GEOMETRIC MORPHOMETRIC STUDY OF MANDIBULAR BODY MORPHOLOGY IN CHILDREN: IMPLICATIONS FOR FORENSIC AGE AND SEX ESTIMATION

KAJIAN MORFOMETRIK GEOMETRI TERHADAP MORFOLOGI BADAN MANDIBULA DALAM KALANGAN KANAK-KANAK: IMPLIKASI TERHADAP ANGGARAN UMUR DAN JANTINA DALAM FORENSIK

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ABSTRACT

The mandible is one of the bones that have special characteristics in comparison to other bones. The mandible is the strongest bone on the face and an important part of the forensic profile. The purpose of this study was to identify differences in the morphology of the mandible body related to age and sex in children used on the panoramic radiograph. Eight anatomical landmarks were digitised on 305 panoramic radiographs (159 male and 146 female) using TPSdig2 software. The shape data were analysed with MorphoJ using Generalised Procrustes Analysis (GPA), Principal Component Analysis (PCA), Canonical Variate Analysis (CVA), and Discriminant Function Analysis (DFA). The shape and size differences were tested by Procrustes ANOVA. Two groups (G1 male and G2 female) were used for the determination of sex, while three age groups (3 to 6, 7 to 9 and 10 to 12 years) were tested for age prediction. Morphological variation was visualised with wireframe and lollipop diagrams. The total shape variation was explained by the first four principal components (PC1–PC4) covering 82%. DFA accuracy to classify sex was 64.15% (G1) and 67.12% (G2), and of cross validation was 61.64%, and 63.70%. While in age group, the accuracy between 80.17% to 93.68%. Procrustes ANOVA revealed no difference in centroid size for the sexes, but significant differences in shape ($p < 0.001$). Shape variations were significant between age groups ($p < 0.001$). Geometric morphometric techniques can demonstrate discriminatory features in mandibular body shape for age and sex. It's a useful screening tool for forensics in cases involving children.

Keywords: Forensic odontology, Geometric morphometrics, Mandible, Age estimation, Sex estimation, Panoramic radiograph

ABSTRAK

Mandibula merupakan salah satu tulang yang mempunyai ciri khas berbanding tulang lain. Ia adalah tulang paling kuat pada bahagian wajah dan memainkan peranan penting dalam profil forensik. Kajian ini bertujuan mengenal pasti perbezaan morfologi badan mandibula yang berkaitan dengan umur dan jantina dalam kalangan kanak-kanak melalui radiograf panoramik. Sebanyak lapan titik anatomi telah didigitalkan pada 305 radiograf panoramik (159 lelaki dan 146 perempuan) menggunakan perisian TPSdig2. Data bentuk dianalisis melalui MorphoJ menggunakan Analisis Prokrustes Teragih (GPA), Analisis Komponen Utama (PCA), Analisis Variat Kanonikal (CVA), dan Analisis Fungsi Diskriminan (DFA). Perbezaan bentuk dan saiz diuji menggunakan Procrustes ANOVA. Dua kumpulan (G1 lelaki dan G2 perempuan) digunakan untuk penentuan jantina, manakala tiga kumpulan umur (3–6, 7–9 dan 10–12 tahun) diuji untuk ramalan umur. Variasi morfologi divisualisasikan melalui rajah wayar (wireframe) dan lollipop. Jumlah variasi bentuk dijelaskan oleh empat komponen utama pertama (PC1–PC4) meliputi 82%. Ketepatan DFA dalam mengklasifikasikan jantina ialah 64.15% (G1) dan 67.12% (G2), manakala ketepatan pengesahan silang ialah 61.64% dan 63.70%. Bagi kumpulan umur, ketepatan klasifikasi adalah antara 80.17% hingga 93.68%. Procrustes ANOVA mendapati tiada perbezaan saiz centroid antara jantina, namun terdapat perbezaan signifikan dalam bentuk (p < 0.001). Variasi bentuk juga signifikan antara kumpulan umur (p < 0.001). Teknik morfometrik geometri berupaya menunjukkan ciri diskriminatif dalam bentuk badan mandibula bagi tujuan anggaran umur dan jantina. Ia merupakan alat saringan yang berguna dalam bidang forensik melibatkan kes kanak-kanak.

Kata kunci: *Odontologi forensik, morfometrik geometri, mandibula, anggaran umur, anggaran jantina, radiograf panoramik*

Introduction

The mandible is unique both structurally and functionally compared to other craniofacial bones. It is structurally part of the lower face, contributes to mastication, and serves as an insertion for several muscles of speech and facial expression (Toneva et al. 2023). As it is the only bone capable of movement in the skull, its form presents combined genetic and environmental information. The mandible remains intact after decomposition and is resistant to trauma due to its thick cortical bone, thus being an important component in forensic recovery (Motawei et al. 2020). These features make the mandible an important part of forensic odontology, especially when other skull bones are missing. However, its shape varies between populations, so specific morphometric standards are needed for each group.

