The Sizing and Suitability of Non-Spherical Humeral Heads for Total Shoulder Arthroplasty

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I. Abstract

Eight paired cadaveric humeri underwent reconstruction for anatomic total shoulder arthroplasty. Following the resection of the humeral head the perimeter of the resection plane was traced with an optical tracking system stylus. The perimeter of the resection plane was better represented with elliptical rather than circular humeral head components, as quantified by less overhang, and more total coverage. Elliptical heads were found to provide more cortical coverage unless they were undersized by more than -2.25%, in which cases circular heads outperformed. Elliptical heads were preferable in all metrics, but care should be taken to not under-size them to ensure superior cortical contact.

II. Introduction

Total shoulder arthroplasty implants have evolved to include more anatomically shaped components that replicate the native state. The geometry of the humeral head has been shown to be non-spherical [6],with a mismatch in the sagittal and frontal diameters, resulting in a resection plane with non-circular geometry. The sagittal diameter of the base of the head has been quantified to be up to 6% larger than the frontal diameter [2]; however, others have reported that the frontal diameter is between $2.1 - 3.9mm$ larger than the sagittal diameter [4], [5]. An assessment of anatomic, non-circular humeral head shapes has demonstrated their potential to better mimic the kinematics of the native joint [3]. Additionally, recent finite element analysis of the implant-bone load transfer at the proximal humerus has shown that humeral backside contact with the cortex at the resection plane level may yield better load transfer characteristics, thereby mitigating proximal stress shielding [8]. Despite these findings, the majority of anatomic total shoulder arthroplasty humeral head implants available on the market are spherical.Furthermore, achieving complete humeral head coverage of the resection plane can result in a portion of the implant projecting beyond the cortex resulting in articular overhang. Downsizing the humeral head can eliminate overhang but this can result in regions of the resection plane remaining uncovered.

The purpose of this study was to assess the morphology of humeral head resection planes of 8 cadaveric shoulders that underwent total shoulder arthroplasty reconstruction to gain insight into:

I. The differences in resection plane coverage of optimally fitted circular and ovular humeral heads.
II. The trade-off between implant overhang and resection coverage when sizing circular and ovular humeral heads

III. Methods

Eight paired male cadaveric humeri (age: 75 ± 15 years) were prepared for reconstruction with a short stem anatomic total shoulder arthroplasty humeral component (Preserve™ short stem; Exactech Inc, Gainesville, FL) by an experienced orthopaedic surgeon who selected and prepared the anatomic humeral resection plane and using a cutting guide and a reciprocating sagittal saw. The humeral head was resected and the resulting cortical boundary of the resection plane was digitized using a stylus and an optical tracking system with sub-millimeter accuracy (Optotrak, NDI Inc, Waterloo, ON). Two full passes were made around the cortical boundary and anatomic landmarks including the Greater Tuberosity, and Lesser Tuberosity were digitized. Extraneous points like those collected when the stylus was lifted from the cortical rim after 2 full traces, were removed when further than 2 standard deviations away from the mean with z-scores. A plane was fit to the trace data using the sum of least squares error to the resection plane. A transformation was applied to move the view perpendicular to the resection plane and remove the out-of-plane dimension. Average residual out-of-plane data was $3.5 \pm 2.5mm$. Part of the residual data was extraneous data that was not completely removed when filtering with z-scores.

A preliminary ellipse was fitted to determine the center of the trace data and all data was translated so the center lied upon the origin (0,0). Ellipse fitting was done using the python package lsq-ellipse 2.0.1 [7]. The y-axis of the coordinate system was defined by a line coincident with the resection plane and between the digitized greater tuberosity and the origin. Trace data was simplified by discretizing the resection plane into 360 equally spaced radial segments. All points within the group were averaged such that 360 points remained. A Savitzky–Golay filter was applied to smooth out the resulting 360 points.

