A geometric morphometric evaluation of facial hard tissue patterns

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Abstract

OBJECTIVE: The purpose of this study was to investigate the size and shape variations of hard tissue patterns in different skeletal relations in Malaysian Malay subjects using the two-dimensional geometric morphometrics method.

MATERIALS AND METHODS: A total of 188 lateral cephalograms of adult Malay subjects (aged between 18 and 40 years) with Class I, II, and III skeletal relations were collected. Ten two-dimensional hard tissue landmarks were applied on lateral cephalograms which underwent landmark application and shape analyses as Procrustes ANOVA analysis, principal component analysis, canonical variate analysis, and discriminant function analysis. Statistical analyses were performed to find the mean and variance of each landmark using one-way ANOVA. The raw data from shape analysis were used to calculate the link between landmarks.

RESULTS: Skeletal relations showed 16 Principal Components which indicated that variances existed in 16 different dimensions. In Procrustes ANOVA, the Centroid size was significantly different in genders and skeletal relations ($P < 0.01$). Canonical variate analysis showed the highest Mahalanobis distances and Procrustes distances between Class II and III among skeletal relations and between gender groups ($P < 0.0001$). Discriminant function analysis showed the classification was mostly accurate, especially for Class II and Class III with success rates of 90.6% and 83.3%, respectively, after cross-validation. The statistical analysis showed significant differences ($P < 0.05$) in hard tissue landmarks.

CONCLUSION: There were different ANB angles in different skeletal relations. The GMM could be used as an alternative tool for diagnosis and treatment planning for craniofacial shape evaluations for future orthodontists and maxillofacial surgeons.

Keywords:
Geometric morphometrics method, Hard tissue patterns, Skeletal relations

Introduction

Among diagnostic aids in orthodontics, cephalometric analyses have been for many years the gold standard for analyzing the patients` orthodontic cases for diagnosis and collecting cephalometric values. It is crucial to understand the awareness of the usual dentofacial patterns of ethnic groups and racial differences in facial traits because the morphological characteristics of races and ethnic groups are distinct from each other and will ensure better treatment success in establishing optimal facial harmony.[1] Currently, most orthodontists rely on cephalometric norms for the assessment of skeletal and soft tissue patterns. These norms are based on studies conducted on mostly Caucasian samples, which do not reflect all populations` norms. Moreover, the cephalometric-based method has drawbacks, being two-dimensional and linear in nature. The linear nature of cephalometric data does not allow for partitioning shape and size components therefore, the analysis of the shape details was only calculated as a size-based measurement. The geometric morphometrics method (GMM) is a complementary and

effective approach to solving unresolved issues relevant to conventional cephalometric analysis. The GMM is a new approach that analyzes the shape variations regardless of size components changes.[2,3] GMM is based on Cartesian coordinates of landmarks which helps to overcome the cephalometric method shortcomings. Morphometrics is the quantitative study of biological shape variation and covariation. The quantitative study of size and shape was most closely associated with the field of allometry until the development of morphometric methods for data collecting and analysis.[4] GMM can be used as a useful tool to define the two and three-dimensional shapes of surfaces. Variability can be measured via the Principal component analysis and can contribute to identifying shape patterns and origins of shape variation, regardless of size changes.[5] Furthermore, the use of GMM with other methods is widespread in the creation of artificial intelligence (AI) systems for predicting facial morphology in orthodontic treatment and orthognathic surgery. Artificial intelligence (AI) has revolutionized the field of dentistry in recent years. Artificial neural networks (ANNs) and convolutional neural networks (CNNs) are used in the majority of these artificial intelligence models, as well as deep learning (DL). AI-based technology has been employed as a clinical decision support system to assist clinicians in making decisions. AI systems may streamline tasks and produce results quickly, saving the dentist time. The new technologies have shown to be effective in predicting diagnoses and assisting clinicians with treatment planning.[6,7]

