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Anatomic variations in glenohumeral joint: an interpopulation study

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A R T I C L E I N F O

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Level of evidence: Anatomy Study, Imaging

Background: This study focused on the unique aspect of investigating shoulder morphometric differences between 2 distinct populations.
Methods: We used 90 computed tomography images of cadaveric shoulders for this study; 45 scans belonged to the South African (SA) cohort (49.74 ± 15.4 years) and the rest were Swiss (CH; 53.8 ± 21 years). The articulating surfaces of the glenohumeral joint were extracted, and their morphometric features, such as head circular diameter, glenoid and humeral head radius of curvature, head height, and humeral height, were measured.
Results: The mean interpopulation difference in the circular diameter of the humerus was 2.0 mm ($P = .017$) and 1.86 mm ($P > .05$) in the anterior-posterior and superior-inferior directions, respectively. The difference in the radius of curvature between the populations was 1.17 mm ($P = .037$). The SA shoulders were found to be longer than the CH shoulders by 8.4 mm ($P > .05$). There was no significant difference in the glenoid radius of curvature. The SA shoulders had higher glenohumeral mismatch ($P = .005$) and lower conformity index ($P = .001$) in comparison to the CH shoulders.
Conclusion: This study presents anatomic differences between African and European glenohumeral articulating surfaces. The results suggest that the glenohumeral geometry is both gender and population specific, and future joint replacements may be designed to address these differences.

Anatomic total shoulder arthroplasty (ATSA) surgically replaces the arthritic articulating surfaces of the glenohumeral joint (GHJ),[39] in the presence of intact rotator cuffs, with an anatomic total shoulder prosthesis (ATSP).[3,19,20,28,30,32,49] Although the current design of the ATSP has been successful in alleviating shoulder joint pain and restoring the functionality of the joint, underlying complications, such as glenoid component loosening and humeral head subluxation, reduce the success of this surgical intervention.[4,19,21,22,25,28,33,40,45,46,56] The initial design of the ATSP as proposed by Neer was aimed toward mimicking the anatomy of the GHJ.[9] Since then, modifications have been made to accommodate the head inclination angle and retroversion angle, and implants have also become more modular to accommodate reverse shoulder prostheses.[5,23,31,42] The current trend followed by various shoulder prosthesis manufacturers (eg, DePuy Synthes [West Chester, PA, USA], Global Shoulder System; Tornier [Bloomington, MN, USA], Aequalis prosthesis) is to provide surgeons with humeral heads of various heights.[54] Keeping in mind the evolution of the shoulder prosthesis design, it can be predicted that future prosthesis designs will likely be patient specific as seen in knees.

In sub-Saharan Africa, shoulder arthritis is a common joint disease.[2,41] Orthopedic-related disorders feature in the top 10 burden of diseases in South Africa.[14,59] Annually, around 5000 ATSPs are implanted in South Africa, and most of the prostheses used are imported. The average annual trade deficit for the South African medical industry including orthopedic implants is ZAR 8 billion.[51] Postsurgical complications and implant failure are also common. Worldwide, 21%-32% of ATSAs have to be revised because of postsurgical complications like glenoid loosening.[4,8,25,50] The "rocking horse" effect has been identified as one of the main causes of glenoid loosening.[33,55] Improper understanding of shoulder anatomy, which varies according to the geographic location of the population,[11,34,57] may result in nonanatomic alignment of the prosthesis, leading to uncharacteristic kinematics and finally failure of the implant.[8,23,37]

The shoulder geometry of the native South African (SA) population has rarely been studied. Along with this, keeping in mind the financial burden, there is a need to develop ATSPs specific to the native SA population. This aim of this study was to measure and to compare the GHJ morphometric features of native SA and native Swiss (CH) populations.

The Department of Surgery Research Committee of the University of Cape Town approved this study: Project 2013/060.

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Materials and methods

Experimental setup

A database of 90 humeri and scapulas (average age, 50.9 ± 17.9 years) was created from upper body (hip and above) computed tomography (CT) scans of 90 embalmed cadavers. Of the 90 shoulders, 45 belonged to the CH data set and the other 45 belonged to the SA data set. Any scan with visible bone spur, deformation, or fracture was rejected. Details about the data sets are provided in Table I.

