JSES International 4 (2020) 453–463

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

An interpopulation comparison of 3-dimensional morphometric measurements of the proximal humerus

Adijat O. Inyang, PhD [a,*], Stephen Roche, MD [b], Sudesh Sivarasu, PhD [a]

[a] *Orthopaedic Biomechanics Lab, Division of Biomedical Engineering, Department of Human Biology, University of Cape Town, South Africa*
[b] *Department of Orthopaedic Surgery, University of Cape Town, South Africa*

ARTICLE INFO

Keywords:
Shoulder
arthroplasty
prosthesis
morphometry
population
humerus
sex
race

Level of evidence: Anatomy Study; Imaging

Background: Precise anatomic reconstruction of the proximal humerus is essential to a favorable outcome of total shoulder arthroplasty. Because of the wide variation in the geometric features of the proximal humerus, prosthetic designs incorporating these disparities are being developed.
Methods: The aim of this study is to use data obtained from cadavers and computed tomographic scans to investigate the 3-dimensional morphometric parameters of the proximal humerus of South African and Swiss samples and make an interpopulation comparison. In addition, the study combines the interarticular variations between populations with the differences in sex and shoulder sides. With the aid of medical imaging techniques and engineering design tools, various geometric features were measured.
Results: The results obtained from these analyses revealed several differences in sex and shoulder sides. On average, the Swiss were larger in most of the measured parameters than the South Africans. The male shoulders of Swiss and South Africans were observed to significantly vary in 4 of the parameters measured. The South African male and female right shoulders varied considerably in one-fourth of the measured shoulder variables. Generally, for both populations, the left and right shoulders of the same individuals were not different in all the measured variables irrespective of sex.
Conclusion: The knowledge acquired in this study is expected to assist in the development of a population-specific shoulder prosthetic design and surgical planning procedures.

© 2020 The Authors. Published by Elsevier Inc. on behalf of American Shoulder and Elbow Surgeons. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

There have been marked improvements in shoulder prosthetic components since the initial concept of Neer et al's[29] Vitallium shoulder replacement design that was developed by earlier researchers.[24,29] Up to now, various prosthetic designs have been explored with the aim of improving patients' clinical experience after total shoulder arthroplasty.[31,37]

The quality and accuracy of prosthetic components are major factors in the outcome of total shoulder arthroplasty (TSA) surgeries. Deviations in the anatomy of these prostheses may change the biomechanics of the shoulder joint, which may lead to its failure.[20] The performance of shoulder prostheses can be improved by closely mimicking the geometry of the proximal humerus, which has been shown to vary widely.[4] To accommodate these variations, researchers have adopted different implant designs.[2,4,12,20,32–36]

In order to investigate the 3-dimensional (3D) morphometric features of the proximal humerus, several researchers have studied different specimen types using diverse approaches, from simple to highly sophisticated methods.[4,16,27,32,35] Shoulder morphometric data have been analyzed through direct manual surface evaluation, radiographic measurements, magnetic resonance imaging tools, algorithmic computer programs, radiologic data measurements, digitized 3D analysis, computed tomographic scan, and modeling modalities.[1,3,6,8,9,19,25,30,33] More recently, morphometric information has been retrieved in vivo using computed tomographic arthrography and 3D geometric modeling tools.[31,35,38,41]

Furthermore, different characteristic features of the humeral morphology have been investigated with respect to specific populations,[5,26,27,40,41] bilateral humeri,[6,7] and sex.[18,26] Most of these analyses have been focused on the whites, Japanese, and recently on the Asian population, whereas these crucial data for African populations are considerably rare in the literature.[17] To date, few studies have been conducted that combined the assessment of the variability in the geometry of the proximal humerus within a specific population with respect to the differences in sex as well as bilateral humeri. Furthermore, to our knowledge, there are limited data specifically and sufficiently describing the shoulder

---

Institutional Review Board approval was received from the Departmental Research Committee, Department of Surgery, University of Cape Town, South Africa (Project 2013/060).

* Corresponding author: Adijat O. Inyang, PhD, Department of Human Biology, Faculty of Health Sciences, University of Cape Town, South Africa, Private Bag X3, Observatory 7925, Cape Town, South Africa.
E-mail address: wumi.inyang@gmail.com (A.O. Inyang).

https://doi.org/10.1016/j.jseint.2020.03.003
2666-6383/© 2020 The Authors. Published by Elsevier Inc. on behalf of American Shoulder and Elbow Surgeons. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

morphology of the South African (SA) population. This study combines the uniqueness of analyzing the morphometric variations of the SA proximal humerus with a comparative analysis of the SA shoulders with the Swiss shoulders. Therefore, we have investigated the 3D morphometric parameters of the proximal humerus of the SA and Swiss populations and thereafter made an interpopulation comparison between these populations.

Materials and methods

Data description and 3D reconstruction modeling of the proximal humerus

Forty-two SA fresh-frozen cadaveric humeri and 58 Swiss humeri were used in this study. These data sets were obtained from bilateral shoulders. Of all the shoulders analyzed, 18 pairs were for women (Table I). They were collected from the Clinical Anatomy and Biological Anthropology Division of the University following the institutional review board approval of the Departmental Research Committee of the University's Department of Surgery. With the aid of a Phillips Brilliance 64-slice computed tomography scanner (Philips Medical Systems, Cleveland, OH, USA), the cadavers were scanned at a resolution of 0.65 mm at a slice thickness of 0.9 mm and an increment of 0.45 mm per rotation. The computed tomographic scans for the Swiss data were obtained from a Swiss repository.[22] Physically or pathologically defective specimens and those on which surgeries had been previously performed were left out from the study. The 3D reconstructed models of the humeri were semiautomaticaly generated in Mimics (Materialise NV, Leuven, Belgium), and exported as a stereolithography file for further processing.

Table I
Descriptive data analysis

Population	South Africans	Swiss
Source of data	Cadaver lab, Clinical Anatomy and Biological Anthropology Division	SICAS Medical Repository, Switzerland
Number of shoulders		
Left	21	29
Right	21	29
Paired	21	29
Total population (male)	21 (13)	29 (19)
Age, yr, mean ± SD	47.9 ± 14.7	49.4 ± 19.7

SD, standard deviation; *SICAS*, Swiss Institute for Computer Assisted Surgery.