In forensic odontology, the mandible is a critical parameter for sex and age estimation, often in cases of incomplete-skeletal remains. Morphological characteristics of ramus height, gonial angle, and corpus thickness have been shown to be significantly different between males and females (Fan et al. 2019; Toneva et al. 2023). The maturational and remodelling processes of the mandible that allow to estimate age in children also represent the basis for sexual dimorphic changes induced by hormonal or biomechanical regulators at any stage of life (Smith et al. 2021). These dimorphic patterns were shown to also be present in adolescents and therefore useful for subadult identification (Puspa Larasati et al. 2025). Radiographic imaging is commonly used by the forensic experts to measure such variations non-invasively (Sharma et al. 2025). These analyses allow for an objective evaluation of the mandibular form and dimensions in terms of quantitative parameters. Nevertheless, sexual dimorphism varies between populations, and the general use of existing reference data remains difficult.

The estimation of age using mandible morphology has also gained attention in paediatric forensic research. The mandible undergoes significant growth and remodelling throughout childhood and adolescence, accompanied by dental eruption and skeletal maturity (Hsiao et al., 2020). Geometric morphometric analysis emerges as a robust method to quantify these changes by assessing the spatial arrangement of anatomical landmarks (Toneva et al., 2023). Studies have shown that mandibular measurements, particularly in the body and alveolar regions, exhibit predictable age-related changes (Smith et al., 2021). The formulation of age-related trends in the mandibular structure enhances the reliability of biological profiles for immature individuals. However, the diverse growth patterns observed in children from different ethnic groups pose a challenge in developing age estimation models that are applicable to all age stages.

Geometric morphometric analysis has revolutionised the study of skeletal variation by focussing on shape rather than size. Unlike traditional morphometric methods, it maintains the spatial relationship between landmarks, enabling detailed visualisations of shape differences (Fan et al. 2019; Vila-Blanco et al. 2021). This approach has been successfully applied to assess mandibular asymmetry, growth trends, and sexual dimorphism in various populations (Puspa Larasati et al. 2025). Techniques like Procrustes and principal component analysis further aid researchers in separating biologically based shape variation from measurement error, providing insights into the developmental processes that shape the mandible. In addition, radiographic imaging combined with a geometric morphometric approach increases the accuracy of the forensic application, but its reliability depends on the proper placement of the landmark and image registration.

More recent technological advances, particularly the integration of artificial intelligence (AI) and deep learning, have revolutionised the morphometry process. These automated algorithms for landmark identification and shape recognition enhance efficiency and minimise observer bias (Vila-Blanco et al. 2021). In addition, these methods can efficiently analyse vast radiographic datasets, enabling the extraction of crucial morphometric variables to determine sex and age (Sharma et al. 2025). Automated-assisted morphometrics not only enhances replicability and objectivity, but also facilitates the detection of subtle morphological variations, contributing to robust forensic identification. However, it is essential to exercise caution when relying solely on algorithmic models without context-specific validation, as this approach may oversimplify the intricate biological variability inherent in human anatomy. This study aims to assess the morphology of the mandibular body in children, considering their age and sex, using panoramic radiographs. The mandibular body is a suitable choice because it allows the evaluation of relatively stable and less influenced dental structures. Geometric morphometrics will be used to study shape variations between age groups and between males and females, enabling the generation of quantitative data for forensic evaluations (Puspa Larasati et al. 2025). Appreciating these differences will help to create population-based databases that improve precision in paediatric forensic recognition. However, further validation in diverse paediatric populations is necessary to assess the forensic reliability of this digital factor and its broader applicability.

Methodology

A total of 305 panoramic radiographs (159 males and 146 females) were used to digitize eight anatomic landmarks on TPSdig2 software (version 2.32). Landmark data were analysed in MorphoJ using Generalized Procrustes Analysis (GPA) for superimposition of position, scale and orientation. Additional analyses comprised PCA to compare overall shape differences, CVA to estimate morphological divergence between groups, and DFA as a measure of sex and age-related classification accuracy. Differences in shape and size were investigated by Procrustes ANOVA. The sex character of the samples was classified as G1 (male) and G2 (female). In case of age estimation, the samples were grouped into three different age categories: 3-6 years, 7-9 years and 10-12 years. Shape changes were graphically represented by wireframe and lollipop diagrams as a visualization of morphological variation. This research obtained ethics approval from the Research Ethics Committee, Universiti Sains Islam Malaysia, with the ethics number USIM/JKEP/2024-299.