The raw data (Digital Imaging and Communications in Medicine) from the CT scans were reconstructed to create 3-dimensional (3D) models of the humerus and the glenoid using the Mimics (Materialise, Leuven, Belgium) program (Fig. 1) by applying a process similar to that detailed by Bryce et al.[10] The 3D model of the humerus was exported to SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France) as a mesh file. In the 3D computer-aided design software, the humeral articular surface was separated by performing an in silico ATSA (Fig. 2). This was performed under the guidance of a single trained surgeon specialized in ATSA, adhering to the surgical technique described by Duquin et al.[17]

The retrieved humeral head was assigned an independent coordinate system to facilitate the retrieval of the morphometric features. A feature extracting pipeline was generated to calculate the anterior-posterior (AP) and superior-inferior (SI) circular diameter (Fig. 3) and the height of the articular surface using MATLAB (MathWorks, Natick, MA, USA). A sphere-fit algorithm was implemented to calculate the spherical radius of curvature (RoC) of the humeral head and the glenoid fossa (Fig. 4). The mismatch in the RoC was measured by calculating the difference between the glenoid fossa RoC and the humeral head RoC.[53] The conformity index was given by the ratio of the glenoid RoC over the humeral head RoC. The humerus height was measured by calculating the length of a line passing through the center of the humeral shaft, perpendicular to the line joining the distal condyles, toward the humeral head.

Table I
Information of the computed tomography scans obtained for the current study

	Swiss data set	South African data set
Racial distribution	Caucasian	NonCaucasian
Acquired from	SICAS Medical Image Repository	University of Cape Town Cadaver Laboratory
Age (y)	53 (19-90)	49 (20-82)
Male:female	20:25	26:19

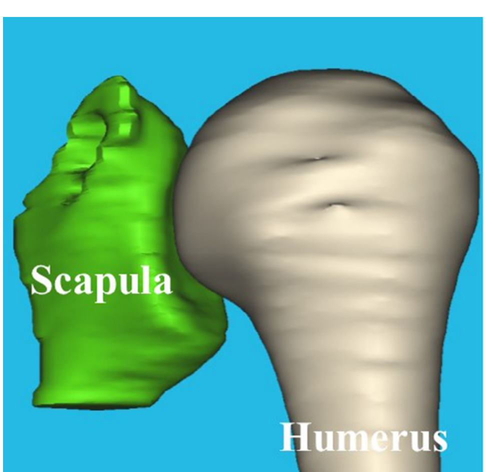

Figure 1 Three-dimensional reconstructed models of the humerus and glenoid.

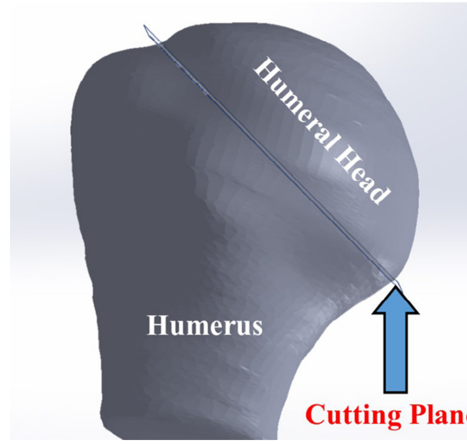

Figure 2 The in silico surgical process to retrieve the humeral head from the reconstructed humerus.

Automatic detection of morphometric features was implemented as it has less chance of encountering human error compared with manual measurements.[5,10]

Statistical analysis

The statistical analyses were performed in R software package. The observed data were separated, into various data sets, according to their country of origin (CH and SA), position in the body (left and right), and gender (male and female). Of the 90 reconstructed shoulders, 2 reconstructed heads were found to be not suitable (fractured) for the morphometric feature extraction process. Shapiro-Wilk tests were performed to analyze the distribution of the observations for each of the parameters in each data set. Along with the tests for normality, quantile-quantile plots were generated to support the tests. To determine whether the observed differences, between the data sets, were significant, *t*-tests were performed for the normally distributed parameters and Wilcoxon signed rank tests for the rest. A 2-tailed post hoc power analysis was performed for the 2 population and gender groups using G*Power[18] for a value of $\alpha = .05$.

Results

The obtained results are divided into population-, bilateral-, and gender-specific variations. Each variation is further divided into subdivisions according to the studied morphometric features.