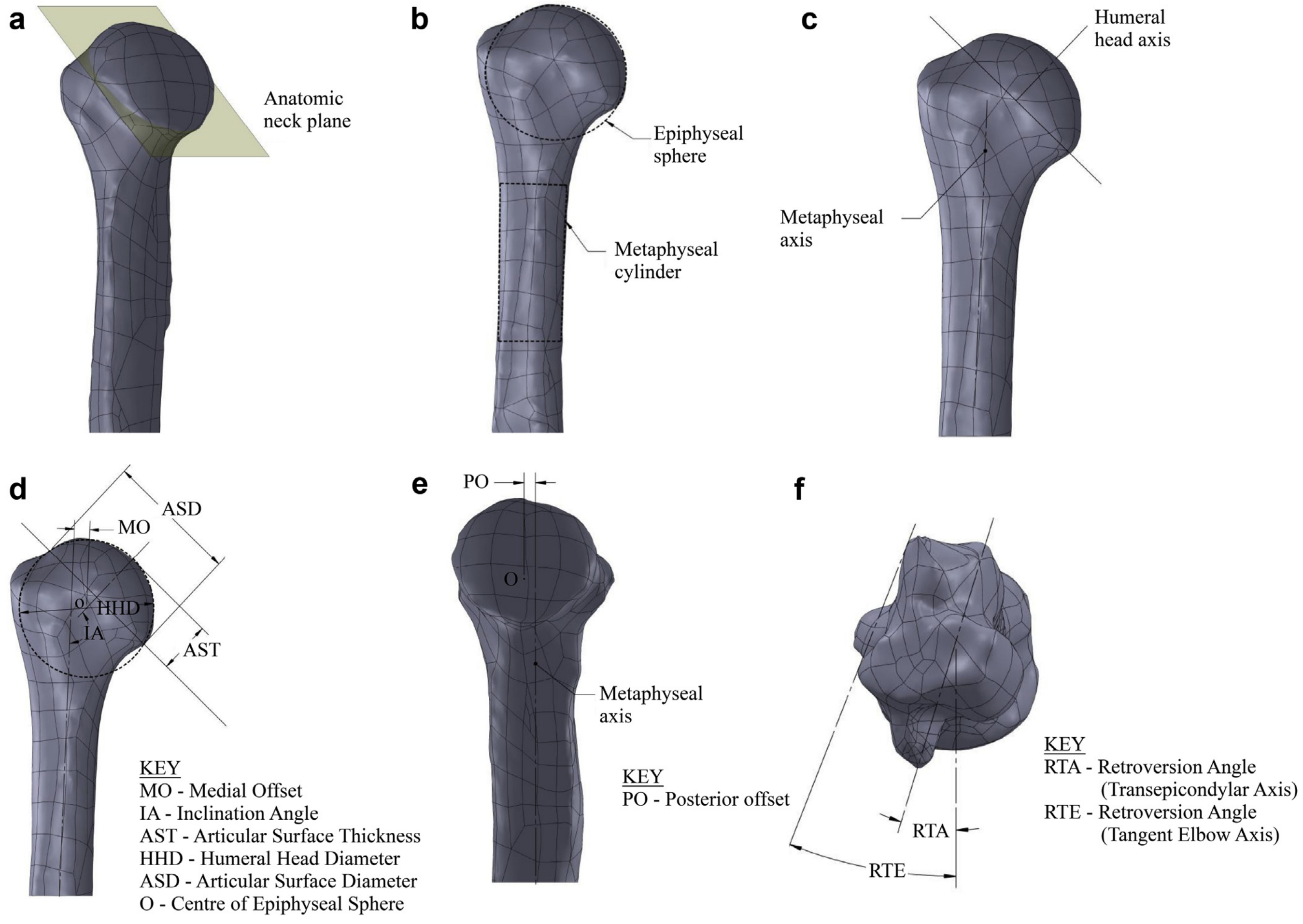

Figure 1 Three-dimensional reconstructed geometric models of the proximal humerus showing the (a) axes, (b) planes, (c) measurements characterizing the proximal humerus geometry, (d) posterior offset, and (e) retroversion angles.

Table II
Quantitative summary of the shoulder data set and the variables that were analyzed in the study

	Minimum	Quantile			Maximum	Mean	SD
		25%	50%	75%			
Age							
SA	20.00	36.00	50.00	55.00	78.00	47.86	14.65
Swiss	21.00	33.00	51.00	60.00	90.00	49.41	19.85
HHD							
Left							
SA	38.18	41.74	44.22	46.78	53.22	44.63	4.11
Swiss	39.34	44.5	49.14	51.18	53.58	47.63	4.16
Right							
SA	38.94	42.2	43.9	47.6	54.82	45.02	4.16
Swiss	39.98	44.34	48.22	50.42	52.84	47.43	3.99
AST							
Left							
SA	15.33	18.26	19.53	21.38	27.87	19.94	2.91
Swiss	14.61	18.93	20.76	22.31	25.36	20.66	2.49
Right							
SA	15.04	18.53	20.49	21.77	26.09	20.50	2.75
Swiss	16.97	18.57	20.48	21.47	24.94	20.42	2.19
ASD							
Left							
SA	37.73	41.10	43.93	46.61	53.17	44.18	4.04
Swiss	39.31	44.43	48.48	50.76	53.37	47.09	4.15
Right							
SA	38.08	41.79	43.84	47.09	54.76	44.70	4.16
Swiss	39.50	43.91	47.74	50.23	52.64	47.00	4.03
IA							
Left							
SA	122.00	129.00	132.80	135.30	141.90	132.10	5.92
Swiss	112.50	133.00	135.50	138.30	143.60	134.40	6.79
Right							
SA	122.30	127.10	130.90	135.50	138.80	131.10	5.24
Swiss	127.40	133.80	136.70	137.90	141.50	135.70	3.74
MO							
Left							
SA	3.89	5.40	5.76	6.91	9.60	6.16	1.48
Swiss	3.62	5.40	6.78	7.32	14.19	6.70	2.33
Right							
SA	4.28	5.60	6.19	7.64	9.83	6.66	1.58
Swiss	3.45	5.50	6.08	7.04	8.40	6.22	1.29
PO							
Left							
SA	0.02	0.51	0.99	2.85	5.88	1.64	1.64
Swiss	0.07	0.89	1.57	2.87	11.32	2.15	2.28
Right							
SA	0.00	0.43	1.10	2.23	4.93	1.52	1.37
Swiss	0.06	0.84	1.72	2.44	4.45	1.77	1.22
RA1							
Left							
SA	0.63	24.54	28.19	34.32	42.47	25.78	11.43
Swiss	4.74	10.68	25.43	37.76	61.51	26.56	16.55
Right							
SA	10.87	20.89	28.23	32.34	42.11	27.05	7.89
Swiss	3.66	13.01	20.63	29.45	44.10	22.26	10.45
RA2							
Left							
SA	5.23	27.02	31.95	33.88	46.97	28.26	10.37
Swiss	2.72	14.14	27.29	35.60	71.39	27.70	17.39
Right							
SA	11.39	25.91	28.59	34.35	44.59	29.67	9.13
Swiss	5.68	17.53	22.86	33.22	48.00	25.96	11.92

HHD, humeral head diameter; *AST*, articular surface thickness; *ASD*, articular surface diameter; *IA*, inclination angle; *MO*, medial offset; *PO*, posterior offset; *RA1*, retroversion angle 1; *RA2*, retroversion angle 2; *SA*, South African; *SD*, standard deviation. Sample demographics: female sex = 18; male sex = 32; N: 21 (South Africa) + 29 (Switzerland); total pairs of shoulders = 50.

Geometry extraction and parameter measurements

Each of the stereolithography files were imported into the reverse engineering environment of Solidworks (Dassault Systemes, Véilzy-Villacoublay, France). In preparation for geometry extraction, the relatively small detached mesh patches around the bone were first removed from the mesh, after which it was smoothened and then the humeral shaft was aligned along the Z-axis. These operations produced no noticeable change in the size and shape of the mesh; that is, the processes reduced the total number of faces in the mesh by less than 0.1%. The anatomic neck plane was defined as the plane that best fits the periphery of the articular surface, which was selected manually based on the observable boundary between the clearly spherical region and its surrounding as illustrated by Iannotti et al[15] (Fig. 1, *a*). Afterward, the epiphyseal sphere was generated as the sphere that best fits the region of the mesh representing the articular surface using the spherical surface fitting tool of Solidworks (Fig. 1, *b*). Similarly, the metaphyseal cylinder was obtained from the region representing the upper humeral shaft, which is the part of the shaft above the deltoid tuberosity, using the cylindrical surface fitting tool (Fig. 1, *b*). Next, the metaphyseal axis was defined as the central axis of the metaphyseal cylinder (Fig. 1, *c*), and the humeral head axis was created as a line passing through the center of the epihyseal sphere and perpendicular to the anatomic neck plane (Fig. 1, *c*). The last step was to obtain relevant dimensions and measurements as follows:

