REVIEW ARTICLE

Application of Three Dimensional Geometric Morphometric Analysis for Sexual Dimorphism of Human Skull: A Systematic Review

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ABSTRACT

The present systematic review explores the most sexually dimorphic parameters by using geometric morphometric analysis of human skull. An extended search was conducted in Google Scholars and PubMed (published between 2005 and 2017). The main inclusion criteria were research articles published in English, and studies that used geometric morphometric analysis for classification of human skull. The literature search identified 54 potential relevant articles whereby, five had met the inclusion criteria. Most studies reported positive contribution of geometric morphometric as an alternative and accurate tool for classification of unknown human crania. Geometric morphometric method resulted in a high classification accuracy of sexual dimorphism among different populations. Further studies are required to approach the best method used for varied types of postcranial bones equipped with a more advanced meta-analysis of the results.

KEYWORDS: Forensic anthropology, crania, sex, geometric morphometrics.

INTRODUCTION

Morphometrics is considered a subdivision of statistics, which involves measurement of shape. In 1888, Galton used correlation coefficient in the measurement of human shape.[1] Later, Bookstein-shape coordinateswereadded in 1907, and multivariate morphometrics was used for multivariate statistical application. In 1980, a great invention of coordinate-based methods and application of statistical shape theory were introduced. This is called geometric morphometrics, which maintains the geometry of landmark configuration and analysis of shapes and forms. In geometric morphometrics, the data can be organized in *2D* or *3D* coordinates of landmark points. Distances can be measured with a better adequacy than that in traditional morphometrics. Graphical display can be evaluated to check the adequacy in covering the area of interest.[2]

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Geometric morphometrics has varied applications in different scientific fields. For instance, it can be used in forensic anthropology, zoology, biology and archaeology. Geometric morphometrics has an important role in forensic anthropology for determination of sexand ancestry.[3] For instance, Buikstraand Ubelaker (1994) developed standards for collection of data from unknown skeletal remains.[4] Geometric morphometrics is an advantageous qualitative analysis because it can assess the traits by quantitative method, and precisely determine the different characteristics between males and females with a higher classification accuracy.[3]

Several approaches are used for shape analysis depending on the collection of coordinate data that can be used in forensic anthropology. The approaches include Euclidean distance matrix analysis and elliptic Fourier analysis. The elliptic Fourier analysis is uncommon nowadays, and several studies have been done to compare bias and errors of mean shape by geometric morphometric approaches such as Euclidean distance matrix analysis.[5] Generalized procrustes analysis is superior, and is the most widespread to other approaches. This is because it is the simplest and the best understoodand easily approach method with statistically and mathematically illustrations.[6]

Identification of human remains is very essential both in natural or unnatural disasters for reasons that many cases are radically mutilated, dismembered, and/or decomposed, which makes identification more complicated. The recognition of these remains is necessary for legal purposes. The data retrieved from the bones provides a beneficial information with regards to sex, ancestry, age at death, stature, manner and cause of death. This can narrow down the list of unknown remains, and assists in the identification of an individual.[7, 8]

Several studies have used crania for sexual dimorphism in many different populations. Determination of ancestry must be done before determining the sex as there are great variations in sexual dimorphism among different ancestries. For instance, sexual dimorphism and difference in size are highly significant between American blacks and American whites. In contrast, skeletal differences between Southeast Asians showed less sexual dimorphism and less size difference between males and females. Sometimes, a Southeast Asian male skeleton may be mistakenly identified as an American female skeleton.[9]

Variation between sexes in different populations with regards to human osseous nose is important in various scientific fields such as physical, evolutionary and forensic anthropology,[20] in which the palate is a significant sex indicator. The cranial base is the most durable part of the cranium, and is known to be sexually dimorphic.[42] There are classic osteological description variant of the skull, which include the nasal aperture, zygomatic bones, mandible, orbits, glabella, supraorbital ridges, mastoid process, forehead shape, palate and occipital region. The most common cranial measurements for sexual dimorphism included maximum length, maximum breadth, facial breadth, skull height, upper facial height and total facial height.[29] The aim of this study was to to determine the most sexually dimorphic parameters by geometric morphometric analysis of human skulls.

MATERIALS AND METHODS

The systematic review search protocol PRISMA was adopted in this research, which is illustrated in Figure 1.

Literature Review

A systematic review on the literature was conducted to identify relevant studies about the use of geometric morphometric analysis in sexual dimorphism of human crania. In order to conduct a comprehensive search of health science journals, Google Scholars (published between 2005 and July 2017) and PubMed (published between 2005 and 2017) were used. The search strategy involved a combination of two sets of key words i.e. geometric morphometrics and sexual dimorphism. These keywords were used because they can achieve and cover the articles related to the research question.

Selection of Research Articles

The results were limited to studies that were published in English language including the abstracts. The studies included for review were studies that addressed the application of geometric morphometric analysis in sexual dimorphism of human crania by using *3D* scan either computed tomography or laser scan. Review articles, news, letter, editorials or case studies were excluded from the review. Studies that used *2D* radiographs or *3D* images were excluded.

