ORIGINAL ARTICLE

Two-Dimensional Geometric Morphometric Method on Frontal Sinus for Race Estimation: A Lateral Skull Radiograph Study

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ABSTRACT

Introduction: Race estimation of unknown individual is essential in forensic investigation. The resiliency of frontal sinus makes it a potential tool for biological profiling, particularly in cases where fragmented skeleton persists. Geometric morphometrics is an efficient way to characterise shape. However, the use of frontal sinus to identify race of Malaysians is yet to be investigated. This research employed a two-dimensional (2D) geometric morphometric to examine the morphological differences of the frontal sinus among the major races in Malaysia. **Methods:** Lateral skull radiographs which comprising of 453 adult Malaysian (151 Malays, Chinese and Indian respectively) were used. The 2D landmarks of eight were placed on the digitalized radiographs and 2D geometric morphometric analysis was performed using MorphoJ software. **Results:** Procrustes ANOVA revealed a significantly different frontal sinus shape (p-value < 0.05) between races. Canonical variate analysis showed significantly different frontal sinus morphology (p-value < 0.05) between Malay and Indian as well as Chinese and Indian. Discriminant function analysis with cross-validation demonstrated a 57.4% accuracy rate. **Conclusion:** This population-specific study based on frontal sinus of Malaysians using the 2D geometric morphometric, though less reliable, sheds new light on the potential applicability of this method for race estimation purpose.
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Keywords: Forensic identification, Frontal sinus, Malaysian population, Race estimation, Two-dimensional geometric morphometric

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INTRODUCTION

Forensic anthropology is concerned with evaluation of human skeletal remains. It allows forensic anthropologists to obtain significant biological data and categorise bones based on various biological profiles, such as age, sex, race, and stature (1, 2, 3). Identification is an important step in determining the identity of unknown decedents when visual inspection such as facial recognition and fingerprinting is not possible (4). Correct identification of biological profile is crucial to narrowing the identity search of unknown individuals (5). Race identification is one of the vital biological components to be established in order for investigators to reach accurate identity of the deceased (5, 6).

The application of the term race and ancestry has always been a heated topic of debate in the field of forensic anthropology. However, Malaysia known as a multiracial country is predominantly defined by three major races: Malays, Chinese, and Indians (7). Thus, the term race has been a salient identity marker to differentiate the population groups that exist in the Malaysian population instead of the term ancestry. This term is used not only in official government webpages but has also been widely used in the literature of various fields including forensic anthropology (6, 8, 9, 10). Therefore, since the study focuses on the Malaysian population alone, the term race will be used in this article. Nevertheless, as the terms race and ancestry are used interchangeably in many places in the literature, thus, when the term 'ancestry' is used in the literature that is being discussed, this term is used instead of the race.

Conventionally, the linear measurement method is used to evaluate the morphological differences of skeletal remains between individuals. This method relies primarily on linear measurement of quantitative variables such as length, width, and height using callipers (11). However, linear measurement technique is highly inconsistent as measurement points are changeable depending on the observer's point of view, leading to measurement errors affecting the reliability and validity of skeletal measurement (12, 13). Moreover, linear measurement disregards information regarding the skeletal shape and requires intact bones, which can be challenging to obtain during forensic investigations (14, 16). Contrarily, the two-dimensional (2D) geometric morphometric method presents a more efficient alternative as it uses the landmark-based approach that enhances reliability (17). Besides, this approach maintains the geometric data of the bone throughout the analysis process, enabling visual representation of shape variations (14).

Several studies have utilized different skeletal elements to aid forensic investigations, such as the cranium, which has provided robust racial evidence for identification purposes (5). Nevertheless, mass fatality or destruction incidents can cause fragmentation or loss of skeletal parts, making identification a more challenging process (18, 19). Hence, exploring other regions of the skeleton may offer alternative and corroborative methods for forensic identification (6).

The frontal sinus can serve as a valuable tool for biological profiling, as its distinct pattern plays a crucial role in forensic identification (20, 21). Similar to fingerprints, each individual has a unique frontal sinus pattern, including identical twins. (22). Additionally, the occasional absence of one or both sides of the frontal sinuses is regarded as another significant morphological characteristic that to establish a definite and reliable biological profile (23). As an internal body structure, the arched feature of the frontal bone shields the frontal sinus from decomposition and damage, ensuring its preservation and intactness in human skeletal remains (24). Moreover, the frontal sinus anatomy remains constant throughout life after completion of growth at the age of 20 years old (25, 26). Therefore, frontal sinus may be a suitable structure to be considered for forensic identification.

