1), the slope and y-intercept values are practically equal for males vs. females. Again, because the slope values for the gender-based trend lines are approximately equal to 0.7, it is evident that for both sexes, D^S increases in length at a slower rate than D^F as the heads become larger. When the difference between D^F and D^S was plotted relative to the length of D^F for both males and females (Fig. 5, *A*), the results show that regardless of gender, the length of D^F becomes longer relative to the length of D^S as head size increases. Based on these findings, we conclude that in general, the elliptical shape of the base of the humeral head elongates in the frontal plane as head size increases irrespective of gender.

Much emphasis has been placed on replicating normal, prepathologic anatomy during shoulder reconstructive surgery.[4,12] Use of a prosthetic head that is inaccurately sized or positioned may lead to poor clinical outcomes, including shoulder stiffness and rotator cuff tearing.[6,15,21-23] It has been reported that alterations to humeral head geometry may produce eccentric loading at the prosthetic glenoid that may contribute to early component wear and loosening.[5] Biomechanical studies have confirmed that altering the size and position of the articular surface by 4 or 5 mm changes the kinematics and forces across the glenohumeral joint[16,22]; when examining the graph in Figure 5, *A*, it is interesting to note that for smaller head sizes ($D^F < 45$ mm), the difference between D^F and D^S measurements is always less than or equal to about 4 mm, but once D^F increases to beyond 52 mm, the difference is always >4 mm. Taking this into account, the effect of the mismatch seen with use of a spherical prosthetic head is more likely to be of consequence in patients with larger humeral heads. For example, if the D^S measurement were used in sizing a spherically shaped head during arthroplasty surgery, the mismatch in the D^F direction would be at most 4 mm for a smaller patient; but in larger patients, the mismatch would be 4 mm at a minimum, and it could be >9 mm in some patients. It is therefore possible that for a large patient, the magnitude of the altered joint forces that would be caused by use of a spherically shaped head could outweigh other factors that are known to alter joint kinematics, such as incorrect head height or improper offset. In our study, no biomechanical analysis was performed, and further biomechanical and clinical studies are needed before any firm conclusions can be drawn.

Although we have mathematically described the various dimensional relationships of the humeral head, we acknowledge that our conclusions might not be applicable to all populations because of potential size differences. The bone database that was available to us for this study was obtained from computed tomography scans of white subjects, but in a very recent anthropometric study that was limited to Japanese subjects, the authors reported smaller values in the size of the humeral head compared with past analyses in which most of the subjects were white.[11] To determine the mathematical head measurement relationships for a given population, the methods presented in this study would ideally be applied to a humeral bone database that has been obtained from the population of interest. This would allow the creation of anatomically shaped prosthetic humeral heads that are more likely to fit individuals within a particular ethnic or regional population.

A secondary goal of this study was to add to the currently available anthropometry data pertaining to the proximal humerus. The proximal humerus measurement findings from this study are largely consistent with what has previously been reported by others.[1,3-5,7-9,17,19,20] A table comparing the anthropometric results from our study to those of prior studies is provided (Supplementary Table SI).

When analyzing our anthropometric data, we found that the size of the head was not related to its position relative to the long axis of the humerus. HHH was strongly correlated with critical distance ($R = 0.526$) in this study, but no strong correlation was found between the humeral head size parameters and any of the other anthropometric measurements. Specifically, no strong correlation was found in comparing medial offset or posterior offset to the humeral head size parameters D^F, D^S, HHH, ROC^F, and ROC^S (Supplementary Table SII). These findings support the conclusions of others[4,7] that a prosthesis system should have the capability for adjustment of offset if the goal of arthroplasty is to replicate normal anatomy.

One weakness of this study is that the specimen sample size was relatively small (N = 79). It is certainly possible that our results might have been different had a larger number of specimens been available for study. However, we think that the consistency between our anthropometric measurements and those from prior studies (Supplementary Table SI) supports the notion that our specimens as a group were similar in morphology to those that were used in prior studies. For example, the average inclination angle in our study was 135°, and we found that the inclination angle fell between 130° and 140° for 81% (64/79) of our specimens. These results are very similar to what was reported by Jeong et al,[9] who employed a much larger specimen database (N = 2058). Nonetheless, we acknowledge that applying the methods used in this study to a larger specimen database would likely lead to refinement of the humeral head dimensional relationship formulae.

