Journal of Dental Sciences 19 (2024) 364–376

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.e-jds.com

Journal of Dental Sciences

Original Article

# Comparison of the transverse cranial base dimension in different craniofacial skeletal relationships: A cone-beam computed tomography study

**Szu-Ting Chou [a,b], Shih-Hsuan Lin [a,b], Shih-Chieh Chen [a,b], Chun-Ming Chen [a,c], Yu-Chuan Tseng [a,b*]**

[a] *School of Dentistry, College of Dental Medicine, Kaohsiung Medical University, Kaohsiung, Taiwan*
[b] *Department of Orthodontics, Kaohsiung Medical University Hospital, Kaohsiung, Taiwan*
[c] *Department of Oral and Maxillofacial Surgery, Kaohsiung Medical University Hospital, Kaohsiung, Taiwan*

Received 30 May 2023; Final revision received 15 July 2023
Available online 26 July 2023

**KEYWORDS**
Cone-beam computed tomography;
Cranial base;
Transverse dimension;
Craniofacial skeletal pattern;
Sexual dimorphism

**Abstract** *Background/purpose:* In comparing the cranial base's size, most cephalometric studies focused on the length and angle in the anteroposterior direction. However, investigating the anterior, middle, and posterior cranial base's transverse dimensions is challenging. This study aimed to investigate the transverse dimensions of the cranial base in different craniofacial skeletal patterns and sexes using cone-beam computed tomography (CBCT).
*Materials and methods:* A total of 210 adults (105 males and 105 females), including three different skeletal relationships, were included in the study. The cranial base dimensions were measured on a three-dimensional image structure rendered by CBCT. Statistical methods included the Kappa statistic for analysis of consistency and reproducibility and the independent *t*-test for differences in cranial base dimensions between sexes. A general linear model (GLM) was used to compare the transverse size of the cranial base among skeletal Class I, II, and III groups. The Pearson correlation coefficient explored the correlation among the cranial base dimensions.
*Results:* The cranial base dimensions did not differ significantly between skeletal Class I, II, and III. The more prominent cranial base size was found in males than females, except for the crista galli length (CGL) and cribriform ethmoid plate width (CEPW). The cranial base dimensions did not differ significantly between different skeletal relationships. Most dimensions have significant correlations in the middle and the posterior cranial base.

* Corresponding author. School of Dentistry, College of Dental Medicine, Kaohsiung Medical University, 100 Shih-Chuan, 1st Road, Kaohsiung 80708, Taiwan.
*E-mail address:* tsengyc@kmu.edu.tw (Y.-C. Tseng).

https://doi.org/10.1016/j.jds.2023.07.018

*Conclusion:* The cranial base's transverse dimensions in Taiwanese adults show no significant differences between craniofacial skeletal relationships. In the middle and posterior cranial base, transverse measurements reveal significant sexual dimorphism.


## Introduction

The cranial base forms the base of the cranial vault, extending backward from the foramen cecum in the front and to the basioccipital bone in the back. The cranial base belongs to the midline structure, including part of the nasal, orbital, ethmoid, sphenoid, and occipital bone. The cranial base comprises the anterior limb, which is from sella (S) to nasion (N), and the posterior limb, which is from S to basion (Ba), divided by the sella turcica.[1] The extent to which the cranial base affects sagittal malpositions of the jaws cannot be ruled out since the maxilla is connected to an anterior cranial base, and the mandible is connected to the structure of the posterior cranial base.[2] In previous studies,[1—3] S—N and S—Ba were widely used to measure anteroposterior cranial base length. N—S—Ba and N—S-Articulare (Ar) were used to measure the cranial base angle. However, the relationship between these measurements and sagittal malocclusion is still under debate.[3]

The cranial base region significantly influences the development of the entire facial protrusion and the anterior-posterior relationship between the maxilla and mandible. Malocclusions with skeletal discrepancies may result from abnormalities in the shape, size, and position of the cranial base, maxilla, and mandible.[4] The leading growth site of the cranial base after birth is the spheno-occipital synchondrosis, which elongates the cranial base. The maxilla is located in front of the synchondrosis, while the mandible joins posteriorly so that the synchondrosis may factor in facial incongruity, resulting in malocclusion. Knowing the typical pattern of cranial base development can help identify abnormalities in craniofacial growth. The cranial base is a template for facial development; thus, directly related to the growth and displacement of the maxilla and mandible.[5]

Regarding the cranial base size between different skeletal relationships, previous studies[6—11] mainly used lateral cephalometric X-rays to measure the anteroposterior length of the cranial base on the mid-sagittal plane. Patients with a skeletal Class III relationship have a smaller cranial base length than those with a normal skeletal (skeletal Class I relationship).[6] However, other studies have found no difference in cranial base length.[7] Al Maaitah et al.[8] evaluated linear and angular cranial base measurements in different anterior-posterior skeletal relationships (Class I, Class II, Class III) and concluded that anterior cranial base length (N—S) and posterior cranial base length (S—Ar), no significant difference exists between different skeletal relationships. Wilhelm et al.[9] observed no difference in cranial base measurements between Class I and II malocclusions. In contrast, previous studies[10,11] found that cranial base angle and linear measurements were greatest in skeletal Class II, followed by skeletal Class I, and smallest in skeletal Class III. Enlow[12] suggested that there is an association between the cranial base structure and malocclusion type. People with severe skeletal Class II relationship tend to have a horizontal and broad middle cranial fossa, while the situation of Class III is the opposite. The anterior cranial fossa in Class II individuals is longer and shorter in Class III individuals. Controversy still exists regarding the differences in cranial base size between different skeletal relationships, and these inconsistent conclusions may be due to the need for more consideration of individual differences.

The cone-beam computed tomography (CBCT) study by Silveira et al.[13] compared skeletal Class II (N = 47) and skeletal Class III (N = 48). Regarding gender, the S—N length of the anterior cranial base is more significant in males, and the sella diameter and volume in the middle cranial base are more prominent in females. In the comparison between skeletal Class II and Class III, there is no significant difference in the S—N length of the anterior cranial base, and there is no significant difference in the sella width, height, diameter, and volume of the middle cranial base. This study did not discuss the transverse dimensions of the anterior and posterior cranial bases. The transverse dimensions of the middle cranial base only measured sella width and information about other transverse dimensions of the middle cranial base needed to be included. The CBCT study by Akay et al.[14] compared skeletal Class I (N = 20), Class II (N = 20), and Class III (N = 20) among different genders; the distance between the anterior clinoid processes of the middle cranial base was more extensive in males than females. There was no significant difference in the sella dimensions of the middle cranial base between different skeletal classes.[14] Chou et al.'s[15] CBCT study compared sella width, including anterior clinoid distance (ACD) and posterior clinoid distance (PCD), to access the transverse dimension of the sella turcica. This study[15] found significant differences in ACD and PCD between the sexes but did not find a significant difference in sella width between different skeletal relationships. The above studies still lack the transverse size measurement of the anterior and posterior cranial bases.[14,15]

Most of the past cephalometric analysis studies focused on the length and angle of the cranial base in the anteroposterior direction. However, due to the nature of the research materials, these studies did not compare the transverse dimensions of the cranial base.[6—11] Furthermore, to the best of our knowledge, there have been no CBCT studies on the transverse dimensions of the cranial base among different skeletal relationships. Therefore, through this study, it is helpful to establish the benchmark data of the cranial base size of males and females in Taiwan and the reference of the cranial base size of people with various skeletal relationships. This study can provide epidemiological data reference to compare with relative cranial base lesions. This study aimed to use CBCT to study the cranial base's transverse dimension and the correlation in different craniofacial skeletal relationships for the anterior, middle, and posterior cranial bases and also compared the differences between genders.

