Topology of the Humeral Head Articular Surface

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1. Introduction

- Sphere shape models dominate biomechanical models of shoulder and humeral head implant designs. However, many authors have recorded non-spheroid dimensions of the humeral articular surface.
- Even slight differences in humeral curvature can have biomechanical consequences and may be applicable to implant design.
- The *purpose* of this study is to compare the goodness of fit for three spheroidal shape models to the articular cartilage and subchondral bone surfaces of the humeral head:
  - Sphere
  - Ellipsoid
  - Ovoid
- We *hypothesize* the following:
  - The humeral head is spherical in the central portion of the articulating surface of the humeral head and becomes non-spherical along the periphery (closer to the surgical neck).
  - The humeral head is non-spherical and will be best approximated by either the ellipsoid or ovoid shapes.

2. Methods

- Articular cartilage and subchondral bone surfaces were scanned using a three-dimensional optical digitizing system (Steinbichler Optotechnik, Neubeurn, Germany). **(Figure 1)**
- A least-squares fitting algorithm was used to fit 54 cadaveric specimens (cartilage and subchondral bone) to three spheroidal shapes: sphere (eq. 1), ellipsoid (eq. 2), and ovoid shape models (eq. 3). **(Figure 2)**

$$(x-x_0)^2+(y-y_0)^2+(z-z_0)^2=r^2 \qquad (1)$$

$$\frac{(x-x0)^2}{a^2}+\frac{(y-y0)^2}{b^2}+\frac{(z-z0)^2}{b^2}=1 \qquad (2)$$

$$\frac{(x-x0)^2}{(a_{ov})^2(1+k_a(x-x0)^2}+\frac{(y-y0)^2}{(b_{ov})^2(1+k_b(y-y0)^2}+\frac{(z-z0)^2}{(c_{ov})^2(1+k_c(z-z0)^2}=1 \qquad (3)$$

- The goodness of fit measure for the spheroid shape models was accomplished by measuring the coefficient of determination (R^2), sphericity, and greatest $|\Delta r|$.
- The convergence (portion of the surface data within certain thresholds of $|\Delta r|$) of $|\Delta r|$ values for all three shapes were plotted to observe the models' fit to the surfaces.
- Statistics: A general linear model ANOVA (GLM) was used to analyze the variances. When appropriate, Tukey's post-hoc tests were utilized to compare differences in means for any appropriate statistically significant GLM comparisons. The level required to accept a significant difference between means was set to $p \leq 0.05$ for the GLM and post-hoc procedures.

Figure 1

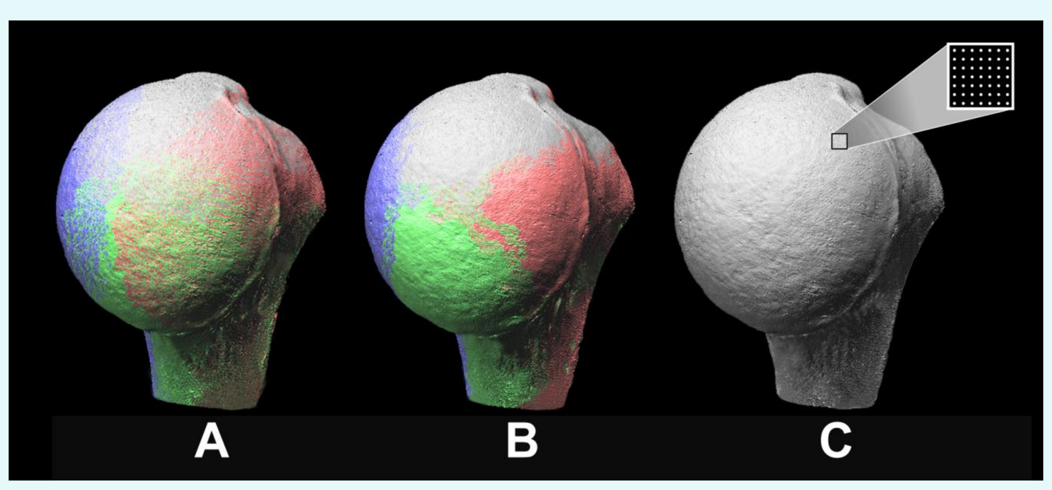

Figure 1. The reconstruction of the structured light surface data. (A) Humeral surface reconstruction using raw data. (B) The reduction of surface data overlap on the humeral head. (C) The finished product of humeral head surface data with an evenly spaced data distribution.