Landmark applications

Landmarks were digitized using tpsDig2 (Ver. 2. 32) programme. In this study, a total of eight two dimensional bone markers as defined in Table 1 and Figure 1. The landmark marking was first demonstrated by the supervisor and then tested using Kappa correlation intra-rater reliability test to know how much of accuracy and consistency they have in landmarking done with respect to the students, also an inter-rater reliability test 2 weeks later to obtain acquired accuracy and consistency between two students on landmarking mandible. The landmark was modified and chosen from previous study (Rosli et al. 2025).

Table 1. Definition and number of landmarks on the mandibular body of panoramic radiographs

No.	Landmark	Definition
1	Mandibular bodyr notch (Bmn)	The deepest part on body of mandible (right)
2	Mental Foramen	Mental foramen (right)
3	Gnathion (Gn)	The middle point on the lower border of mandible
4	Mental Foramen	Mental foramen (left)
5	Mandibular bodyr notch (Bmn)	The deepest part on body of mandible (left)
6	First molar (Fm)	Distal to first molar of lower arch (left)
7	Incisor (Icr)	Between two mandible central incisors
8	First molar (Fm)	Distal to first molar of lower arch (right)

Figure 1. 8 mandibular body landmarks on panoramic radiograph

Analysis of data

The 2D coordinates of the landmarks were analysed with the shape analysis programme MorphoJ. In order to eliminate the nonshape variation in sample, a generalized Procrustes analysis (GPA) of raw landmark coordinates from each mandibular body in the panoramic radiograph was executed. The following are procedures that include translation, rescaling, and rotation. In order to scale the landmark data in an anatomically realistic way, a scaled version of the landmark coordinates was used as a measure of total size of the hard tissue image. Consequently, each mandibular body possesses a unit centroid size in panoramic radiographs.

Data were classified based on shape similarity by principal component analysis (PCA). PC scores and wireframe overlays were employed to help identify and illustrate the shape differences identified by PCA. Canonical variate analysis (CVA) was used as an exploratory technique for the grouped data. The distances between groups were computed by CVA according to group centroid based on the sample.

Accuracy of the classification was assessed with discriminant function analysis with cross-validation. The scores on the PC from GPA/PCA of the sample were used as input in both analyses.

Results

Generalized Procrustes Analysis (GPA)

The effect of nonshape variation among the samples was eliminated using GPA where interlandmark distances, resulting from each specimen's position during digitalisation, were minimised and sizes were standardised. Data set contained 305 panoramic radiographs with 8 landmarks (Figure 2). The blue dots correspond to the mean landmark positions, and the little black dots to the landmark position in each configuration of a sample. The numbering and location of the landmarks are given in red numbers.
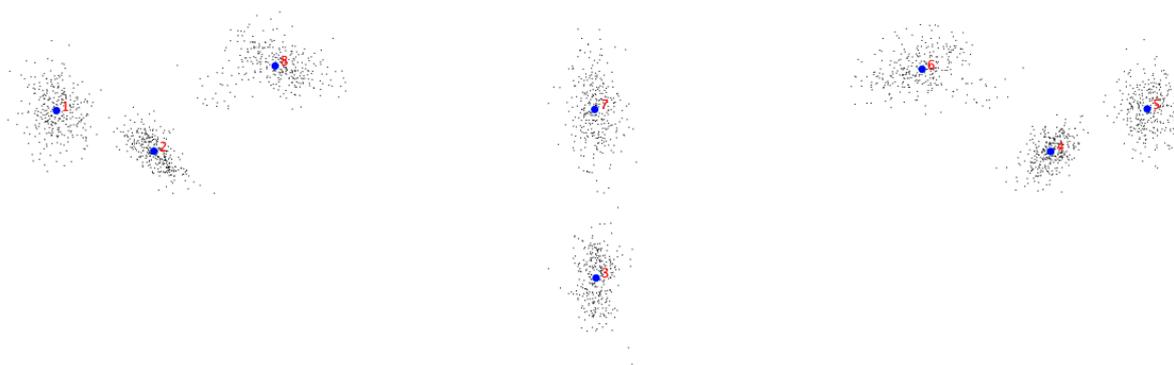

Figure 2. Generalized Procrustes Analysis (GPA)

Principal Component Analysis (PCA)

PCA is a technique for multivariate exploratory analysis. It does have a role as displaying the primary modes of shape variation in a data set and as an ordination technique that reveals pattern. Results of the main component analysis 12 main components responsible for distributing 100% of the variation shown by mandibular body were generated through this main component analysis. This also suggested that there were 12 factors involved in the formation of the shape of mandibular body, where the number of PCs was related to the count data. The analysis showed 12 principal components, hence, there were variances in 12 aspects to the data. Total variance of data set was 0.005 that is small variance. The PCA derived eigenvalue, principal component and the percentage total variance of which are provided in Table 2. Equivalent plot of the percent variance and principal components are provided in Fig. 3.