## Materials and methods

In this study, from the database of the Department of Dentistry, Kaohsiung Medical University Chung-Ho Memorial Hospital, the files of adult patients who underwent head CBCT for diagnosis and treatment from July 2017 to May 2020 were collected. Moreover, the CBCT file is processed through the image rendering (rendering) program to capture the lateral cephalometric X-ray of the right side. According to the medical records, the age, sex, and craniofacial skeletal relationship of the cases were recorded. This study was approved by the Institutional Review Board of Kaohsiung Medical University Chung-Ho Memorial Hospital), and the IRB number is KMUHIRB-E(II)-20210140.

According to the ANB angle in the cephalometric analysis of the research samples, the craniofacial skeletal relationship is classified into three groups: skeletal Class I (ANB angle 0–4°), skeletal Class II (ANB angle >4°), and skeletal Class III (ANB angle <4°).

The inclusion criteria were over 20 but under 40 years old, with head CBCT files with clear and good image quality for differential diagnosis. Exclusion criteria were systemic diseases, severe craniofacial abnormalities, cleft lip and palate, facial bone trauma, and unclear CBCT images. Furthermore, review the medical records and record the age, sex, and craniofacial bony relationship of the cases. A compute achieved power as a post hoc was established by effect size as the mean difference of anterior clinoid distance (ACD) between gender, with sample size and alpha level less than 0.05. The power was more significant than 0.86, and the research results have adequate power.

We performed the 3D image editing in 3D Slicer (www.slicer.org) via the SlicerCMF project (cmf.slicer.org) to reorganize the DICOM file output by CBCT into a three-dimensional (3D) structural image of the head. The calibration of the head position is done according to the Frankfort horizontal (FH) plane (Porion-right, Porion-left, Orbitale-right) and the mid-sagittal plane (Glabella, Nasion, Basion). Adjust the left and right orbital positions to the frontal plane. After the image calibration, we extract the cranial base structure separately to allow subsequent size measurements to be blinded to the operators. The definitions of cranial base measurements are shown in Table 1, Fig. 1. The definitions of the landmarks of the anterior cranial base are shown in Fig. 2. The definitions of the landmarks of the sella turcica area are shown in Fig. 3. The definitions of the landmarks of the middle cranial fossa are shown in Fig. 4. The definitions of the posterior cranial base landmarks are shown in Figs. 5 and 6.

Statistical methods included the Kappa statistic for analysis of consistency and reproducibility and the Independent *t*-test for differences in cranial base size between males and females. A general linear model (GLM) was used to compare the differences in skull base size among skeletal Class I, II, and III groups. The Pearson correlation coefficient explored the correlation among the dimensions of the cranial base. All statistical calculations were performed using the SPSS 20 (SPSS, Chicago, IL, USA).

## Results

We included 210 Taiwanese adults aged 20–40 in this study, with an average age of 26.49 ± 5.34 years. The mean ages of the male and female samples were 26.53 ± 5.30 and 26.45 ± 5.41 years, respectively, and there was no significant difference in age between the two groups ($P = 0.908$). The samples in this study include skeletal relationships of Class I, Class II, and Class III, with 70 people in each group (35 males and 35 females). The age group is divided into 20–29 and 30–39. There is no significant difference in the distribution of each age group among different skeletal relationships ($P = 0.552$). They were divided into male and female groups according to individual skeletal relationships, and there was no significant difference in the distribution of different age groups ($P = 0.900$) (Table 2).

The cranial base dimension, except for the CGL and CEPW of the anterior cranial base, all other items are significantly more prominent in males than females. In the middle cranial base and posterior cranial base, the measurements significantly differ between males and females ($P < 0.001$) (Table 3). The dimensions of the middle and posterior cranial bases of males are significantly larger than those of females.

The average ages of the skeletal Class I, Class II, and Class III are 26.69 ± 5.66 years old, 27.81 ± 5.06 years old, and 24.97 ± 4.96 years old, respectively, among which the age of Class I and Class II is older than that of Class III ($P = 0.006$). The CGL, CEPW, TDOC, ACPW-max, ACPW-min, ACD, PCD, PCPW-max, FML, FMW, TDFR, MDFO, SBSW, and HgCW did not significantly differ between different skeletal relationships. Only PCPW-min shows larger values in skeletal Class I and III than in Class II ($P = 0.001$) (Table 4).

Table 5 shows the correlation between different cranial base dimensions. The CGL of the anterior cranial base was only significantly correlated with PCPW-min and MDFO. The CEPW was only significantly correlated with FML but not other middle and posterior cranial base dimensions. As for the middle and the posterior cranial base, most of the dimensions have significant correlations. There was also a significant positive correlation between FML and FMW at the posterior cranial base.

The author measured all samples, and after one month, the author randomly selected 20 samples to repeat the measurement of cranial base dimensions. The intraclass correlation coefficient ranged from 0.899 to 0.990, indicating good and excellent reliability. Regarding the interclass correlation coefficient, a postgraduate student repeated measurements on the cranial base dimensions of the 20 randomly selected samples above. The interclass correlation coefficient ranged from 0.873 to 0.989, indicating good and excellent reliability.

**Table 1** The definitions of the measurement for the cranial base dimensions.

| Cranial base dimensions | Definitions |
|---|---|
| Crista galli length (CGL) | Anteroposterior length of the crista galli process. Observation in norma verticalis. (the distance between the most anterior point of the crista galli process at the foramen cecum to the most posterior point of the crista galli process) |
| Cribriform ethmoid plate width (CEPW) | Maximum width of the cribriform ethmoid plate. Observation in norma verticalis. (the distance between the leftmost lateral point of the cribriform ethmoid plate and the rightmost lateral point of the cribriform ethmoid plate) |
| Transverse distance between optical canals (TDOC) | Transverse distance between optical canals.Observation in norma verticalis. (the distance between the most lateral point of the left optical canal and the most lateral point of the right optical canal) |
| Maximum width of the anterior clinoid process (ACPW-max) | Maximum width of the anterior clinoid process of the sphenoid.Observation in norma verticalis. (The distance between the most lateral point of the left anterior clinoid process of the sphenoid and the most lateral point of the right anterior clinoid process of the sphenoid.) |
| Minimum width of the anterior clinoid process (ACPW-min) | Minimum width of the anterior clinoid process of the sphenoid.Observation in norma verticalis. (The distance between the most medial point of the left anterior clinoid process of the sphenoid and the most medial point of the right anterior clinoid process of the sphenoid.) |
| Anterior clinoid distance (ACD) | The distance between the apex of the anterior clinoid process on the left side and the anterior clinoid process on the right side. |
| Posterior clinoid distance (PCD) | The distance between the apex of the posterior clinoid process on the left side and the posterior clinoid process on the right side. |
| Maximum width of the posterior clinoid process (PCPW-max) | Maximum width of the posterior clinoid process of the sphenoid.Observation in norma verticalis/occipitalis. (The distance between the most lateral point of the left posterior clinoid process of the sphenoid and the most lateral point of the right posterior clinoid process of the sphenoid.) |
| Minimum width of the posterior clinoid process (PCPW-min) | Minimum width of the posterior clinoid process of the sphenoid.Observation in norma occipitalis/verticalis. (The distance between the most medial point of the left posterior clinoid process of the sphenoid and the most medial point of the right posterior clinoid process of the sphenoid.) |
| Foramen magnum length (FML) | Maximum anteroposterior length of the foramen magnum. Observation in norma verticalis. (The distance between the most anterior point of the foramen magnum to the Opisthion) |
| Foramen magnum width (FMW) | Maximum width of the foramen magnum. Observation in norma verticalis. (The transverse diameter from the leftmost lateral point of the foramen magnum to the rightmost lateral point of the foramen magnum.) |
| Transverse distance between foramen rotundum (TDFR) | Transverse distance between foramen rotundum. Observation in norma verticalis. (The maximum distance between the most lateral point of the left foramen rotundum of the sphenoid and the most lateral point of the right foramen rotundum of the sphenoid) |
| Maximum distance between foramen ovale (MDFO) | Maximum distance between foramen ovale. Observation in norma verticalis. (The transverse distance between the most lateral point of the left foramen ovale of the sphenoid and the most lateral point of the right foramen ovale of the sphenoid) |
| Sphenobasilar synchondrosis width (SBSW) | Transverse widths of the sphenobasilar synchondrosis at the Minimum width of the basal portion of the occipital clivus.Observation in norma verticalis. (The distance between the leftmost lateral point of the basal portion of the occipital clivus and the rightmost lateral point of the basal portion of the occipital clivus at the location of the sphenobasilar synchondrosis) |
| Hypoglossal canal width (HgCW) | Transverse width between hypoglossal canals. (The distance between the midpoint of the left hypoglossal canal on the sagittal plane to the midpoint of the right hypoglossal canal on the sagittal plane.) |

## Discussion

The CBCT study included 210 adults, and the results can help establish a database as a reference for Taiwanese's average cranial base size (Table 4). To the best of our knowledge, there are no CBCT studies on the transverse dimensions of the cranial base between different skeletal relationships.