Racial estimation remains a vital aspect in anthropological research (6). This field grapples with identifying human remains in diverse cases, necessitating a robust biological profile, including race, to establish identities accurately (5, 6). Preceding studies in relation to frontal sinus and biological profiling have been conducted (2, 19, 20, 27). However, there are limited studies evaluating the reliability of using frontal sinus for race identification (2, 28). By contrast, more studies have been conducted using frontal sinus for sex identification rather than race (19, 27, 29, 30). Previous study on frontal sinus for race estimation relied on linear distance measurement (2). For instance, a study on the New Mexican population using linear measurement methods on frontal sinus to evaluate the correlation between racial dimorphism and the frontal sinus size (2). Despite the significance of frontal sinus in forensic setting, studies applying geometric morphometric analysis on frontal sinus is scarce (27).

To our best knowledge, there has been no prior investigation into the potential utilisation of frontal sinus in biological profiling of Malaysian population, especially for race identification. Considering the importance of frontal sinus characteristic in forensic investigation, it is reasonable to create a new technique for determining race profile in the Malaysian population using frontal sinus. The vast database of Malaysian adults, which uses the 2D geometric morphometric method on lateral skull radiographs to analyse the frontal sinus, can be leveraged to aid forensic personnel. The validation of frontal sinus racial dimorphism in different populations, including Malaysia, can enhance the applicability of this method in identifying unknown individuals. This study aimed to evaluate the potential utility of the frontal sinus for race identification of Malay, Chinese and Indian racial groups among the Malaysian population using 2D geometric morphometric method.

MATERIALS AND METHODS

Study design and place

This inferential, cross-sectional study was carried out using lateral skull radiographs collected from University Malaya Medical Centre (UMMC) between 2015 and 2021 (31). The study population consisted of individuals with documented race.

Ethical permission

The study was conducted with an ethical approval of Medical Research Ethics Committee, UMMC (Ethics Number: 2022119-10937).

Study population

This study estimated the necessary sample size using sample size determination method of two independent means formula, with the power of the test at 80%, margin error at 5% and confidence level at 95%, after consulting with medical statistician. Probability systematic random sampling method were used by selecting every 5th sample from the data list. The study included 453 lateral skull radiographs, comprising 228 males and 225 females, which were collected based on racial subgroups in Malaysia. The racial subgroups included Malays (n=151), Chinese (n=151), and Indians (n=151). The three racial groups studied, are the major race groups in Malaysia, make up 89.6% of the population, and could collectively represent the Malaysian population (32). The selected subjects were within age range of 20 to 79 years old encompassing the adult population in Malaysia, which generally starts at 19 years old (33). This age range of 20 to 79 years old was determined taking into consideration the completion of frontal sinus growth at around 20 years (34) and following the age range from previous research (31).

Data collection

The data used in this study was lateral skull radiographs retrieved retrospectively from the Picture Archiving Communication System (PACS) at the Department of Biomedical Imaging in UMMC (31). The lateral view of the skull was used due to the unique nature of the frontal sinus morphology (35). Geometric morphometric analysis requires application of homologous landmarks on anatomical features of the studied samples (1, 13). However, establishing homologous landmarks of the frontal sinus on the antero-posterior view between each studied samples are challenging due to the high variation of frontal sinus patterns from one sample to another (35). Homologous landmark of the frontal sinus can be obtained from its lateral view as demonstrated in a previous study that yielded significant results for the application of geometric morphometric analysis on the lateral view of the frontal sinus for sex estimation among Malaysians (31).

The race, age and sex of the subjects were obtained from the patient's medical records. This study included radiographs of good quality without any sinonasal pathology and excluded radiographs of subjects with a history of clinical characteristics of bone diseases, maxillofacial trauma, non-Malaysian and those with absence of frontal sinus after being reviewed by a radiologist (31).The TpsDig2 software (version 2.31) was utilized to apply landmarks, while data analysis was performed using GraphPad Prism and MorphoJ (version 1.06d) software (31). Additionally, other software such as Excel, Inkscape, and Notepad++ were used for data management (31).