Data Extraction and Management

Papers were screened in three phases before being included in the review. In the first phase, papers that did not match the inclusion criteria were excluded, and it was mainly based on the title screening. In the second phase, abstracts of the leftover papers were screened, and papers that did not meet the inclusion criteria were excluded. In the final phase, the remaining papers were screened to exclude papers that did not focus on the scope of the literature. Duplicates were removed, and remaining papers were reviewed by three reviewers. There was appraisal to select the final five papers through discussion among two reviewers, and the third reviewer had agreed with the results of the two reviewers in selecting the final five papers. This was to ensure high quality of the selected papers.

After discussion between the reviewers, full papers that matched the inclusion criteria were chosen, and focus was made on the scope of the literature. In order to standardize the data collection, data extraction was performed independently with the use of a data collection form. The following data were recorded from the studies: (1) the title of the study and authors (2) a brief description of the sample/population of the study, (3) a short description of the methods used for the study, (4) the brief description of the results from the study, and (5) comments and conclusion from the study.

Inclusion and exclusion criteria

The inclusion criteria included the primary studies i.e. studies that are related to human and studies related to skull. The exclusion criteria were the review articles i.e. studies that are not related to human or studies not related to skull.

Results

Search Results

The literature search identified 54 potential relevant articles. Two reviewers independently assessed all articles for inclusion and exclusion criteria based onthe title and abstract. A total of 5 articles were retrieved for further assessment and data extraction. 49 articles were excluded because they did not focus on primary studies or because they were not related to crania and sexual dimorphism and geometric morphometrics or the studies did not meet the inclusion criteria. Differences of opinion between the reviewers regarding the inclusion or exclusion of the full articles were resolved by discussion. The remaining 5 articles fulfill all inclusion and exclusion criteria, and were included for the purpose of this review. A flow chart of the selection and paper processing including reasons for exclusion is shown in Figure 1.