Interpopulation variations

The average circular diameters in the AP and SI axes were found to be 44.6 ± 4.1 mm and 49.7 ± 4.5 mm, respectively, for the SA population and 46.6 ± 3.5 mm and 51.6 ± 4.6 mm for the CH population. The observed difference in the AP direction was found to be significant ($P < .05$), but the difference in the SI direction was not significant ($P > .05$). The average CH population was found to have larger spherical RoC (24.4 ± 2.5 mm) for the humeral head, but the glenoid RoC (30.3 ± 5.1 mm) was smaller than that of the SA population, whose average humeral head RoC and glenoid RoC were measured to be 23.2 ± 2.6 mm and 31.1 ± 3.9 mm, respectively. The difference in the humeral RoC was found to be significant ($P < .05$), but the difference in glenoid RoC was not significant ($P > .05$). The average SA humerus (323.4 ± 21.9 mm) was found to be larger than the average CH humerus (315.0 ± 21.1 mm). An average difference of about 8.4 mm was observed. This difference was found not to be

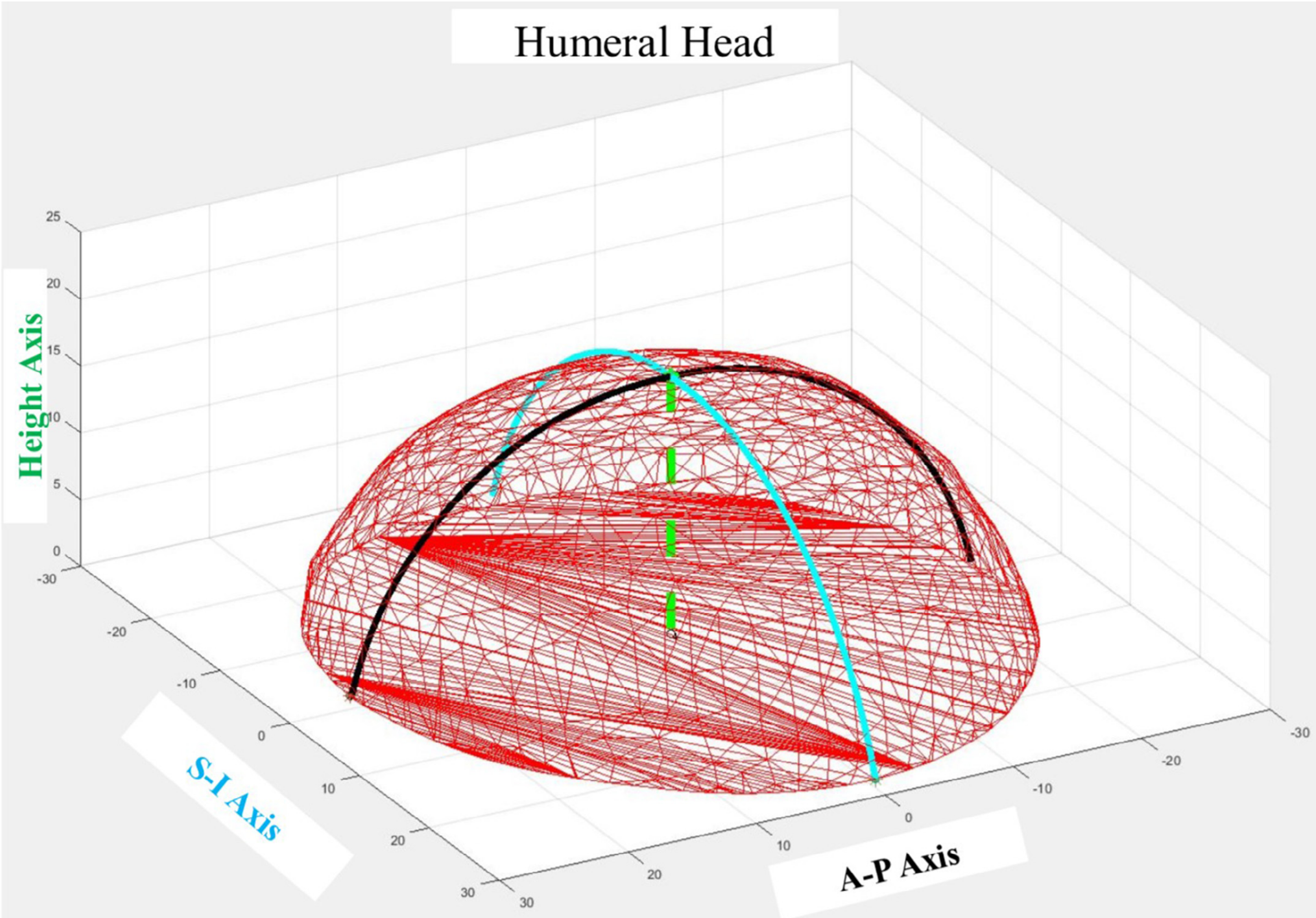

Figure 3 Automatic calculation of the circular diameter of the humeral head and the humeral head height using the feature extracting pipeline. *A-P*, anterior-posterior; *SI*, superior-inferior.

significant ($P > .05$). The average CH humeral head (19.5 ± 1.9 mm) was found to be thicker than the average SA humeral head (18.9 ± 2.2 mm) by 0.5 mm. This observed difference was found to be not significant ($P > .05$). GHJs of the SA population had higher RoC mismatch (7.9 ± 3.1 mm) compared with their CH (5.7 ± 3.9 mm) counterparts. The average difference was about 2.2 mm, and this difference was found to be significant ($P < .05$). The observed conformity index for both populations was <1, suggesting that the humeral head RoC was smaller than the glenoid RoC. The average conformity index for the CH population (0.8 ± 0.1) was higher than that for the SA population (0.75 ± 0.07) by a value of 0.06, and this difference was found to be significant ($P < .001$).

Bilateral variations