As can be seen from Table 2, the reduction in percent variance was somewhat less marked although there was a greater fall between PC1 and PC4. PC1 accounted for 38,13% of the sample total variance, PC2 contribute 28.43%, PC3 was around to contribute 9.88% and PC4 contribute 5.68%. Scatters plots for any combination of the 12 PCs can be run in MorphoJ, but given that the first PCs describe most of the variance in the entire sample, interpretation will concentrate on these first ones. The 12 primary factors of this study were divided into four PCs, PC1 through PC4 all showing significant differences (Table 2, Figure 3).

Table 2. Table of Eigenvalues, percent variance and cumulative percent of each principal component

PC	Eigenvalues	% Variance	Cumulative %
1.	0.00216519	38.133	38.133
2.	0.00161465	28.437	66.570
3.	0.00056139	9.887	76.457
4.	0.00032282	5.686	82.142
5.	0.00028256	4.976	87.119
6.	0.00021203	3.734	90.853
7.	0.00017681	3.114	93.967
8.	0.00014456	2.546	96.513
9.	0.00009441	1.663	98.176
10.	0.00005270	0.928	99.104
11.	0.00004073	0.717	99.821
12.	0.00001014	0.179	100.000

The changes in the average shape and its variability across PCs can be illustrated using wireframe plots. Wireframe graph based on the components is given in Figure 4 that depicts shape variation evaluated from the components. The wireframe plot depicted in Figure 4 illustrates the shape changes represented by PC1. Each point is a landmark on the mandibular body, with the light blue line showing the mean form and the dark blue line showing variation at that location. In PCA, the variance is explained by PC and PCs are ordered according to their decreasing importance. PC1 explains the largest proportion of variation in the sample, and subsequent PCs explain remaining decreasing portions (that is, PC2 explains more than PC3, which in turn explains more than PC4).
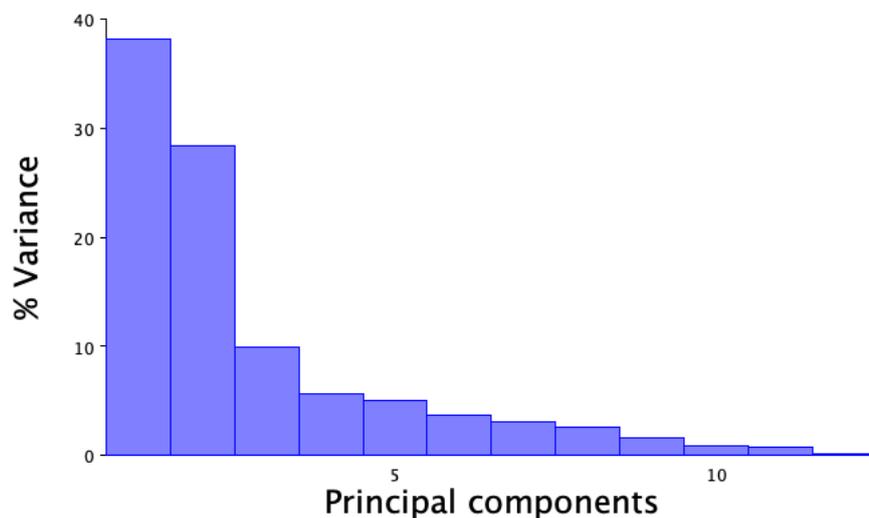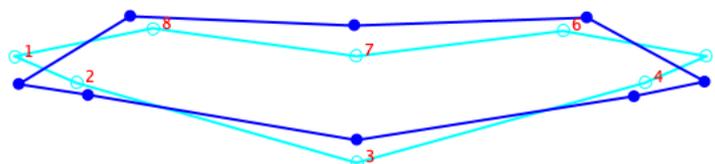
**Figure 3.** Screen plot that denotes the variance of mandibular body shape

PC1

As it is observed in the table of eigenvalues (Table 2), 12 PCs explain the 100% of variance on mandibular body sample, though differences between one PC and another are small except for PC2 and PC3. PC2 explained 28.43% of the variation (Figure 5). The PC3 accounted for 9.88% of the variation (Figure 6) and the PC 4 variance 5,68% (Figure 7).
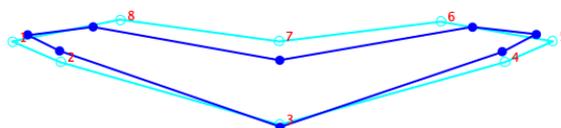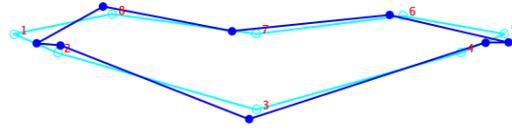