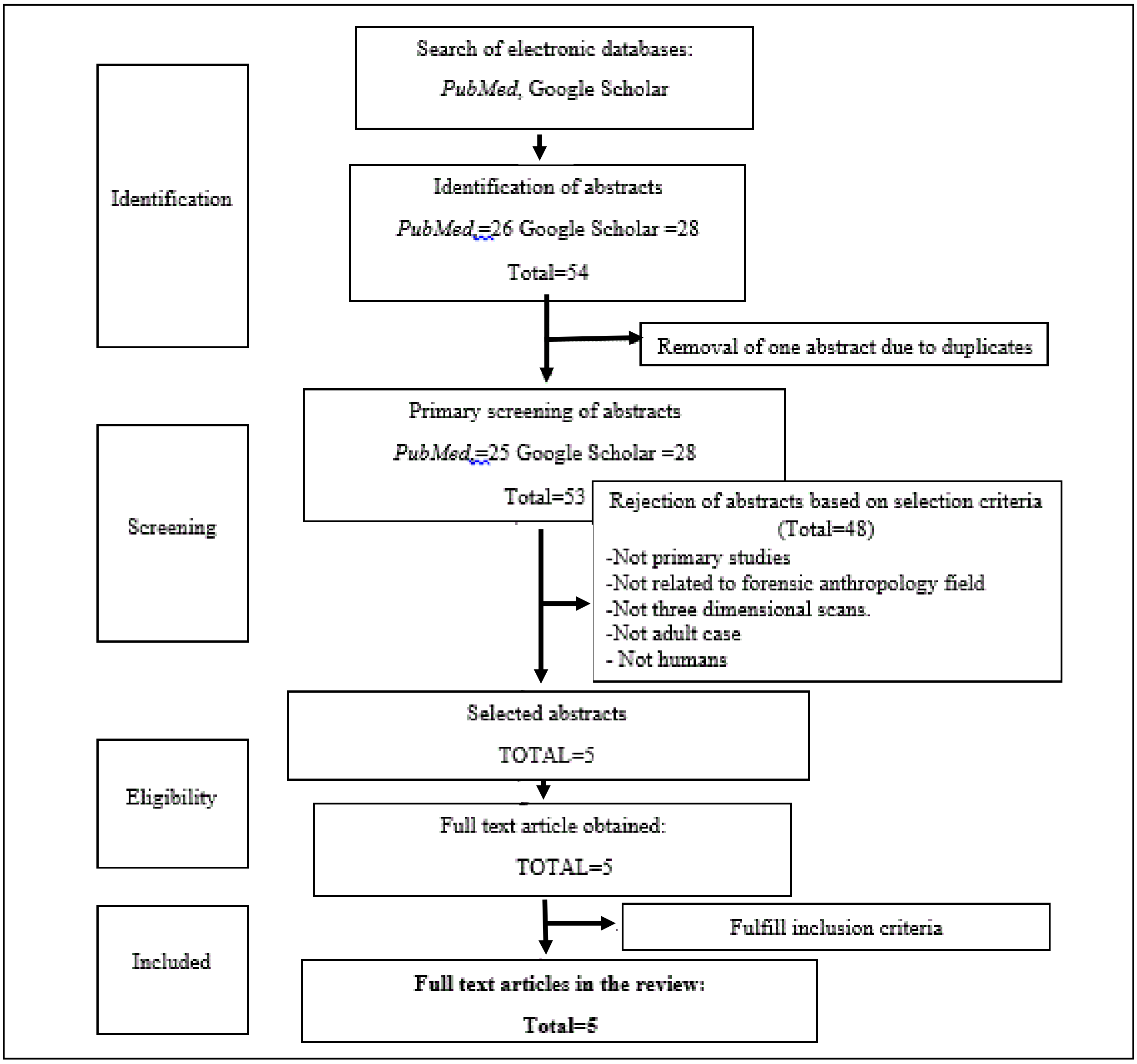

Figure 1 Flow chart to show selection process of articles in systematic review

Study Characteristics

A summary of characteristics of all studies is displayed in Table I. All studies were published between the years 2005 to 2017. Based on the used landmarks and regions of the crania, Ducker (2014) used 35 standard landmarks all over the craniofacial morphology.[13] Lesciotto*et al.* (2016) used 19 landmarks on lower and upper face to shape the prognathism.[14] Schlager and Rudell (2015) put 14 anatomical landmarks on triangular meshes of the bony nose.[20] Chovalopulou *et al.* (2013) used 30 landmarks on the outer surface of skull at palate and cranial base.[30] Chovalopulou *et al.* (2016) studied 31 landmarks on upper face, 10 landmarks on orbit and 8 landmarks on the nasal region.[32]

Data Analysis

Ducker (2014) used geometric morphometric methods for studying the cranial size and shape for sexual dimorphism in Hispanics in comparison with the American Blacks and American Whites. Ducker (2014) exhibited significant sex-specific differences in size among the population groups. Several areas of the cranium were sexually dimorphic, particularly in shape differences. The most sexually dimorphic areas in the cranium were posterior and superior vault shape, with some differences in the nasal and orbital areas in the American Black sample. However, in the Hispanic sample, the shape differences were mainly discovered in the vault, including the posterior, superior and lateral vault, as well as the basicranium and glabellar region. The midface (nasal, cheek and orbit areas) and the basicranium represented the most differences in the American White sample.

Chovalopulou et al. (2013) applied *3D* geometric morphometric method to assess sexual dimorphism in the palate and base of adult crania, where there was significant shape difference in males and females. In males, the cranial base is short, and the palate is deep and more elongated. Sex-specific shape differences for the cross-validated data gave better classification results in the cranial base (77.2 %) when compared to the palate (68.9 %). Size alone yielded better results for cranial base (82%) as oppose to the palate (63.1 %). The classification accuracy was improved when both size and shape were combined (90.4% for cranial base, and 74.8% for palate).

Lesciotto et al. (2016) performed geometric morphometrics to assess whether the gnathic index is a reliable indicator of subnasal prognathism, and explored the effects of sex, population, and allometry on this trait. Lesciotto et al. (2016) yielded that the gnathic index was significantly correlated with PCs 1 and 3, which appeared to capture prognathic shape change, but also with PCs 2 and 6, which reflected other craniofacial shape changes. Population difference in the level of prognathism were identified, but no significant effect of sex or allometry were found.

Schlager and Rudell (2015) compared shape differences in the osseous nose in a large sample of Chinese and Germans, modern male and female by focusing on the osseous tissue of the outer nose. The landmarks for different studies were shown in Table 2. Schlager revealed great variations in size between males and females. For symmetric variation, the area around the spina nasalis was slightly more pronounced in males, with females having an upward inclination, similar in both populations. The piriform aperture tended to be slightly narrower in males than females. For asymmetric variation, there was more asymmetry in males than females in both populations.

Chovalopulou et al. (2016) explored the most sexually dimorphic regions of cranium, upper-face, orbits and nasal by *3D* geometric morphometrics, and investigated the effectiveness of the method in determining sex from the shape of these regions. Chovalopulou et al. (2016) showed that there were shape differences between males and females in the upper-face and orbits. The upper-face region yielded the highest shape classification rate. Besides, the centroid size of orbital and craniofacial regions were greater in males than females. In addition, for the evaluation of sexual dimorphism, it was found that the size was significant in the upper-face region. The classification accuracy was improved when both size and shape were combined.

Table I. Characteristics of studies in this review.