Both circles and ellipses were then fitted to the filtered traces using the sum of least squares error method. The resultant fitted traces are shown in figure 4. An n-sided polygon was created with the filtered trace data to describe the geometry of the humeral resection rim. The circles and ellipses were intersected with the n-sided polygon and the

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	major [mm]		minor [mm]		
	ellipse	circle	ellipse	circle	θ_{GT} [deg.]
mean	25.1	23.7	22.5	23.7	-3.7
std	1.2	1.2	1.4	1.2	16.0
min	23.0	21.8	20.7	21.8	-25.6
max	27.4	26.5	25.7	26.5	24.9
diff.	-1.4 ± 0.3		1.3 ± 0.3		
P-value	< 0.001		< 0.001		

TABLE I

RESECTED HUMERUS MORPHOLOGY

	Total Coverage %		Overhang %		Cortical Coverage %	
	ellipse	circle	ellipse	circle	ellipse	circle
mean	98.2	95.9	1.7	3.8	79.8	60.4
std.	0.6	0.9	0.7	0.8	8.2	6.9
min	96.4	94.1	1.1	2.1	57.8	48.1
max	98.8	97.7	3.7	5.3	90.1	74.3
diff.	-2.3 ± 0.3		2.0 ± 0.1		-19.5 ± 1.3	
P-value	< 0.001		< 0.001		< 0.001	

TABLE II

ASSESSMENT METRICS FOR LSE CIRCLE AND ELLIPSE FITS.

	Upsizing %		Overhang %	
	ellipse	circle	ellipse	circle
mean	5.4	8.9	9.8	15.2
std.	1.7	2.1	3.0	3.1
min	3.2	5.8	6.0	10.4
max	8.8	13.3	15.4	21.8
diff.	3.4 ± 2.2		5.4 ± 3.5	
P-value	< 0.001		< 0.001	

TABLE III

RESULTANT OVERHANG FROM 100% TOTAL COVERAGE

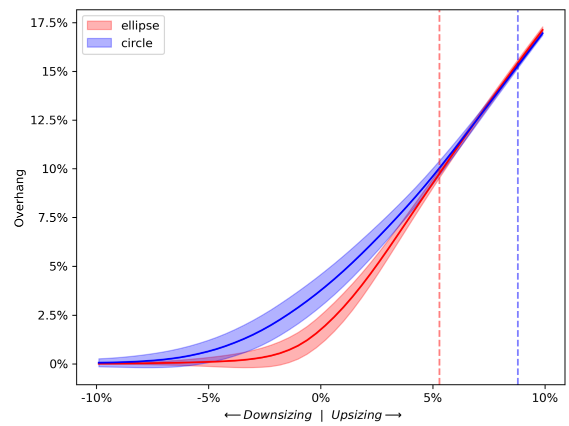

Fig. 1. Effect of varying implant sizing $\pm 10\%$ from LSE fit on overhang for circular and elliptical heads. Vertical dotted line indicates up-sizing needed to each achieve 100% coverage of the resection for ellipses (red) and circles (blue).

resultant area represented the total coverage on the humeral resection. The n-sided polygon was also subtracted from both circle and ellipse areas to determine the area of overhang produced by each fit. Cortical coverage was determined by intersecting the outer 2% of the n-sided polygon's area with both ellipse and circle fits.

To investigate the effects of achieving either 100% total coverage or 0% overhang, both the circular and ellipse fits were scaled uniformly along their major and minor (for the ellipse) axes until the respective thresholds for each condition were reached. Upsizing was defined as the percentage of area added with respect to initial size during scaling, whereas downsizing was the percentage of area removed. To reach the 100% total coverage condition upsizing occurred and for 0% overhang downsizing occurred.

Total coverage, overhang, and cortical coverage were compared statistically for independence between circular and ellipse fits using a two-tailed, paired, Student's t-Test, with $\alpha = 0.05$.

IV. RESULTS

The individual ellipses and circles fitted to the traces of each specimen are shown in figure 4. For all specimens tested, fitted ellipses had an average major axis of $25.1 \pm 1.2mm$ and an average minor axis of $22.3 \pm 1.3mm$, and the fitted circles had an average radius of 23.6 ± 1.2. On average the major axis was $1.4 \pm 0.3mm$ greater than the circle's radius and the minor axis was $1.3 \pm 0.3mm$ smaller. The previously described morphology is presented in Table I, as well as the angle of deviation of the major axis from the greater tuberosity (θ_{GT}) for the ellipsoid fits.

