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ORIGINAL ARTICLE

Morphometric variations of three sub-adult populations in Malaysia using multi-slice computed tomography data

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ABSTRACT

Background: This study aimed to determine the differences in cranial measurements in three sub-adult populations in Malaysia using multi-slice computed tomography (MSCT) data.

Materials and methods: A total of 521 cranial MSCT datasets of Malaysian sub-adults (0–20 years old) consisting of Malay, Chinese, and Indian populations were analysed and constructed into three-dimensional (3D) cranial models using Mimics software version 21. Fourteen selected craniometric parameters were measured on the 3D models, adhering to the plane-to-plane protocol. All measurements were statistically analysed using discriminant function analysis.

Results: Cranial measurements such as maximum cranial width, biasteronic width, and occipital chord showed significant differences among Malays, Chinese, and Indians. In addition, a high similarity of the measurements between Chinese and Malays compared to Indians and Malays and Chinese and Indians was demonstrated. The highest classification accuracy was obtained by the age group of 10–12 years old, with Indians achieving the highest accuracy (72.2%), followed by Chinese (71.8%) and Malays (58.3%). The accuracy percentages between the pooled-sex and male/female formulas were relatively similar.

Conclusions: This study demonstrated the presence of morphometric variations among the three different sub-adult populations in Malaysia using MSCT datasets.

Keywords: morphometrics, discriminant function analysis, sub-adults, cranium, Malaysia

INTRODUCTION

Malaysia is an incredibly diverse country that consists of three major population groups, namely the Malays and indigenous populations (67.4%), Chinese (24.5%), and Indians (7.3%) [13]. Each population group has its own population history within the country. In the nineteenth century, during the British Empire's reign, there was a substantial influx of Chinese from Southern China and Indians from South India for the tin mines and rubber plantation industries [23]. Consequently, the inflow of genes between Malays and Indians, Arabs, and Chinese traders in addition to the European colonists during the last 500–600 years was likely to have a substantial impact on their gene pools [4, 7]. Hence, modern Malays today show some admixture of genetic components from populations in Arabia, India, China, Java, Sumatra, and Thailand [16].

Population differences have been demonstrated in the adults' crania [8, 17]. However, the differences are less explored in sub-adults. This may be due to the assumption that population variation in the crania remains greatly undeveloped before puberty [21]. Most previous sub-adult studies have been conducted based on traits of temporal bone [19], mandible [2], and cranial regions [26]. However, a lack of consistency in which traits were diagnostic for each population group was observed [26]. In contrast, craniometric methods had achieved high classification accuracy depending on the population under study, level of sexual dimorphism, and secular change [9, 11, 18]. Therefore, this has brought to light the need for metric studies on cranial sub-adults and the necessity for population-specific standards in Malaysia.

Two-dimensional (2D) radiographic techniques, such as lateral and posteroanterior cephalograms, have been one of the main diagnostic tools in the field of biological anthropology. However, 2D images have inherent limitations in providing a comprehensive understanding of the complex 3D craniofacial structures [20]. The introduction of computed tomography (CT) scanning has revolutionised the field of craniofacial imaging, enabling comprehensive visualisation and precise analysis of the entire craniofacial complex [1]. Furthermore, it can obtain comparable accuracy with the metrical measurements of bone collections [5]. Hence, this study was conducted to determine the differences in cranial measurements in three sub-adult populations in Malaysia using multi-slice computed tomography (MSCT) data.

MATERIALS AND METHODS

Study sample

This was a retrospective study that was conducted in accordance with the Medical Research Ethics Committee, University Malaya Medical Centre (MREC ID NO: 202147-10039). A total of 521 MSCT images, retrieved from the Radiology Department of the University Malaya Medical Centre (UMMC), spanning from 2011 to 2021, were included in the study. These images comprised 221 Malays, 145 Chinese, and 155 Indians aged 0 to 20 years old, with a sex distribution of 279 males and 242 females. Prior to each scan, the name, age, sex, ethnic background, and identification number of each individual were obtained and recorded in the hospital's health database. This information was obtained from birth certificates issued by the Malaysian government at the time of birth. The images were taken using a tube voltage of 120 kV, 110-450 mAs, 1 mm slice thickness, and 0.4 s exposure time, and then converted into DICOM (Digital Imaging and Communications in Medicine) format. Individuals over the age of 20 and from other ethnicities were excluded from this study. In addition, CT images showing a history of surgery, deformity, or other abnormal pathology, as well as images with artefacts and poor resolution, were excluded from the study. Samples were divided into six age groups: 0–2, 3–6, 7–9, 10–12, 13–15, and 16–20 (Fig. 1).

Measurements

Mimics software (version 21.0; Materialise, Leuven, Belgium) was utilised to analyse the MSCT dataset on multiplanar reconstruction views. Fourteen selected craniometric parameters [maximum cranial length (MCL), bilateral lateral cranial length (LCL), bilateral nasio-occipital length (NOL), maximum cranial width (MCW), interporion width (IPW), biasteronic width (BAW), cranial height (CH), frontal chord (FC), occipital chord (OC), parietal chord (PC), cranial base length (CBL), foramen magnum length (FML), foramen magnum width (FMW)] were measured on cranial 3D models using a computer-assisted cranial vault evaluation protocol based on the plane-to-plane concept [14]. This protocol depends on the semi-automated plane placement between the offset or extreme position planes on the curves (Fig. 2). The protocol uses a reference plane system to define the extremities of surface-rendered models. In the present study, the reference system was generated using anatomical planes such as the midsagittal (MSP), Frankfort horizontal (FH), and coronal planes. Then, offset planes (planes parallel to each anatomical plane) and extreme planes were created on a 3D cranial model or curve. Definitions of all the measurements are presented in Table 1.

Statistical analysis

Descriptive statistics were computed to obtain the means and standard deviations of the measurements. An ANOVA test was performed to compare the means of the independent parameters among Malays, Chinese, and Indians across various age groups and sexes. Bonferroni's post-hoc test was used to identify which specific groups showed statistically significant differences from each other. The independent t-test was conducted to compare the measurements between males and females when the populations were pooled together. Additionally, two-way multivariate analyses of variance (MANOVA) were conducted to determine the effects of population groups, sex, age groups, and the interactions between population groups and sex, as well as between population groups and age groups, on the measurements.

Discriminant function analysis (DFA) was conducted to produce multivariate models for all age groups. Two main assumptions need to be fulfilled before conducting DFA: a multivariate normal distribution and homogeneity of variance–covariance matrices. Pairwise comparisons were calculated on the measurements in each age group to indicate levels of similarity and dissimilarity among the population groups. Discriminant function models were derived from unstandardised coefficients and constants for all age groups. Discriminant score plots were produced to demonstrate multivariate separation among the three population groups. Finally, the models were validated using leave-one-out cross-validation. Statistical analysis was conducted using IBM SPSS (version 26.0; IBM, Armonk, NY, USA).