Study 1	Population	Methodology	Results	Conclusion
Ducker (2014) Cranial sexual dimorphism in Hispanics using geometric morphometrics [13]	• 400 Hispanic crania (339 males + 61 females) • American Blacks (60 males + 15 females) • American Whites (250 males + 134 females)	• 35 landmarks by Microscribe 3D Digitizer.[10] • Analysis by MorphoJ 1.06.[11] • Procrustes analysis. MANOVA by SAS 9.3.[12] • Canonical variate analysis. Wireframe graphs.	Size • Hispanic males were smaller in centroid size from the American Black. • Negative difference between the means of Hispanic females and Hispanic males. Shape • Greater shape differences between sexes in the American Black in inferior and posterior vault shape with little distinctions at the nasal and orbital area. • Greater shape dimorphism for the American Black than the American White and Hispanic samples. • The Hispanic sample differed markedly in superior, posterior lateral vault, basicranium and glabellar region. • More robust glabellar region in males than females. • Greater Nasal height and orbit height in Hispanic males than females.	• Sexual shape dimorphism in the cranium was evident in the Hispanic sample mainly, in the vault, glabellar regions and basicranium. • The Hispanic sample showed the smallest level of sexual shape dimorphism when compared with the American Black and White samples.
Study 2	**Population**	**Methodology**	**Results**	**Conclusion**
Lesciotto *et al.* (2016) A morphometric analysis of prognathism and evaluation of the gnathic index in modern humans.[28]	• Nineteen craniofacial landmarks.[10] • Five population groups: US White, US Black, Portuguese, Nubian and Native American. • Total of 192 skulls (78 females + 114 males): • American Blacks (40 males + 29 females). • American Whites (27 males + 11 females). • Nubians (12 males + 12 females). • Portuguese (21 males + 19 females). • Native American (14 males + 7 females).	• 3D surface scans collected by a NextEngine Desktop Scanner (model 2020i).[15] • Osteological techniques and associated pelvic material were used for sexual dimorphism.[16, 17] • Generalized procrustes analysis by Morphologika software.[18, 19] • MANOVA was performed to estimate the effect of sex and ancestry on the cranial shape. • Posthoc Tukey's tests. Two-factor ANOVAs for sex and population • effects on the individual PCs. • Linear regression to evaluate the influence of allometry on prognathism. •	• The first six PCs accounted for 5% with a cumulation of 55% of the total variance. • PCs 1 and 3 were correlated with the gnathic index. • PC1 accounted for 17.2% of the total shape variations and represented the main prognathic shape change. • In positive PC1, prosthion and the entire maxillary region presented an anterior projection compared to the inferior nasal aperture. • PC1 accounted for 36% of the variance of gnathic index. • PC3 accounted for 15% of the variance of gnathic index. • PC2 and PC6 were significantly correlated with gnathic index. • Booth sex and population had a significant effect on shape by two-factor MANOVA test. • No relation between population and sex. • Native Americans was similar to the US Whites group, the US Blacks and Portuguese group. • The Nubian sample was significantly different from all the other groups. • Sex had significant correlation with all of the PC scores. • With respect to PC3, the US White male, pooled female and US White female samples showed evidence of allometry.	• Depending on gnathic index, it can only explain a small portion of the prognathic variation unless accompanied by the corresponding comparison of the crania themselves. • This morphometric analysis provided a preliminary step towards the investigation of prognathism, which indicated that sexual dimorphism has no relation with prognathism.

Study 3	Population	Methodology	Results	Conclusion
Schlager and Rudell (2015) Analysis of the human osseous nasal shape-population differences and sexual dimorphism.[20]	• 534 CT scans of the crania. The collected data were age, sex and different population (Chinese or German). - Germans (140 females + 127 males). - Chinese (135 females + 132 males).	• Triangular surface meshes by Voxim software. • Fourteen anatomical landmarks were collected. • Three curves were manually created at the surface by (IDAV) landmark software program. • One curve connects between nasion and rhinion along the ridge on the back of the nasal bones. • The other two curves connect the nariale, alare and nasomaxillare. • Nasomaxillare and alare were prone to inter- and intra-observer error testing,[21] • All analyses were achieved by the R-package Morpho.[22] generalized procrustes analysis (GPA) with object symmetry.[23-25] Procrustes ANOVA [24] was run to test statistical significance of fluctuating asymmetry. • Significance of group differences was assessed by using 50-50 MANOVA and permutation testing. Discriminant function analysis (DFA) was run to calculate the classification accuracy.	• Symmetric variation • The variance explained 32.4% of overall shape variation. • The overall accuracy was 97.2% with correct classification rate of 97.0% for Germans and 97.4% for Chinese. • The classification accuracy between-group was 93.8% for Germans and 96.1% for Chinese. • The strongest population-specific differences by thin-plate spline (TPS) were represented in the shape of the os nasale i.e. more projected in Germans. • The distance between maxillofrontale and nasion was much larger in Germans. • The spina nasalis was more prominent in Germans, with a similar inclination in both populations. • The shape of the apertura piriformis was more elongated in Germans compared to the more roundly-shaped and wider mean shape of the Chinese. • The saddle made up by the nasal bones was narrower in Chinese mean shape than in the German. • More forward pointing spina nasalis in the German with slightly forward-moved region around right and left nariale. • Asymmetric variation • Significant individual asymmetry within the German population. • Allometry for sexual dimorphism exhibited that females and males differed significantly in size. • ANOVA revealed that sex was the most important factor for centroid size variation, and explained 34.1% of its variance. • DFA determined the cross-validated sexing accuracy to be 72.7% in German sample, 69.1% in pooled sample and 72.3% in Chinese. Centroid size was strongly associated with sex.	• Significant shape differences between Chinese and German with a longer and slightly narrower piriform aperture in German, which were mainly induced by a steeper angle of the nasal bones at nasion. • Sexual dimorphism was significant, showing a narrower and protruding bony nose in males. • The use of a dense set of semi-landmarks allowed to visualize more shape features than simple metric measurements, and geometric. • Morphometrics was based on sparsely placed landmarks. • Leftward trend of the nasal bones for asymmetry. • Asymmetry was stronger in males in both populations when compared to females and stronger in the German sample than in the Chinese sample due to the more projected features among Germans.