PC2

Figure 5. Wireframe graph with mandibular body shape changes of the PC2
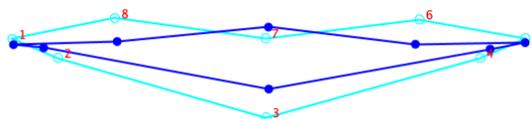
PC3

Figure 6. Wireframe graph with mandibular body shape changes of the PC3

PC4

Figure 7. Wireframe graph with mandibular body shape changes of the PC4
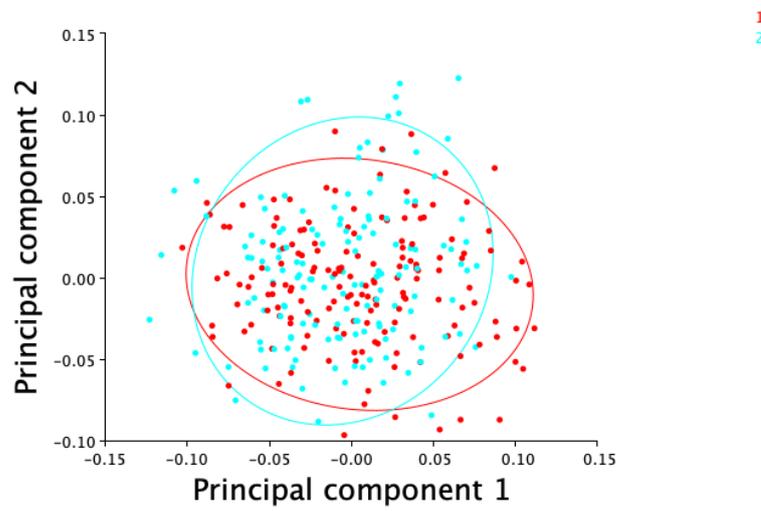

Figure 8. Principal component analysis in different sex groups (red: male, blue : female)
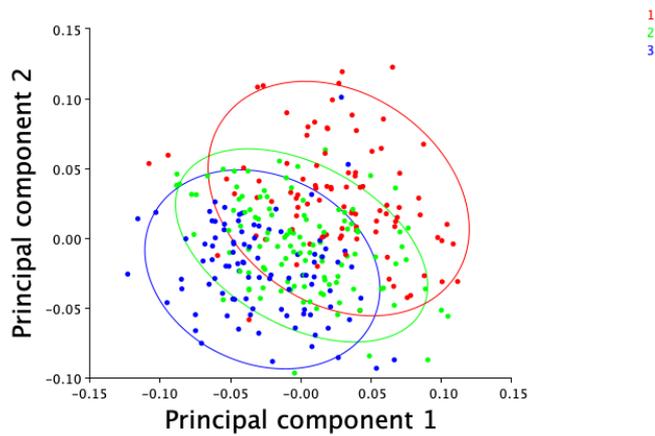

Figure 9. Principal component analysis in different age groups
(red : group 1, green : group 2, blue : group 3)

Procrustes ANOVA

Procrustes ANOVA can be used to test differences between individuals and estimate error in the samples. The morphological effects (sex, and age group) explained were given by the Procrustes ANOVA analysis and presented in different ANOVA tables for size and centroid shape (Table 3, Table 4). The centroid size in this study did not differ among the sex group, and age groups.

Results indicated that percent of total sum of square (SS) shape were higher for age characteristic as 92.30% and lower percent was for sex parameter as 7.0%, respectively (Table 4). In the age group, there was a significant mandibular body variation according to Procrustes ANOVA (p< 0.01). The shape was found with a significant effect in sex and age but with smaller effect in the sex group. Morphological variation in Procrustes ANOVA The shape component of the variation among the sex and age groups was significant (p< 0.0001) (Table 4).

Table 3. The effect of size on the age and sex groups

Effect	SS	SS%	MS	dF	F	P
Age	872169.973593	99.04	436084.986796	2	19.54	0.0487
Sex	8403.215315	0.96	8403.215315	1	0.38	0.6019
Total	880573.188908	100				

Sums of squares (SS), mean squares (MS), degrees of freedom (df)

Tabel 4. The effect of shape on the age and sex groups

Effect	SS	SS%	MS	dF	F	P
Age	0.28511292	92.30	0.0118797048	24	11.03	<.0001**
Sex	0.02375558	7.70	0.0019796318	12	1.84	0.0988
Total	0.3088685	100				

Sums of squares (SS), mean squares (MS), degrees of freedom (df), **p<0,01

Canonical Variate Analysis (CVA)

Subsequent geometric morphometric analysis was used to explore which landmarks could be the most important in biological profile and subgroups. Differences in the biological profile with more than two categories (sex and age) were tested using CVA. CVA is a multivariate statistical procedure to ascertain shape characters that can discriminate between groups of samples.