Observer error assessment

The intra- and inter-observer error study was conducted by two investigators: a postgraduate student and an oral and maxillofacial radiologist. Initially, the postgraduate student measured 521 cranial datasets. Over the following two weeks, the two investigators re-measured a randomly selected subset of 30 cranial MSCT datasets, which represented various age groups, sexes, and population groups. To evaluate both intra- and inter-observer errors, technical error of measurement (TEM), relative technical error of measurement (rTEM), and coefficient of reliability (R) were calculated, with an acceptable range set at rTEM < 1.5% and R > 0.95 [24]. The TEM is a calculation method used to assess the precision of both intra- and inter-observer errors. It estimates the standard deviation of the differences between two measurements of a parameter. The rTEM is calculated by dividing the technical error of measurement (TEM) by the mean of the measurements and then multiplying by 100 to express the result as a percentage. This calculation provides insight into the proportion of error relative to the average size of the measurements. The coefficient of reliability (R) refers to the correlation coefficient between repeated measurements. It indicates the extent to which the measurements are consistent across different trials or observers. This study recorded rTEM values of 0.20% and 0.34% for both intra- and interobserver error evaluations, respectively. In addition, significant R values (> 0.98) were observed for the measurements in both intra- and interobserver error evaluations (Suppl. Tab. 1).

RESULTS

Descriptive statistics, ANOVA and MANOVA

Table 2 shows the descriptive statistics for all craniometric parameters divided by sex, age groups, and population groups. On average, the measurements for males were greater than those for females. In all age groups, the ANOVA results indicated significant differences ($p < 0.05$) among all three populations for most measurements, except for IPW, PC FC, CH, and FML in males. Specifically for females, significant differences were found in MCW and OC ($p < 0.05$). For males, the post hoc Bonferroni test revealed statistically significant differences between Malays and Chinese in LCL, MCW, BAW, OC, and FMW. Significant differences were also observed between Malays and Indians in MCL, NOL, MCW, and CBL. Furthermore, comparisons between Chinese and Indians indicated significant differences in MCW, BAW, and OC. For females, across all age groups, significant differences between Chinese and Indians were identified for BAW and OC (Suppl. Tab. 2). Independent t-tests demonstrated significant differences ($p < 0.05$) between the sexes for all the measurements when the three population groups were pooled, particularly evident in the older age groups (10–20 years) (Suppl. Tab. 3).

The MANOVA results showed statistically significant differences among different populations, age groups, and sexes for several measurements (Suppl. Tab. 4). Significant differences were observed among Malay, Chinese, and Indian populations in two parameters (MCW and CBL) and between males and females in MCW and FML. All measurements except PC showed statistically significant differences between all age groups. In addition, no significant interaction was observed between population groups and sex, as well as between population groups and age groups for all parameters.

Discriminant function analysis (DFA)

Discriminant scores were calculated for each age group and plotted (Fig. 3). Although Malays were clustered in between Chinese and Indians, they were closer to Chinese compared to Indians. In addition, pairwise comparisons were calculated and demonstrated that all parameters among the three population groups were significantly different from each other ($p < 0.001$). Overall, Malay and Chinese samples were the most similar (5.729), then Malay and Indian samples (10.986), and finally Chinese and Indian samples (14.637).

The new classification models and classification accuracy for original and cross-validated data were developed using canonical discriminant functions 1 and 2 (F1, F2) for all age groups (Tab. 3). These models were created using stepwise DFA. From stepwise DFA, 5 parameters (LCL, MCW, OC, FC, and CBL) and 2 parameters (MCW and FC) were identified for the age groups of 0–2 and 3–6, respectively. Moreover, 3 parameters (age group 7–9: BAW, IPW, and CBL), 4 parameters (age group 10–12: LCL, BAW, IPW, and CBL), 3 parameters (age group 13–15: MCL, MCW, and OC), 6 parameters (age group 16–20: MCL, LCL, BAW, IPW, CBL, and FMW) were selected for the model.

Classification accuracy for cross-validated data was in the range from 56.0% to 67.4% for pooled sex. The highest classification accuracy was obtained by the age group of 10-12 years old. Indians obtained the highest accuracy (72.2%), followed by Chinese (71.8%) and Malays (58.3%). Overall, a higher percentage of Malays were misclassified as Chinese (25–38.1%) than Indians (16.7–33.3%). Similarly, the majority of Chinese were misclassified as Malays (16.7–33.3%) than Indians (5.6–13.8%). However, the misclassified accuracy was minimal in Indians, with the majority being misclassified as Malay (6.3–26.5%) than Chinese (4.2–11.8%) (Tab. 3). When each sex was treated separately, 5 parameters (LCL, MCW, IPW, FC, CBL) and 2 parameters (MCW, CBL) resulted in cross-validated correct classifications of 54.5% and 55.4% for males and females, respectively (Tab. 4).

DISCUSSION AND CONCLUSIONS

Knowledge of anatomical variations among populations is essential in anthropology, forensic science, and medical research. The present study examines cranial measurements in three unique sub-adult populations in Malaysia using MSCT data. Analysing these measurements can provide insights into possible morphological differences and their significance in population studies and clinical practices.

Cranial growth is ongoing during the sub-adult age. Hence, cranial variation between younger and older sub-adults is certainly connected to the different growth paths and onset of puberty between males and females [25]. In the current study, population differences were not remarkable in younger age groups (< 6 years old), but the differences became more evident with age. This observation might be attributed to a parallel growth pattern observed for males and females of Malay, Chinese, and Indian populations before 6 years old. Contrarily, differences in the onset of puberty between males and females around 10–12 years old have resulted in an increased level of population differences in the crania of Malaysian subpopulation samples. This has resulted in the highest classification accuracy observed in that age group (67.4%).

Cranial features exhibit significant differences among various population groups [11]. The current study observed several parameters, such as MCW, BAW, and OC, to have significant differences between Malays, Chinese, and Indians. Similarly, previous studies have also reported that these parameters indicated significant differences between different populations, such as Japanese (6), Thai (6), Turks (13), Cypriots (13), and Cretans (13). Therefore, these parameters offer insights into potential morphological variations observed in the crania of sub-adults.