Study 4	Population	Methodology	Results	Conclusion
Chovalopulou *et al.* (2013) Sex determination by 3D geometric morphometric of the palate and cranial base.[26]	Palate • Five landmarks from a sample of 103 crania (58 males, 45 females).[27] Cranial base • 25 landmarks from a sample of 167 individuals (89 males + 78 females).	•The 3D data were collected with a microscribe 3DX. •Generalized Procrustes Analysis. Procrustes coordinates were analyzed through Principal Component Analysis (PCA) utilizing Morphologika software.[32] •A Goodall's F test was run to examine the overall shape difference between the sexes.[40] •A permutation test (n = 1600) was performed to estimate the significance of the results achieved by the Goodall's F test. •Wire-frame models and thin-plate splines (TPS) were performed to illustrate the relevant shape variations.[26, 28] •Discriminant function analyses were done. •Logistic regression was applied to the optimal combination of the variables.	• Shape analysis of the palate • Significant Procrustes distance between males and females. • The first seven PCs described 99.2% of variation. • PC2 accounted for 27.5%, while PC6 accounted only 4.3% of the sample's diversity. • The classification accuracy of the original group was 68.9%. • The correlation between PCs and sex was 25.8 % by logistic regression. • Size analysis of the palate • The cut-off point of centroid size was 53.8 for males and 39.1 for females. • The classification accuracy of the original group was 72.4 % for males and 51.1 % for females. • The average weighted accuracy of 63.1 % for the entire sample. • Form (size and shape) analysis of the palate. • The first eight PCs described 99.43% of variation. • PC1 accounted for 39.7%, whereas PC7 accounted for 2.9% of the sample variation. • The size was insignificant. • Cross-validation was 68.9% for females and 79.3% for males. • The logistic regression analysis was 39.8%. • Cranial base; the procrustes distance between sexes was significant. • Shape analysis of the cranial base. • The first 15 PCs described 73.35% of variations. • Size analysis of the cranial base. • The cut-off point was 180.1 for female and 208.1 for males. The classification accuracy for the entire sample was 82%. • Form (size and shape) analysis of the cranial base. • The first ten PCs described 68.7% of variations. • PC1 accounts for 22.66 % of the sample variation. • The classification accuracy after cross-validation was 85.9% and 94.4% for females and males, respectively. • Logistic regression revealed 79.7 % correlation between sex and PCs.	• The 3D geometric morphometrics allows for accurate shape comparison of skeletal features. The present study demonstrated that discriminant • function analysis led to an accurate assignment of sex to accurately identify both shape and size differences between females and males cranium. In bioarchaeological and forensic examination, 3D GM is an essential tool for estimation of sex in the modern Greek populations.

Study 5	Population	Methodology	Results	Conclusion
Chovalopulou *et al*. (2016) Sex determination by 3D geometric morphometric of craniofacial form.[29]	• 31 landmarks • 176 crania from Athens Collection in • landmarks on the upper-face. • Eight landmarks on the nasal region. • Ten landmarks on the orbit region.[30,32]	• Microscribe 3DX. • A generalized procrustes analysis to calculate centroid size and shape difference between females and males.[40] • A permutation test. Both Goodall's F and the permutation tests were applied by simple 3D-IMP software.[33] • The TPS by Morphologika software -MorphoJ was used to create wireframe models.[11] • The Morphologika software was used to analyze the results of GPA through principal component analysis (PCA). [32] • Discriminant function analyses were run. • Logistic regression to estimate the correlation between independent (PCs) and dependent (sex) variables.	• Shape analysis of the upper-face • The Procrustes distance between female and male individuals was significant. • The first 15 PCs described 72.14% of variation. • By logistic regression, correlation between PCs and sex was 60.5%. • The classification accuracy for females and males was 81.8% and 84.3%, respectively. • Size analysis of the upper-face • The cut-off point was 234.9 for females and 277.8 for males. • The average classification accuracy for the entire sample was 76.5%. • Discriminant function analysis indicates that the size was relevant for sexual dimorphism in the upper-face region. • Shape analysis of the orbits • The procrustes distance was statistically significant • The first five PCs described 81.27% of variation. • Correlation between PCs and sex was 35.5% by logistic regression. • The classification accuracy for females and males was 70.4% and 74.4%, respectively. • Size analysis of the orbits • The cut-off point of the original group was 105.15 for females, and 129.6 for males. • The average classification accuracy for the entire sample was 72.7%. • Form analysis of the orbits • The first six described 86.42% of the variation. • By logistic regression, the correlation between PCs and sex was 57.4%. • The classification accuracy for females and males was 82.7%, and 83.3%, respectively. • Nasal region • Wireframe and Thin-Plate Spline. In the forehead region, all angles and distances were sexually dimorphic. • In zygomatic region, all angles showed significant differences between sexes, except for angle formed by frontomalare temporale, jugale and zygotemporale superior. • At the orbits, all angles were sexually dimorphic, except for the angle formed by supraconchion maxillofrontale and frontomalare orbitale. • In the nasal region, all distances and angles were sexually dimorphic. • The shape of the nasal region was not sexually dimorphic.	• The shape of the orbits and upper face proved to be good for sexual dimorphism. • The nasal region was not sexually dimorphic. • The orbital region was unreliable and inaccurate for sexual dimorphism due to its lower classification rate. • The craniofacial shape showed a good indicator for sexual dimorphism.