Age Group

Participants were separated into three age categories. Among 305 specimens, 94 subjects were group 1 (3-6 years old), 116 with group 2 (7 to 9 years old) and the rest of research 95 samples were Group 3(10-12 years old). The illustrated change with wireframe graph in Figure 10. Figure 8 demonstrated a significantly difference between group 1, group 2 and group 3 distributed in the centre of regarding ages. The Mahalanobis distances indicated a shape difference between age groups (p<0.0001). The p-values are from the Permutation test (10000 permutations) for the Mahalanobis distances between groups (Table 5). The distances among the age groups presented a considerable difference in mandible size from the permutation test (10000 permutations rounds) between the distance in relation to the ages (p<0.0001).
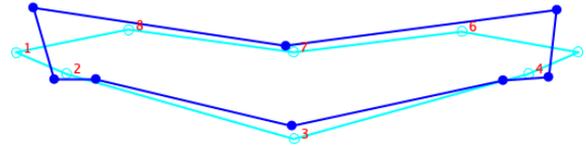
CV1

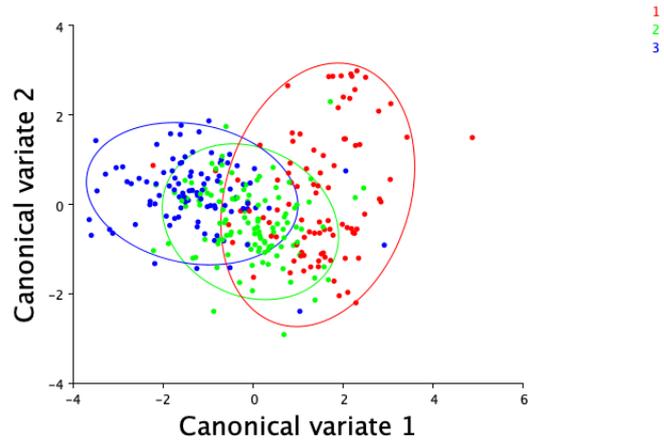**Figure 10.** Wireframe graphs illustrating the shape changes on the CV1

Figure 11. Canonical variate analysis in different age groups
(red : group 1, green : group 2, blue : group 3)

Table 5. Mahalanobis distances and Procrustes distances among age groups

	Mahalanobis distance			Procrustes distance	
Age group	Group 1	Group 2	Age group	Group 1	Group 2
Group 2	1.6137 **p<0.0001		Group 2	0.0437 **p<0.0001	
Group 3	2.7892 **p<0.0001	1.4412 **p<0.0001	Group 3	0.0762 **p<0.0001	0.0360 **p<0.0001

P Values from permutation test (10000 permutations rounds) for mahalanobis distances among groups, **p<0,01
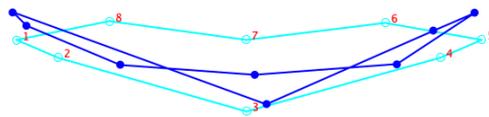
Sex Group

Subjects were categorized according to sex. Among 305 cases, there were Group 1 (Male) having 159 specimens and Group 2 (Female) with 146 ones. The body of mandibular differences in male and female is not very distinct.

As it was observed in Fig 12, there were no statistically significant differences between group 1 and group 2 due to both bar overlapped each other. According to mahalanobis distances, shape was significantly different among sex groups (p< 0.0001). The p values were based on permutation test (10000 times of permutations) for group differences of the mahalanobis distance (Table 6). The

procrustes distances between the sex groups were significantly different according to permutation test (10000 permutation rounds) of the procrustes distance among age classes (p< 0.0030) (Table 6).