The current study demonstrated a high similarity of the measurements between Chinese and Malays compared to Indians and Malays and Chinese and Indians. This can be supported by genetic data studies that demonstrate higher genetic similarities between Malays and Chinese than Indians. This has resulted in a great partition of the two groups (Malays/Chinese vs. Indians) [27]. This finding is consistent with a study conducted by Hisham and Ibrahim in the Malaysian adult population, where 80% of Indian crania were correctly classified, compared to 61% for Malays and 68% for Chinese [10]. Similarly, a previous study of the Singaporean population observed that Malays and Chinese exhibited a stronger anthropological affinity with each other than with Indians [28].

Sex can influence the variations in size observed between male and female crania [17]. The present study observed a low level of sexual dimorphism in the Malaysian subpopulation samples. This finding may be attributed to previous reports indicating that the crania of Asian individuals are smaller and less robust [22], along with studies highlighting a similar pattern of low sexual dimorphism [6, 10, 22]. In concordance with a previous study on adult samples, no differences were found based on sex between Thai and Japanese skulls [17]. Contrary to studies on the Caribbean [9] and Mediterranean [11] populations, where higher sex-specific cross-validated classification accuracies were observed in males than in females.

Advances in imaging techniques, such as CT, offer anatomically-precise characterisation of skeletal architecture that surpasses the conventional morphometric practices [5]. This is evident in the present study from the observation of low TEM (0.20 mm) and high R (> 0.98) values. Similarly, Lottering et al. (2014) [15] observed low values of TEM for intra- and inter-observer error virtual reconstructions of 10 sub-adult crania using two cranial measurements: maximum cranial length and maximum cranial breadth. Another study on 3D cranial reconstructions of 12 individuals ranging in age from birth to 20 years demonstrated a low TEM value (0.05 mm) and rTEM percentage (0.073%) for all tested craniometric parameters [3]. Thus, all these studies have confirmed that high reliability can be achieved when obtaining cranial measurements on 3D virtual renderings of a sub-adult's cranium.

This present study has bridged the gap in population-specific cranial data among Malaysian sub-adults. In addition, this study demonstrates the presence of craniometric variations among the three different sub-adult populations in Malaysia using MSCT datasets. These findings highlight the potential contribution of craniometric measurements to medicolegal examinations of sub-adult skeletons found in Malaysia. Additionally, the results provide a foundation for the further development of growth pattern standards specific to the diverse ethnicities within the Malaysian population. Nonetheless, the results presented here are only representative of this population. These results may or may not reflect similar patterns in other population groups. To increase the level of accuracy, future work should extend the analysis to the full craniofacial skeleton, especially in the nasal and temporal regions. Additionally, choosing the most appropriate landmarks on the cranium should be considered.

ARTICLE INFORMATION AND DECLARATIONS

Data availability statement

All the relevant data used in this study can be accessed upon reasonable request from the corresponding author.

Ethics statement

Study approval was obtained from University Malaya Medical Centre's Ethics Committee (approval number 202147-10039). The study was conducted adhering to the principles laid out in the Declaration of Helsinki. Written informed consent was not needed and this requirement was exempted by the Ethics Committee because the study used a retrospective design. Procedures in the study were done according to relevant guidelines and regulations.

Author contributions

Sharifah Nabilah Syed Mohd Hamdan: investigation, data collection, data curation, formal analysis, methodology, writing — original draft. **Rabiah Al-Adawiyah Rahmat:** supervision, conceptualization, methodology, review, and editing. **Fathilah Abdul Razak:** supervision, project administration, conceptualization, review, and editing. **Khairul Azmi Abd Kadir:** supervision, resources. **Erma Rahayu Mohd Faizal Abdullah:** supervision, formal analysis. **Norliza Ibrahim:** supervision, conceptualization, software, review, and editing.

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Conflict of interest

The authors declare that they have no competing interest.

Supplementary material

Supplementary material is available on Journal's website. It includes:

Supplementary Table 1. Intra- and inter-observer errors, technical error of measurement (TEM), relative TEM (%TEM) and coefficient of reliability (R).

Supplementary Table 2. *Post-hoc* Bonferroni test.

Supplementary Table 3. Mean differences between males and females for all craniometric parameters.

Supplementary Table 4. Interaction for the effects of age groups, sex, population groups, and interactions between sex and population groups on the cranial measurements for Malay, Chinese, and Indian samples.

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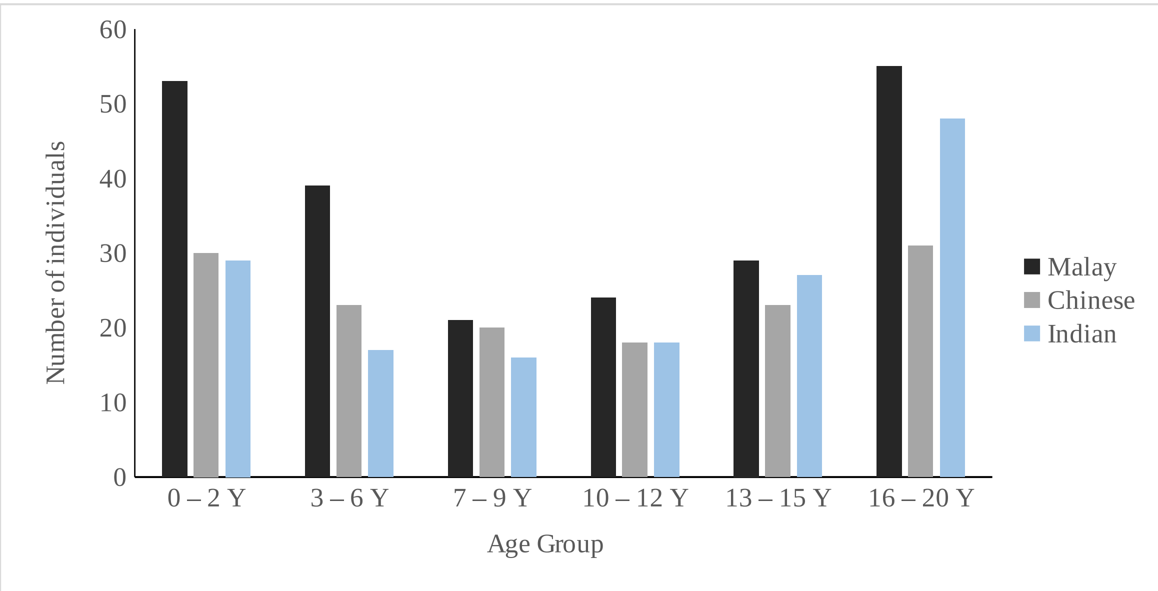
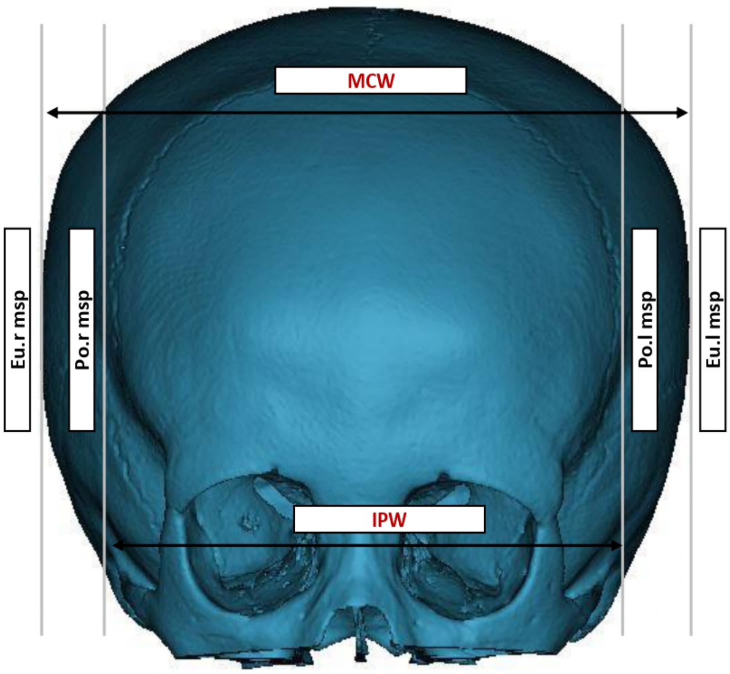