Figure 2

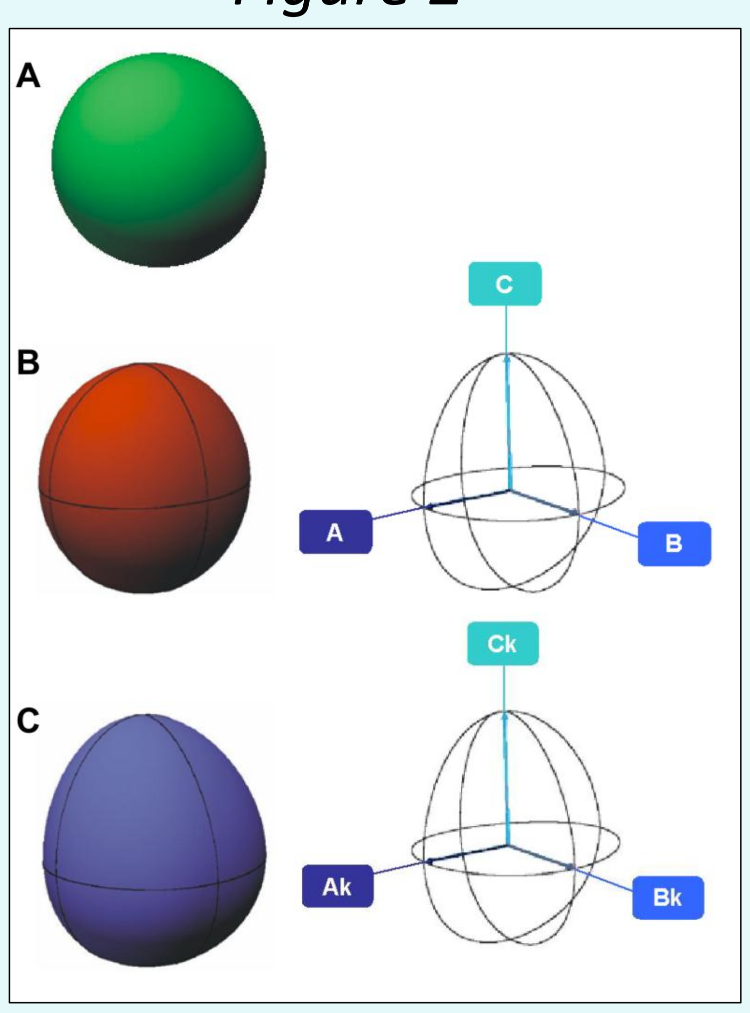

Figure 2. The three-dimensional spheroid geometric shapes: (A) Sphere, (B) Ellipsoid, (C) Ovoid.

3. Results

- **Figure 3** shows the percentage of total data points within specified $|\Delta r|$ tolerances for both the cartilage and bone articular surfaces.
  - The *ovoid model* had a highly significant reduction in fit error between the surface data and the model when compared to the sphere model ($p < 0.0001$) and the ellipsoid model ($p < 0.0001$) for both the cartilage and underlying bony humeral head articular surfaces.
  - The *ellipsoid model* had a highly significant reduction in fit error when compared to the sphere model ($p < 0.0001$) for both the cartilage and underlying bony humeral head articular surfaces. The ellipsoid model was also found to have an underlying repeating pattern of general orientation with the largest of the three orthogonal radii pointing laterally, the second largest pointing posteriorly, and the smallest pointing anteriorly.