Lesciotto et al. (2016) addressed the variations in the prognathism by *3D* geometric morphometric analysis of craniofacial landmarks, and compared the results with morphometric features provided by the gnathic index.[14] Moreover, they studied the differences in prognathism between sexes throughout different populations, which included the effects of size on the prognathic shape. It was proven that the gnathic index was not correlated with subnasal prognathism. However, the study also proved that the gnathic index was correlated with the changes in the height of cranial vault, and facial height or cranial flexion between the two regions, which is not anadequate measure for prognathism.[4,29]

The inferior and posterior vault shape represented the greatest shape differences between sexes in the American Black. However, the nasal and the orbital area represented the latest distinctions. The superior, posterior, lateral vault, basicranium and glabellar region exhibited the highest sexual dimorphism in the Hispanic sample. There was greater nasal height, orbital height and more robust glabellar region in males than females in Hispanic.[13] In the Germans, the strongest population-specific differences by thin-plate spline (TPS) were represented by the os nasale shape, which was more projected. The distance between maxillofrontale and nasion was larger. The spina nasalis was more prominent, with similar inclination in both populations.

In addition, the shape of apertura piriformis was more elongated in the Germans in comparison to the more roundly-shaped and wider in the Chinese. The saddle made up by the nasal bones was narrower in its mean shape in the Chinese than Germans. More forward-pointing spina nasalis with slightly forward-moved region around the right and left nariale were revealed in the Germans.[20] However, the angle defined by the landmarks i.e. left foraminolaterale, opisthion and right foraminolaterale were greater in males.[26] Significant shape differences of the palate between male and female groups were explained by wire frames, lollipop graphs and thin plate spline transformation grids. The angle defined by the landmarks i.e. infraorbitale, infratemporale and ovale mediale for both left and right sides were greater in female. The positive findings were determined by Schlager and Rudell (2015) who showed 97% classification accuracy.[20] Besides, Chovalopulou et al. (2013) yielded 72% classification accuracy,[26] and revealed 81.8% and 84.3% classification accuracy in females and males, respectively.[29]

Schlager and Rudell (2015) compared the variations on nose shape in the Germans and Chinese of both sexes by *3D* geometric morphometric analysis on osseous tissue of the outer nose by utilizing the anatomical landmarks and semilandmarks. They investigated the discriminatory power of sexual dimorphism and the variations in population-specific shape concerning the bony nose on Chinese and German samples. Moreover, they also studied the relation between asymmetry and projected nose in Germans. The modes of variation can provide the baseline data on variation that are present in specific group population.[20]

Chovalopulou *et al.* (2013) suggested that application of distinct numbers of morphological features of the crania leads to a higher classification accuracy and better sexual dimorphism.[26] Chovalopulou *et al.* (2016) examined the most common sexual dimorphic skull traits namely,forehead shape, orbits, nasal aperture, zygomatic bones and glabella to estimate their reliability for sexual dimorphism.[29] Moreover, they are useful components for determination of sex from skeletal remains in Greek population. They studied the validity and workability of geometric morphometric tools for estimation of sex.

Size and Sexual Dimorphism

Duecker (2014) compared the centroid sizes of each group by sex and proved that the size of analyzed Hispanic crania differed significantly from the size of the cranium of the American Black and American White populations.[13] It was shown that the size of the crania of American Blacks were more sexually dimorphic than the American Whites and Hispanics.[34]

Earlier studies have proven that the size of the palate was a sexually dimorphic character. Larnach (1966) studied the Coastal New South Wales series, Macintosh (1970) studied the Queensland series, while Woo (1949) studied a large population of Native Americans (American Indians), American Whites, Blacks (Negroes), Central Asians (Mongolians) and Inuit (Eskimo). All the researchers proved that the palate was greater in males.[26] Sumati and Phatak (2012) utilized metric measurements for the palate of the North-Indian population, and showed that the classification accuracy according to size was 70%, in which the palate was greater in males, a trend that was supported by Chovalopulou *et al.* (2013).[35]

Chovalopulou *et al.* (2013) showed that female individuals in Greek population exhibited a higher classification accuracy rate of size analysis. López *et al.* (2009) estimated sex through the size of the piriform aperture, and its correlation with Brazilian skin color.[38] The upper and lower width and the height of the piriform aperture were measured using digital calipers. It was concluded that only the piriform aperture height was significantly higher in all the male groups.