Total coverage for the fitted ellipses was found to be $98.2 \pm 0.6\%$ and fitted circles was $95.9 \pm 0.9\%$. The ellipses provided an extra $2.3 \pm 0.3\%$ ($P < 0.001$) coverage on average for the resected humerus. The overhang for fitted ellipses and circles was $1.7. \pm 0.7\%$ and $3.8 \pm 0.8\%$ respectively, defined as a percentage of the total shape that exceeded the bounds of the humerus resections. Circular heads were found to result in $2.0 \pm 0.1\%$ ($P < 0.001$) greater overhang than ellipse fits. Cortical coverage, defined as the coverage of the outer 2% of the humeral resection plane, was found to be $79.8 \pm 8.2\%$ and $60.4 \pm 6.9\%$ for ellipses and circles respectively. Ellipses possessed $19.5 \pm 1.3\%$ ($P < 0.001$) more cortical coverage than fitted circles. The values for the above metrics and the differences between ellipse and circular fits are tabulated in Table II.

To compliment the "ideal" least squares fit two extreme scenarios were investigated: 100% coverage, and 0% overhang.

Table III describes the scenario in which all ellipse and circular fits were up-sized uniformly along the major and minor axes until 100% total coverage was reached. To reach 100% resection coverage the ellipse required $5.4 \pm 1.7\%$ upsizing and the circle $8.9 \pm 2.1\%$ upsizing. The ellipse also produced $5.4 \pm 3.5\%$ ($P < 0.001$) less overhang than the circle when full coverage occurred. The dotted vertical bars in figure 1 represent where 100% total coverage occurred when upsizing circular and elliptical heads.

For the 0% overhang case to be met, the ellipse required $-5.2 \pm 2.4\%$ downsizing and the circle $-9.1 \pm 2.3\%$ down-

	Downsizing %		Coverage %		Cortical Coverage %	
	ellipse	circle	ellipse	circle	ellipse	circle
mean	-5.2	-9.1	89.9	82.4	13.2	6.5
std.	2.4	2.3	4.3	4.1	9.3	3.5
min	-10.4	-16.4	80.1	70.2	2.6	0.2
max	-2.8	-6.9	94.3	86.5	34.4	12.7
diff.	-3.9 ± 1.5		-7.5 ± 2.8		-7.9 ± 8.2	
P-value	< 0.001		< 0.001		= 0.010	

TABLE IV

RESULTANT TOTAL COVERAGE AND CORTICAL COVERAGE FROM NO OVERHANG

sizing. Shown in table IV, total coverage was $7.5 \pm 2.8\%$ ($P < 0.001$) greater for the ellipse, and cortical coverage was $7.9 \pm 8.2\%$ ($P = 0.01$) greater as well, when the 0% overhang condition was met. Dotted lines in figure 2 illustrate where the condition was met while downsizing.

V. DISCUSSION

The sagittal and frontal diameters of the humeral resection plane are unlikely to be equivalent in clinical practice given humerus morphology and the variability in resection plane selection. The head neck angle variation in the clinical population when coupled with differences in head resection depth also contributes to the high degree of variability seen in resection plane shapes. The differences in major and minor axes of the fitted ellipses reported here fall within the values previously reported in the literature [1], [2].

A small but statistically significant increase in total coverage of the resection plane is observed when switching from a least squares circle fit to an elliptical one. However, this small $2.3 \pm 0.3\%$ ($P < 0.001$) increase in resection total coverage corresponded to a much larger and significant $19.5 \pm 1.3\%$ ($P < 0.001$) increase in cortical coverage for elliptical fits compared to circular ones. Increased cortical coverage has been suggested to lead to more effective load transfer characteristics, as previous work has indicated cortical head-back contact is a factor in preventing stress-shielding induced bone resorption [8].

Greater cortical coverage can be achieved by upsizing the humeral heads; however, the resultant increased overhang beyond the resection plane may affect adjacent capsule and rotator cuff attachments to the humerus. Elliptical heads required $3.4 \pm 2.2\%$($P < 0.001$) less up-sizing to cover the entire cortical than their circular counterparts. The vertical dotted lines shown in figure 1 indicate where 100% cortical and total coverage occurred when up-sizing for both head types. The elliptical heads also outperformed the circular heads by producing $5.4 \pm 3.5\%$ ($P < 0.001$) less overhang when upsized to cover the entire cortical boundary.