Landmarking application

The morphology of the frontal sinus was analysed using the landmark-based geometric morphometric method. Eight 2D landmarks were applied on the lateral skull radiographs using TPS Dig2 software (version 2.31), to outline the frontal sinus morphology (31). The landmarks used were adapted from previous studies (27, 36) and included several new landmarks (type III landmarks) to better outline the frontal sinus morphology. Table I and Fig. 1 presented the description and visualisation of landmark points on the lateral skull radiographs.

Table I: Frontal sinus landmark point description on lateral skull radiograph

Landmark	Type	Description
1	Type II	The highest point of frontal sinus on the posterior wall of frontal sinus
2	Type I	Glabella –The most anterior point in midsagittal plane between the superciliary arches
3	Type I	Nasion – The most anterior point on the frontonasal suture in midsagittal plane
4	Type II	The lowest point of frontal sinus on the posterior wall of frontal sinus
5	Type III	Midpoint between landmark 1 and landmark 2
6	Type III	Midpoint between landmark 2 and landmark 3
7	Type III	Midpoint between landmark 3 and landmark 4
8	Type III	Midpoint between landmark 4 and landmark 1

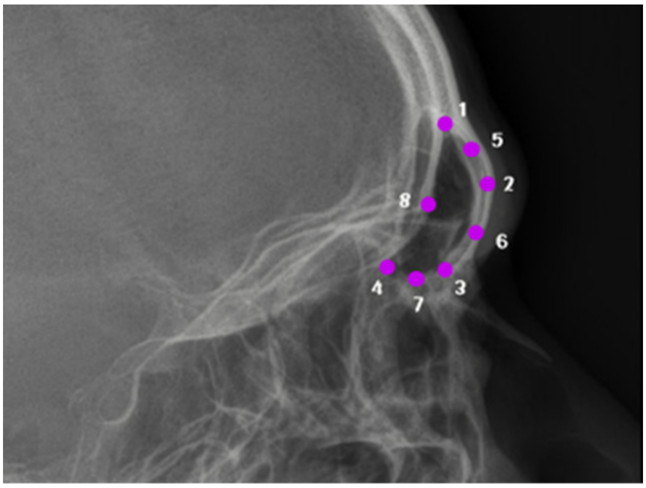

Figure 1: Map of eight landmarks of frontal sinus applied on lateral skull radiographs.

Intra- and inter-observer analysis

To ensure the accuracy and reliability of the landmark-based geometric morphometric method used in this study, both intra- and inter-observer error analyses were performed. The author of the study manually plotted the landmarks on 40 random lateral skull radiographs, and repeated the measurements after two weeks to assess the intra-observer error (31). Forty samples were used for intra- and inter-observer analysis, after consulting with medical statistician and with reference from other study (31). Calibration was conducted with an expert prior to the landmarking. The normality of the data was tested, confirming normal distribution. The Paired T-test was used to evaluate the landmarks that were applied twice by the same observer (6). For inter-observer error analysis, two independent observers performed the measurements, and the landmarks they applied were evaluated using Independent T-test (6). These analyses were conducted to ensure that the data collected were consistent and reliable.

Statistical analysis

2D geometric morphometric analysis was conducted via Morpho J software (version 1.06d). Procrustes ANOVA was used to examine the differences in centroid size and shape among Malay, Chinese and Indian (31).

Additionally, Canonical Variate Analysis (CVA) was conducted to assess variations between each different racial groups (6). CVA involves generating canonical variates (CV) through scaling and rotating the centres and calculating the Mahalanobis distance between groups based on sample centroids (38). Discriminant Function Analysis (DFA) was used to determine the classification accuracy (31, 39). It evaluate the degree to which groups can be accurately classified based on their differences from each other (6).

RESULTS

Intra- and inter-observer analysis

No significant differences (p-value > 0.05) were observed for intra-observer analysis, indicating that the landmarks were applied consistently by the same observer (Table II). There were also no significant differences for the inter-observer analysis, indicating consistent application of landmarks by two different observers (Table II).