It is substantial to consider the skeletal characteristics of the type of malocclusion present with the patient before diagnosis and orthodontic planning. Diagnosis and treatment planning have been dependent for many years on the norms of Caucasian groups, which are entirely different and do not reflect the Malaysian population norm. There are studies accomplished in Malaysian sub-ethnic groups and evaluated the Cephalometric norms.[8-11] Such a database may provide a way of analyzing differences in clinical characteristics and may be useful for orthodontic diagnosis and assessment of treatment. Although these studies included the hard tissue and soft tissue evaluation by using cephalometric analysis of Malaysian sub-ethnic groups, these studies had evaluated one type of malocclusion and did not involve the assessment of all types of malocclusions and gender groups therefore, this study aimed to investigate the size and shape variations of hard tissue patterns in different skeletal relations in adult Malays using the geometric morphometrics method which could develop an AI system for Malaysian Malay population for the future orthodontist and maxillofacial surgeons.

Materials and Methods

Study design
This study was a retrospective study and was conducted at the Faculty of Dentistry, Universiti Teknologi Mara (UiTM) and Faculty of Dentistry, Universiti Sains Islam Malaysia (USIM). The data were taken from UiTM Dental Hospital and USIM Dental Clinic databases. This research was approved by the Research and Ethics committee of UiTM and USIM. The Ethics approval codes for this study were {REC/09/2020 (MR/245)} from UiTM and (USIM/JKEP/2021/125) from USIM.

Data collection and analysis
The inclusion criteria for the patients were subjects aged between 18-40 years old, Malay ethnic group patients, diagnostically acceptable lateral cephalograms, and patients with full permanent dentition (excluding the 3rd molars).[12] Patients with craniofacial anomalies, patients with a history of Orthognathic surgery, history of orthodontic treatment, non-Malay, and patients with mixed dentition were excluded in this study. The sample size was determined using G*Power software calculation version 3.0.10. The sample size for each type of skeletal relation group was 64. A total of 188 lateral cephalograms of skeletal relations were collected with the age range of 18-40 years and comprised of 117 females and 71 males for all analyses [Table 1].

In this study, the Software, namely tpsDig2 version 2.31[13] and MorphoJ version 1.07a,[14] were used as research tools. The tpsDig2 software version 2.31[13] was utilized for the landmark application. The MorphoJ software version 1.07a[14] was used for shape analysis. Other software, namely Notepad++ version 7.8.2 and Microsoft office program Excel 2011, were used in managing the data. First, the data underwent landmarking application using tpsDig2 software version 2.31,[13] and then the shape analyses as Generalized Procrustes Analysis (GPA), Procrustes ANOVA, Principal component analysis (PCA), Canonical variate analysis (CVA), and Discriminant function analysis (DFA) using MorphoJ software version 1.07a[14] were done to determine the differences in morphology and size.[15] In this study, a total of ten two-dimensional hard tissue landmarks were applied; these landmarks are defined in Table 2.[16] The landmarks were digitized using tpsDig2 software in their exact locations [Figure 1].

Table 1: Number of patients and distribution of genders in each class

	Class I	Class II	Class III
Females	37	36	44
Males	27	28	16
Total	64	64	60

Statistical analysis

The other statistical analysis was done by IBM SPSS Statistics 26 (IBM Corp, Armonk, New York, NY, USA). The data were analyzed to find the mean and variance of each landmark, as well as five parameters [Table 3], were analyzed using one-way ANOVA with Post Hoc Tests (Tukey HSD and Bonferroni). The independent T-test was used to explore the difference between male and female subjects by comparing the centroid size of objects.

Results

Shape analysis

In this study, the Generalized Procrustes Analysis (GPA) was done to eliminate the non-shape variation in the sample. The GPA superimposed each set of ten landmark

Figure 1: Map of the ten hard tissue landmarks

configurations on all 188 lateral cephalograms and changed the raw landmark coordinates of the data to a new Procrustes fit.