1. Humeral head diameter (HHD): the diameter of the epiphyseal sphere (Fig. 1, *d*)
2. Articular surface thickness (AST): the normal distance between the crest of the articular surface and the anatomic neck plane (Fig. 1, *d*)
3. Articular surface diameter (ASD): the diameter of the intersection circle between the epiphyseal sphere and the anatomic neck plane (Fig. 1, *d*)
4. Medial offset (MO): the normal distance between the center of the epiphyseal sphere and the metaphyseal axis both projected onto the axial plane (Fig. 1, *d*)
5. Inclination angle (IA): the angle between the humeral head axis and the metaphyseal axis (Fig. 1, *d*)
6. Posterior offset (PO): the normal distance between the center of the epiphyseal sphere and the metaphyseal axis measured on the coronal plane (Fig. 1, *e*)
7. Retroversion angle A1 (RA1) (transepicondylar): the angle between the transepicondylar axis and the humeral head axis, both projected on the dorsal plane (Fig. 1, *f*) (the transepicondylar axis is the line joining the innermost part of the medial epicondyle and the outermost part of the lateral epicondyle)
8. Retroversion angle A2 (RA2) (tangent elbow): the angle between the projections of the tangent elbow axis and the humeral head axis on the dorsal plane (Fig. 1, *f*).

All the axes and planes are as defined in Boileau and Walch.[4]

Statistical analysis

All the statistical analyses were implemented with R (R Core Team, 2016; R Foundation for Statistical Computing, Vienna, Austria) statistical software. The analyses were performed in order to investigate the differences and similarities between populations from South Africa and Switzerland, as a function of various humeral characteristics. Linear correlation analysis was first used to assess the relationship between all the pairs of the continuous variables in the humeral morphologic data. A Student *t* test and 2-tailed, paired, and unpaired tests were used to determine whether there are differences in the geometry of the proximal humerus between male and female samples as well as between paired shoulders. A logistic

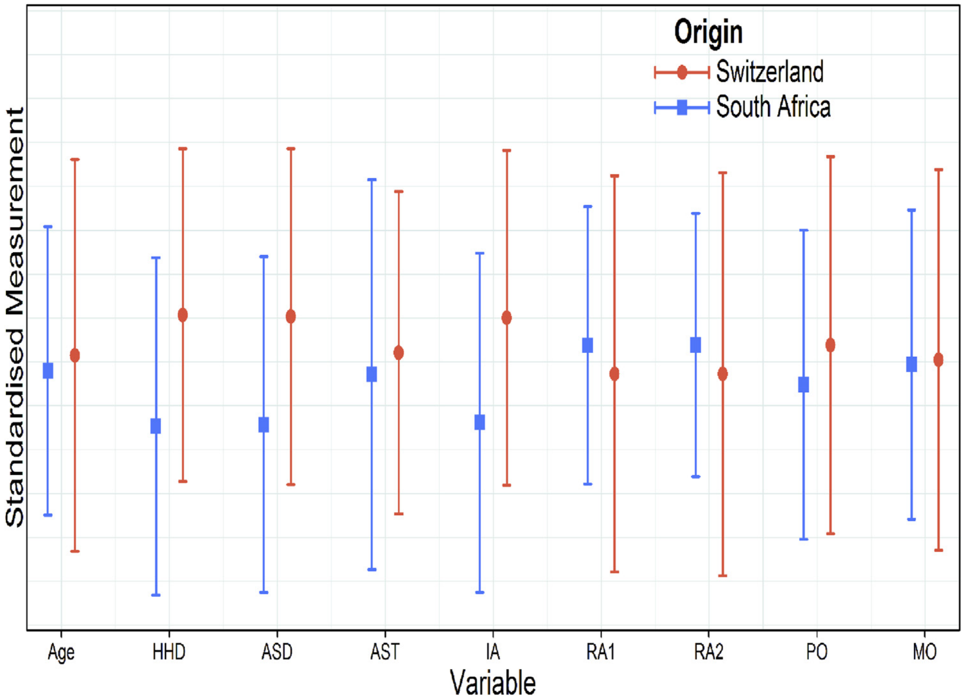

Figure 2 Summary of the distributions of all the measured variables using standardized values. *HHD*, humeral head diameter; *ASD*, articular surface diameter; *AST*, articular surface thickness; *IA*, inclination angle; *RA1*, retroversion angle 1; *RA2*, retroversion angle 2; *PO*, posterior offset; *MO*, medial offset.

regression analysis was then used to perform an interpopulation comparison with respect to each of the measured variables. In other words, logistic regression was implemented in order to identify the combination of the measured variables that could differentiate between humeri of separate nations or sexes. Prior to proceeding with the main logistic regression analysis, the degree of linear relationship between pairs of the shoulder specimen variables with continuous measurements was analyzed. Correlation coefficients vary between −1 and +1. The sign of the value indicates the direction of the linear relationship. The absolute value of the coefficient represents the degree of the relationship: 0 implies no linear correlation, whereas 1 implies perfect relationship. Two perfectly correlated variables are expected to contribute similar information to a regression model and need not be both included in the same model to avoid redundancy.

Results

The distributions of all the variables analyzed in this study are summarized in Table II. The table contains the counts for the qualitative measurements and 5-number summaries, means, and standard deviations. The table is supplemented with a graphical summary in Fig. 2. The plot illustrates the distributions of all the measured variables using standardized values. The choice of standardized measurements for the plot is to enhance visibility. Table II and Fig. 2 show that the Swiss and South African data were similarly distributed with respect to age and the AST, RA1, RA2, PO, and MO measurements, except that the Swiss have more variable age, RA1, RA2, PO, and MO whereas South Africans have more variable AST. It is also apparent that the South African specimens produced lower HHD, ASD, and IA measurements.

Figure 3 describes how the measured parameters compares between the 2 population groups, provided that the subjects were of the same sex and shoulder side. On average, the values for all the parameters were not different statistically, for SA and Swiss female shoulders, as none of the corresponding *P* values was less than .05. We assert that AST, MO, and PO variables were, on average, not significantly different between SA and Swiss male shoulders because the comparisons yielded *P* values that were greater than .092. On the other hand, there is a significant difference in the average values of HHD, ASD, and IA variables between SA and Swiss male shoulders. These parameters had *P* values that ranged between <.001 and .021. Both retroversion angle variables did not show any evidence to indicate that they were different between the left shoulders of SA men and their Swiss counterparts. Based on the magnitude of the *P* value of .058 for the comparison of RA2 between the right shoulders of SA and Swiss males, it is apparent that the evidence in the analyzed data is inconclusive. Given the corresponding *P* value of .027, it is evident that the retroversion angles, RA1s, for the right shoulders of SA men were significantly higher, on average, than those of their Swiss counterparts. Figure 4 contains boxplots that illustrate how the shoulder specimen variables compare between sexes within country as a function of shoulder side. The *P* values were obtained from unpaired Student *t* tests that were independently conducted to verify the null hypothesis that variables do not differ between sexes within country for a specific shoulder side. It is apparent from the plots that on average the HHD, ASD, AST, and IA parameters differ significantly between Swiss male and female shoulders, provided that shoulder side and nationality were kept unchanged. Unlike the Swiss, there were significant differences between male and female MO and RA1 measurements at the right shoulders of SAs. The difference in the estimated averages of MO and RA1 were higher for right shoulders of SA males. Figure 5 was generated in order to illustrate the comparisons between shoulder sides within the subjects when sex and country of origin were kept constant. It can be observed that, as expected, the interquartile boxes all overlap, except for a few variable scenarios. Generally, the *P* values were greater than .05, and this agrees with the implications of the overlaps observed with the