Overhang of the humeral head past the resected area can be minimized but this comes at the expense of total coverage and especially coverage of the cortical bone. The circular heads required $3.9 \pm 1.5\%$ ($P < 0.001$) more down-sizing than their elliptical counterparts. This left the circular heads

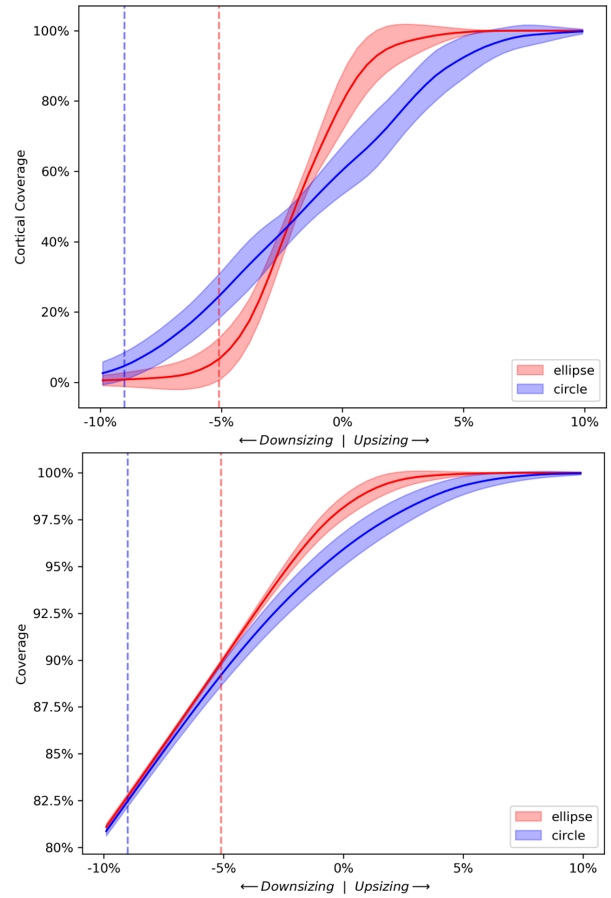

Fig. 2. Effect of varying implant sizing $\pm 10\%$ from LSE fit on cortical coverage, and total coverage for circular and elliptical heads. Red (ellipses) and blue (circles) vertical lines represent the downsizing needed for 0% overhang.

exposing $7.5 \pm 2.8\%$ ($P < 0.001$) more of the resection. The downsizing required to eliminate overhang for both types is indicated by the vertical dotted lines in figure 2. Both circular and elliptical fits provided poor coverage of the cortex ($13.2 \pm 9.3\%$ and $6.5 \pm 3.5\%$) respectively, when downsized to eliminate overhang. The elliptical fit did provide $7.9 \pm 8.2\%$ ($P = 0.01$) more cortical coverage, but the large amount of variance in the performance of the elliptical fits lead to a large standard deviation for the difference between fits.

In figure 3 all assessed metrics are combined, illustrating the effect sizing had for both shapes investigated. For total coverage, down-sizing smaller than -5% leads to convergence for both humeral head types. The elliptical heads approach full coverage more rapidly when up-sizing from -5% compared to their circular counterparts. This suggests that appropriately sizing an elliptical humeral head implant could be easier if full coverage is the desired outcome. For overhang, up-sizing above 5% the relationship with overhang converges for both types. Down-sizing from the $+5\%$ threshold, the overhang reduces more rapidly for ellipses than circles. Elliptical humeral head-back shapes could minimize implant overhang during reconstruction. For cortical coverage, a point of cross-over occurs when shrinking the heads by -2.25%. Since the ellipse more accurately matches the