The shape and size analyses were done for Class I, II, and III skeletal relations by Principal component analysis (PCA). Skeletal relations (Class I, II, and III) showed 16 PC scores which indicated that variances existed in 16 different dimensions [Table 4]. The PC1 to PC5 showed significant differences among the 16 principal components that cumulatively accounted for 80% of total shape variance. The first three PCs were statistically meaningful. GMM support diagrams using wireframes for visualizing shape changes in two or three dimensions. Figure 2 showed the lollipop and wireframe graphs of the most dominant variant shape of hard tissue patterns for Class I, II, and III skeletal relations. All ten landmarks displayed some level of variation from the mean. B-point, Pogonion, menton, Gonion, and Condylyion showed the most obvious variance from the mean. ANS and A-point showed significant variances, while other landmarks showed little or no variance in the specimens.

The Procrustes ANOVA evaluated the variation among individuals and error measurement in specimens. The result of the Procrustes ANOVA analysis represented the different effects (skeletal relations and gender groups) that were demonstrated for centroid size and shape. In this study, the gender groups showed significant differences in centroid size ($P < 0.01$), while the skeletal relations showed no differences ($P < 0.01$). Procrustes ANOVA showed significant variation of shape for skeletal relations and gender groups ($P < 0.0001$).

Table 2: Definition of hard tissue landmarks

Number point	Landmarks	Definition
1	Nasion (N)	The most anterior point of the frontonasal suture in the middle.
2	Anterior Nasal Spine (ANS)	The tip of bony anterior nasal spine in the middle or median plane.
3	A-point (A)	The deepest point on the curved bony outline between the anterior nasal spine (ANS) and prosthion (Pr).
4	B-point (B)	The deepest midline points on the mandible between infradentale and pogonion.
5	Pogonion (Pog)	The most anterior point on the symphysis of the mandible.
6	Menton (Me)	Lower most point of the contour of the chin.
7	Gonion (Go)	The midpoint mediolaterally on the posterior border of each gonial angle.
8	Posterior Nasal Spine (PNS)	The intersection of a continuation of the anterior wall of the pterygopalatine fossa and the floor of the nose.
9	Condylyion (Cd)	Most medial aspect of condyle. Bilateral structure.
10	Sella (S)	The midpoint of sella turcica or hypophyseal fossa or pituitary fossa.

Table 3: Parameters of the hard tissue patterns in skeletal relations and their description

No	Parameters	Landmarks	Description
1	A	1-2	The distance between Nasion and Anterior Nasal Spine.
2	B	2-3	The distance between Anterior Nasal Spine and A-point.
3	C	1-3	The distance between Nasion and A-point.
4	D	3-4	The distance between A-point and B-point.
5	E	4-5	The distance between B-point and Pogonion.

The Canonical variate analysis (CVA) was done to find the differences between three different types of skeletal relations in the shape feature. There was a significant

Table 4: Eigenvalues, percent variance, and cumulative percent of each principal among skeletal relations