Table II: Intra-observer and inter-observer error analysis

Landmarks	Intra-Observer Analysis	Inter-Observer Analysis
	p-value	*p*-value
Landmark 1	0.73	0.08
Landmark 2	0.83	0.90
Landmark 3	0.95	0.72
Landmark 4	0.74	0.05
Landmark 5	0.66	0.49
Landmark 6	0.90	0.65
Landmark 7	0.67	0.25
Landmark 8	0.73	0.62

**p*-value>0.05 is no significant different

Procrustes ANOVA

The shape of the frontal sinus was found to have a significant difference (p-value < 0.05), with Goodall's F statistic (F) showing a variation range of F=1.77 (Table III). In contrast, there was no significant difference in the centroid size of the frontal sinus between Malay, Chinese and Indian group (p-value > 0.05, F=0.49). F value indicated a higher variation in the shape of the frontal sinus compared to the centroid size.

Canonical variate analysis

In this study, CVA was employed to compare different races, and the results showed that some races had little to no overlap, with the largest separation observed between Chinese and Indians (Fig. 2).

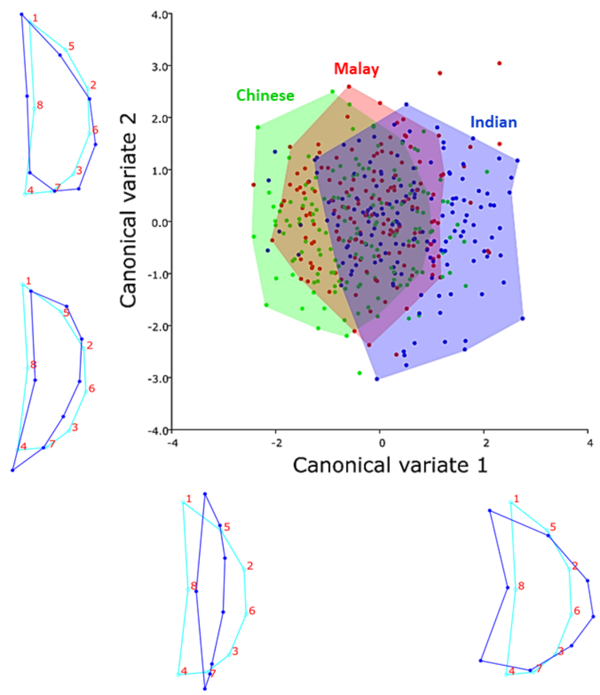

Figure 2: Scatter plot of frontal sinus shape from CVA analysis for race. Malay group represented by red-filled region, Chinese group by green-filled region and Indian group by blue-filled region. The wireframe diagrams illustrating the shape changes corresponding to scores of -4 and 4 for CV1 and CV2.

Wireframe diagrams were used to compare the mean shape in the positive and negative directions, with a scaling factor ranging from -4 to 4 for CV1 and CV2 (Fig. 2). The frontal sinus shape in the positive direction of the x-axis appeared shorter and wider than the average shape. Indians tended the most towards this variation, followed by Malays and Chinese. Contrarily, the negative x-axis direction showed a longer and narrower frontal sinus shape than the mean shape. Chinese showed a greater deviation towards the negative direction than the Malays and Indians. The shape changes in relation to the y-axis were clearly seen on the highest and lowest point of the frontal sinus. The positive direction in the y-axis showed a narrower and superiorly deviated highest point of frontal sinus than the average shape. Malays and Chinese were prone to this deviation compared to Indians. The negative direction in the y-axis represented a narrower and inferiorly deviated lowest point of the frontal sinus than the mean shape. The Indians distributed more in the negative direction on the y-axis than the Malays and Chinese.

Table III: Procrustes ANOVA of centroid size and shape of frontal sinus for race

Effect	SS	SS%	MS	df	F	*p*-value
Centroid Size	1306.16	0.37	653.08	2	0.49	0.6256
Shape	0.3694	2.91	0.0154	24	1.77	< 0.0001*

SS-Sum of Squares, MS-Mean Squares, df-Degree of freedom, F-Goodall's statistic
**p*-value<0.05 is significant

The Mahalanobis distance (MD) is a statistical measure of the distance between a point and a distribution. It quantifies the standard deviations that a point is away from the mean of a distribution. A larger distance indicates a greater deviation between a sample and a distribution. The significant differences between races were only seen between Malay and Indians, and Chinese and Indians, with p-value < 0.05 (Table IV). The greatest MD was noted between the Chinese and Indian populations, with MD = 0.9233. The lowest MD was seen between Malay and Chinese, with MD = 0.4041.