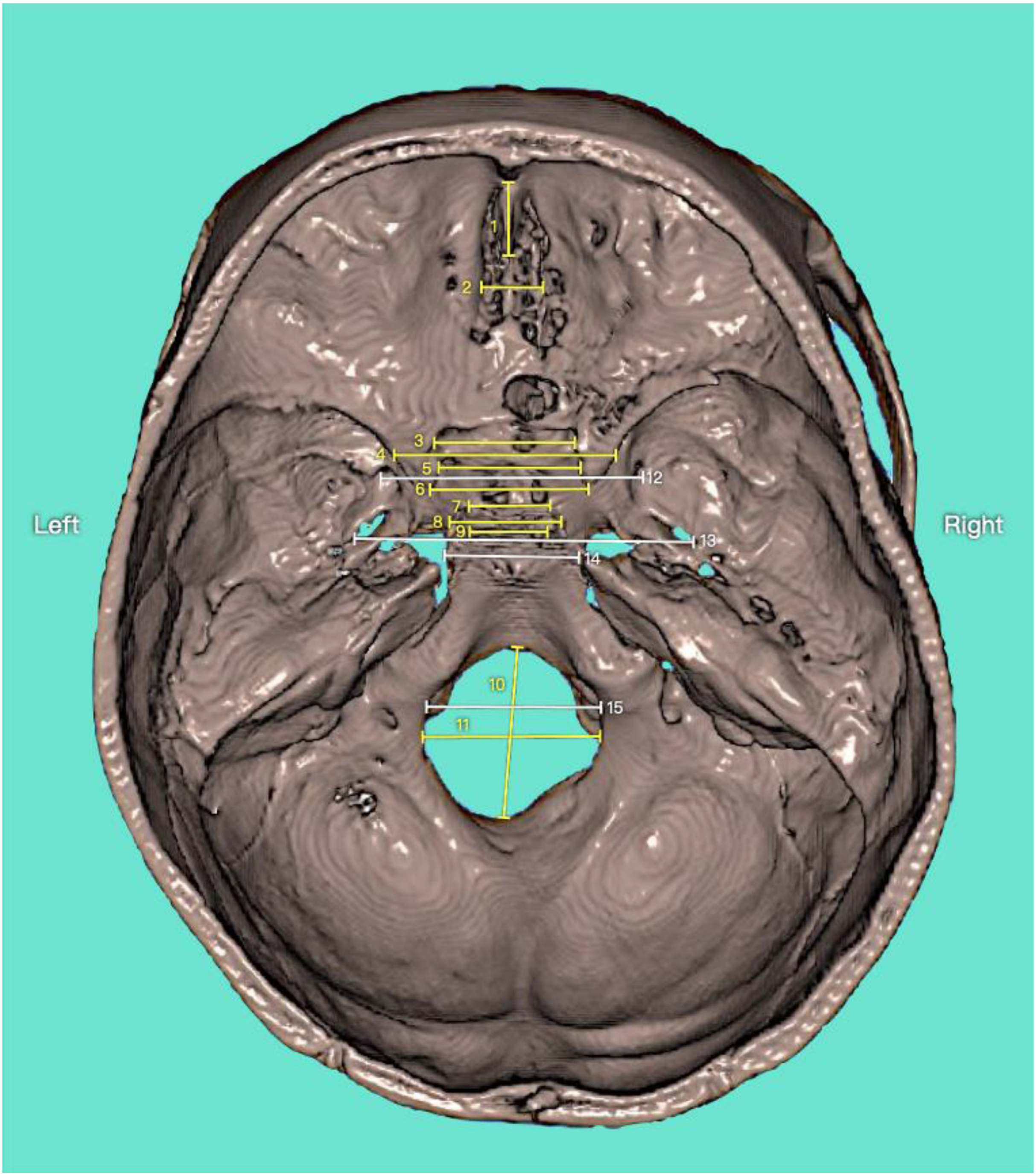


**Fig. 1** Definitions of cranial base dimensions: (1) Crista galli length (CGL): anteroposterior length of the crista galli process; (2) Cribriform ethmoid plate width (CEPW): maximum width of the cribriform ethmoid plate; (3) Transverse distance between optical canals (TDOC): the distance between the most lateral point of the left optical canal and the most lateral point of the right optical canal; (4) Maximum width of the anterior clinoid process (ACPW-max): between the most lateral point of the left anterior clinoid process of the sphenoid and the most lateral point of the right anterior clinoid apophysis of the sphenoid; (5) Minimum width of the anterior clinoid process (ACPW-min): between the most medial point of the left anterior clinoid process of the sphenoid and the most medial point of the right anterior clinoid apophysis of the sphenoid; (6) Anterior clinoid distance (ACD): between the apex of the anterior clinoid process on the left side and the anterior clinoid process on the right side.; (7) Posterior clinoid distance (PCD): between the apex of the posterior clinoid process on the left side and the posterior clinoid process on the right side; (8) Maximum width of the posterior clinoid process (PCPW-max): between the most lateral point of the left posterior clinoid process of the sphenoid and the most lateral point of the right posterior clinoid apophysis of the sphenoid; (9) Minimum width of the posterior clinoid process (PCPW-min): between the most medial point of the left posterior clinoid process of the sphenoid and the most medial point of the right posterior clinoid apophysis of the sphenoid; (10) Foramen magnum length (FML): between the most anterior point of the foramen magnum to the Opisthion; (11) Foramen magnum width (FMW): the transverse diameter from the