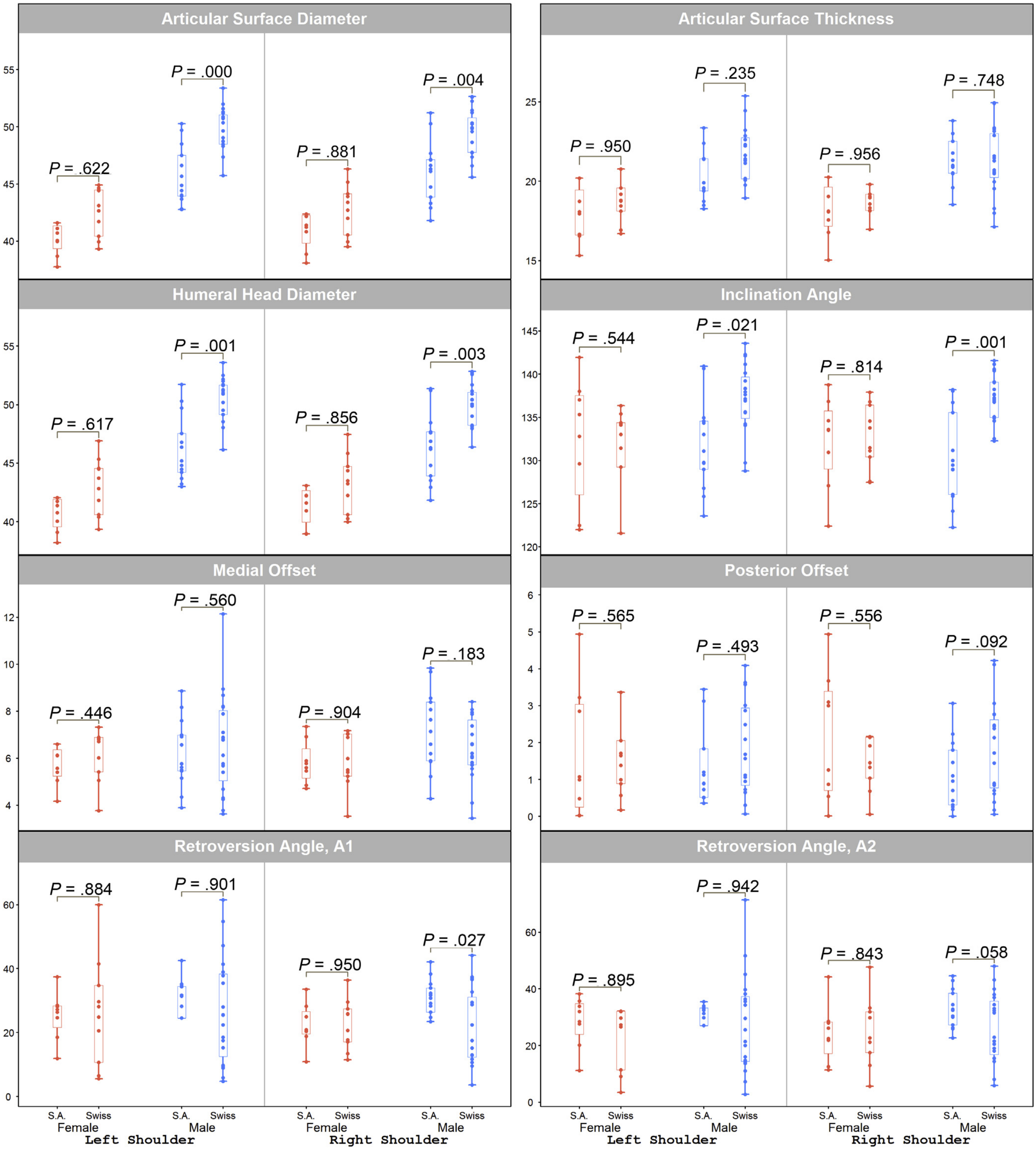

Figure 3 Box plots illustrating how the measured variables compare between South Africans and Swiss subjects. The *P* values were obtained from unpaired *t* tests to verify the hypotheses of equal mean values. *SA*, South African.

boxes. Therefore, it can be clearly seen that all the parameters tend to be the same for both left and right shoulders for a randomly chosen male or female sample from either SA or Switzerland. The small *P* values obtained for HHD and ASD within-subject comparisons for SA women contradict expectations and are interesting for future investigations.

A graphical exploratory summary of the degree of linear relationship between pairs of the shoulder parameters is presented in Fig. 6. It is evident that the HHD-ASD, RA1-RA2, ASD-AST, and AST-HHD pairs were strongly correlated. Of the identified pairs, the HHD-ASD pair has the strongest correlation (≈0.99). Consequently, and without loss of generality, the HHD variable was omitted from