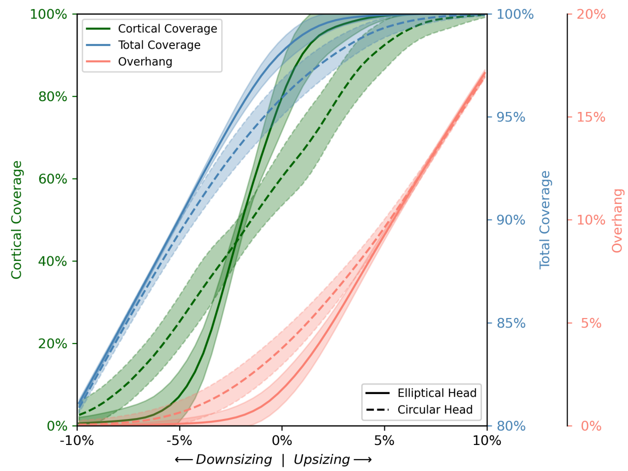

Fig. 3. Interaction between total coverage, cortical coverage, and overhang when varying implant sizing $\pm 10\%$ from LSE fit for circular and elliptical heads

cortical boundary in the best fit size (0%), it falls off more rapidly than the circle which will cover part of the resection for a longer period of time due to greater initial overhang. Up-sizing from -2.25% results in the ellipse significantly outperforming the circular head. While the ellipse provides significantly better performance in all previously discussed metrics it is important not to under-size less than -2.25% or it will provide less cortical coverage. These findings suggest that if cortical coverage is the desired outcome then care should be taken not to under-size humeral head components; and over-sizing may be favourable to avoid loss of cortical contact. Slight over sizing of the implant from the best fit is less problematic for ellipses than circles as the drawbacks of overhang are less severe as shown in figure 3.

VI. Clinical Significance

The results of this study demonstrate that surgical resection of the humeral head during shoulder arthroplasty results in an ellipsoid resection plane. Reconstruction with elliptical heads results in a small, but significantly greater coverage of the resection area that corresponds to a marked significant increase in the amount of cortical coverage which may lead to more favourable loading characteristics on the remaining bone. The use of elliptical heads can achieve greater cortical bone coverage while producing less overhang than circular heads. Care should be taken when sizing elliptical heads as downsizing below -2.25% results in worse cortical coverage than a circular head design because of the close match between resection and implant shape.

VII. Acknowledgments

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References

[1] J. P. Iannotti, J. P. Gabriel, S. L. Schneck, B. G. Evans, and S. Misra, "The normal glenohumeral relationships: An anatomical study of one hundred and forty shoulders," *The Journal of Bone and Joint Surgery*, vol. 74-A, no. 4, pp. 491–500, Apr. 1992.

[2] R. Hertel, U. Knothe, and F. T. Ballmer, "Geometry of the proximal humerus and implications for prosthetic design," *Journal of Shoulder and Elbow Surgery*, vol. 11, no. 4, pp. 331–338, Jul. 2002, ISSN: 10582746. DOI: 10.1067/mse.2002.124429.

[3] B. J. Jun, J. P. Iannotti, M. H. McGarry, J. C. Yoo, R. J. Quigley, and T. Q. Lee, "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," *Journal of Shoulder and Elbow Surgery*, vol. 22, no. 10, pp. 1423–1432, Oct. 2013, ISSN: 10582746. DOI: 10.1016/j.jse.2013.01.002.

[4] C. S. Humphrey, B. W. Sears, and M. J. Curtin, "An anthropometric analysis to derive formulae for calculating the dimensions of anatomically shaped humeral heads," *Journal of Shoulder and Elbow Surgery*, vol. 25, no. 9, pp. 1532–1541, Sep. 2016, ISSN: 10582746. DOI: 10.1016/j.jse.2016.01.032.

[5] C. S. Humphrey and A. L. Gale, "Spherical versus elliptical prosthetic humeral heads: A comparison of anatomic fit," *Journal of Shoulder and Elbow Surgery*, vol. 27, no. 6, S50–S57, Jun. 2018, ISSN: 10582746. DOI: 10.1016/j.jse.2018.03.002.

[6] J. P. Iannotti, B. J. Jun, J. Teplensky, and E. Ricchetti, "Humeral head shape in native and prosthetic joint replacement," *Journal of Shoulder and Elbow Arthroplasty*, vol. 3, pp. 1–5, Jan. 2019. DOI: 10.1177/2471549219848150.

[7] B. Hammel and N. Sullivan-Molina, *Bdhammel/least-squares-ellipse-fitting: V2.0.1*, version v2.0.1, Mar. 2020. DOI: 10.5281/zenodo.3723294.