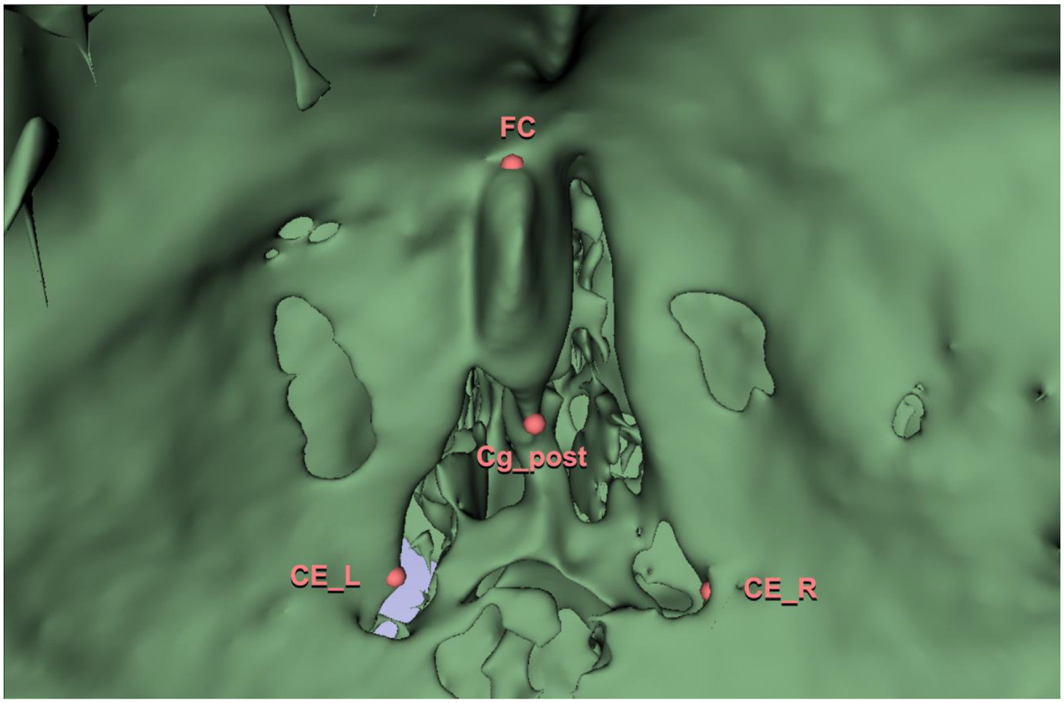


**Fig. 2** Definitions of the landmarks of the anterior cranial base: 1) foramen cecum (FC): the most anterior point of the crista galli process at the foramen cecum; 2) crista galli_posterior (Cg_post): the most posterior point of the crista galli process; 3) cribriform ethmoid plate_left (CE_L): the leftmost lateral point of the cribriform ethmoid plate; 4) cribriform ethmoid plate_right (CE_R): the rightmost lateral point of the cribriform ethmoid plate.

Traditional cephalometric analysis may be insufficient in analyzing changes in the complex craniofacial shape or locating the actual position of skeletal changes. Chang et al.[16] performed thin-plate spline graphical analysis on cephalometric X-ray films of Asians. The results showed that the most significant differences among Asians were in the anterior cranial base and upper midface, in which horizontal compression combined with vertical expansion change was noted. The author suggested a morphological predisposition to Class III malocclusion in Asian populations with facial flattening and forward placement of the temporomandibular joint, leading to relative retrusion of the nasomaxillary complex and protrusion of the mandible.

The current study showed no significant difference in the transverse dimensions of the cranial base except for PCP-min (Table 4). Past research rarely studied transverse width when comparing cranial bases with different skeletal relationships. Alhazmi et al.[17] studied CBCT images of 132 (60 males and 72 females) Saudi Arabian adults and found no significant differences in cranial width and transverse jaw dimensions between skeletal groups. Furthermore, compared with the skeletal Class I and Class III, the skeletal Class II has a smaller posterior cranial base and total cranial base. However, most studies focused on the anteroposterior length and angle of the cranial base. The meta-analysis conclusion of Gong et al.[18] pointed out that compared with Class III malocclusion, Class II malocclusion has a larger cranial base angle, anterior cranial base length, and total cranial base length. Gong et al.[18] did not find a relationship between posterior cranial base length (PCBL) and sagittal skeletal discrepancies and suggested further studies using 3D imaging techniques. In the lateral cephalometric radiograph study by Chin et al.,[11] the posterior cranial base length (S—Ba) was found to be only associated with maxillary and mandibular length in skeletal Class I cases and not in Class II or III cases. Cranial base length (N—Ba) was closely related to maxilla and mandible length in skeletal class I cases but only to maxilla length in skeletal Class III cases. Chin et al.[11] suggested that the shorter the cranial base, the shorter the maxillary length, which leads

leftmost lateral point of the foramen magnum to the rightmost lateral point of the foramen magnum; (12) Transverse distance between foramen rotundum (TDFR) (white line): the maximum distance between the most lateral point of the left foramen rotundum of the sphenoid and the most lateral point of the right foramen rotundum of the sphenoid; (13) Maximum distance between foramen ovale (MDFO) (white line): the transverse distance between the most lateral point of the left foramen ovale of the sphenoid and the most lateral point of the right foramen ovale of the sphenoid; (14) Sphenobasilar synchondrosis width (SBSW) (white line): the distance between the leftmost lateral point of the basal portion of the occipital clivus and the rightmost lateral point of the basal portion of the occipital clivus at the location of the sphenobasilar synchondrosis; (15) Hypoglossal canal width (HgCW) (white line): between the midpoint of the left hypoglossal canal on the sagittal plane to the midpoint of the right hypoglossal canal on the sagittal plane.

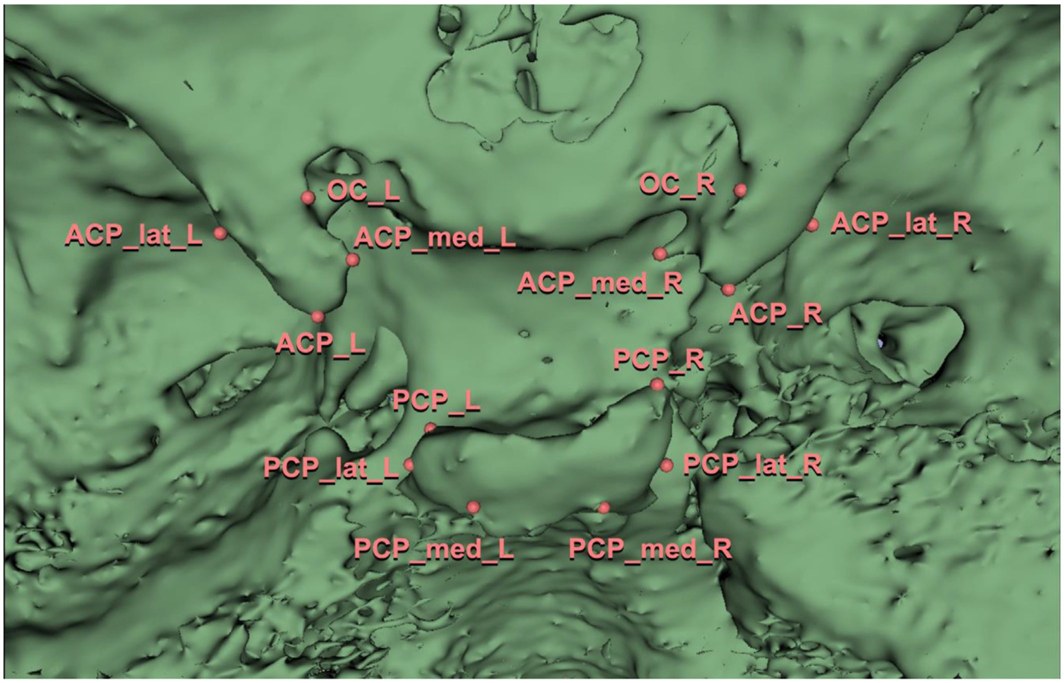


**Fig. 3** Definitions of the landmarks of the sella turcica area: 1) optical canal_left (OC_L): the most lateral point of the left optical canal; 2) optical canal_right (OC_R): and the most lateral point of the right optical canal; 3) anterior clinoid process_lateral_left (ACP_lat_L): the most lateral point of the left anterior clinoid process of the sphenoid; 4) anterior clinoid process_lateral_right (ACP_lat_R): and the most lateral point of the right anterior clinoid process of the sphenoid; 5) anterior clinoid process_medial_left (ACP_med_L): the most medial point of the left anterior clinoid process of the sphenoid; 6) anterior clinoid process_medial_right (ACP_med_R): the most medial point of the right anterior clinoid process of the sphenoid; 7) anterior clinoid process _left (ACP_L): the apex of the anterior clinoid process on the left side; 8) anterior clinoid process _right (ACP_R): the apex of the anterior clinoid process on the right side(ACP_R); 9) posterior clinoid process _left (PCP_L): the apex of the posterior clinoid process on the left side; 10) posterior clinoid process_right (PCP_R): the apex of the posterior clinoid process on the right side; 11) posterior clinoid process_lateral_left (PCP_lat_L): the most lateral point of the left posterior clinoid process of the sphenoid; 12) posterior clinoid process_lateral_right (PCP_lat_R): and the most lateral point of the right posterior clinoid process of the sphenoid; 13) posterior clinoid process_medial_left (PCP_med_L): the most medial point of the left posterior clinoid process of the sphenoid; 14) posterior clinoid process_medial_right (PCP_med_R): the most medial point of the right posterior clinoid process of the sphenoid.

to a Class III problem. These results further demonstrate that the correlation of the cranial base to the jaw base is more pronounced in skeletal Class III cases.