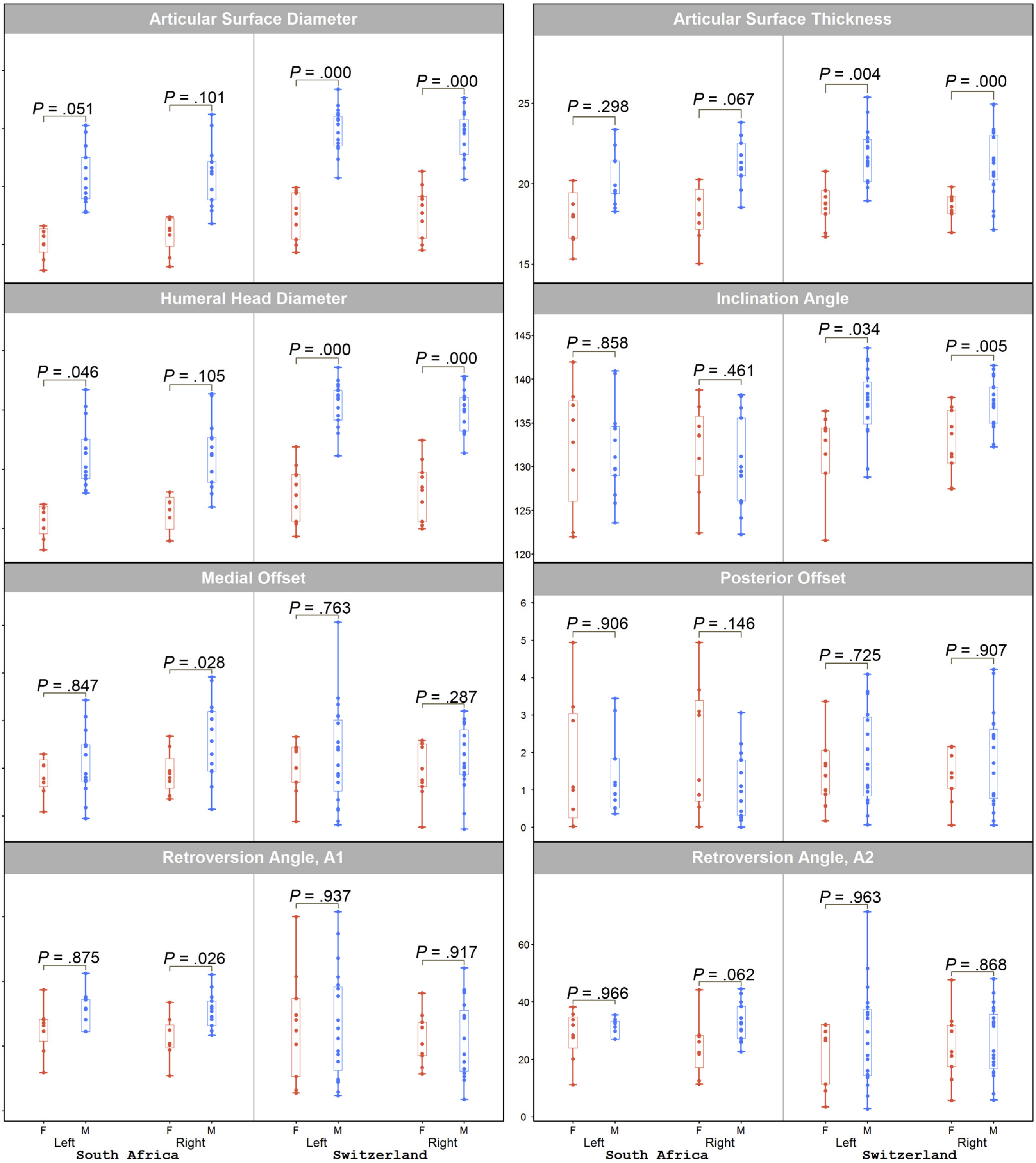

Figure 4 Summaries of interpopulation comparisons with respect to sex. The *P* values were obtained from *t* tests to verify the hypothesis of equal mean values. *F*, female; *M*, male.

the regression analysis. The strength of correlation of the other identified pairs could be accommodated in the model and were therefore retained. Results from the logistic regression models are summarized in Table III. The baseline for the sex and nationality models were male and South Africa, respectively. In all parameters measured, AST, IA, RA1, and RA2 contribute significantly to differentiating between humeri of separate nations or sexes (Table III). Interestingly, the analysis on sex relating to the left shoulder indicated significant differences with respect to AST, IA, RA1, and RA2, whereas on the right shoulder the differences were related to IA and RA1. In contrast, on the left shoulder, significant differences were observed between South African and Swiss data

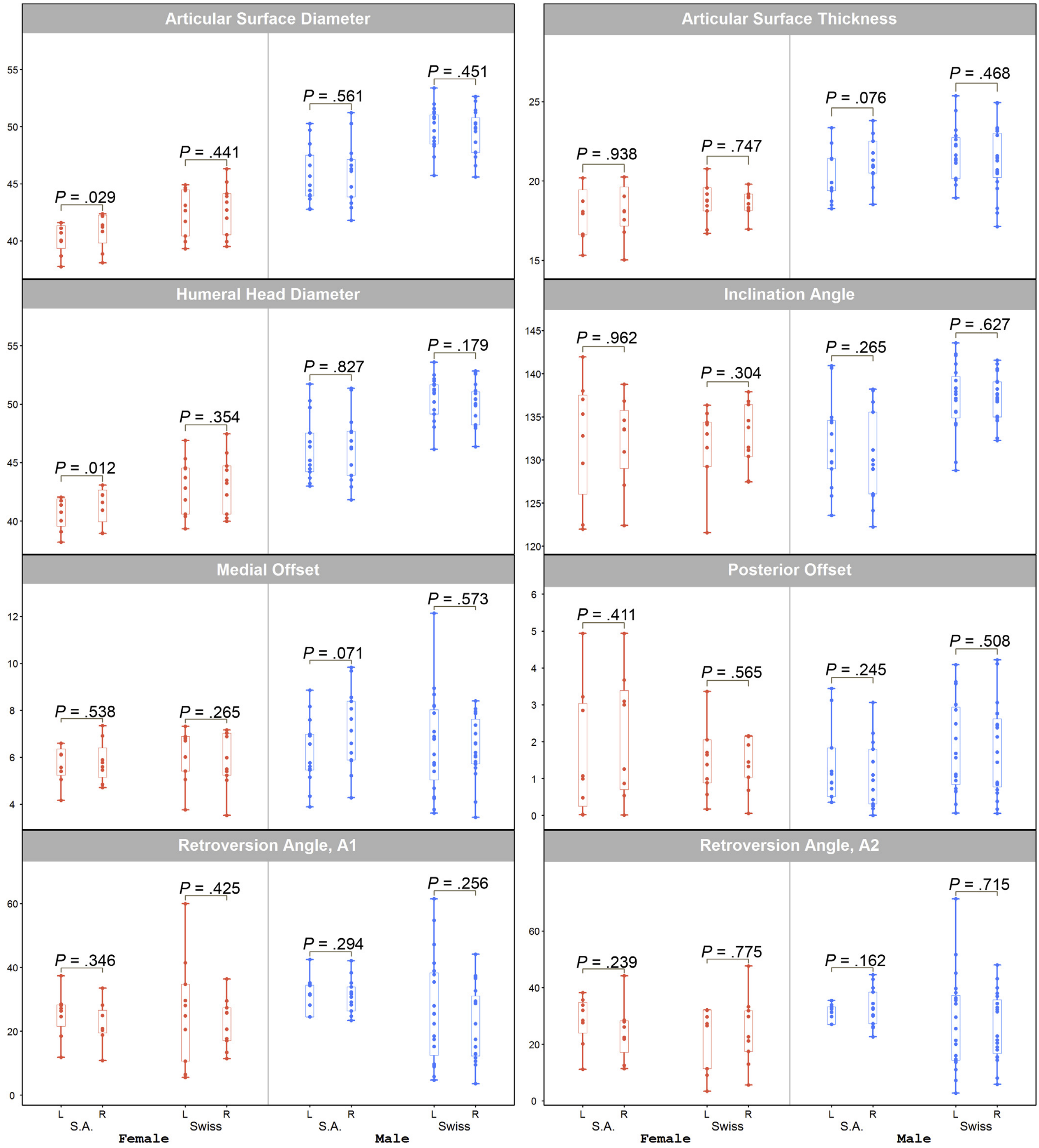

Figure 5 Parametric and visual summaries of the interpopulation comparisons of the measurements. The *P* values were recorded from paired *t* tests designed to verify the null hypothesis that left shoulders were equal to right shoulders, on average. *L*, left; *R*, right; *SA*, South African.

with regard to AST and RA2, whereas on the right shoulder, AST, IA, and RA1 were significantly different.

Discussion

The results obtained from this study reveal interesting differences in sex and sides in the proximal humeral morphometric parameters. Although many studies have been conducted earlier on the 3D morphometric analysis of the proximal humerus,[4,16,27,32,35] most of them have focused on Western populations; of these, a few have considered either sides or sex differences[6,7,18,26] and a few have compared populations involving an African origin.[17] One of the strong points of this study is that the comparison was made across continents—the SA population having rarely been