The average circular diameter in the AP and SI axes was found to be 45.5 ± 3.9 mm and 50.4 ± 4.6 mm, respectively, for the left humeral head and 45.6 ± 3.9 mm and 50.8 ± 4.7 mm for the right humeral head. The average right humeral RoC was measured to be 23.7 ± 2.5 mm, and the average left humeral RoC was measured to be 23.8 ± 2.8 mm. The difference in the spherical RoC for the humeral head and the glenoid was <1 mm. The right humerus height (319.7 ± 22.5 mm) and the humeral head thickness (19.4 ± 1.9 mm) were found to be greater than the left humerus height (318.1 ± 21.3 mm) and humeral head thickness (19.0 ± 2.3 mm) by 1.5 mm and 0.3 mm, respectively. The glenohumeral mismatch and the conformity index were found to have similar values for the average right (7.0 ± 3.5 mm and 0.7 ± 0.1) and left (6.7 ± 3.9 mm and 0.8 ± 0.1) humerus. All the observed differences for the bilateral humerus were statistically not significant ($P > .05$).

Gender variations

The average circular diameter in the AP and SI axes was found to be 47.1 ± 3.1 mm and 52.9 ± 3.5 mm, respectively, for the male humeral head and 44.1 ± 4.1 mm and 48.2 ± 4.5 mm for the female humeral head. The differences in the SI (4.7 mm) and the AP (3.0 mm) direction were found to be statistically significant (for both the cases, $P < .001$). The average spherical RoC of the humeral head and the glenoid cavity were found to be greater for the male (24.9 ± 1.9 mm and 32 ± 4.04 mm) compared with the female (22.6 ± 2.7 mm and 29.4 ± 4.7 mm) shoulders by 2.3 mm and 2.7 mm, respectively. These differences were found to be significant ($P < .001$ for humeral head RoC and $P = .02$ for glenoid RoC). The humeral height and the humeral head height were larger for the male (327.9 ± 17.6 mm and 19.7 ± 1.6 mm) than for the female (309.2 ± 21.8 mm and 18.7 ± 2.4 mm) shoulders, and the observed differences were 18.7 mm and 0.98 mm, respectively. The noted differences were significant ($P < .001$ for humeral height and $P = .02$ for humeral head height). The intergender differences of the glenohumeral mismatch, 6.8 ± 3.6 mm for male shoulders and 6.6 ± 3.8 mm for female shoulders, and the conformity index, 0.8 ± 0.1 for male shoulders and