Our results indicated no significant sex difference in the CGL and CEPW of the anterior cranial base (Table 3). Our finding is inconsistent with the conclusion of Isaza et al.,[19] which suggested that the maximum width of the cribriform ethmoid plate (CEPW) has more significant variability in females. On the other hand, Jhamb et al.[20] conducted a CBCT study on the anterior cranial base of 30 children aged 6—11. They noted no significant difference in anterior cranial base volume change between male and female subjects. However, the measurement on the right side of the anterior cranial base showed more growth than on the left side. Since the cribriform ethmoid plate completes its growth by the end of the second year of life,[21] the pubertal growth spurt has less pronounced effects on the anterior cranial base, which may explain the lack of significant sex differences of the anterior cranial base in our findings. Melsen[22] also pointed out that at seven years of age, the growth of the sphenoethmoidal and sphenofrontal suture of the anterior cranial base usually stops. The brain almost stops growing at 7—8 years of age, after which growth at the anterior cranial base is still necessary for continued facial development, which occurs almost entirely due to increased pneumatization of the frontal and ethmoid bones. The growth of the frontal bone further increases the Sella—Nasion distance.

In the transverse dimension on the front portion of the middle cranial base, our study observed that TDOC, ACD-max, ACD, ACD-min, and TDFR were significantly larger in males ($P < 0.001$) (Table 3). According to Sgouros et al.,[23] the middle cranial bases of both sexes grow similarly before the age of five. At this time, the ACD of both sexes grows rapidly, showing increased width between the left and right anterior clinoid processes. However, in late childhood, between the ages of 12 and 15, males exhibited another increase in ACD width not seen in females, corresponding to an increase in ACD width during a pubertal growth spurt in addition to increased mandibular length,[23] which is also consistent with our findings: ACD width at males was significantly larger than females (Table 3).

Our study measured the transverse dimension on the rear portion of the middle cranial base, including PCPW-

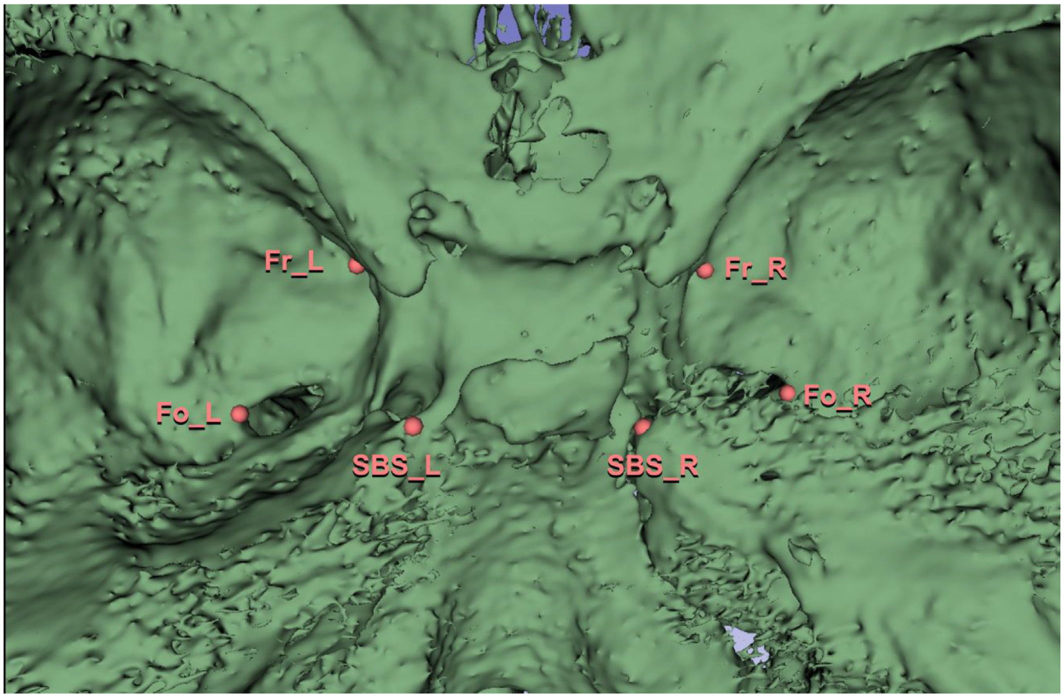


**Fig. 4** Definitions of the landmarks of the middle cranial base: 1) foramen rotundum_left (Fr_L): the most lateral point of the left foramen rotundum of the sphenoid; 2) foramen rotundum_right (Fr_R): the most lateral point of the right foramen rotundum of the sphenoid; 3) foramen ovale_left (Fo_L): the most lateral point of the left foramen ovale of the sphenoid; 4) foramen ovale_right (Fo_R): and the most lateral point of the right foramen ovale of the sphenoid; 5) sphenobasilar synchondrosis_left (SBS_L): the leftmost lateral point of the basal portion of the occipital clivus; 6) sphenobasilar synchondrosis_right (SBS_R): and the rightmost lateral point of the basal portion of the occipital clivus at the location of the sphenobasilar synchondrosis.

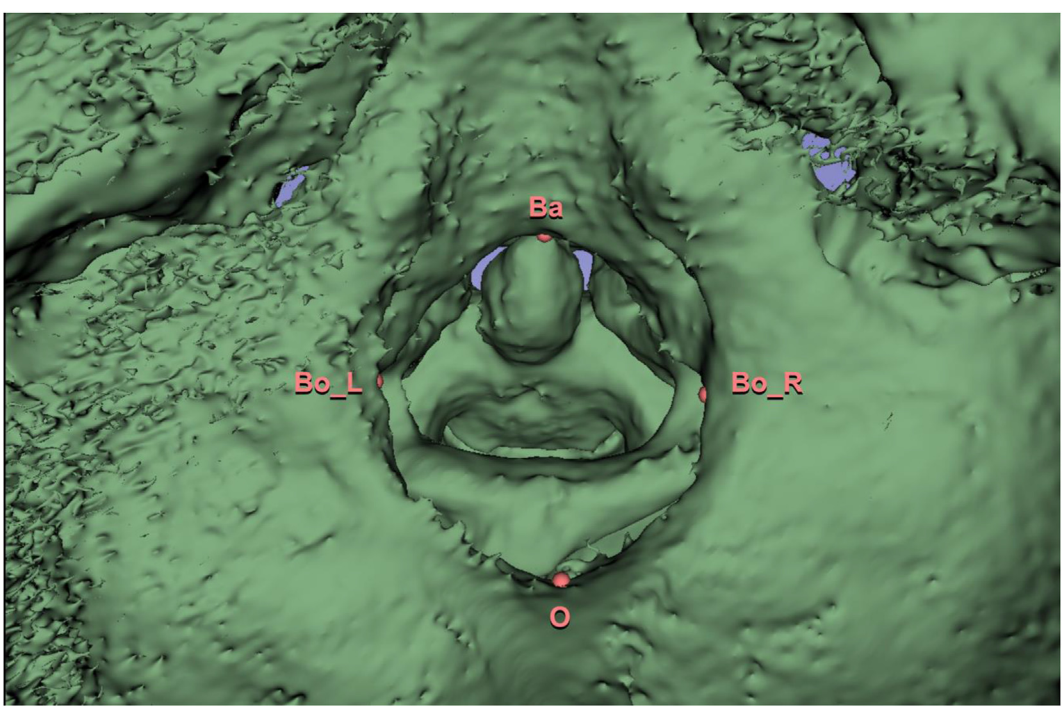


**Fig. 5** Definitions of the landmarks of the foramen magnum in the posterior cranial base: 1) basion (Ba): the most anterior point of the foramen magnum; 2) opisthion (O): to the most posterior point of the foramen magnum; 3) bolton_left (Bo_L): the leftmost lateral point of the foramen magnum; 4) bolton_right (Bo_R): to the rightmost lateral point of the foramen magnum.