Allometry

Lesciotto *et al.* (2016) studied allometry that represented the effect of size on shape, and the results showed no significant effect on prognathism, which was proven by the absence of correlation between centroid size and PC1, but reflected the highest prognathic variation. PC1 and PC3 gave a better capture for prognathic shape changes. PC1 and PC3 were not markedly correlated with the centroid size. In contrast, the length of facial skeleton showed a significant correlation with centroid size. They included bregma in the study for reasons that it may bea cause for correlation or a lack of correlation with centroid size.[14] However, cranial height has a high effect on the centroid size between individuals with differing basion-bregma heights. In contrast, Rosas and Bastir (2002) included bregma in the study of allometry in craniofacial complex, and documented that the effect of size variation leads to increase in subnasal prognathism.[37] This discrepancy between Lesciotto *et al.* (2016) and Rosas and Bastir (2002) may be attributed to the use of primary broad range facial landmarks including cranial base, posterior vault in Lesciotto *et al.* (2016), and mandible by Rosas and Bastir (2002). The second possibility is probably the presence of non linear correlation between size and some PC shape scores.[14,37]

Shape Variations and Sexual Dimorphism between Populations

Schlager and Rudell (2015) had documented excellent classification between population shape variations in bony nose between Chinese and German populations.[20] The shape differences in nasal region might be attributed to climate factor that matched with previous studies. The smaller and more rounded nasal opening in the Chinese sample matched with warm and/or humid populations, whereas the larger and narrower nasal opening observed in the German population confirmed the shape found for populations living in cold and/or dry climates.[38,39]

Also, Schlager and Rudell (2015) exhibited that males had more upward pointing nasal bones than females.[20] On lateral view, the lower part of male nasal bones exhibited a slightly more convex shape. The piriform aperture appears to be slightly wider in females than in males. The piriform aperture tends to be elongated that is supported by the spina nasalis, which points more upwards in females. These shape variations proved greater nasal cavities in males that confirm previous studies on sexual dimorphism, which showed that males exhibit larger cranial airways due to increased airflow demands caused by higher-energy expenditure. It was also stated that nasal height is a clear indicator for sex, while nasal breadth shows a weak discrimination between sexes by using linear measurements. These results matched with those in the literature.[20,40]

Additionally, Schlager and Rudell (2015) studied the relevant population particularly, sexual dimorphism concerning symmetric shape component. The variations in particular shape features are the cause for population specific sexual dimorphism. In the Chinese sample, the angle of spina nasalis was sexually dimorphic than in the German sample. Moreover, protrusion of nasal bones when compared between sexes, German male nasal bones were found to be more protruding than females. After visualization, it appeared to be subtle due to its small angle, which was consistent with previous study by Bastir *et al.* (2011).[20,40]

Chovalopulou *et al.* (2013) suggested that using distinctive numbers of morphological features of crania led to successful identification of sex with a high level of classification accuracy. Chovalopulou *et al.* (2013) proved that arch width and arch depth of palate were good sexual discriminators,[26] Gapert *et al.* (2009) investigated the accuracy of foramen magnum in the estimation of sex in a sample of 158 (82 males/76 females) British adults.[41] The classification accuracy rate was 70.3% for males and 69.7% for females. Chovalopulou *et al.* (2013) documented a higher classification accuracy than Gapert *et al.* (2009).[26] This may be attributed to the fact that Chovalopulou *et al.* (2013) had combined a great number of cranial landmarks to determine sex, which matched with the study by Holland (1986), who also found a high level of classification accuracy in sexual dimorphism (up to 91%) by using linear discriminant function analysis on nine measurements from the cranial base on 100 crania derived from the Terry's collection.[42]

Chovalopulou *et al.* (2013) also indicated that male individuals in Greek population exhibited a higher classification accuracy rate independent of either form or shape analysis.[26] According to Chovalopulou *et al.* (2016), the upper-face shape analysis was a significant method for estimation of sex.[29] Nevertheless, there was a disagreement with Hennessy & Stringer (2002), who indicated no sexual dimorphism in the crania, which may be attributed to the small number of landmarks used.[43]

Chovalopulou *et al.* (2016) indicated that analysis of orbital region by shape was inaccurate for determination of sexual dimorphism.[29] While Bigoni *et al.* (2010) were agreeable with Chovalopulou *et al.* (2016). Lidstone (2011) was in disagreement.[29, 31,44] In contrast to Chovalopulou *et al.* (2016), Bigoni *et al.* (2010) documented a significant sexual dimorphism in the nasal region by utilizing nine landmarks. Besides, the classification accuracy for sexual dimorphism of the nasal region had achieved to about 77%.[31]

Strength and Limitation of the Review

The *3D* scan geometric morphometric analysis of human skull had shown promising results in terms of sexual dimorphism. The present search identified five research articles that were included in this review, and to the best of our knowledge, this is the most relevant critical review that focuses on the use of *3D* scan geometric morphometric analysis of human skull.