Figure 1. Distribution of age and population groups in the study samples.


MCW
Eu.r msp
Po.r msp
Po.l msp
Eu.l msp
IPW

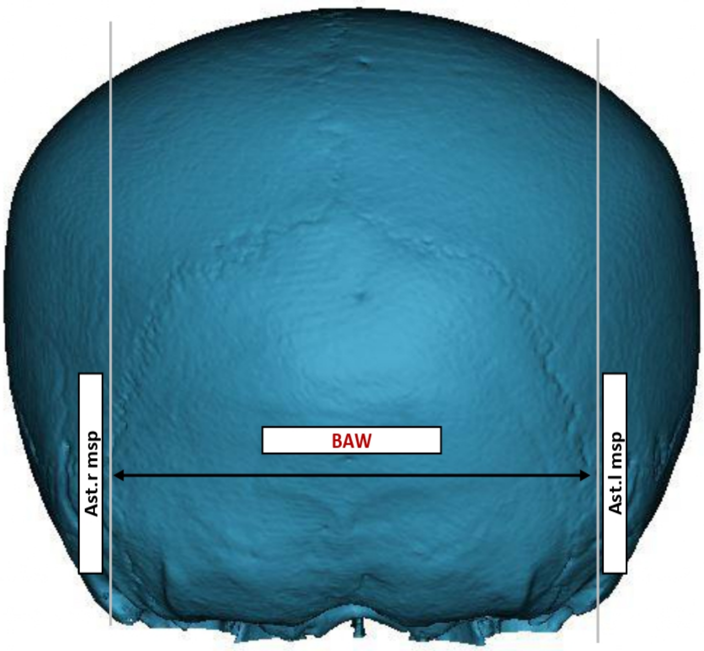

BAW
Ast.r msp
Ast.l msp

Figure 2. Example of the measurements using PTP protocol from anterior and posterior views. BAW — biasteronic width; IPW — interporion width; MCW — maximum cranial width.

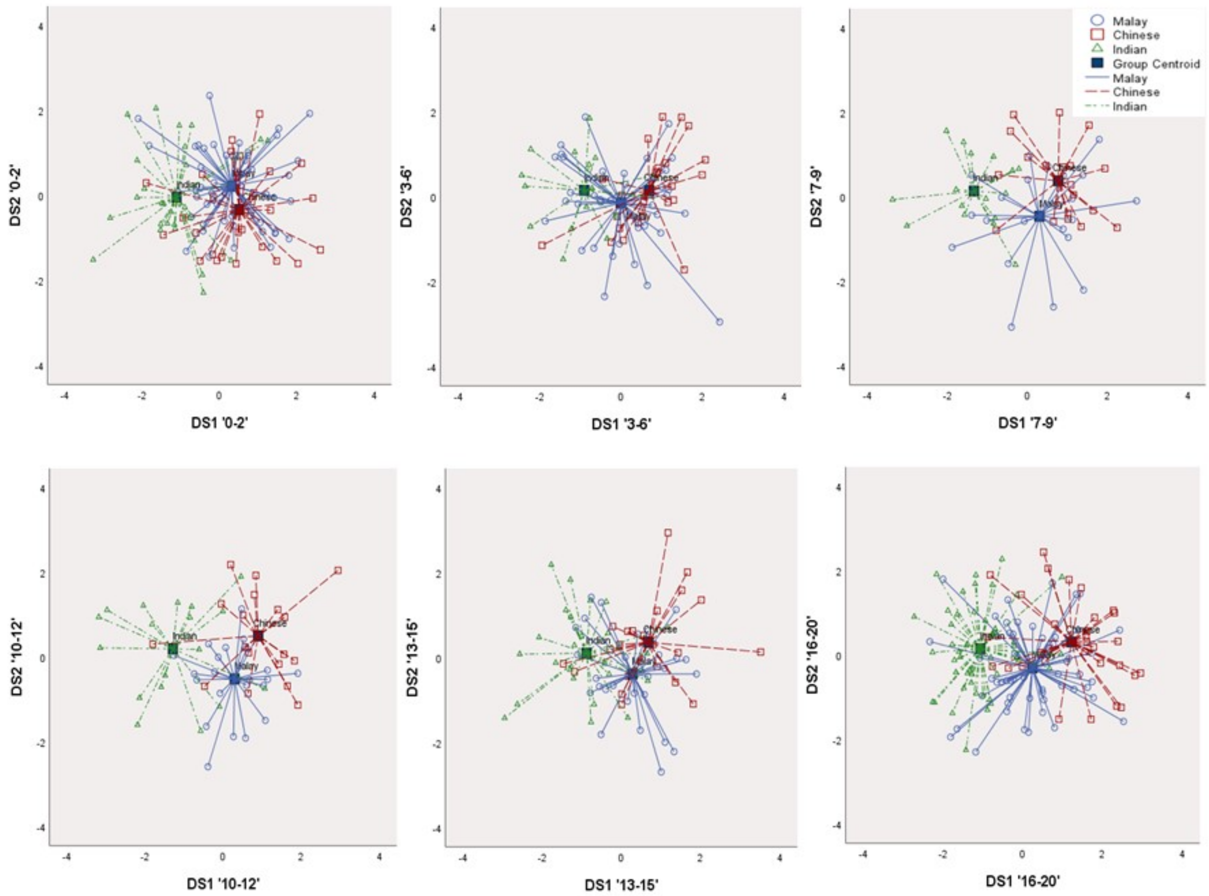


Figure 3. Discriminant score plots developed from classification models for all age groups.