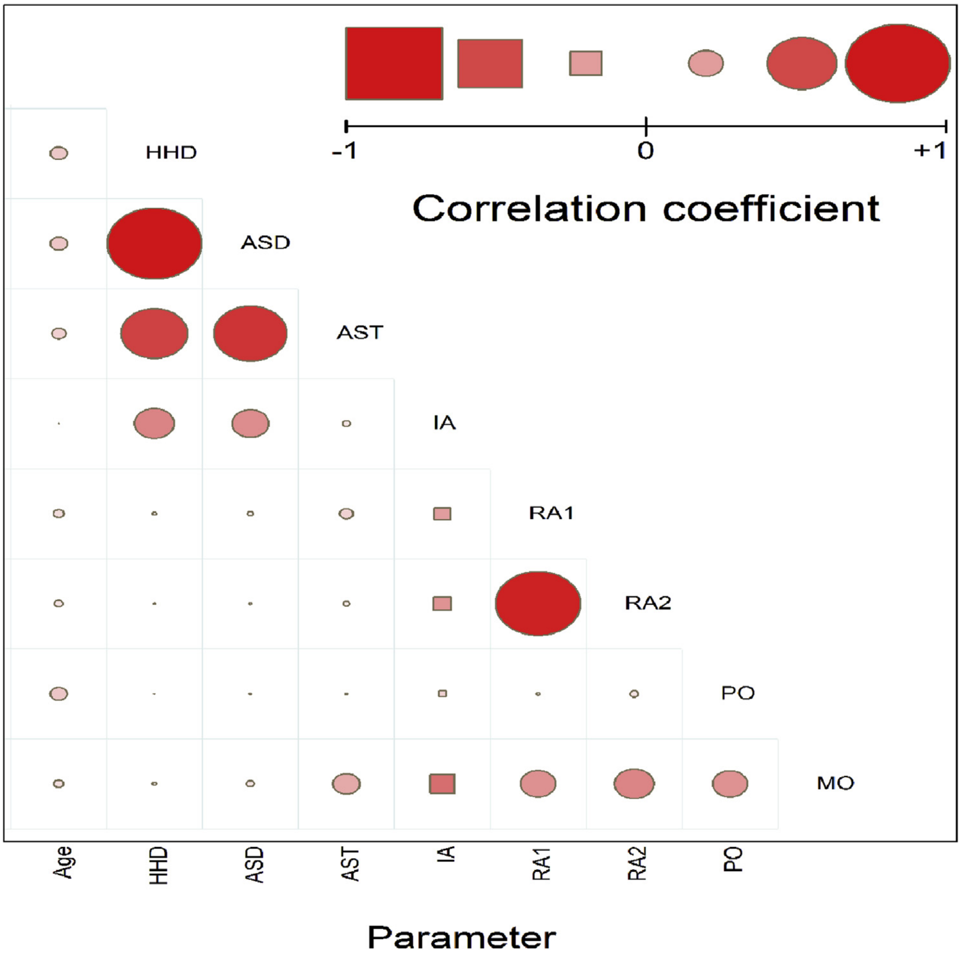

Figure 6 Correlation plot of the linear relationship between all pairs of the continuous measurements. *HHD*, humeral head diameter; *ASD*, articular surface diameter; *AST*, articular surface thickness; *IA*, inclination angle; *RA1*, retroversion angle 1; *RA2*, retroversion angle 2; *PO*, posterior offset; *MO*, medial offset.

studied—with the 2 populations having a statistically comparable age and sex distribution.

These results revealed variations in the proximal humeral morphology, with the Swiss population being larger or more variable than the SA population in most of the measured parameters. In general, the left and right shoulders of same individuals for both SAs and Swiss were not different in all the measured variables irrespective of sex. This is consistent with the findings of Delude

Table III
Summarized outputs from logistic regression models fitted for the shoulder morphometric data

	Left shoulder		Right shoulder	
	OR (95% CI)	*P* value	OR (95% CI)	*P* value
Sex				
Age	1.017 (0.968, 1.072)	.503	0.991 (0.943, 1.039)	.718
ASD	1.017 (0.987, 1.053)	.282	1.008 (0.984, 1.036)	.529
AST	0.019 (0.000, 0.288)	.032	0.206 (0.009, 1.584)	.264
IA	0.946 (0.891, 0.992)	.039	0.957 (0.915, 0.990)	.028
RA1	4.058 (1.662, 15.924)	.020	2.564 (1.319, 6.587)	.020
RA2	1.038 (1.006, 1.080)	.035	0.993 (0.968, 1.017)	.566
PO	1.003 (0.884, 1.082)	.953	0.962 (0.863, 1.082)	.445
MO	1.013 (0.987, 1.043)	.346	1.002 (0.976, 1.029)	.889
Nationality				
Age	1.013 (0.966, 1.065)	.600	0.987 (0.940, 1.033)	.578
ASD	1.004 (0.977, 1.032)	.772	1.003 (0.982, 1.025)	.756
AST	0.489 (0.246, 0.809)	.015	0.533 (0.342, 0.745)	.001
IA	0.975 (0.938, 1.008)	.169	0.965 (0.93, 0.992)	.020
RA1	1.724 (0.969, 3.589)	.093	2.130 (1.292, 3.969)	.007
RA2	1.036 (1.004, 1.074)	.037	0.993 (0.968, 1.016)	.543
PO	1.002 (0.898, 1.069)	.963	0.990 (0.948, 1.094)	.712
MO	1.013 (0.988, 1.042)	.316	1.002 (0.976, 1.028)	.901

ASD, articular surface diameter; *AST*, articular surface thickness; *IA*, inclination angle; *RA1*, retroversion angle 1; *RA2*, retroversion angle 2; *PO*, posterior offset; *MO*, medial offset; *OR*, odds ratio; *CI*, confidence interval.

Table IV
Comparison of the morphometric measurements with previous published studies

Parameter	Present study, mean ± SD		Previous studies, mean ± SD		
	SA (n = 42)	Swiss (n = 58)			
HHD	44.83 ± 4.09	47.53 ± 4.04	46.0 ± 4.00[35]	46.2 ± 5.40[4]	45.0 ± 3.60[10]
			47.8 ± 2.80[11]	48.8 ± 5.00[23]	42.8 ± 5.80[42]
			50.6 ± 4.60[33]	48.0 ± 4.20[16]	44.0 ± NR[2]
			50.3 ± 0.00[34]	42.9 ± 3.60[26]	44.2 ± 3.80[41]
			44.6 ± 4.40[40]		
ASD	44.44 ± 4.06	47.04 ± 4.06	43.3 ± 4.30[4]	41.4 ± 3.70[26]	42.9 ± 3.60[41]
AST	20.22 ± 2.82	20.54 ± 2.33	15.2 ± 1.60[4]	19.0 ± 2.00[35]	18.7 ± 2.10[23]
			18.5 ± 2.00[33]	20.0 ± 2.00[15]	13.2 ± 1.70[26]
			17.0 ± 1.70[13]	16.9 ± 1.50[41]	16.7 ± 1.90[40]
IA	131.58 ± 5.54	135.02 ± 5.47	129.6 ± 2.90[6]	131.0 ± 3.00[35]	135.0 ± 3.00[27]
			137.0 ± 3.62[35]	133.0 ± 3.10[25]	132.0 ± 4.70[26]
RA1	26.41 ± 9.72	24.41 ± 13.89	17.9 ± 13.70[4]	19.0 ± 6.00[35]	21.4 ± NR[34]
			32.0 ± 11.00[13]	22.6 ± 10.20[41]	21.1 ± 12.20[40]
RA2	28.97 ± 9.68	26.83 ± 14.80	21.5 ± 15.10[4]	23.3 ± 11.75[35]	
PO	1.58 ± 1.49	1.96 ± 1.82	2.6 ± 1.80[4]	2.0 ± 2.00[35]	4.7 ± NR[34]
			2.0 ± NR[2]	0.9 ± 1.10[26]	1.4 ± 1.43[13]
			0.40 ± 0.8[41]	3.5 ± 1.6[40]	
MO	6.41 ± 1.53	6.46 ± 1.88	6.9 ± 2.00[4]	7.0 ± 2.00[35]	11.0 ± NR[2]
			6.2 ± 1.40[26]	6.0 ± 1.81[13]	6.3 ± 0.90[41]
			5.0 ± 1.60[40]		

HHD, humeral head diameter; *ASD*, articular surface diameter; *AST*, articular surface thickness; *IA*, inclination angle; *RA1*, retroversion angle 1; *RA2*, retroversion angle 2; *PO*, posterior offset; *MO*, medial offset; *SD*, standard deviation; *NR*, not reported.