CV1

Figure 11. Wireframe graphs illustrating the differences of body mandibular in male and female children

Table 6. Mahalanobis distances and Procrustes distances among sex groups

Mahalanobis distance		Procrustes distance	
Sex group	Male	Sex group	Male
Female	0.7735	Female	0.0177
	**p<0.0001		**p<0.0030

P Values from permutation test (10000 permutations rounds) for mahalanobis distances among groups, **p<0,01
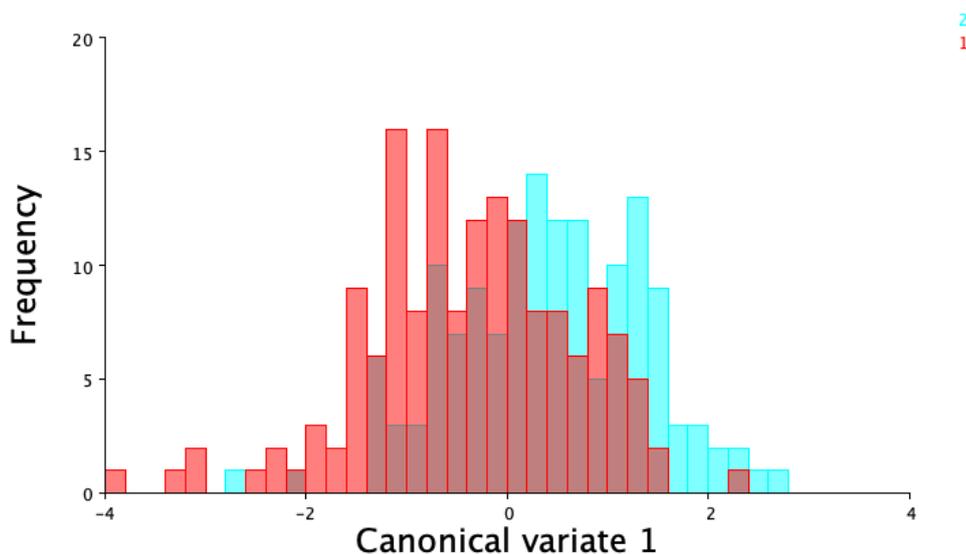

Figure 12. Canonical variate analysis in different sex groups (red : male, blue : female)

Discriminant Function Analysis **(DFA)**

The discriminant function test was also computed in MorphoJ. Procrustes distances for each individual along each reference point were measured.

Age Group

The percentage of correctly classified cases were between 80.17 % and 93.68 % of the grouped original cases. Cross-validation was done only for these cases in the analysis. During the cross-validation, each patient was categorized by the classifiers that were trained on all patients. Between 75.86% and 92.63% of the cross-validated grouped cases were classified correctly by age (Table 7).

Table 7. Discriminant function analysis and cross validation in different age groups

Group	Group 1	Group 2	Group 3	Total	Percentage
Discriminant function analysis					
Group 1	76	18	-	94	80.85
Group 2	18	98	-	116	84.48
Group 1	86	-	8	94	91.49
Group 3	6	-	89	95	93.68
Group 2	-	93	23	116	80,17
Group 3	-	18	77	95	81.05
Cross validation					
Group 1	74	20	-	94	78.72
Group 2	26	90	-	116	77.59
Group 1	84	-	10	94	89.36
Group 3	7	-	88	95	92.63
Group 2	-	88	28	116	75.86
Group 3	-	23	72	95	75.79

Sex Group

Around 64.15% of the original cases well-clustered were correctly identified. Cross-validation was only performed over those cases in analysis. Each subject was classified by cross-validation with all subjects. Cross-validated accuracy rate of age group was 61.64% (Table 8).

Tabel 8. Discriminant function analysis and cross validation in different sex groups

Sex	Male	Female	Total	Percentage
Discriminant function analysis				
Male	102	57	159	64.15

Female	48	98	146	67.12
Cross validation				
Male	98	61	159	61.64
Female	53	93	146	63.70

Discussion

Age and sex estimation from skeletal material is a key consideration in forensic odontology, especially in subadult identification. When analysis cannot be performed on the dental eruption because of unerupted or missing teeth, the mandible is a structurally reliable element to assess (Rosli et al. 2025). The mandible is the largest and strongest bone of the face, therefore it could withstand post-mortem damage and is usually found intact even in advanced trauma (Fekonja & Čretnik 2022). It also offers morphological traits that are un-ambiguous and amenable to the quantitative assessment using geometric morphometric techniques (Zulkifli et al. 2023). These methods provide for the detailed shape comparison through superimposition of the homologous landmarks, when it comes to age or gender variation (Klop & MAGIC Amsterdam 2021). The mandible has been demonstrated to be both functionally and developmentally adaptive through growth (O'Sullivan et al 2022). The theoretical basis is borne out in the present study, which shows that body mandibular shape constitutes a significant parameter for estimating age of children with the use of panoramic radiographs.