Table 1. Measurements used in the three-dimensional analysis based on the plane-to-plane concept.

Measurement	Landmarks	Definition
MCL	g — op	The distance between glabella (g) and opisthocranion (op)

		in the midsagittal plane, measured in a straight line. Adjustment: The distance from the most anterior point on the mid-sagittal curve to the extreme position plane.
LCL R/L	ast.r/ast.l — pt.r/pt.l	The linear measurement from the anterior pterion (pt) to the asterion (ast), noted separately for each side.
NOL	n — op	The maximal length from nasion (n) to opisthocranion (op), measured along the midsagittal plane.
MCW	eu.r — eu.l	The maximum width of the skull extends from the right euryon (eu.r) to the left euryon (eu.l), perpendicular to the midsagittal plane, at the lateral points of the temporal bones.
IPW	po.r — po.l	The distance from the right porion (po.r) to the left porion (po.l).
BAW	ast.r — ast.l	The distance from the right asterion (ast.r) to the left asterion (ast.l).
CH	ba — b	The direct distance from basion (the lowest point on the anterior margin of the foramen magnum) (ba) to bregma (b).
FC	n — b	The distance from nasion (n) to bregma (b), measured along the midsagittal plane.
OC	l — o	The distance from lambda (l) to opisthion (o), measured along the midsagittal plane.
PC	b — l	The distance from bregma (b) to lambda (l), measured along the midsagittal plane.
CBL	ba — n	The distance from basion (ba) to nasion (n).
FML	ba — o	The distance from basion (ba) to opisthion (o), measured along the midsagittal plane.
FMW	fol.r — fol.l	The distance from the foraminolaterale (fol) on both the left and right sides at the point of the greatest lateral curvature.

BAW — biasteronic width; CBL — cranial base length; CH — cranial height; FC — frontal chord; FML — foramen magnum length; FMW — foramen magnum width; IPW — interporion width; LCL R/L — lateral cranial length (right and left); MCL — maximum cranial length; MCW — maximum cranial width; NOL — nasio-occipital length; OC — occipital chord; PC — parietal chord.

Table 2. Descriptive statistics (mean ± standard deviation) of all measurements for three different sub-adult populations in Malaysia across all age groups.

Para-meters		0–20 years	0–2 years	3–6 years	7–9 years	10–12 years	13–15 years	16–20 years	F-value	P-value
Males	**N**	M = 119, C = 79, I = 81	M = 29, C = 16, I = 16	M = 22, C = 13, I = 8	M = 13, C = 12, I = 10	M = 14, C = 9, I = 7	M = 15, C = 11, I = 15	M = 26, C = 18, I = 25		
MCL	M C I	165.93 ± 13.95 170.00 ± 13.54 170.64 ± 14.32	147.71 ± 11.62 152.43 ± 12.68 148.86 ± 12.12	163.85 ± 6.33 164.40 ± 6.49 163.23 ± 5.93	170.35 ± 6.50 169.15 ± 5.80 170.87 ± 5.67	169.40 ± 6.87 174.08 ± 4.11 175.00 ± 2.80	173.58 ± 7.44 180.30 ± 8.50 177.60 ± 7.80	179.50 ± 5.06 181.91 ± 7.40 181.46 ± 6.32	3.437	**0.034**
LCL	M C I	89.30 ± 10.35 93.29 ± 9.93 89.57 ± 10.03	75.77 ± 8.50 79.71 ± 7.57 73.96 ± 7.58	87.08 ± 4.70 89.13 ± 4.36 85.05 ± 3.44	92.13 ± 5.06 92.18 ± 5.20 90.84 ± 2.98	92.97 ± 3.85 98.83 ± 5.40 96.73 ± 2.99	96.15 ± 4.54 100.17 ± 3.84 93.86 ± 5.13	98.95 ± 4.62 102.14 ± 5.64 95.92 ± 6.05	4.153	**0.017**
NOL	M C I	160.25 ± 16.26 165.53 ± 13.96 166.45 ± 15.29	140.56 ± 10.95 146.61 ± 11.50 142.46 ± 11.53	159.22 ± 6.46 159.38 ± 7.42 157.95 ± 5.09	160.18 ± 2.69 165.40 ± 5.73 167.70 ± 6.44	165.68 ± 7.57 170.86 ± 4.16 171.97 ± 3.43	169.02 ± 7.61 176.29 ± 9.34 174.16 ± 8.37	175.13 ± 5.08 177.64 ± 6.91 177.87 ± 6.27	4.853	**0.008**
MCW	M C I	140.73 ± 9.61 144.91 ± 9.87 136.65 ± 9.04	129.86 ± 8.96 132.071 ± 0.25 123.65 ± 7.63	139.99 ± 6.20 144.71 ± 5.76 136.25 ± 6.61	144.58 ± 8.71 146.05 ± 5.87 139.31 ± 6.25	144.24 ± 4.84 147.28 ± 5.20 139.20 ± 5.33	143.94 ± 5.91 150.67 ± 6.99 140.82 ± 4.18	147.81 ± 5.97 150.99 ± 6.89 140.81 ± 6.71	15.012	**<0.001**

ANOVA test, bold indicates statistically significant at $p < 0.05$, *post hoc* test Bonferroni.
BAW — biasteronic width; C — Chinese; CBL — cranial base length; CH — cranial height; FC — frontal chord; FML — foramen magnum length; FMW — foramen magnum width; I — Indian; IPW — interporion width; LCL R/L — lateral cranial length (right and left); MCL — maximum cranial length; M — Malay; MCW — maximum cranial width; N — number of samples; NOL — nasio-occipital length; OC — occipital chord; PC — parietal chord.

Table 3. Discriminant models and classification accuracy for three different sub-adult populations in Malaysian sub-adults across all age groups.