and coauthors,[7] where the study was carried out on specimens obtained from Canada. The male shoulders of Swiss and SAs were observed to significantly vary in 4 of the parameters measured. In these parameters, male Swiss were found to be larger on average than their female counterparts while considering the same shoulder sides. This follows a similar trend as in earlier studies.[18] Specifically, a considerable amount of variations was noticed between the SA male and female right shoulders in one-fourth of the measured shoulder variables, the males being distinctly larger than the females. It was observed that a wide variation in the side differences exists between different persons and between different population groups.[7]

The means and standard deviations of most morphologic measurements for both population groups computed in the present study were analogous both in magnitude and variations to those previously reported in literature (Table IV). The average HHD for SA (44.83 mm) compares favorably with that reported by Zhang et al (44.6 mm),[40] whereas the HHD for Swiss (47.53 mm) compares with the findings of Harrold and Wigderowitz (47.8 mm).[11] Our result for the ASD for SA (44.44 mm) is identical with that of previous work reported by Boileau and colleagues (43.3 mm).[4] Although Swiss ASD was slightly higher than the available published data,[4,26] it was closer to the value obtained by Boileau and Walch.[4] This could be because their data were from similar population groups. Also, our results for AST for both populations were quite similar both in magnitude and variation to that of Iannoti et al.[16] Likewise, the IA for both population groups agrees well with earlier published work.[26,35] In addition, SA and Swiss PO values were comparable to those of previous studies,[13,35] despite the fact that there was a high variation in the values obtained in earlier studies.[26,34,40,41] Similarly, the values of MO for both population groups were comparable to the published data.[26,41] The association found between these results corroborate our results and establish that the mean values obtained cannot be used on their own as they can misinform because quite a number of the measured humeral parameters were influenced by sex.

On the other hand, the average values recorded for RA1 and RA2 for both population groups were distinct from the available values in literature, where a wide variation also existed.[4,13,26,34,35,40,41] The RA1 did not exceed the combined range recorded in the literature, but the RA2 exceeded those previously reported. This disparity could be related to the different methods of measurement; for instance, Hertel et al[13] used measurements based on photographic projection. In general, the discordance among studies could be related to the differences in sample size, methodology, and measurement approach. In addition, the differences in the population groups can also influence the results because the studied population cannot be a characteristic sample of the other ethnic groups.

It was observed that there is a strong linear correlation between ASD and HHD for bilateral shoulders. This implies that we could accurately predict HHD values from their corresponding ASD measures. The regression outputs highlight that there are statistically significant differences in the shoulder sides between male and female samples, and between the Swiss and SAs, in the shoulder characteristic measurements, except for age, ASD, PO, and MO (Table III). Considering the left shoulder, men tend to have a larger AST compared with women of otherwise similar shoulder specimens. Besides, women were inferred to have larger retroversion angles, A1, irrespective of the shoulder side. In terms of nationality, the Swiss tend to have larger RA1 and RA2 on the right and left sides, respectively, and smaller AST regardless of shoulder side. Because there are limited data on the shoulder morphometry of the SA population, the result of the humeral analyses conducted in this study will be beneficial to the understanding of the failure associated with TSA using imported prostheses in SA. It will assist with the determination of the size and dimensions required for a new shoulder prosthesis design targeted for the SA population.

Furthermore, this could be applicable in biomechanical joint modeling. It is expected to have an influence on computer-aided navigation during TSA in ensuring accurate positioning of the component and, as a result, prevent instability and loosening, leading to nil postoperative complications.[14,28] Because the goal of TSA is to restore shoulder biomechanics, relieve pain, and improve function, this study will contribute to shoulder anatomic reconstruction that closely mimics that of a healthy contralateral shoulder and hence improved patient experience.[21,39]

Future studies will look at incorporating the findings of this study into a new prosthesis design putting into consideration the variations with respect to sex, sides, and population. The following limitations are associated with this study. The sample size is relatively small. More data would have improved the precision of the inferences. For example, the inconclusiveness of the RA2 comparison of the right shoulder between nationalities and the unexplainable differences inferred for HHD and ASD within-subject comparisons for SA female specimens could be resolved. Another limitation is that the left and right sides were chosen based on position and not on handedness. A follow-up study could investigate the influence of this choice on the inferences, if any. Also, the height of the subject, which is related to bone dimensions, is not included in this study because this information was not available in the data. Lastly, extension of the regression analyses could be undertaken by considering, for example, other discriminant analysis varieties. Because the SA population inherently comprises heterogeneous ethnic groups, further analyses should interrogate the population more thoroughly in terms of race—black, mixed, and white—and allow an intrapopulation analysis in comparison with the Swiss. Such an analysis would provide information as to which of the ethnic groups in SA influence the results, if any.

Conclusions

This work has focused on investigating the morphologic measurements from a 3D analysis of the proximal humerus based on an interpopulation comparison between SA and Swiss shoulders. The study has shown that some humeral parameters are nationality- and sex-biased in morphology. The distinctiveness of this all-encompassing study stemmed from the fact that it has incorporated a number of variables including sex and bilateral humeri as well as conducting morphologic differences between different ethnicities. This inimitable approach provides valuable information for both biomedical engineers and clinicians. It could provide useful information during surgery or for prosthesis design by using the contralateral healthy shoulder as a basis for the affected shoulder.

The morphometric data on the African shoulder are very limited, and this study will significantly contribute to the shoulder data repository for the SA population. The findings of this work can be adapted clinically to provide analog humeral implants that would favorably suit the SA patients and hence serve as an extension to the African population in the near future, consequently minimizing postsurgical complications. In conclusion, it is envisaged that the findings from this study will facilitate the design of a new shoulder prosthesis for the African populace.

Disclaimer

The National Research Foundation (NRF) South Africa provided financial assistance for this study. Opinions expressed and conclusions arrived at are those of the author and are not necessarily to be attributed to the NRF.

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

Acknowledgments

The authors acknowledge the contributions of Dr Tinashe Mutsvangwa, Mr Hassan Sadiq, and Mr Edward Olayemi to this work. We also thank the Schlumberger Foundation Faculty for the Future for providing Postdoctoral Fellowship for one of the authors.