Figure 3

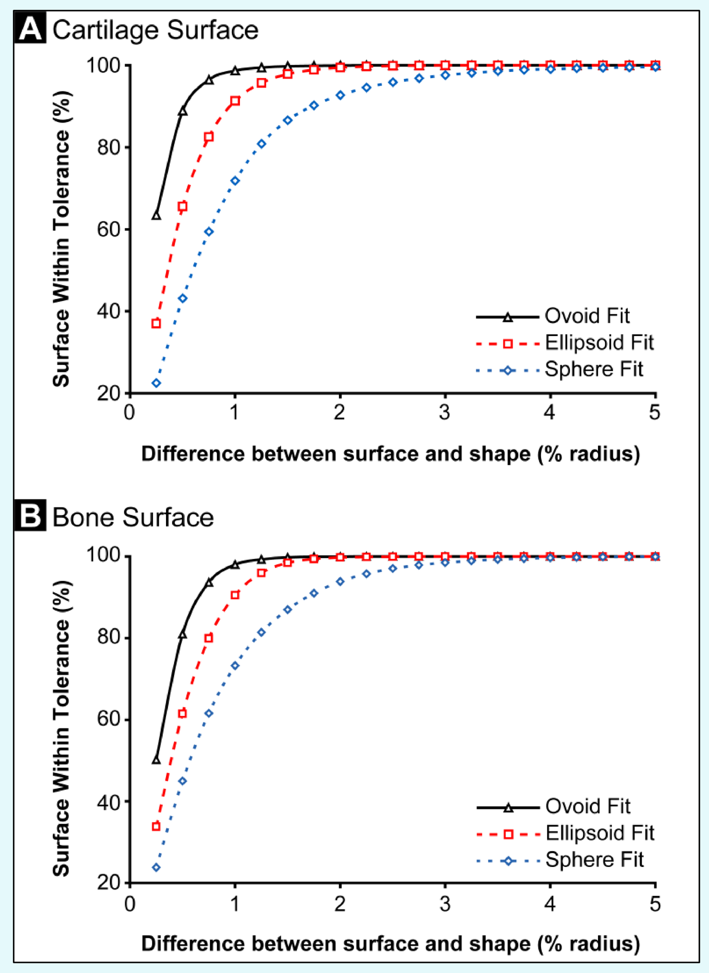

Figure 4

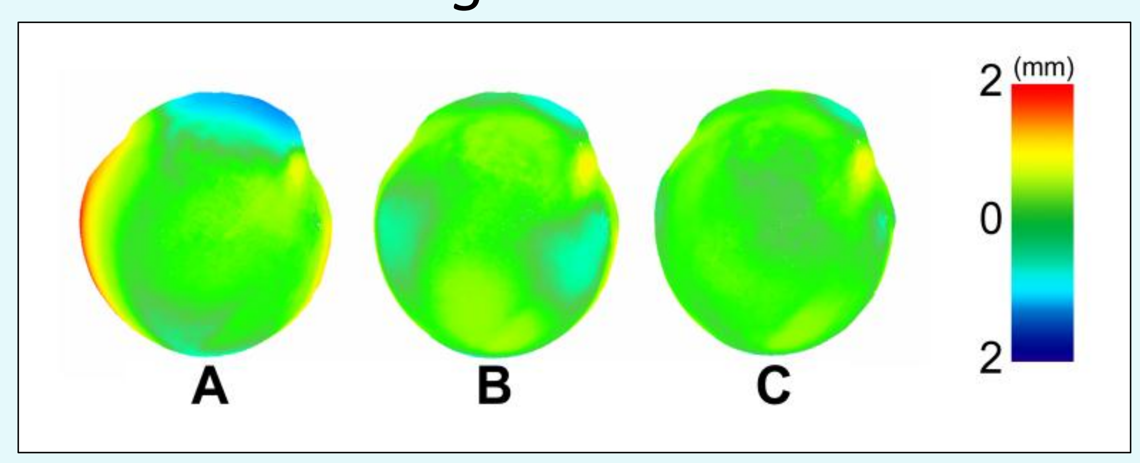

Figure 4. Error maps of the three spheroid shapes least-squares fit to the humeral head articular cartilage surface. (A) The sphere model. (B) The ellipsoid model. (C) The ovoid model. The error is measured as $|\Delta r|$, the perpendicular distance from the articular surface to the surface of the shape models.

Figure 3. Convergence graph showing the percentage of total data points within specified $|\Delta r|$ tolerances. To normalize the $|\Delta r|$ values between subjects they were calculated as a percentage of the sample's least-squares fit sphere radius. The average combined gender $|\Delta r|$ results for the entire (A) cartilage articular and (B) bone surface sample set are displayed for the sphere, ellipsoid, and ovoid fits.

- Error maps of the three spheroid shapes least-squares fit to the humeral head articular cartilage surface are shown in **figure 4**. Overall, the ovoid shape had the best fit to both the cartilage and bone surfaces of the humeral head followed closely by the ellipsoid shape. The worst fit was the sphere shape.

- The quality of fit measurements for all three spheroidal shapes are shown in **Table 1**.
  - Sphericity is the average fit error as a percentage of least-squares fit radius. Greatest $|\Delta r|$ is the greatest error between the articular surface point cloud data and the idealized shape models.
  - R^2 is the coefficient of determination.

Table 1. Quality of fit for the three speroidal shape models.

	Sphericity*	Greatest $\|\Delta r\|$*	R^2
	Cartilage		
Sphere	0.28 ± 0.07	1.33 ± 0.38	NA
Ellipsoid	0.14 ± 0.03	0.62 ± 0.16	0.94 ± 0.05
Ovoid	0.08 ± 0.02	0.42 ± 0.15	0.96 ± 0.03
	Bone		
Sphere	0.24 ± 0.06	1.01 ± 0.24	NA
Ellipsoid	0.14 ± 0.03	0.53 ± 0.14	0.91 ± 0.06
Ovoid	0.09 ± 0.02	0.43 ± 0.14	0.95 ± 0.03

4. Conclusions

- In all measures of fit, the ovoid model best replicated the osteo and chondral surfaces of the humeral head.
- The radii of the elliptical shape best predicted anatomic dimensions.
- The results of this investigation provide evidence that the humeral head articular surface is more complicated than that of a sphere.