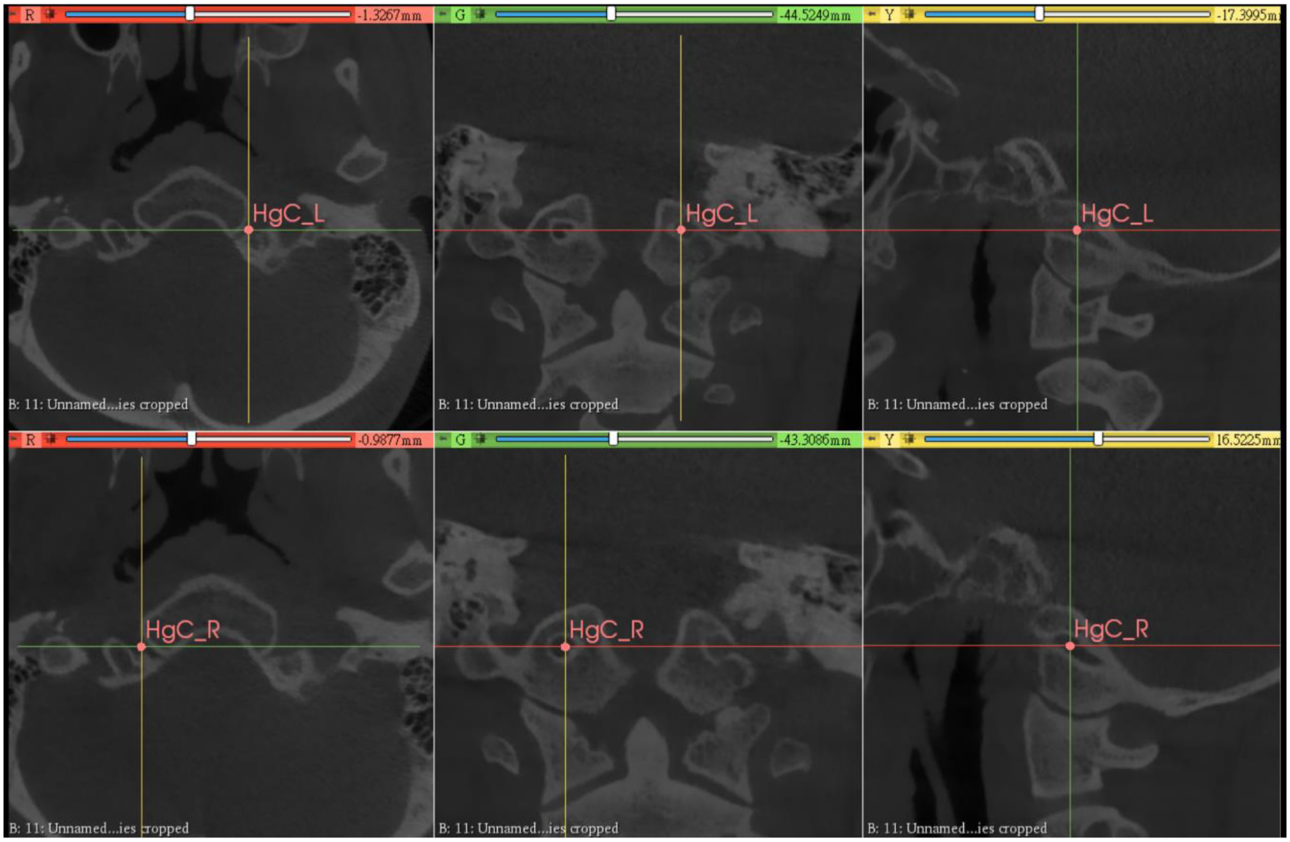


**Fig. 6** Definitions of the landmarks of the hypoglossal canal in the posterior cranial base: 1) hypoglossal canal_left (HgC_L): the midpoint of the left hypoglossal canal on the sagittal plane; 2) hypoglossal canal_right (HgC_R): to the midpoint of the right hypoglossal canal on the sagittal plane. The red frame is the axial view. The green frame is the coronal view. The yellow frame is the sagittal view.

max, PCD, PCPW-min, MDFO, and SBSW, all showed a significantly larger dimension in males than females ($P = 0.002 \sim P < 0.001$) (Table 3). On the contrary, Sakran et al.[24] studied the distance between bilateral posterior clinoid processes and found no significant sex difference. The study by Isaza et al.[19] analyzed the maximum distance between the foramen ovale as greater in males than in females and identified sexual dimorphism. Our findings are only partially consistent with past studies.[19,24] In a previous study targeting gender differences, males exhibited significantly greater anterior (N—S) and posterior (S—Ar) skull base lengths than females.[8] The CBCT study by Chou et al.[15] found that the size of the sella turcica on the midsagittal plane included sella length, depth, and diameter, and there was no significant gender difference. ACD and PCD, representing the anterior and posterior transverse width of the sella turcica, were significantly more prominent in males than females.[15] The development of the

**Table 2** Age distribution of patients by skeletal groups and sex.

| Age (year) | | Class I | | Class II | | Class III | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Male | Female | Male | Female | Male | Female | Total | χ2 | df | *P* |
| **20—29** | Count | 29 | 28 | 26 | 26 | 29 | 27 | 165 | 1.612 | 5 | 0.900 |
| | % within Age (year) | 17.6% | 17.0% | 15.8% | 15.8% | 17.6% | 16.4% | 100.0% | | | |
| | % within Class | 82.9% | 80.0% | 74.3% | 74.3% | 82.9% | 77.1% | 78.6% | | | |
| **30—29** | Count | 6 | 7 | 9 | 9 | 6 | 8 | 45 | | | |
| | % within Age (year) | 13.3% | 15.6% | 20.0% | 20.0% | 13.3% | 17.8% | 100.0% | | | |
| | % within Class | 17.1% | 20.0% | 25.7% | 25.7% | 17.1% | 22.9% | 21.4% | | | |
| **Total** | Count | 35 | 35 | 35 | 35 | 35 | 35 | 210 | | | |
| | % within Age (year) | 16.7% | 16.7% | 16.7% | 16.7% | 16.7% | 16.7% | 100.0% | | | |
| | % within Class | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | | | |

χ2: Chi-square value; df: degree of freedom; *P*: *P* -value. Statistically significant at $P < 0.05$. $^*P < 0.05$.