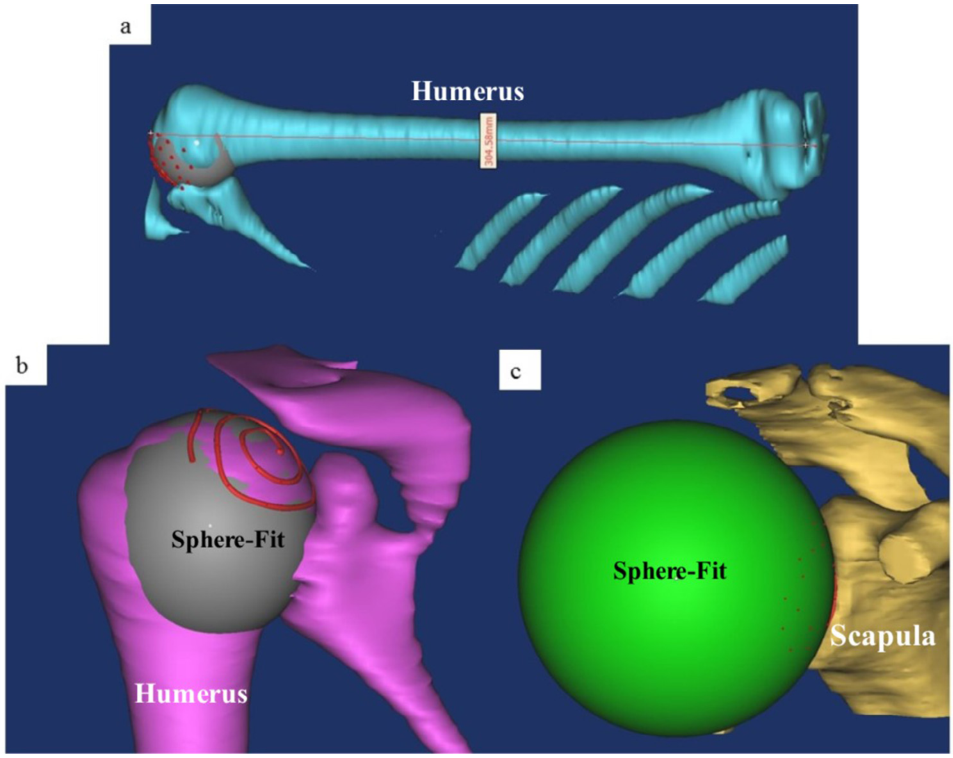

Figure 4 Measurement of the (**A**) length of the humerus, (**B**) the radius of curvature of the humeral head, and (**C**) the glenoid fossa.

0.8 ± 0.9 for female shoulders, were found to be not significant ($P > .05$).

Discussion

Various authors[6,7,10,12,20,27,34,35,38] have studied the underlying anatomy and the morphometric differences of normal and diseased[26,29,43,44] GHJs. To the best of our knowledge, the morphometric variances of healthy GHJs between 2 different populations have not been extensively studied with the aim of developing a population-specific shoulder implant in a process suggested by Aitchison et al.[1] This study finds significant morphometric differences in the GHJ articulating surfaces of the CH and SA populations. The post hoc power analysis performed on the 2 population sets showed that the calculated differences had an effect size of 0.52, and the power to detect this effect size was 0.7. The analysis gave an estimate of the sample size (n = 58) per population set required to achieve a statistical power of 0.8.[13] Inadequate sample size of the 2 data sets was the first limitation of this study. For the gender groups, the calculated effect size for $\alpha = .05$ was 0.81, which can be considered a large effect,[13] and the power for this study to detect the effect was found to be 0.97. The observations from the CT scan data were not compared with corresponding radiographs, and this can be considered the second limitation of the study.

According to the literature, the humeral head has a dual curvature spherical geometry, and its circular diameter varies in the SI and AP axes.[26,29,34,43] Similar variation in circular diameter of the head was observed in this study. This validates the method applied in this study. Circular diameter of the humeral head provides a snapshot of the otherwise spherical humeral head. One study found that measuring the circular dimensions of the humeral head gives a better understanding of its morphometry.[36] Boileau and Walch studied a group of 65 French humeri and found the average humeral head diameter in the AP axis to be 46.2 mm.[7] In our study, we found the average diameter in the same axis for the CH population to be 46.6 mm (Fig. 5). This suggests that the European humeral articulating surfaces are of similar size. The average SA circular diameter and humeral RoC were found to be significantly smaller than in the CH group (Fig. 5). The literature suggests that individuals belonging to the SA population of European descent have larger humeral heads than the rest of the population.[52] Average humeral articular surface diameter of a set of Chinese humeri was reported to be 42.9 ± 3.6 mm,[57] which is similar to the Japanese population[34] but lower than the average SA and CH articular surface diameter. This suggests that there exists a distinct variation in humeral head sizes among populations originating from different geographic locations. Extensive studies have not been performed on the glenohumeral surface geometry of the Sub-Saharan population; hence, it can be assumed that the current design of the ATSP is based on the European and American samples. The third limitation of this study is that although it points out differences between 2 distinct population groups, it fails to show any conclusive evidence of whether there is a need for a population-specific total shoulder prosthesis.