Age groups (years)	**Variables**	**Unstandardized coefficients**		**Canonical correlation**		**Centroids**		**Classification accuracy for original sample [%]**	**Classification accuracy for cross-validated sample [%]**
		F1	**F2**	**F1**	**F2**	**F1**	**F2**		
0–2	LCL MCW OC FC CBL (Constant)	0.053 0.118 0.075 –0.070 –0.213 –3.309	–0.257 0.073 0.013 0.182 –0.048 –4.062	0.557	0.227	M: 0.318 C: 0.510 I: –1.110	M: 0.216 C: –0.336 I: –0.047	M: 50.9 C: 53.3 I: 79.3 T: 61.2	M: 50.9 C: 53.3 I: 77.9 T: 60.7
3–6	MCW FC (Constant)	0.188 –0.108	–0.025 0.222	0.497	0.150	M: –0.0	M: –0.1	M: 33.3 C: 65.2 I: 70.6	M: 33.3 C: 65.2 I: 69.7

		–14.967	–19.397			06 C: 0.685 I: –0.912	51 C: 0.145 I: 0.149	T: 56.4	T: 56.0
7–9	BAW IPW CBL (Constant)	0.182 0.043 –0.177 –8.213	–0.177 0.239 0.045 –11.032	0.662	0.351	M: 0.295 C: 0.763 I: –1.341	M: –0.461 C: 0.376 I: 0.134	M: 38.1 C: 65.0 I: 87.5 T: 63.5	M: 38.1 C: 65.0 I: 85.9 T: 63.0
10–12	LCL BAW IPW CBL (Constant)	0.061 0.108 0.143 –0.211 –13.503	0.141 –0.081 0.024 0.093 –16.189	0.670	0.411	M: 0.292 C: 0.897 I: –1.287	M: –0.518 C: 0.500 I: 0.191	M: 58.3 C: 72.2 I: 72.2 T: 67.6	M: 58.3 C: 71.8 I: 72.2 T: 67.4
13–15	MCL	–	0.122	0.55	0.29	M:	M:	M: 44.8	M: 44.8

	MCW OC (Constant)	0.053 0.103 0.125 –18.037	0.061 –0.074 –22.407	5	9	0.277 C: 0.684 I: –0.880	–0.383 C: 0.357 I: 0.107	C: 60.9 I: 66.7 T: 57.5	C: 60.1 I: 66.1 T: 57.0
16–20	MCL LCL BAW IPW CBL FMW (Constant)	–0.072 0.129 0.085 0.110 –0.122 0.052 –11.432	–0.018 –0.021 0.020 –0.054 0.127 0.357 –13.903	0.665	0.256	M: 0.241 C: 1.223 I: –1.065	M: –0.305 C: 0.309 I: 0.150	M: 41.8 C: 71.0 I: 83.3 T: 65.4	M: 41.8 C: 71.0 I: 82.5 T: 65.1
0–20	LCL MCW IPW OC FC CH CBL (Constant)	0.063 0.090 0.053 0.038 –0.116 0.050 –0.170 –6.117	0.126 –0.038 0.030 –0.056 –0.116 0.045 0.019 0.944	0.578	0.150	M: 0.200 C: 0.786 I: –1.021	M: –0.171 C: 0.176 I: 0.0	M: 36.7 C: 64.8 I: 74.2 T: 58.6	M: 36.2 C: 62.1 I: 74.2 T: 57.5

				79			

BAW — Biasteronic width; C — Chinese; CBL — Cranial base length; CH — Cranial height; FC — Frontal chord; FML — Foramen magnum length; FMW — Foramen magnum width; I — Indian; IPW — Interporion width; LCL R/L — lateral cranial length (right and left); M — Malay; MCL — maximum cranial length; MCW — Maximum cranial width; NOL — nasio-occipital length; OC — Occipital chord; PC — Parietal chord;

Table 4. Classification accuracy for original and cross-validated data for males and females.

Sex	**Parameters**	**F1**	**F2**	**Classification accuracy [%] (Original & cross validated)**			
				Malay (n = 119/102)	**Chinese (n = 79/66)**	**Indian (n = 81/74)**	**Total**
Male	LCL	0.075	0.082	38.7	63.3	77.8	57.0
	MCW	0.094	0.039	37.0	60.8	74.1	54.5
	IPW	0.071	–0.047				
	FC	–0.088	–0.111				
	CBL	–0.156	0.124				
	(Constant)	–3.901	–7.318				
Female	MCW	0.156	0.040	40.2	65.2	70.3	56.2
	CBL	–0.13	0.064	39.2	63.6	70.3	55.4

(Constant)	0 – 9.84 5	– 11.18 1

CBL — cranial base length; FC — frontal chord; IPW — interporion width; LCL R/L — lateral cranial length (right and left); MCW — maximum cranial width; N — number of males/number of females.

Supplementary Table 1. Intra- and inter-observer errors, technical error of measurement (TEM), relative TEM (%TEM) and coefficient of reliability (R).

	Intra-observer error			**Inter-observer error**		
	TEM [mm]	**rTEM [%]**	**R**	**TEM [mm]**	**rTEM [%]**	**R**
MCL	0.240	0.135	0.989	0.182	0.121	0.982
LCL (R)	0.192	0.182	0.986	0.217	0.233	0.983
LCL (L)	0.235	0.246	0.986	0.152	0.162	0.985
NOL	0.280	0.157	0.989	0.220	0.134	0.982
MCW	0.150	0.097	0.987	0.228	0.163	0.982
BAW	0.229	0.211	0.991	0.286	0.274	0.981
IPW	0.193	0.164	0.992	0.263	0.225	0.980
PC	0.266	0.242	0.990	0.282	0.258	0.990
OC	0.294	0.280	0.988	0.285	0.318	0.982
FC	0.247	0.239	0.988	0.337	0.283	0.982
CH	0.305	0.239	0.985	0.256	0.189	0.991
CBL	0.254	0.251	0.984	0.278	0.236	0.984
FML	0.179	0.095	0.988	0.458	1.310	0.982
FMW	0.095	0.299	0.994	0.262	0.927	0.982
Mean	**0.226**	**0.203**	**0.988**	**0.265**	**0.345**	**0.983**

BAW — biasteronic width; CBL — cranial base length; CH — cranial height; FC — frontal chord; FML — foramen magnum length; FMW — foramen magnum width; IPW — interporion width; LCL R/L — lateral cranial length (right and left); MCL — maximum cranial length; MCW — maximum cranial width; NOL — nasio-occipital length; OC — occipital chord; PC — parietal chord.

Supplementary Table 2. *Post-hoc* Bonferroni test.