The Procrustes Distance (PD) provides information on the difference in average shape between different racial groups. The PD results of the study showed that there were significant differences in the shape of the frontal sinus between racial groups. Specifically, there were significant differences between Malays and Indians, as well as between Chinese and Indians (p-value < 0.05), as indicated in Table IV. Among these comparisons, the PD between Chinese and Indians was found to be the largest, with a value of 0.0669. This was followed by the distances between Malays and Indians, with a value of 0.0462, and Malays and Chinese, with a value of 0.0270.

Table IV: Mahalanobis and Procrustes distance of race groups

	Mahalanobis Distance		Procrustes Distance	
	Malay	**Chinese**	**Malay**	**Chinese**
Chinese	0.4041 (0.3977)	-	0.0270 (0.0889)	-
Indian	0.7242 (0.0002)*	0.9233 (<0.0001) *	0.0462 (0.0016) *	0.0669 (<0.0001) *

**p*-value<0.05, is significant

Discriminant function analysis

DFA results between Malay and Chinese (Table V) found that 60.0% of Malays were correctly classified into the Malay group, and 58.9% of Chinese were correctly assigned into the Chinese group. Yet, the average percentage after cross validation is 50% of Malays and Chinese were correctly classified into their respective groups. DFA results between Malay and Indian (Table V) demonstrated that frontal sinus could be correctly classified into Malay and Indian groups with 62.9% classification accuracy for both groups and after cross validation, the average percentage accuracy was found to be 60.6%. Meanwhile, according to DFA results between Chinese and Indian (Table V), frontal sinus can be classified accurately according to Chinese and Indian groups with 65.6% for both races, and after cross validation, the average percentage seen was 61.6%.

Overall, the result showed that frontal sinus shape has a race classification accuracy of 57.4%. The classification accuracy was highest between Chinese and Indian (61.6%), followed by Malay and Indian (60.6%), meanwhile the least accurate was between Malay and Chinese (50.0%).

DISCUSSION

Ancestry or race identification is one of the four basic components of forensic anthropological investigations and is considered population-specific (5, 6). Race estimation relies on the assessment of morphological and metric features of human skeletal remains that are indicative of their genetic and geographical origin (6).

Table V: Discriminant function analysis with cross validation for race groups: Malay and Chinese, Malay and Indian, Chinese and Indian

	Malay		Chinese		Total	Original (%)	Cross Validation (%)
	Original	**Cross Validation**	**Original**	**Cross Validation**			
Malay	86	73	65	78	151	60.0	48.3
Chinese	62	73	89	78	151	58.9	51.7
		Average (%)				59.5	50.0

	Malay		Indian		Total	Original (%)	Cross Validation (%)
	Original	**Cross Validation**	**Original**	**Cross Validation**			
Malay	95	92	56	59	151	62.9	60.9
Indian	56	60	95	91	151	62.9	60.3
		Average (%)				62.9	60.6

	Chinese		Indian		Total	Original (%)	Cross Validation (%)
	Original	**Cross Validation**	**Origina**	**Cross Validation**			
Chinese	99	94	52	57	151	65.6	62.3
Indian	52	59	99	92	151	65.6	60.9
		Average (%)				65.6	61.6

The skull is considered to be the most useful part of the skeleton for ancestry identification, specifically the facial region which is considered the most indicative of variation between different geographic locations (14). Frontal sinus a part of the facial region, may contribute to differences in morphology among Malaysians. Our study showed that morphology of the frontal sinus is significantly different amongst the three races in Malaysia which are Malay, Chinese and Indian.