The average ratio of the AP and SI base width of the humeral head was found to be 1.09 for the whole data set, and the geographic location of the shoulder did not have any effect on this. The ratio increased with the increase in the AP and SI circular diameter as shown by Humphrey et al.[26] The average difference in the SI and AP width was 4.07 ± 1.9 mm; this average mismatch increased to 5.23 mm when the SI width was >52 mm. The majority of the humeral head prostheses are designed with a constant AP and SI base width. The observations from this study suggest that when the spherical RoC of the humeral head is >48 mm, the base width ratio is >4. This is a design criterion that might have been overlooked until now.

Variation in humeral head size is a better discriminating parameter between men and women compared with femoral heads.[38] This study found that the average male humeral head circular diameter and the spherical RoC of both the head and the glenoid were

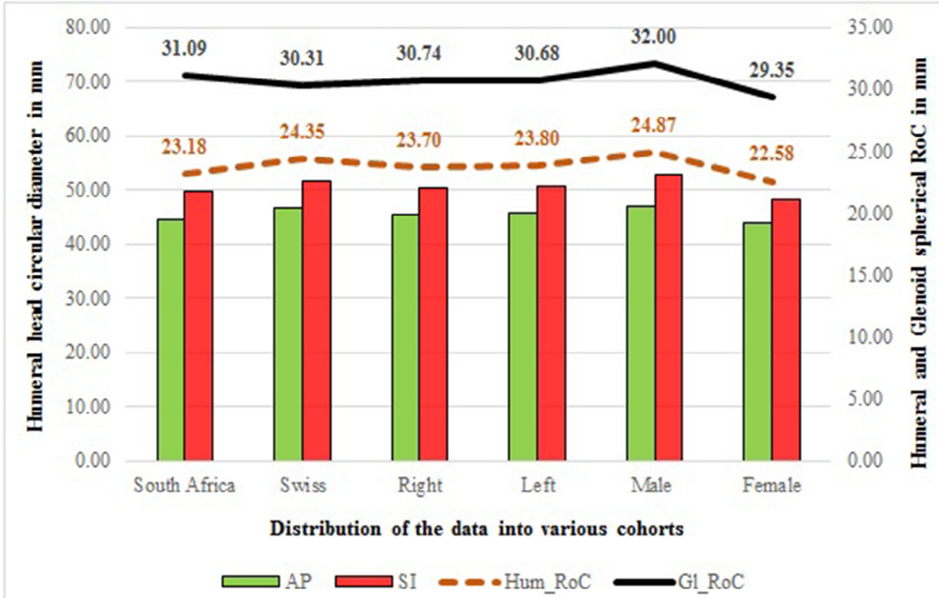

Figure 5 The variation of humeral head circular diameter, glenoid radius of curvature (*Gl RoC*), and humeral radius of curvature (*Hum RoC*) across the study cohorts. *A-P*, anterior-posterior; *SI*, superior-inferior.

significantly larger than their female counterparts. This is in line with past studies.[26,41,47,52] In this study, significant differences were observed between the SA male and CH male cohorts in terms of humeral head circular diameter, in both the SI and AP directions, and the spherical RoC. This study failed to establish similar significance for the female cohort, which can be attributed to the fact that there was a higher difference in the number of female subjects in the SA and CH populations under study.

No significant differences were found in any of the morphometric parameters for the bilateral humerus in either of the populations, suggesting that the left and right shoulders in healthy individuals are similar in anatomy. Previous studies have shown that there is no geometric difference in the dominant and nondominant shoulders of an individual in both healthy and diseased populations.[43]

This study does not find any significant differences in the glenoid spherical RoC, the humerus height, and the humeral head height between the CH and SA populations. Churchill et al, in their study of 172 scapulas, were unable to report any significant differences between the American and non-American glenoid articulating surface.[12] These findings indicate that glenoid articulating surfaces do not vary as extensively as the humeral head.