Dependent variables	(I) Race	(J) Race	Females			Males		
			Mean Difference (I–J)	**Std. Error**	**Sig.**	**Mean Difference (I–J)**	**Std. Error**	**Sig.**
Maximum cranial length	Malay	Chinese	–0.23173	2.08570	1.000	–4.07857	2.02464	0.135
		Indian	–1.37727	2.01609	1.000	–4.71489	2.00956	**0.049**
	Chinese	Malay	0.23173	2.08570	1.000	4.07857	2.02464	0.135
		Indian	–1.14554	2.23535	1.000	–0.63632	2.20600	1.000
	Indian	Malay	1.37727	2.01609	1.000	4.71489	2.00956	**0.049**
		Chinese	1.14554	2.23535	1.000	0.63632	2.20600	1.000
Lateral cranial length	Malay	Chinese	–2.35490	1.46411	0.327	–3.98622*	1.47244	**0.022**
		Indian	–0.55652	1.41524	1.000	–0.26764	1.46147	1.000
	Chinese	Malay	2.35490	1.46411	0.327	3.98622*	1.47244	**0.022**
		Indian	1.79838	1.56916	0.759	3.71858	1.60434	0.064
	Indian	Malay	0.55652	1.41524	1.000	0.26764	1.46147	1.000
		Chinese	–1.79838	1.56916	0.759	–3.71858	1.60434	0.064
Nasio occipital length	Malay	Chinese	0.00912	2.24823	1.000	–5.28419	2.22964	**0.055**
		Indian	–1.81818	2.17319	1.000	–6.20625*	2.21303	**0.016**
	Chinese	Malay	–0.00912	2.24823	1.000	5.28419	2.22964	0.055
		Indian	–1.82730	2.40954	1.000	–0.92206	2.42936	1.000
	Indian	Malay	1.81818	2.17319	1.000	6.20625*	2.21303	**0.016**
		Chinese	1.82730	2.40954	1.000	0.92206	2.42936	1.000
Maximal cranial width	Malay	Chinese	–2.54696	1.50136	0.273	–4.17458*	1.38322	**0.008**
		Indian	3.18953	1.45125	0.087	4.08370*	1.37292	**0.010**
	Chinese	Malay	2.54696	1.50136	0.273	4.17458*	1.38322	**0.008**
		Indian	5.73649*	1.60908	**0.001**	8.25829*	1.50712	< **0.001**
	Indian	Malay	–3.18953	1.45125	0.087	–4.08370*	1.37292	**0.010**
		Chinese	–5.73649*	1.60908	**0.001**	–8.25829*	1.50712	< **0.001**
Biasteronic width	Malay	Chinese	–1.36638	1.42347	1.000	–3.87233*	1.26183	**0.007**
		Indian	1.46892	1.37596	0.860	1.85470	1.25243	0.419
	Chinese	Malay	1.36638	1.42347	1.000	3.87233*	1.26183	**0.007**
		Indian	2.83530	1.52561	0.193	5.72704*	1.37486	< **0.001**

	Indian	Malay	–1.46892	1.37596	0.860	–1.85470	1.25243	0.419
		Chinese	–2.83530	1.52561	0.193	–5.72704*	1.37486	**< 0.001**
Interporion width	Malay	Chinese	–3.58756	2.36975	0.394	–5.32224	2.37053	0.077
		Indian	–0.37892	2.29066	1.000	–0.08980	2.35287	1.000
	Chinese	Malay	3.58756	2.36975	0.394	5.32224	2.37053	0.077
		Indian	3.20864	2.53978	0.623	5.23244	2.58287	0.131
	Indian	Malay	0.37892	2.29066	1.000	0.08980	2.35287	1.000
		Chinese	–3.20864	2.53978	0.623	–5.23244	2.58287	0.131
Parietal cord	Malay	Chinese	0.08947	1.30077	1.000	–2.20220	1.15332	0.172
		Indian	0.55704	1.25736	1.000	–2.02927	1.14473	0.232
	Chinese	Malay	–0.08947	1.30077	1.000	2.20220	1.15332	0.172
		Indian	0.46756	1.39410	1.000	0.17293	1.25663	1.000
	Indian	Malay	–0.55704	1.25736	1.000	2.02927	1.14473	0.232
		Chinese	–0.46756	1.39410	1.000	–0.17293	1.25663	1.000
Occipital cord	Malay	Chinese	–0.74960	1.28582	1.000	–2.82421*	1.15904	**0.046**
		Indian	2.53411	1.24290	0.128	1.42594	1.15041	0.649
	Chinese	Malay	0.74960	1.28582	1.000	2.82421*	1.15904	**0.046**
		Indian	3.28371	1.37808	**0.044**	4.25015*	1.26286	**0.003**
	Indian	Malay	–2.53411	1.24290	0.128	–1.42594	1.15041	0.649
		Chinese	–3.28371	1.37808	**0.044**	–4.25015*	1.26286	**0.003**
Frontal cord	Malay	Chinese	–0.31711	1.55338	1.000	–1.25906	1.45917	1.000
		Indian	–1.29430	1.50153	1.000	–1.99730	1.44831	0.507
	Chinese	Malay	0.31711	1.55338	1.000	1.25906	1.45917	1.000
		Indian	–0.97719	1.66483	1.000	–0.73824	1.58988	1.000
	Indian	Malay	1.29430	1.50153	1.000	1.99730	1.44831	0.507
		Chinese	0.97719	1.66483	1.000	0.73824	1.58988	1.000
Cranial height	Malay	Chinese	–1.73889	1.88932	1.000	–2.88854	1.76420	0.308
		Indian	–0.71354	1.82627	1.000	–1.87984	1.75106	0.852
	Chinese	Malay	1.73889	1.88932	1.000	2.88854	1.76420	0.308
		Indian	1.02535	2.02488	1.000	1.00870	1.92223	1.000
	Indian	Malay	0.71354	1.82627	1.000	1.87984	1.75106	0.852
		Chinese	–1.02535	2.02488	1.000	–1.00870	1.92223	1.000
Cranial base length	Malay	Chinese	–0.41164	1.66907	1.000	–2.47979	1.68400	0.426
		Indian	–3.26061	1.61336	0.133	–5.19993*	1.67146	**0.006**

	Chinese	Malay	0.41164	1.66907	1.000	2.47979	1.68400	0.426
		Indian	–2.84897	1.78882	0.338	–2.72014	1.83485	0.418
	Indian	Malay	3.26061	1.61336	0.133	5.19993*	1.67146	**0.006**
		Chinese	2.84897	1.78882	0.338	2.72014	1.83485	0.418
Foramen magnum length	Malay	Chinese	–0.04847	0.48736	1.000	0.10660	1.28773	1.000
		Indian	–0.45167	0.47109	1.000	0.76241	1.27814	1.000
	Chinese	Malay	0.04847	0.48736	1.000	–0.10660	1.28773	1.000
		Indian	–0.40320	0.52233	1.000	0.65581	1.40308	1.000
	Indian	Malay	0.45167	0.47109	1.000	–0.76241	1.27814	1.000
		Chinese	0.40320	0.52233	1.000	–0.65581	1.40308	1.000
Foramen magnum width	Malay	Chinese	–0.61407	0.43111	0.467	–1.16325*	0.42757	**0.021**
		Indian	–0.04343	0.41673	1.000	–0.47600	0.42439	0.789
	Chinese	Malay	0.61407	0.43111	0.467	1.16325*	0.42757	**0.021**
		Indian	0.57065	0.46205	0.654	0.68724	0.46587	0.424
	Indian	Malay	0.04343	0.41673	1.000	0.47600	0.42439	0.789
		Chinese	–0.57065	0.46205	0.654	–0.68724	0.46587	0.424

Post-hoc Bonferroni test, bold indicates statistically significant at $p < 0.05$.