| PC	Eigenvalues	Percent variance %	Cumulative variance %
1	0.00153771	31.235	31.235
2	0.00130909	26.591	57.825
3	0.00054143	10.998	68.823
4	0.00026447	5.372	74.195
5	0.00023989	4.873	79.068
6	0.00022904	4.652	83.720
7	0.00017632	3.581	87.302
8	0.00016299	3.311	90.613
9	0.00012024	2.442	93.055
10	0.00010512	2.135	95.190
11	0.00007556	1.535	96.725
12	0.00007023	1.427	98.152
13	0.00003770	0.766	98.917
14	0.00002367	0.481	99.398
15	0.00002132	0.433	99.831
16	0.00000831	0.169	100.000
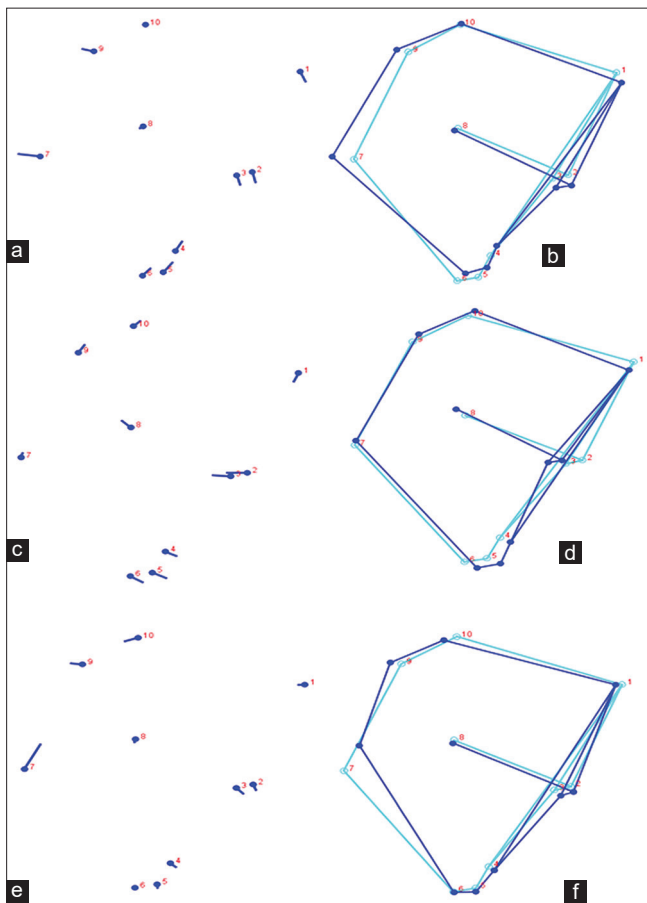
Figure 2: Lollipop and wireframe graphs of PC1, PC2, and PC3 shapes of hard tissue landmarks in different skeletal relations: (a and b) Graphs of PC1; (c and d) Graphs of PC2; (e and f) Graphs of PC3

difference between Class I, Class II, and Class III [Figure 3]. Class II and Class III exhibited the highest Mahalanobis distance and Procrustes distances ($P < 0.0001$). It showed significant shape and size differences in hard tissue patterns between Class II and Class III skeletal relations.

Discriminant function analysis (DFA) in different skeletal relations showed the most classification accuracy for Class II and Class III skeletal relations, with success rates of 93.7%, and 86.6%, and after cross-validation, 90.6% and 83.3%, respectively [Table 5]. The classification accuracy was 74.3% for females and 83% for males, while the classification rate from cross-validation showed about 66.6% females and 74.6% males correctly classified [Table 6]. Figures 4 and 5 showed the Discriminant function test and after cross-validation test on MorphoJ software version 1.07a[14] between Class II and Class III and gender groups.

Statistical analysis

The results of the t-test showed, there were significant differences between males and females ($P < 0.05$) [Table 7]. The result of the ANOVA test showed significant differences in some of the parameters between the landmarks. Length D and Length E showed significant differences ($P < 0.05$), while other parameters showed no difference ($P < 0.05$) [Table 8]. Tukey HSD and Bonferroni tests showed significant differences between Class II and Class III in some parameters ($P < 0.05$) than other skeletal relations.

Discussion

GMM has several advantages over previous methods. One of the important advantages of GMM is the ability to determine the percentage of shape variances explained by each PC which allows us to keep just the most important and significant components for further analysis and visualizing the shape variations in wireframe models by PCA.[17] In this study, different skeletal relations showed 16 PCs while a previous study on the Malaysian population based on GMM showed 14 PCs[11] and the difference between this study result and their result was the number of landmarks that were used. Woon *et al.*[11] used nine hard tissue landmarks on Malaysian three ethnic groups while this study used ten hard tissue landmarks only on Malaysian Malay.