**Table 3** Comparison of cranial base dimensions between sex.

| Measurements | All samples | | | | | | | | P value |
|---|---|---|---|---|---|---|---|---|---|
| | Male (n = 105) | | | | Female (n = 105) | | | | |
| | Mean | SD | Min | Max | Mean | SD | Min | Max | |
| CGL (mm) | 14.59 | 2.72 | 9.19 | 21.54 | 14.57 | 2.62 | 8.02 | 20.83 | 0.958 |
| CEPW (mm) | 13.74 | 3.77 | 8.63 | 25.41 | 13.47 | 3.63 | 7.42 | 25.91 | 0.594 |
| TDOC (mm) | 27.46 | 3.06 | 19.19 | 35.56 | 25.98 | 2.90 | 19.35 | 36.17 | <0.001* |
| ACPW-max (mm) | 39.04 | 2.93 | 30.64 | 46.62 | 36.21 | 2.68 | 29.89 | 44.74 | <0.001* |
| ACPW-min (mm) | 22.80 | 2.09 | 18.25 | 29.27 | 21.31 | 2.11 | 16.05 | 26.84 | <0.001* |
| ACD (mm) | 26.17 | 2.49 | 19.13 | 31.75 | 24.38 | 2.38 | 17.99 | 31.16 | <0.001* |
| PCD (mm) | 18.00 | 3.12 | 11.43 | 26.05 | 16.65 | 2.92 | 9.75 | 24.57 | 0.002* |
| PCPW-max (mm) | 21.48 | 2.82 | 15.59 | 28.61 | 19.59 | 2.92 | 8.35 | 27.52 | <0.001* |
| PCPW-min (mm) | 12.74 | 2.52 | 8.14 | 21.46 | 11.43 | 2.34 | 6.63 | 18.61 | <0.001* |
| FML (mm) | 37.60 | 2.52 | 30.50 | 43.51 | 35.60 | 1.98 | 30.61 | 40.11 | <0.001* |
| FMW (mm) | 32.66 | 2.17 | 26.76 | 38.68 | 31.01 | 2.08 | 25.50 | 36.26 | <0.001* |
| TDFR (mm) | 45.74 | 3.42 | 38.01 | 54.02 | 43.02 | 3.36 | 35.12 | 52.89 | <0.001* |
| MDFO (mm) | 61.65 | 3.79 | 49.31 | 69.87 | 58.87 | 3.60 | 41.88 | 68.76 | <0.001* |
| SBSW (mm) | 24.24 | 2.09 | 16.49 | 31.41 | 22.95 | 2.49 | 15.19 | 31.41 | <0.001* |
| HgCW (mm) | 34.84 | 1.92 | 30.43 | 39.91 | 33.08 | 3.21 | 28.26 | 60.43 | <0.001* |

*$P < 0.05$, CGL: Crista galli length; CEPW: Cribriform ethmoid plate width; TDOC: transverse distance between optical canals; ACPW-max: maximum width of the anterior clinoid process; ACPW-min: minimum width of the anterior clinoid process; ACD: anterior clinoid distance; PCD: posterior clinoid distance; PCPW-max: maximum width of the posterior clinoid process; PCPW-min: minimum width of the posterior clinoid process; FML: foramen magnum length; FMW: foramen magnum width; TDFR: transverse distance between foramen rotundum; MDFO: maximum distance between foramen ovale; SBSW: width of the sphenobasilar synchondrosis; HgCW: width of the hypoglossal canals.

middle cranial base continues until 7—8 years of age, while the development of the lateral cranial base continues until 11—12 years. Since facial development continues until 15—16 years of age, its timing is more related to the development of the lateral cranial base than to the midline basicranium.[25]

**Table 4** Comparison of cranial base dimensions between skeletal relations.

| Measurements | Class I (n = 70) | | Class II (n = 70) | | Class III (n = 70) | | F | P value | Significant |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | | | |
| CGL (mm) | 14.56 | 2.78 | 14.44 | 2.65 | 14.74 | 2.60 | 0.219 | 0.803 | |
| CEPW (mm) | 13.71 | 3.84 | 13.04 | 3.42 | 14.08 | 3.78 | 1.430 | 0.242 | |
| TDOC (mm) | 26.61 | 3.15 | 27.10 | 3.33 | 26.45 | 2.68 | 0.843 | 0.432 | |
| ACPW-max (mm) | 37.42 | 3.17 | 38.23 | 3.29 | 37.22 | 2.90 | 2.039 | 0.133 | |
| ACPW-min (mm) | 22.18 | 2.11 | 22.29 | 2.43 | 21.69 | 2.11 | 1.426 | 0.243 | |
| ACD (mm) | 25.45 | 2.68 | 25.54 | 2.70 | 24.84 | 2.35 | 1.536 | 0.218 | |
| PCD (mm) | 17.93 | 2.83 | 16.91 | 2.94 | 17.14 | 3.42 | 2.118 | 0.123 | |
| PCPW-max (mm) | 21.00 | 3.10 | 20.34 | 2.90 | 20.26 | 3.04 | 1.253 | 0.288 | |
| PCPW-min (mm) | 12.49 | 2.68 | 11.19 | 2.51 | 12.58 | 2.11 | 7.118 | 0.001* | Class I, III > Class II |
| FML (mm) | 36.89 | 2.15 | 36.52 | 2.65 | 36.39 | 2.60 | 0.775 | 0.462 | |
| FMW (mm) | 31.68 | 2.44 | 32.14 | 2.30 | 31.69 | 2.07 | 0.928 | 0.397 | |
| TDFR (mm) | 44.31 | 3.70 | 43.92 | 3.62 | 44.92 | 3.60 | 1.337 | 0.265 | |
| MDFO (mm) | 60.42 | 3.88 | 60.28 | 4.33 | 60.08 | 3.63 | 0.130 | 0.878 | |
| SBSW (mm) | 23.64 | 2.22 | 23.64 | 2.99 | 23.51 | 1.81 | 0.070 | 0.933 | |
| HgCW (mm) | 33.94 | 2.00 | 34.22 | 3.92 | 33.72 | 2.01 | 0.543 | 0.582 | |

*$P < 0.05$, CGL: Crista galli length; CEPW: Cribriform ethmoid plate width; TDOC: transverse distance between optical canals; ACPW-max: maximum width of the anterior clinoid process; ACPW-min: minimum width of the anterior clinoid process; ACD: anterior clinoid distance; PCD: posterior clinoid distance; PCPW-max: maximum width of the posterior clinoid process; PCPW-min: minimum width of the posterior clinoid process; FML: foramen magnum length; FMW: foramen magnum width; TDFR: transverse distance between foramen rotundum; MDFO: maximum distance between foramen ovale; SBSW: width of the sphenobasilar synchondrosis; HgCW: width of the hypoglossal canals.

**Table 5** Associations among different cranial base dimensions and the Pearson correlation coefficient.

| | CGL | CEPW | TDOC | ACPW-max | ACPW-mim | ACD | PCD | PCPW-max | PCPW-mim | FML | FMW | TDFR | MDFO | SBSW | HgCW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CGL | 1 | 0.035 | −0.050 | 0.044 | −0.081 | −0.022 | 0.021 | 0.107 | 0.168* | −0.108 | −0.131 | −0.024 | −0.140* | 0.094 | 0.086 |
| CEPW | | 1 | 0.023 | 0.012 | 0.091 | −0.007 | 0.015 | −0.008 | 0.112 | 0.139* | 0.068 | −0.016 | 0.035 | 0.041 | 0.041 |
| TDOC | | | 1 | 0.407** | 0.494** | 0.426** | 0.177* | 0.168* | 0.163* | 0.111 | 0.181** | 0.264** | 0.197** | 0.167* | 0.145* |
| ACPW-max | | | | 1 | 0.529** | 0.572** | 0.266** | 0.325** | 0.286** | 0.148* | 0.125 | 0.357** | 0.189** | 0.140* | 0.260** |
| ACPW-mim | | | | | 1 | 0.736** | 0.236** | 0.268** | 0.252** | 0.307** | 0.234** | 0.472** | 0.327** | 0.194** | 0.206** |
| ACD | | | | | | 1 | 0.158* | 0.259** | 0.237** | 0.207** | 0.140* | 0.365** | 0.271** | 0.186** | 0.201** |
| PCD | | | | | | | 1 | 0.705** | 0.516** | 0.103 | 0.217** | 0.220** | 0.098 | 0.146* | 0.242** |
| PCPW-max | | | | | | | | 1 | 0.548** | 0.187** | 0.169* | 0.268** | 0.130 | 0.227** | 0.235** |
| PCPW-mim | | | | | | | | | 1 | 0.126 | 0.154* | 0.201** | 0.036 | 0.046 | 0.135 |
| FML | | | | | | | | | | 1 | 0.456** | 0.335** | 0.295** | 0.192** | 0.320** |
| FMW | | | | | | | | | | | 1 | 0.235** | 0.274** | 0.214** | 0.429** |
| TDFR | | | | | | | | | | | | 1 | 0.471** | 0.350** | 0.301** |
| MDFO | | | | | | | | | | | | | 1 | 0.256** | 0.102 |
| SBSW | | | | | | | | | | | | | | 1 | 0.377** |
| HgCW | | | | | | | | | | | | | | | 1 |

**: Correlations significant at the 0.01 level (2-tailed). *: Correlations significant at the 0.05 level (2-tailed). Crista galli length; CEPW: Cribriform ethmoid plate width; TDOC: transverse distance between optical canals; ACPW-max: maximum width of the anterior clinoid process; ACPW-min: minimum width of the anterior clinoid process; ACD: anterior clinoid distance; PCD: posterior clinoid distance; PCPW-max: maximum width of the posterior clinoid process; PCPW-min: minimum width of the posterior clinoid process; FML: foramen magnum length; FMW: foramen magnum width; TDFR: transverse distance between foramen rotundum; MDFO: maximum distance between foramen ovale; SBSW: width of the sphenobasilar synchondrosis; HgCW: width of the hypoglossal canals.