The results of Procrustes ANOVA indicate that there is no significant variation in the centroid size of the frontal sinus across the different racial groups in Malaysia. This means that race does not have a significant impact on the size of the frontal sinus in this population. A study on the New Mexican population demonstrated a significant frontal sinus size difference between Black and White individuals using the linear measurement method, with Black individuals possessing a greater frontal sinus size than White individuals (2). However, no reasons were stated in the study to explain the size difference (2). Another study using linear measurement methods of frontal sinus amongst the population of United Kingdom showed a noteworthy variation in the frontal sinus volume between White British, Black Africans, and Chinese ancestry (28). The White British seem to possess the largest size, followed by Black Africans and the smallest found amongst Chinese (28). Overall, the non-significant result on frontal sinus size among the different race groups in this study is contrary to the findings when compared to other published literature. The inconsistency may be due to the different methods used, in which Vance et al. (2) used linear measurement methods and Robles et al. (28) used volumetric analysis.

In the case of shape, procrustes ANOVA demonstrated a significant difference (p-value < 0.05) in the shape of frontal sinus between Malays, Chinese and Indians. This study casts a new light on the relationship between frontal sinus shape and race, as it is, to our knowledge, the first study investigating such relations. The different race population has yet to be analysed and compared against each other in this manner of using frontal sinus. Hence, we compared the result of this study with studies that used other parts of the skeleton. A similar pattern of results was obtained by a study using the fourth cervical vertebrae of the Malaysia population conducted via 3D geometric morphometric methods, where results presented a significant difference in the shape of the fourth cervical vertebrae between Malay, Chinese and Indian groups (6). A study of orbital shape in the Thailand and Japanese population also showed significant difference between the two populations using the linear measurement approach (40). Another study of humerus shape among Black, Coloured and White individuals of South African population was also broadly in line with the result of this study, demonstrating a significant humerus shape difference, performed via 3D geometric morphometric method (26).

CVA results showed that the shape of frontal sinus was significantly different only between Chinese and Indians, and Malays and Indians, with the greatest separation between Chinese and Indians (MD = 0.92, PD = 0.07). However, as the study on frontal sinus involving CVA analysis is still limited, comparison of results was made with studies using other bones of the human skeleton. A study of fourth cervical vertebrae between Malays, Chinese and Indians of Malaysian population presented significant difference between the three race groups showing greatest group separation between Chinese and Indians (MD = 1.99, PD = 0.03) (6). This contrasting result may be explained by the different bones of the skeletal remains used in which we used frontal sinus whereas Young et al. (6) used the fourth cervical vertebrae. Maass et al., (26) conducted a study of the humerus shape differences among Black, Coloured and White individuals of South African population using 3D geometric morphometric method (26). The results showed significant shape difference between the three ancestral groups, and the greatest group separation was seen between Black and White individuals with MD = 2.9. Another study among South Africans presented a significant difference of the cranium shape found between Black, Coloured and White individuals, with the greatest separation seen between Black and White individuals using 3D geometric morphometric method (25). A possible explanation for the contradictory results of this current study from Maass et al. (26) and Stull et al. (25) might be the difference of the studied population.

This present study exhibited that after cross validation, the DFA results demonstrated overall classification accuracy of 57.4%. The Chinese-Indian comparison exhibited the highest level of accuracy, followed by the Malay-Indian and Malay-Chinese comparisons. The preceding studies in relation to frontal sinus and ancestry did not report the percentage of classification accuracy (2, 28). Comparing the classification accuracy of frontal sinus with other bones of human skeletons among Malaysian, Young et al. (6) evaluated race classification accuracy of the fourth cervical vertebrae between Malay, Chinese and Indian among Malaysian population using 3-dimensional (3D) geometric morphometric method, with 66.5% accuracy which is higher than this current study (6). This is likely to be related to the different bones used in the same studied population. Another study on the humerus shape among South African population using 3D geometric morphometric method revealed an ancestry accuracy rate of 85.3% in classifying Black, Coloured and White individuals into their respective groups (26). Furthermore, a study on cranium shape between South African as well had an overall correctly classified Black, Coloured and White individuals with 79% of classification accuracy rate using 3D geometric morphometric method (25). Another study on orbital shape between Thailand and Japanese ancestry had a cross-validated accuracy of 80.7% using linear measurement method (40). Regardless of identification method used, all classification rates of the compared preceding studies from other population were greatly higher than the study done in the Malaysian population. This might be explained by the different populations studied.