The interesting finding in GMM is the description of shape variability by principal components (PCs), while the size is assessed by the centroid size of each structure.[18] In this study, when the Class I, II, and III skeletal relations were evaluated, the shape variation for hard tissue patterns in PCA was obviously different according to the wireframe graphs and landmarks

deviation from mean. The skeletal relations showed 16 shape variances; therefore, the use of wireframe models of these shape variances could develop novel artificial intelligence systems for predicting skeletal and facial morphology of Malay subjects as a guide in diagnosis and treatment planning by orthodontists and maxillofacial surgeons. This study findings display similarity and agree with previous studies that also used the geometric morphometrics method on dental and skeletal relations; Muñoz & Soto,[2] found that Class I, II, and III had statistically significant differences in a sagittal maxillo-mandibular relationship. Freudenthaler *et al.*[18] evaluated the different malocclusion groups on Caucasians and reported there were significant differences in mean shape among malocclusion groups in which the shape and size of the mandible showed more variations. Woon *et al.*[11] reported a similar result that there were significant differences of ANB angle in all angles` malocclusion groups [Table 9].

The result of Procrustes ANOVA showed that skeletal relations had significant shape differences ($P < 0.0001$) while no differences in centroid size ($P > 0.01$), which resembled a previous study by Woon *et al.*[11] on angle malocclusion groups. As the GMM distinguished the size and shape and showed the shape of the objects regardless of size. The result of this study revealed that the difference between skeletal relations is because of shape variability, and not size.

CVA discovers the shape features that well differentiate between multiple groups of objects. CVA is a common technique designed to classify unknown individuals into pre-specified groups.[17] CVA in this study showed the shape of different skeletal relations had overlapping, as Class I was located between Class II and III. However, skeletal Class II and III had very negligible overlapping [Figure 3]. Also, in CVA, the highest

Mahalanobis distances and Procrustes distances were exhibited by Class II and III among skeletal relations which showed significant differences between Class II and III skeletal relations ($P < 0.0001$). These findings are in agreement with previous studies which evaluated dental and skeletal relations, which were conducted on Chilean samples,[2] on Caucasian samples by Freudenthaler *et al.*[18] and on a Malaysian sample,[11] therefore, this study findings support a separate and distinct craniofacial shape for different patterns and relations especially for Class II and III with a negligible shape similarity.

As mentioned in this study, the skeletal Class II and III shapes were different and had very negligible shapes overlapping in CVA. Moreover, previous different studies also reported significant differences between Class II and III relations. For instance, the condylar parameters and position in the glenoid fossa of TMJ in patients with Class II and Class III malocclusions depicted statistically significant differences. Also, statistical differences in the height of the condylar process were found in Class II and Class III malocclusions.[19] Distal position of the glenoid fossa is a possible diagnostic feature of Class II, while condyle in Class III groups has a superior position in respect to Class II.[2,20] Also, regarding differences
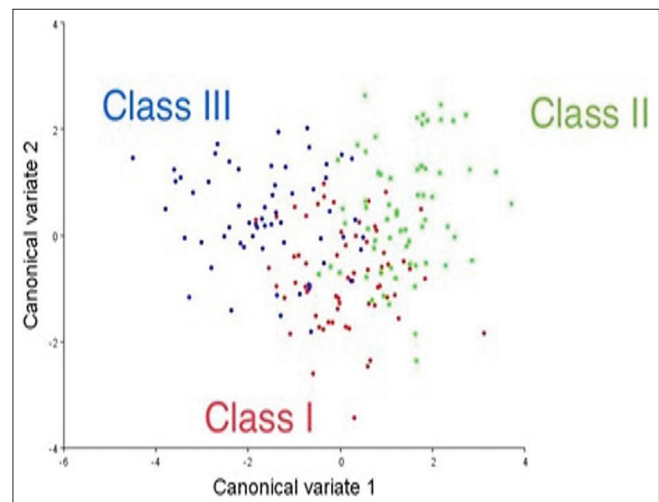

Figure 3: Canonical variate analysis between class I, class II, and class III skeletal relations

Table 5: Discriminant function test and cross-validation test on class II and III

	Class II (Cross-validation)	Class III (Cross-validation)	Total	Classification accuracy (Cross-validation) (%)
Class II	60 (58)	4 (6)	64	93.7% (90.6%)
Class III	8 (10)	52 (50)	60	86.6% (83.3%)