Many morphometric studies have studied the mandibular landmarks and their association with developmental modifications. Gonial angle, height of the ramus and curvature of the corpus were found to differ significantly according to age during progressive ossification and remodelling (Toneva et al. 2023). Procrustes superimposition removes nonshape variation, and Principal Component Analysis (PCA) reveals the major directions of shape variance (Zulkifli et al. 2023). The first four principal components accounted for greater than 80 per cent of the total shape variance in this study, which was similar to that reported in 2D and 3D models describing mandibular growth (O'Sullivan et al. 2022). Wireframe technique was used for visualization and it showed the developmental trend, in which mandible became elongated posteriorly (due to increased growth of condylar process) and depressor anterior margin with increasing age, which was also consistent with paediatric developmental trends (Ulusoy & Ozkara 2022). These morphological shifts correspond with changes in mastication and tooth eruption (Hsiao et al. 2020). In general, the results support that mandibular body remodelling follows closely biological maturation trends in this sample.

The Procrustes ANOVA identified age as having a significant effect on mandible shape, but sex differences not reaching statistical significance (Rosli et al., 2025). This observation is consistent with a previous finding that sexual dimorphism appears after 11.5 years of age (Fan et al. 2019). A CVA showed distinct age separation but sexually high overlapped shapes again, indicating little morphological disparity during the course of childhood (Fekonja & Čretnik 2022). Previous studies also showed that children's mandibular development was growth-related remodeling but not hormone dependent (Motawei et al. 2020). Additionally, the Mahalanobis and Procrustes distances yielded also supported that there was an increased degree of shape variation between birth – 2 years, 2 – 6 years, and 2 – 12.9 years old (Smith et al. 2021). These results are matched with normal standards of growth patterns from morphometric studies on paediatric developing body forms (Zulkifli et al. 2023). The finding at the present thus suggested that age is a predominant factor for consideration of mandibular body shape among children in the sample studied here.

The age group classification is also relatively good (80-93%) by the DFA, even with cross-validation (Puspa Larasati et al. 2025). This proves that it is effective tool for recognizing development stages in subadults (Rosli et al. 2025). In contrast, sex classification accuracy was strikingly lower, reflecting that the dimorphism in the mandible emerges at post-pubertal ages (Toneva et al. 2023). Parallel findings were mentioned in panoramic and CBCT studies (Ulusoy & Ozkara 2022). Geometric morphometrics therefore represents a stronger avenue for age estimation rather than sex determination

in children (Bertsatos et al. 2019). These findings confirm the applicability of landmark-based morphometric techniques in constructing population-specific forensic models of identification (Zulkifli et al. 2023). The relatively high precision in age classification documented by this study further indicates the reliability of the mandibular body as a morphologic surrogate marker for developmental stage estimation.

The mandible has been well established in forensic odontology as a persistent and diagnostic part for human identification. its cortical density and preservation make it well suited for recovery and analysis from even decomposed or damaged remains (Toneva et al. 2023). Geometric morphometric techniques, which retain information on positional relationships of landmarks, provide greater accuracy than traditional linear metrics (Vila-Blanco et al. 2021). Panoramic radiographs offer an efficient, non-invasive, and low-cost imaging medium for use in morphometric analysis within large paediatric populations (Sharma et al. 2025). Although 2D, it is still accepted as a valid image modality of reference asking for forensic evaluation in absence of 3D imaging (Zulkifli et al. 2023). The future development of software allowing automatic detection by artificial intelligence (AI), particularly for landmarks, could also enhance reproducibility and reduce the bias associated with human observers (Alahmari et al. 2025). These methodological qualities combine to validate the application of mandibular body morphometrics for age estimation in paediatric forensic identification.

Nevertheless, there are some points worth considering when interpreting the present results. First, the number of anatomical landmarks was low and possibly minimised the impact of the inclusion of a complicated mandibular shape change (Puspa Larasati et al. 2025). One shortcoming is the case where 2D measurements are restricted to assessing asymmetry and volumetric depth when a full 3D image could have contained the same information (Natarajan et al., 2024). Environmental and biological influences, such as diet, race, and dental eruption, can shape mandibular morphology (Medialdea et al. 2021). Construction of 3D statistical models from multiethnic samples can improve transferability of geometric morphometric result (Klop & MAGIC Amsterdam 2021). It would be possible to enhance the accuracy of shape extraction and evaluation by associating it with AI based image segmentation (Alahmari et al. 2025). Increased data representation through cooperative data analysis will improve population-specific forensic reference models for age estimation in subadults (Rosli et al., 2025). In this context, all those comments present evidence of the relevance of our paper as pioneering and base laying enterprise on geometric morphometrics applications in paediatric forensic odontology.

Conclusions

This study demonstrated that Geometric morphometric analysis is a useful tool for age-related variation in the mandibular body in children. The results also showed a greater significance of age in determining the shape of the mandible than sex, suggesting that the mandible undergoes an active bone remodelling during growth. The method was reliable in estimating the age of children based on panoramic radiographs. Ultimately, the shape of the mandibular body can be a useful and robust line of evidence for forensic identification in subadult individuals.

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