[8] A. Tavakoli, K. Faber, and G. Langohr, "The effect of humeral head backside contact on humeral bone stress following total shoulder arthroplasty with a short humeral stem," *Orthopaedic Proceedings*, vol. 103-B, no. SUPP_1, pp. 1–1, 2021. DOI: 10.1302/1358-992X.2021.1.001.

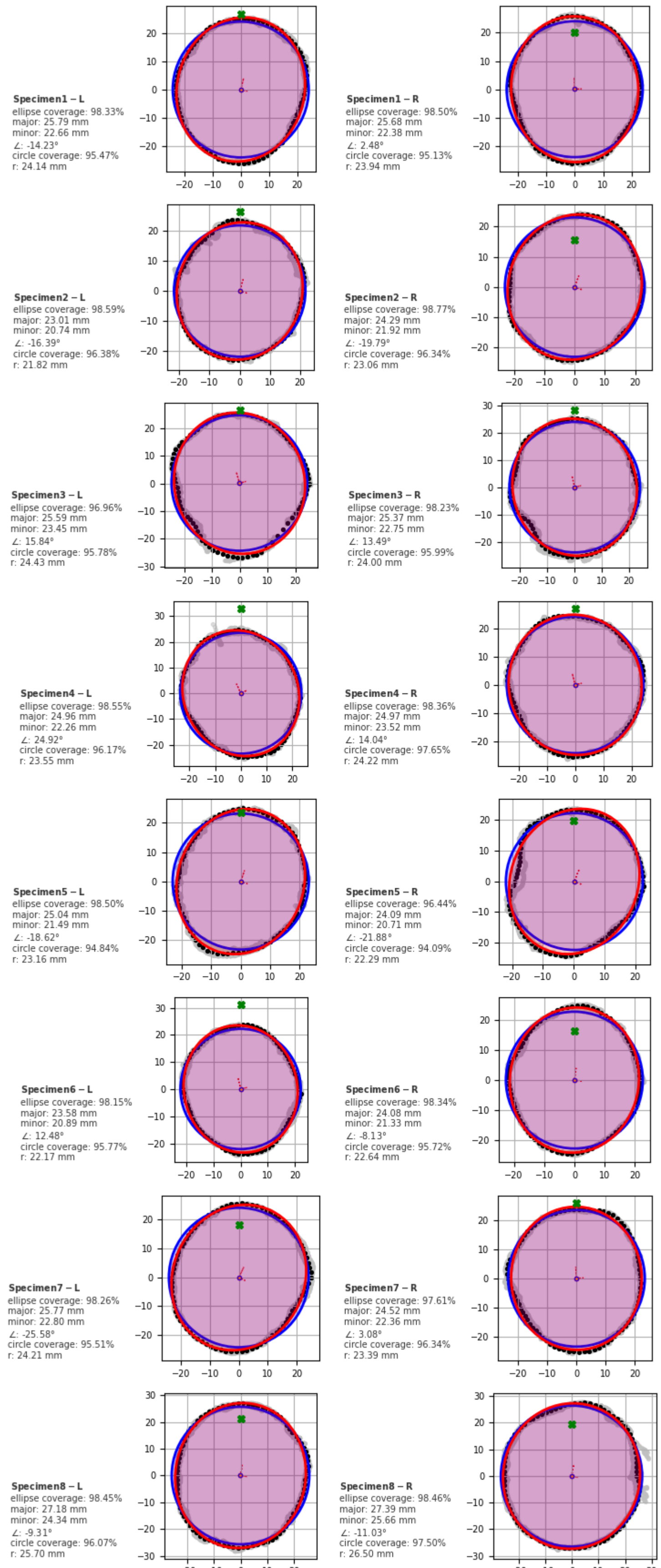

Fig. 4. Specimens 1 through 8 are shown with left and right humeri. Digitized humeral rim traces for each (light-grey) and the filtered points (black) are plotted with fitted ellipses (red) and circles (blue). Major and minor axes of the ellipse are represented with perpendicular red dotted lines emanating from the centre and the greater tuberosity is shown with a green cross. Units of graph scales are in mm.