References

1. Akman ŞD, Karakaş P, Bozkir MG. The morphometric measurements of humerus segments. Turk J Med Sci 2006;36:81–5.
2. Ballmer FT, Sidles JA, Lippitt SB, Matsen FA III. Humeral head prosthetic arthroplasty: surgically relevant geometric considerations. J Shoulder Elbow Surg 1993;2:296–304.
3. Bicknell RT, DeLude JA, Kedgley AE, Ferreira LM, Dunning CE, King GJ, et al. Early experience with computer-assisted shoulder hemiarthroplasty for fractures of the proximal humerus: development of a novel technique and an in vitro comparison with traditional methods. J Shoulder Elbow Surg 2007;16:S117–25. https://doi.org/10.1016/j.jse.2006.08.007.
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. Cabezas AF, Krebes K, Hussey MM, Santoni BG, Kim HS, Frankle MA, et al. Morphologic variability of the shoulder between the populations of North American and East Asian. Clin Orthop Surg 2016;8:280–7. https://doi.org/10.4055/cios.2016.8.3.280.
6. De Wilde LF, Berghs BM, VandeVyver F, Schepens A, Verdonk RC. Glenohumeral relationship in the transverse plane of the body. J Shoulder Elbow Surg 2003;12:260–7. https://doi.org/10.1016/s1058-2746(02)86884-7.
7. DeLude JA, Bicknell RT, MacKenzie GA, Ferreira LM, Dunning CE, King GJ, et al. An anthropometric study of the bilateral anatomy of the humerus. J Shoulder Elbow Surg 2007;16:477–83. https://doi.org/10.1016/j.jse.2006.09.016.
8. Doyle AJ, Burks RT. Comparison of humeral head retroversion with the humeral axis/biceps groove relationship: a study in live subjects and cadavers. J Shoulder Elbow Surg 1998;7:453–7.
9. Farrokh D, Fabeck L, Descamps PY, Hardy D, Delince P. Computed tomography measurement of humeral head retroversion: influence of patient positioning. J Shoulder Elbow Surg 2001;10:550–3.
10. Gebhart JJ, Miniaci A, Fening SD. Predictive anthropometric measurements for humeral head curvature. J Shoulder Elbow Surg 2013;22:842–7. https://doi.org/10.1016/j.jse.2012.08.020.
11. Harrold F, Wigderowitz C. A three-dimensional analysis of humeral head retroversion. J Shoulder Elbow Surg 2012;21:612–7. https://doi.org/10.1016/j.jse.2011.04.005.
12. Harryman DT, Sidles JA, Harris SL, Lippitt SB, Matsen F 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.
13. Hertel R, Knothe U, Ballmer FT. Geometry of the proximal humerus and implications for prosthetic design. J Shoulder Elbow Surg 2002;11:331–8. https://doi.org/10.1067/mse.2002.124429.
14. Hopkins AR, Hansen UN, Amis AA, Emery R. The effects of glenoid component alignment variations on cement mantle stresses in total shoulder arthroplasty. J Shoulder Elbow Surg 2004;13:668–75. https://doi.org/10.1016/j.jse.2004.04.008.
15. Iannoti JP, Williams GR, Miniaci A, Zuckerman JD. Disorders of the Shoulder: Reconstruction. Philadelphia, PA: Lippincott Williams & Wilkins; 2013.
16. Iannotti JP, Gabriel JP, Schneck S, Evans B, Misra S. The normal glenohumeral relationships. An anatomical study of one hundred and forty shoulders. J Bone Joint Surg Am 1992;74:491–500.
17. Inyang AO, Roche S, Rosch T, Sivarasu S. Investigating the intra-ancestral morphometric variations of the three-dimensional geometry of the proximal humerus. J Musculoskelet Res 2018;21:1850012. https://doi.org/10.1080/00016470510030878.
18. Jacobson A, Gilot GJ, Greene A, Flurin P-H, Wright TW, Zuckerman JD, et al. Glenohumeral anatomy study: a comparison of male and female shoulders with similar average age and BMI. Bull Hosp Jt Dis (2013) 2015;73(Suppl 1):S68–78.
19. Jobe CM, Lannotti JP. Limits imposed on glenohumeral motion by joint geometry. J Shoulder Elbow Surg 1995;4:281–5.
20. Iannotti JP, Williams GR. Total shoulder arthroplasty. Factors influencing prosthetic design. Clin Orthop Relat Res 1998;29:377–91.
21. Kadum B, Wahlström P, Khoschnau S, Sjödén G, Sayed-Noor A. Association of lateral humeral offset with functional outcome and geometric restoration in stemless total shoulder arthroplasty. J Shoulder Elbow Surg 2016;25:e285–94. https://doi.org/10.1016/j.jse.2016.02.021.
22. Kistler M, Bonaretti S, Pfahrer M, Niklaus R, Büchler P. The virtual skeleton database: an open access repository for biomedical research and collaboration. J Med Internet Res 2013;15:e245. https://doi.org/10.2196/jmir.2930.
23. Knowles NK, Carroll MJ, Keener JD, Ferreira LM, Athwal GS. A comparison of normal and osteoarthritic humeral head size and morphology. J Shoulder Elbow Surg 2016;25:502–9. https://doi.org/10.1016/j.jse.2015.08.047.
24. Krueger F. A vitallium replica arthroplasty on the shoulder; a case report of aseptic necrosis of the proximal end of the humerus. Surgery 1951;30:1005.
25. Kummer FJ, Perkins R, Zuckerman JD. The use of the bicipital groove for alignment of the humeral stem in shoulder arthroplasty. J Shoulder Elbow Surg 1998;7:144–6.
26. 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 2016;25:493–501. https://doi.org/10.1016/j.jse.2015.08.003.

27. Milner GR, Boldsen JL. Humeral and femoral head diameters in recent white American skeletons. J Forensic Sci 2012;57:35–40. https://doi.org/10.1111/j.1556-4029.2011.01953.x.
28. Neer C. Anatomy of shoulder reconstruction. Shoulder reconstruction. Philadelphia, PA: WB Saunders Company; 1990. p. 1–39.
29. Neer C, Watson K, Stanton F. Recent experience in total shoulder replacement. J Bone Joint Surg Am 1982;64:319–37.
30. Pearl ML. Proximal humeral anatomy in shoulder arthroplasty: implications for prosthetic design and surgical technique. J Shoulder Elbow Surg 2005;14: S99–104. https://doi.org/10.1016/j.jse.2004.09.025.
31. Pearl ML, Kurutz S. Geometric analysis of commonly used prosthetic systems for proximal humeral replacement. J Bone Joint Surg Am 1999;81:660–71.
32. Pearl ML, Volk AG. Retroversion of the proximal humerus in relationship to prosthetic replacement arthroplasty. J Shoulder Elbow Surg 1995;4: 286–9.
33. Pearl ML, Volk AG. Coronal plane geometry of the proximal humerus relevant to prosthetic arthroplasty. J Shoulder Elbow Surg 1996;5:320–6.
34. Roberts S, Foley A, Swallow H, Wallace W, Coughlan D. The geometry of the humeral head and the design of prostheses. J Bone Joint Surg Br 1991;73: 647–50.
35. 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;82:1594–602.
36. Soslowsky LJ, Flatow EL, Bigliani LU, Mow VC. Articular geometry of the glenohumeral joint. Clin Orthop Relat Res 1992:181–90.
37. Wang VM, Krishnan R, Ugwonali OF, Flatow EL, Bigliani LU, Ateshian GA. Biomechanical evaluation of a novel glenoid design in total shoulder arthroplasty. J Shoulder Elbow Surg 2005;14:S129–40. https://doi.org/10.1016/j.jse.2004.09.029.
38. Wataru S, Kazuomi S, Yoshikazu N, Hiroaki I, Takaharu Y, Hideki Y. Three-dimensional morphological analysis of humeral heads: a study in cadavers. Acta Orthop 2005;76:392–6. https://doi.org/10.1080/00016470510030878.
39. Wolff AL, Rosenzweig L. Anatomical and biomechanical framework for shoulder arthroplasty rehabilitation. J Hand Ther 2017;30:167–74. https://doi.org/10.1016/j.jht.2017.05.009.
40. Zhang L, Yuan B, Wang C, Liu Z. Comparison of anatomical shoulder prostheses and the proximal humeri of Chinese people. Proc Inst Mech Eng H 2007;221: 921–7. https://doi.org/10.1243/09544119jeim267.
41. Zhang Q, Shi LL, Ravella KC, Koh JL, Wang S, Liu C, et al. Distinct proximal humeral geometry in Chinese population and clinical relevance. J Bone Joint Surg Am 2016;98:2071–81. https://doi.org/10.2106/jbjs.15.01232.
42. Zumstein V, Kraljević M, Hoechel S, Conzen A, Nowakowski AM, Müller-Gerb M. The glenohumeral joint—a mismatching system? A morphological analysis of the cartilaginous and osseous curvature of the humeral head and the glenoid cavity. J Orthop Surg Res 2014;9:34. https://doi.org/10.1186/1749-799x-9-34.