The review comprised cranial bones in order to give a good focus on the most recent and reliable classification accuracy of landmarking of the crania for sexual dimorphism. In one study, combinations of three regions of cranial bones were used to determine sex in human crania. The sample size was large enough for a highly accurate result with the sample size comprised 103 crania by Chovalopulou *et al.* (2013) for palate measurements.[26] Different populations with distinctive numbers of landmarks were included. Some authors used wide and extensive number of landmarks, while others used limited numbers, which resulted in good variations of the obtained results. Several limitations were identified in this review. Firstly, the postcranial bones were excluded. Although the review included Asian, Hispanic, Americans and Caucasian, it lacked the details of other ancestries. Different age groups were not done in these studies, and classification according to age groups is important in minimizing the pool of identification.

Table 2: The landmarks used in the studies.

The study	The landmarks
Ducker (2014) Cranial sexual dimorphism in Hispanics using geometric morphometrics [13]	Alare, Glabella, Parietal Subtense Point, Rt and Lt Asterion, Lambda, Rt and Lt Porion, Basion, Metopion, Prosthion, Bregma, Nasion, Rt and Lt Frontotemporale, Rt and Lt Dacryon, Rt and Lt Inf Nasal Border, Cheek Height Inferior, Cheek Height Superior, Rt and Lt Ectoconchion, Occipital Subtense Point, Rt and Lt Eurion, Opisthocranion, Rt and Lt Nasomaxillary Suture Pinch Point, Rt and Lt Frontomalare Ant, Opisthion, Rt and Lt Zygion.
Lesciotto *et al.* (2016) A morphometric analysis of prognathism and evaluation of the gnathic index in modern humans.[28]	Bregma, Nasion, Dacryon, Frontomalare Tempolare, Infraorbital Foramen, Alare, Inferior Nasal Border, Prosthion, Posterior Canine, Posterior M2, Soturion, Basion.
Schlager and Rudell (2015) Analysis of the human osseous nasal shape-population differences and sexual dimorphism.[20]	Nasospinale, Subspinale, Nariale, Nasomaxillary Frontale, Maxillofrontale, Nasion, Alare, Nasomaxillare, Nasion, Alare, Nasomaxillare and Rhinion.
Chovalopulou *et al.* (2013) Sex determination by 3D geometric morphometric of the palate and cranial base.[26]	Opisthion, Basion, Rt and Lt Foraminolaterale, Rt and Lt Occipitocondylion Mediale, Rt and Lt Occipitocondylion Posterior, Rt and Lt Occipitocondylion Laterale, Rt and Lt Occipitocondylion Anterior, Rt and Lt Caroticum Mediale, Rt and Lt Spinale, Rt and Lt Ovale Mediale, Hormion, Rt and Lt Infratemporale, Rt and Lt Mastoidale, Infraorbitale, Rt and Lt Postalverion, Staphylion, Staurion and Foramen Incisivum.
Chovalopulou *et al.* (2016) Sex determination by 3D geometric morphometric of craniofacial form.[29]	Infraorbitale, Nasion, Glabella, Frontotemporale, Zygotemporale Superior, Jugale, Frontomalare Temporale, Zygotemporale Inferior, Zygomaxillare, Frontomalare Orbitale, Supraconchion, Maxillofrontale, Subconchion, Ectoconchion, Apertion, Nasospinale and Maxillonasofrontale.

Recommendations

Using *3D* techniques in geometric morphometric analysis, yields a higher sexual classification accuracy compared to other morphometric techniques. Using extensive numbers of landmarks in different regions of the crania will result in good classification accuracy for sexual dimorphism. Other studies, which include postcranial bones are highly recommended for better overview of the most recent and reliable sexually dimorphic bones. Inclusion of different age groups is recommended to study the effect of age-group variations for sexual dimorphism. More studies by *3D* scan are recommended for identification ofunknown human remains by using different and new anthropological methods.

CONCLUSION

By *3D* scan for geometric morphometrics, differences in the areas of cranium can now be estimated with high accuracy. The crania, being the most sexually dimorphic bone in both shape and size, it can be used for examination of forensic and bioarchaeological remains. Besides, *3D* geometric morphometrics yields higher correct-classification results compared to other morphometric techniques. Moreover, utilization of combined size and shape analysis throughout particular selection of landmarks has proven to produce a significantly high rate of sex classification accuracy. The use of an extensive set of semi landmarks will facilitate the analysis and visualization of hidden shape characters that highly extend the accuracy of geometric morphometrics based on barely placed landmarks and simple metric measurements. Sometimes, sexual dimorphism becomes more significant by removal of effect of size variations between sexes. Finally, further studies are required to validate the best methods for variable types of postcranial bones with a more advanced meta-analysis of results, which will enable accurate shape comparison of the skeletal bone characters.

Conflict Of Interest

The authors confirmed that this article and its content has no conflicting interest.

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