Another weakness of the study is that 1 person (C.S.H.) made the humeral measurements, and therefore interobserver error pertaining to the measuring techniques was not considered as a possible confounding factor. However, the bone landmark identification methods used for the anthropometric measurements in this study were the same as those used by Hertel et al,[7] who validated the technique and found the mean interobserver correlation coefficient to be 0.94. Again, the average measurement results that we found are consistent with what have previously been reported by others, and we think that this speaks for the consistency of the measurement techniques used in this study.

A strength of this study is that the most critical measurements—those that determined one of the main findings of this study regarding the changing elliptical dimensions of the humeral head—were made directly on the computer models by software. It has been reported that the use of 3D models for anatomic studies has advantages over previous study methods that use radiographs, surface scans, or direct measurements.[20] In this study, the 3D humeral models could be precisely oriented, and the scale of the printed images that were used to simulate radiographs for making certain measurements could be adjusted to reflect a true 1:1 ratio. We believe that our technique likely contributed to accuracy of measurement by avoiding projection angle and magnification factor errors that were more likely to have affected previous studies in which measurements were made in a less controlled environment.

Conclusion

We have derived through analysis of anthropometric data a series of formulae that may be used to calculate the dimensional values for anatomically shaped humeral heads of varying size. Formulae for calculating the head height, diameters of the base of the humeral head in the frontal and sagittal planes, and radii of curvature in the frontal and sagittal planes are provided. We observed that females have smaller humeral heads in general than do males, but the dimensional changes that occur with increasing head size appear to happen predictably and proportionally for both males and females. This is the first study to report that on average the elliptical shape of the base of the humeral head elongates with increasing humeral head size; the biomechanical and clinical implications of this phenomenon are not yet well understood. The methods and findings of this study may have implications for future prosthetic shoulder design in which the goal is to replicate normal anatomy.

Acknowledgments

The authors wish to acknowledge Jeff Martin, BS, and Matthew Schultz, BSME, for contributing to discourse pertaining to the topics presented in this study.

Disclaimer

The 3D virtual humeri models that were used in this study were provided by Shoulder Options, Inc. C. Scott Humphrey owns stock and may receive future royalties from Shoulder Options, Inc. Benjamin W. Sears may receive future royalties from Shoulder Options, Inc. Michael J. Curtin owns stock and may receive future royalties from Shoulder Options, Inc. No company had any input into the study design, protocol, testing, data analysis, or manuscript preparation.

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments from any commercial entity related to the subject of this article.

Appendix
Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.jse.2016.01.032.