Table 6: Discriminant function test and cross-validation test on females and males

	Female (Cross-validation)	Male (Cross-validation)	Total	Classification accuracy (Cross-validation) (%)
Female	87 (78)	30 (39)	117	74.3% (66.6%)
Male	12 (18)	59 (53)	71	83% (74.6%)

Table 7: Independent *t*-test between males and females

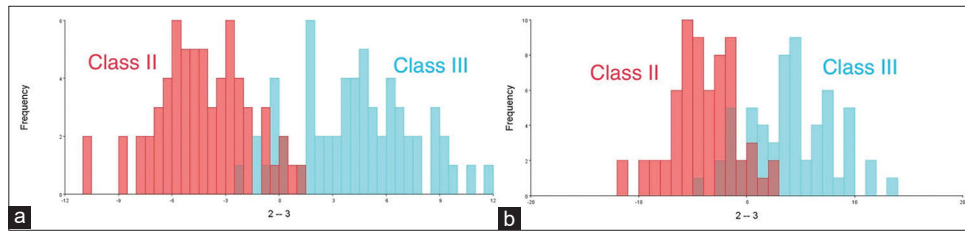|	Gender	N	Mean	Std. Deviation	Std. Error Mean	P
Centroid size	Female	117	7.171137	0.3996864	0.0369510	0.004
	Male	71	7.326236	0.3552805	0.0421640	

Figure 4: Discriminant function analysis graphs between class II and III: (a) Discriminant function score; (b) Cross-validation score
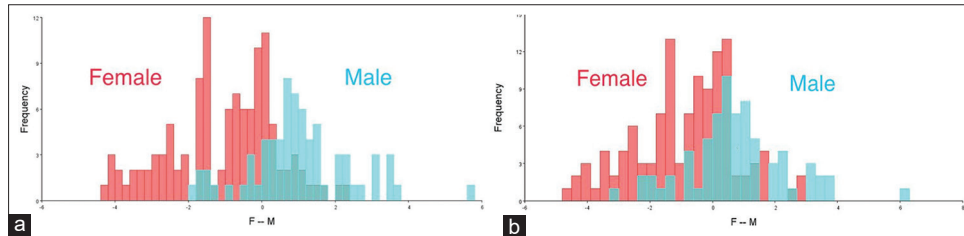

Figure 5: Discriminant function analysis graphs between females and males in class I, II, and III skeletal relations: (a) Discriminant function score; (b) Cross-validation score

Table 8: ANOVA test between parameters (linking of two landmarks)

	df	Mean Square	F	Sig.
Length A				
Between Groups	2	61.238	.006	.994
Within Groups	185	10369.326		
Total	187			
Length B				
Between Groups	2	125.276	.239	.788
Within Groups	185	524.348		
Total	187			
Length C				
Between Groups	2	295.417	.021	.979
Within Groups	185	14109.155		
Total	187			
Length D				
Between Groups	2	66290.954	5.587	.004**
Within Groups	185	11864.860		
Total	187			
Length E				
Between Groups	2	2292.236	3.397	.036*
Within Groups	185	674.742		
Total	187			

Note: **$P<0.01$, significant differences. *$P<0.05$, significant difference

between Class II and Class III skeletal relations, when the shape and size of the sella turcica in Saudi subjects were compared in different skeletal patterns, there were significant differences in the diameter of sella between the Class II and Class III subjects. Skeletal Class III had the larger diameter while Class II subjects had the smaller diameter sizes.[21] Between Class II and III patients, significant variations were discovered in airway volume and mean airway area. Class III patients had a larger axial area and airway morphology than Class I and II patients.[22] The above-mentioned studies showed agreement with the results of this study regarding differences between Class II and Class III skeletal relations in different skeletal landmarks and structures.