The study by Steyn and Işcan suggested that the SA population of European descent had a longer humerus than the native population.[52] This study found the average SA humerus to be longer than the average CH humerus (Fig. 6). The fourth limitation of this study is that the height and weight of the subjects were unknown, and hence the findings of this study cannot be correlated to these factors to generate a conclusive inference.

Humeral head height gives an indication of the correct sizing of the prosthesis to prevent overstuffing or understuffing of the joint.[48] Boileau and Walch calculated the average height of the humeral articular surface to be 15.2 mm.[7] The values observed in our study, for both the CH (19.48 mm) and SA (18.97 mm) populations, were higher than the ones reported in the literature (Fig. 6). The reason for this difference can be attributed to the fact that the authors of the previous study focused on measuring the proximal humerus and not the whole humeral articulating surface. The "hinge point" selected by Boileau and Walch[7] does not match the current surgical procedure specified[16,58] and the suggested humeral articular cutting plane.[15] The average humeral head height observed by Ray et al was 9.2 mm,[47] which was much lower than the values observed in the literature[7,24,29] or the average value observed in our study. One possible reason for this might be that the study of Ray et al[47] was performed on Indian subjects, who might have anatomic features different from those of the European and African populations. Japanese humeral head height[34] was considerably smaller than the observed humeral head height in this study. Male humeral height, humeral head height, and glenoid spherical RoC were significantly greater than the female values, which is in line with the previously conducted studies.[12,52,57] There were no significant differences observed between the SA male and female and CH male and female cohorts for the glenoid spherical RoC, humeral height, and humeral head height. This can be a subject of further research. Future kinematic studies need to be performed to evaluate the effect of the morphometric variations in the gender groups so that comments can be made about gender-specific anatomic shoulder implants.

Conclusion

In this study, the GHJ articulating surfaces of SA and CH populations were measured and compared, and the study found medium-sized (effect) significant differences between the populations. Further study with a larger data set will reveal the full extent of the morphometric variation, and separate kinematic investigations are recommended to find the effect of the geometric differences on the joint's activity. Strong evidence of large morphometric differences between the gender groups was observed in this study. This study may aid in anatomic shoulder prosthesis design in the future for populations of different ethnic origin.

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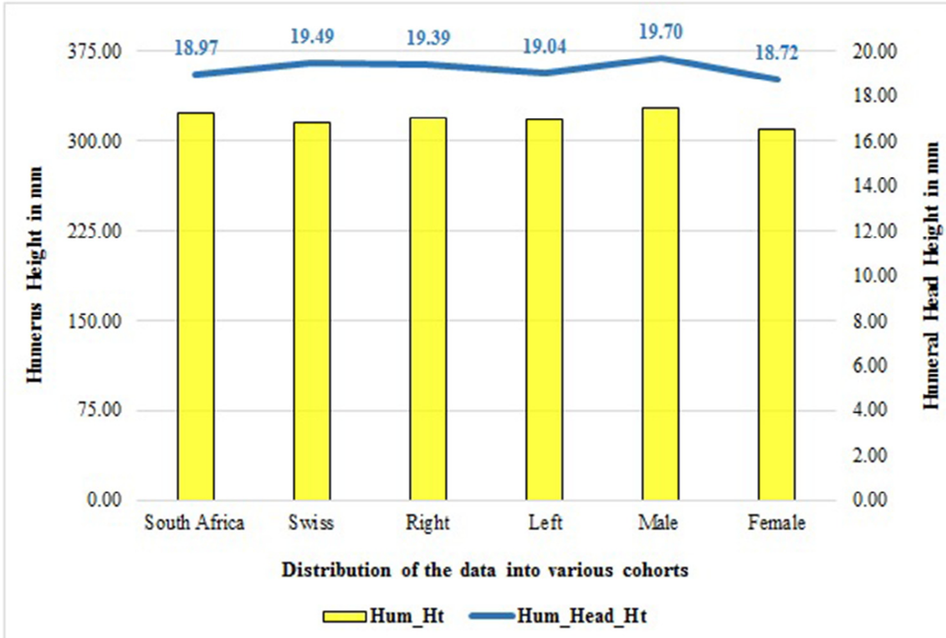

Figure 6 The variation in the humeral height (*Hum Ht*) and the humeral head height (*Hum Head Ht*) across the various cohorts.

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