References

1. Amstutz HC, Clarke IC. United States Patent 4,261,062: natural shoulder joint prosthesis. Berkeley, CA: The Regents of the University of California; 1981 ISBN No. 4,261,062.
2. Amstutz HC, Sew Hoy AL, Clarke IC. UCLA anatomic total shoulder arthroplasty. Clin Orthop Relat Res 1981;7-20.
3. Ballmer FT, Sidles JA, Lippitt SB, Matsen FA 3rd. Humeral head prosthetic arthroplasty: surgically relevant geometric considerations. J Shoulder Elbow Surg 1993;2:296-304.
4. Boileau P, Walch G. The three-dimensional geometry of the proximal humerus. Implications for surgical technique and prosthetic design. J Bone Joint Surg Br 1997;79:857-65.
5. Harrold F, Wigderowitz C. Humeral head arthroplasty and its ability to restore original humeral head geometry. J Shoulder Elbow Surg 2013;22:115-21. http://dx.doi.org/10.1016/j.jse.2012.01.027
6. Harryman DT, Sidles JA, Harris SL, Lippitt SB, Matsen FA 3rd. The effect of articular conformity and the size of the humeral head component on laxity and motion after glenohumeral arthroplasty. A study in cadavera. J Bone Joint Surg Am 1995;77:555-63.
7. Hertel R, Knothe U, Ballmer FT. Geometry of the proximal humerus and implications for prosthetic design. J Shoulder Elbow Surg 2002;11:331-8. http://dx.doi.org/10.1067/mse.2002.124429
8. Iannotti JP, Gabriel JP, Schneck SL, Evans BG, Misra S. The normal glenohumeral relationships. An anatomical study of one hundred and forty shoulders. J Bone Joint Surg Am 1992;74:491-500.
9. Jeong J, Bryan J, Iannotti JP. Effect of a variable prosthetic neck-shaft angle and the surgical technique on replication of normal humeral anatomy. J Bone Joint Surg Am 2009;91:1932-41. http://dx.doi.org/10.2106/JBJS.H.00729
10. Jun BJ, Iannotti JP, McGarry MH, Yoo JC, Quigley RJ, Lee TQ. The effects of prosthetic humeral head shape on glenohumeral joint kinematics: a comparison of non-spherical and spherical prosthetic heads to the native humeral head. J Shoulder Elbow Surg 2013;22:1423-32. http://dx.doi.org/10.1016/j.jse.2013.01.002
11. Matsumura N, Oki S, Ogawa K, Iwamoto T, Ochi K, Sato K, et al. Three-dimensional anthropometric analysis of the glenohumeral joint in a normal Japanese population. J Shoulder Elbow Surg 2015;http://dx.doi.org/10.1016/j.jse.2015.08.003. In press.
12. Neer CS. Shoulder reconstruction. Philadelphia: WB Saunders; 1990. p. 155-7.
13. Neer CS 2nd. Articular replacement for the humeral head. J Bone Joint Surg Am 1955;37-A:215-28.
14. Neer CS 2nd, Watson KC, Stanton FJ. Recent experience in total shoulder replacement. J Bone Joint Surg Am 1982;64:319-37.
15. Nyffeler RW, Sheikh R, Jacob HA, Gerber C. Influence of humeral prosthesis height on biomechanics of glenohumeral abduction. An in vitro study. J Bone Joint Surg Am 2004;86-A:575-80.
16. Pearl ML, Kurutz S, Postacchini R. Geometric variables in anatomic replacement of the proximal humerus: how much prosthetic geometry is necessary? J Shoulder Elbow Surg 2009;18:366-70. http://dx.doi.org/10.1016/j.jse.2009.01.011
17. Pearl ML, Volk AG. Coronal plane geometry of the proximal humerus relevant to prosthetic arthroplasty. J Shoulder Elbow Surg 1996;5:320-6.
18. Phillips J, Runciman RJ, Miniaci A. Mathematical modeling of humeral head geometry. In: Norris TR, Zuckerman JD, Warner JJP, Lee TQ, editors. Surgery of the shoulder and elbow: an international perspective. Selected proceedings of the 9th International Congress on Surgery of the Shoulder. Rosemont, IL: American Academy of Orthopaedic Surgeon; 2004. p. 213-8.
19. Roberts SN, Foley AP, Swallow HM, Wallace WA, Coughlan DP. The geometry of the humeral head and the design of prostheses. J Bone Joint Surg Br 1991;73:647-50.

20. Robertson DD, Yuan J, Bigliani LU, Flatow EL, Yamaguchi K. Three-dimensional analysis of the proximal part of the humerus: relevance to arthroplasty. J Bone Joint Surg Am 2000;82-A:1594-602.
21. Terrier A, Ramondetti S, Merlini F, Pioletti DD, Farron A. Biomechanical consequences of humeral component malpositioning after anatomical total shoulder arthroplasty. J Shoulder Elbow Surg 2010;19:1184-90. http://dx.doi.org/10.1016/j.jse.2010.06.006
22. Williams GR Jr, Wong KL, Pepe MD, Tan V, Silverberg D, Ramsey ML, et al. The effect of articular malposition after total shoulder arthroplasty on glenohumeral translations, range of motion, and subacromial impingement. J Shoulder Elbow Surg 2001;10:399-409.
23. Youderian AR, Ricchetti ET, Drews M, Iannotti JP. Determination of humeral head size in anatomic shoulder replacement for glenohumeral osteoarthritis. J Shoulder Elbow Surg 2014;23:955-63. http://dx.doi.org/10.1016/j.jse.2013.09.005