This study has compared its findings with those of studies that employed 3D geometric morphometric methods, given the limited literature available in similar research manners. While it is true that some studies have employed 3D geometric morphometric methods, the selection of the 2D approach in our study was driven by several important considerations. Firstly, the 2D approach using x-rays offers practical advantages such as cost-effectiveness, less timely, and widespread availability (12). These factors were especially relevant given the resources of our study. Furthermore, it is noteworthy that no prior study had utilized even a 2D geometric morphometric method on frontal sinus for race estimation among Malaysians. This application warranted exploring the potential of the 2D method within this specific context. Lastly, the application of 3D geometric morphometric methods on frontal sinus posed challenges due to the absence of homologous landmarks on the frontal sinus morphology (35). This limitation rendered the use of 3D methods less feasible for this study.

The variation of the skeletal morphology between different ancestral groups is mainly influenced by genetic factors, geographical distance, and socioeconomic conditions of certain ancestry (25, 26). Different ancestral groups carry difference genes from their ancestor which will affect the morphology of the skeleton (5). These genetic variations play a crucial role in shaping the anatomical characteristics of different populations, influencing aspects including bone morphology (5). As a result, these genetic factors may contribute to the diversity in skeletal features including frontal sinus seen between different race groups. Geographical distance is closely related to the genetic distance (6, 25). Stull et al. (25) explained that geographical distance will decrease the groups interaction, hence limit the gene flow between the different ancestry groups, and eventually increase the morphological differences between ancestries (25). Thus, populations living in close geographic proximity are more similar to each other, while populations living far apart are less similar to each other (5). Since the subject population in this present study were from a similar geographic area, hence this could explain the only slight morphological difference of the frontal sinus seen among Malays, Chinese and Indians.

Referring to the socioeconomic conditions, Maass et al. (26) explained that socioeconomic factor occurred in certain country over the past century might had amplified the between-group shape differences between Black and White individuals (26). According to the study, Black groups were associated with poor health care and nutrition, which affected their ability to attain their genetically determined growth potential, and therefore their skeletal morphology (26). Besides, over the past centuries, Black individuals were restricted to perform more physically demanding labour than White individuals, with the trend still persisting till the present day (26). The physicality of the work then increased the muscle mass hence resulting in larger muscle attachment sites (bones) (26). As for Malaysian population, the Malays, Chinese and Indians nowadays have somewhat similar socioeconomic conditions, hence this does not influence much the skeletal shape variation among the studied population (6). Therefore, these three factors of genes, geographic and socioeconomic status, explained the small variations and low accuracy rates between Indian, Malay and Chinese race in Malaysia.

The limitation of this study is that the frontal sinus morphology for identification was not identified among other races in Malaysia. As a result, further research is required to explore the frontal sinus morphology using a 2D geometric morphometric approach that is tailored to all of Malaysia's minority races. Despite this limitation, the study's findings provide an innovative outlook on the potential value of the frontal sinus for identifying the major races in the Malaysian population.

CONCLUSION

To conclude, the study proposed that 2D geometric morphometric analysis of frontal sinus is less reliable to be used for racial identification among Malaysians. Although the frontal sinus morphology is noticeably racially dimorphic, with the shape of the frontal sinus being particularly different between the Chinese and Indian groups in the studied population, the low classification percentage obtained for race estimation implies that it is less suitable for this purpose. Nonetheless, this study introduces new perspective of the potential utility of 2D geometric morphometric method on frontal sinus for race estimation among Malaysians. It offers researchers and anthropologists a framework to critically assess and an choose appropriate method for future race estimation of Malaysians. While this study was conducted in the context of Malaysia, its findings have global relevance. The insights gained can inform similar studies in diverse regions and contribute to the development of a more comprehensive understanding of race estimation methodologies on a broader scale. Furthermore, this study provides a valuable educational resource for students and researchers alike. It offers a comprehensive overview of the 2D geometric morphometric on frontal sinus method's potential and limitations for race estimation, serving as a foundation for further research and discussions in academia.

In lights of our findings, we suggest future studies to use a 3D model of the frontal sinus with volumetric analysis as it may allow interpretation of overall frontal sinus contour and yield a better classification accuracy for race estimation in the future. Additionally, since 2D geometric morphometric of frontal sinus is less reliable to be used for race estimation in Malaysia, future research may explore other sinuses such as maxillary, ethmoid, and sphenoid sinus, and give a new breakthrough in forensic anthropology in Malaysia.

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