Supplementary Table 3. Mean differences between males and females for all craniometric parameters.

Parameters		0–20	0–2	3–6	7–9	10–12	13–15	16–20
MCL	t	**4.549**	1.245	0.954	**2.493**	**3.946**	**3.979**	**9.888**
	P	**< 0.001**	0.216	0.343	**0.016**	**< 0.001**	**< 0.001**	**< 0.001**
LCL	t	**4.620**	1.838	**3.824**	**2.164**	**2.356**	**4.629**	**7.351**
	P	**< 0.001**	0.069	**< 0.001**	**0.035**	**0.022**	**< 0.001**	**< 0.001**
NOL	t	**3.756**	1.541	1.498	0.558	**3.627**	**3.567**	**8.740**
	P	**< 0.001**	0.126	0.138	0.579	**0.001**	**0.001**	**< 0.001**
MCW	t	**4.562**	**2.003**	**3.081**	**2.364**	1.935	**2.758**	**3.871**
	P	**< 0.001**	**0.048**	**0.003**	**0.022**	0.058	**0.007**	**< 0.001**
BAW	t	**3.436**	1.261	1.966	**2.439**	**2.136**	**2.552**	**3.445**
	P	**0.001**	0.210	0.053	**0.018**	**0.037**	**0.013**	**0.001**
IPW	t	**3.375**	1.417	**3.569**	**2.629**	**2.034**	**4.394**	**8.458**
	P	**0.001**	0.159	**0.001**	**0.011**	**0.047**	**< 0.001**	**< 0.001**
PC	t	**4.283**	1.489	0.200	1.638	**3.056**	**2.435**	**4.490**
	P	**< 0.001**	0.139	0.842	0.107	**0.003**	**0.017**	**< 0.001**
OC	t	1.755	0.557	0.607	0.301	1.302	1.897	1.695
	P	0.080	0.579	0.545	0.765	0.198	0.062	0.092
FC	t	**4.248**	**2.057**	**2.590**	**2.473**	**2.823**	**3.665**	**6.099**
	P	**< 0.001**	**0.042**	**0.011**	**0.017**	**0.007**	**< 0.001**	**< 0.001**
CH	t	**3.665**	**2.306**	1.738	1.670	**2.183**	**3.951**	**7.035**
	P	**< 0.001**	**0.023**	0.086	0.101	**0.033**	**<0.001**	**< 0.001**
CBL	t	**3.606**	**2.163**	**2.233**	1.641	1.704	**5.075**	**9.701**
	P	**< 0.001**	**0.033**	**0.028**	0.107	0.094	**< 0.001**	**< 0.001**
FML	t	**3.980**	**3.680**	1.417	**3.477**	**4.348**	**3.883**	**2.034**
	P	**< 0.001**	**< 0.001**	0.161	**0.001**	**< 0.001**	**< 0.001**	**0.047**
FMW	t	**2.226**	**1.821**	**2.931**	**3.652**	2.589	**2.448**	**4.175**
	P	**< 0.001**	**0.07**	**0.004**	**0.001**	0.012	**0.017**	**< 0.001**

Independent *t*-test, bold indicates statistically significant at $p < 0.05$.

BAW — biasteronic width; CBL — cranial base length; CH — cranial height; FC — frontal chord; FML — foramen magnum length; FMW — foramen magnum width; IPW — interporion width; LCL — lateral cranial length; MCL — maximum cranial length; MCW — maximum cranial width; NOL — nasio-occipital length; OC — occipital chord; PC — parietal chord;

Supplementary Table 4. Interaction for the effects of age groups, sex, population groups, and interactions between sex and population groups on the cranial measurements for Malay, Chinese, and Indian samples.

Para-meters	**Age groups**		**Sex**		**Population groups**		**Sex * population groups**		**Age groups * population groups**	
	F-value	**Sig.**	**F-value**	**Sig.**	**F-value**	**Sig.**	**F-value**	**Sig.**	**F-value**	**Sig.**
MCL	12.090	**0.001**	0.541	0.462	3.690	0.055	1.577	0.210	1.158	0.282
LCL	19.301	**0.000**	3.767	0.053	0.041	0.840	0.001	0.982	0.002	0.962
NOL	11.798	**0.001**	0.031	0.860	5.369	0.212	2.306	0.129	0.774	0.379
MCW	6.452	**0.011**	4.495	**0.034**	1.560	**0.021**	0.078	0.780	0.054	0.816
BAW	4.203	**0.041**	2.014	0.156	0.219	0.640	0.000	0.982	0.018	0.893
IPW	35.412	**0.000**	1.911	0.167	0.017	0.897	0.000	0.998	0.031	0.860
PC	3.420	0.065	0.090	0.764	3.442	0.064	2.560	0.110	0.023	0.879
OC	6.770	**0.010**	0.000	0.998	0.012	0.914	0.601	0.438	0.008	0.927
FC	11.757	**0.001**	1.996	0.158	0.748	0.388	0.134	0.714	0.190	0.663
CH	17.124	**0.000**	1.101	0.295	0.734	0.392	0.249	0.618	0.017	0.895
CBL	37.044	**0.000**	0.507	0.477	4.006	**0.046**	0.766	0.382	0.074	0.785
FML	8.969	**0.003**	5.633	**0.018**	0.738	0.391	0.672	0.413	3.687	0.055
FMW	8.938	**0.003**	1.646	0.200	1.303	0.254	0.650	0.421	0.147	0.702

MANOVA test, bold indicates statistical significance at $p < 0.05$. BAW — biasteronic width; CBL — cranial base length; CH — cranial height; FC — frontal chord; FML — foramen magnum length; FMW — foramen magnum width; IPW — interporion width; LCL — lateral cranial length; MCL — maximum cranial length; MCW — maximum cranial width; NOL — nasio-occipital length; OC — occipital chord; PC — parietal chord;