Discriminant function analysis (DFA) is another analysis after Procrustes Superimposition performing was applied to analyze the data. In this study, DFA in different skeletal relations showed the most classification accuracy for Class II and Class III skeletal relations, with success rates after cross-validation, 90.6%, and 83.3%, respectively, which was similar to Woon *et al*.[11] that reported Class II and Class III showed the highest classification accuracy with success rates of 80% and 71% respectively. Regarding Discriminant function analysis in angle malocclusion groups, when the landmarks were located solely on bony structure and regard to their occlusion, 64.5% of the patients were correctly classified. When the landmarks were located on molars and incisors, 80.3% of the patients were correctly classified.[18] A previous study in Germany was performed to distinguish between Class III individuals who can be treated effectively with orthodontics and those who require orthognathic surgery. Twenty linear and angular measurements were used in that study. For dentoskeletal variables identification, discriminant analysis was applied, and the result showed 92% of the patients were correctly classified.[23]

The result of this study could be used for creating an artificial intelligence system in orthodontics and maxillofacial fields. Recently artificial intelligence (AI) technology is broadly used for detecting cephalometric landmarks, predicting the need for orthodontic treatment, determining the tooth extractions needs in

Table 9: Previous similar 2-dimensional geometric morphometric method (GMM) studies

Authors	Sample size	Age ranges	Method of study	Landmarks	Ethnicity	Study groups	Findings
(Díaz Muñoz & Manríquez Soto, 2014)[2]	150	12-20 (Males-females)	2D-GMM	15 hard tissue landmarks	Chilean sample (Santiago, Chile)	Skeletal malocclusions class I, II Division 1 and III	Statistically significant differences in class I, II and III: Greater degree, with a sagittal maxillo-mandibular relationship Lesser degree with a vertical growth pattern.
Freudenthaler *et al*., (2017)[18]	88	7-39 (Males-females)	2D-GMM	16 hard tissue landmarks	Caucasian (Vienna, Austria)	Angle class I, II, and III malocclusions and open bite	Mandible shape variation in malocclusion. Less shape variation maxillary and cranial base.
(Woon *et al*., 2019)[11]	381	18-45 (Males-females)	2D-GMM	9 hard tissue landmarks	Malaysian population (Malay, Chinese and Indian)	Angles class I, II, and III malocclusions	Widest ANB angle in class II Most acute ANB angle in class III.
This study 2021	188	18-40 (Males-females)	2D-GMM	10 hard tissue landmarks	Malaysian Malay	Class I, II, and III Skeletal relations	Different ANB angles. Statistically differences between (A-point and B-point) and (B-point and Pogonion).

orthodontic cases, predicting the facial attractiveness after orthognathic surgery, and orthodontic treatment planning.[6] For instance, Tanikawa & Yamashiro,[7] in their study tried to create artificial intelligence (AI) systems that could predict three-dimensional (3D) facial morphology after orthognathic surgery and orthodontic treatment based on past treatment results. They used landmark-based geometric morphometrics methods (GMM) combined with deep learning methods to develop two AI systems to predict facial morphology after orthognathic surgery and orthodontic treatment, where predictive variables were cephalometric changes throughout treatment and the coordinate values of the faces before to treatment. They successfully developed an AI system with the combination of GMM and deep learning. Therefore, the result of this study combined with deep learning methods could develop an AI system for the Malaysian Malay population for facial morphology prediction in orthodontic treatment, orthognathic and maxillofacial surgeries.

Conclusion

The different skeletal relations had shown different shape and size variations of hard tissue patterns by the geometric morphometrics method. There were different ANB angles in different skeletal relations. The null hypothesis that there is no significant difference in hard tissue characteristics and no significant gender difference between different skeletal relations could be fully rejected. The results of our study provided novel wireframe models for hard tissue patterns of Class I, II, and III skeletal relations. Those wireframe models could be used to develop novel artificial intelligence systems for predicting skeletal and facial morphology of Malay subjects as a guide in diagnosis and treatment planning by orthodontists and maxillofacial surgeons. It is recommended that future studies on facial hard tissue patterns in Malaysia include other racial subgroups in the country.

Conflicts of interest
There are no conflicts of interest.

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