The FML, FMW, and HgCW of the posterior cranial base were also significantly higher in males than in females ($P < 0.001$) (Table 3). Our finding is consistent with Isaza et al.[19] that there is apparent sexual dimorphism in the maximum width of the basal occipital portion and the maximum width of the foramen magnum. Males are more prominent in both measurements than in females. The hypoglossal canal locates in the posterior cranial fossa of the occipital bone. During growth and development, the posterior cranial base will shift backward and downward with the growth of the sphenooccipital synchondrosis. Furthermore, the increase in the width of the posterior cranial base will occur laterally to the hypoglossal canal, and the distance between the left and right hypoglossal canals remains stable during pubertal growth.[26] Our results indicate that although PCD has a significant sex difference ($P = 0.002$), it is not as significant as ACD ($P < 0.001$) (Table 3). Because the dorsum sella and posterior clinoid processes are closer to the sphenooccipital synchondrosis, regional changes with growth are predominantly posterior and inferior displacement of the posterior cranial base with the spheno-occipital synchondrosis, with less variation in width.[26] These differences between the sexes should be considered when treating patients with abnormal cranial base growth.[23,26]

Cranial base size exhibits sexual dimorphism, which has been studied in forensic anthropology and applied to gender estimation for human identification purposes.[27] A volume-rendered computed tomography (CT) study by Isaza et al.[19] on skulls of Colombia's population demonstrated that the foramen magnum's transverse diameter, width, and anterior-posterior diameter are valuable measurements for sex identification. In a study by Gapert et al.,[28] who examined 135 adult skull bases (69 males and 66 females) from the crania of the St. Bride's documented skeletal collection in London, the maximum length of the foramen magnum in males and females was 35.79 $\pm$ 2.36 mm and 34.78 $\pm$ 1.97 ($p = 0.008$), respectively. The maximum width of the foramen magnum was 30.48 $\pm$ 1.86 mm and 29.35 $\pm$ 2.06 mm ($p = 0.001$) in males and females, respectively. Catalina-Herrera[29] studied the skulls of 100 Spanish adults (74 males and 26 females). The sagittal diameter of the foramen magnum was 36.2 $\pm$ 0.3 mm in males and 24.3 $\pm$ 0.4 in females ($p < 0.001$), and the transverse diameter was 31.1 $\pm$ 0.3 mm in males and 29.6 $\pm$ 0.3 in females ($p < 0.001$). The skull study by Gapert et al.[30] believed that the morphometric variables of the foramen magnum have significant sexual dimorphism, so it is still helpful for sex identification when human remains are damaged. According to our research, the FML in males and females is 37.60 $\pm$ 2.52 mm and 35.60 $\pm$ 1.98 mm ($P < 0.001$), and the FMW in males and females were 32.66 $\pm$ 2.17 mm and 31.01 $\pm$ 2.08 m ($P < 0.001$) (Table 3), which can serve as references for clinical diagnosis and forensic research.

Olszewski et al.[31] suggested that conventional cephalometric analysis presents the same limitations as radiographs: geometric distortion of two-dimensional (2D) features and imaged anatomy. Diagnosis based on 2D and 3D analysis is sufficient. However, the 3D analysis provides more information, such as the possibility to compare left and right skulls, and the absence of anatomical overlap improves the visibility of reference landmarks. Olszewski et al.[31] stated further advantages of CT technology: it is possible to make 3D measurements of lines and angles and simultaneously visualize soft tissues, including fat, muscle, and airways.[31] Lagravere et al.[26] published an article on the reliability and accuracy of locating multiple foramina on the cranial base by CBCT images. This study concluded that the foramen spinosa, foramen ovale and rotundum, and the hypoglossal canal were considered suitable landmarks and could be used to establish a reference system for future 3D superimpose analyses. In recent years, volume-rendered 3D reconstructions using computed tomography have enabled researchers to directly measure bone tissue and structure at a 1:1 scale without needing bone specimens since 3D CT allows for easy and rapid assessment of the cranial base.[32] Detailed preoperative information on relationships between skeletal landmarks, 3D CT as a preoperative planning tool for cranial base surgery allows surgeons to assess structural relationships in individual patients.[32]

In this study, samples were collected from July 2017 to May 2020 for analysis, and there may still be inconsistencies with samples from the general population. Also, our samples came from the CBCT database of a dental clinic of a university hospital; there may be some selection bias. Future studies may increase the sample size to verify differences in transverse cranial base dimensions between sexes and craniofacial skeletal relationships. Furthermore, our study only included patients between 20 and 40, so the current study cannot assess the growth changes accompanying puberty. Suppose the sample's age range can be further expanded to include children and adolescents, and even adults over 40 years old. In that case, it will help us better understand the changes in the transverse dimension of the cranial base with age.

In conclusion, the transverse dimensions of the cranial base in Taiwanese adults revealed no significant differences between different craniofacial skeletal relationships. There is no significant sex difference in the CGL and CEPW of the anterior cranial base, and the transverse dimensions of the middle cranial base are significantly more prominent in males than in females. In the posterior cranial base, the length and width of the foramen magnum revealed significant sexual dimorphism.

## Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

## Acknowledgments

This study was funded by the Taiwan Ministry of Science and Technology project fund, project number MOST110-2314-B-037-060.

## References

1. Dhopatkar A, Bhatia S, Rock P. An investigation into the relationship between the cranial base angle and malocclusion. *Angle Orthod* 2002;72:456—63.

2. Bacon W, Eiller V, Hildwein M, Dubois G. The cranial base in subjects with dental and skeletal Class II. *Eur J Orthod* 1992; 14:224–8.
3. Kamak H, Çatalbas B, Senel B. Cranial base features between sagittal skeletal malocclusions in Anatolian Turkish adults: is there a difference? *J Orthod Res* 2013;1:52.
4. Woo SS, Choi YS, Park WH, Yoo IH, Lee YS, Shim KS. A study of position and size of cranial base, maxilla, and mandible in true skeletal Class III patients. *J Korean Assoc Oral Maxillofac Surg* 2002;28:24–30.
5. Ohtsuki F, Mukherjee D, Lewis AB, Roche AF. A factor analysis of cranial base and vault dimensions in children. *Am J Phys Anthropol* 1982;58:271–9.
6. Chang HP, Chou TM, Hsieh SH, Tseng YC. Cranial-base morphology in children with Class III malocclusion. *Kaohsiung J Med Sci* 2005;21:159–65.
7. Ö Polat, Kaya B. Changes in cranial base morphology in different malocclusions. *Orthod Craniofac Res* 2007;10:216–21.
8. Al Maaitah EF, Alomari S, Al-Khateeb SN, Abu Alhaija ES. Cranial base measurements in different anteroposterior skeletal relationships using Bjork-Jarabak analysis. *Angle Orthod* 2022; 92:613–8.
9. Wilhelm BM, Beck FM, Lidral AC, Vig KWL. A comparison of cranial base growth in Class I and Class II skeletal patterns. *Am J Orthod Dentofacial Orthop* 2001;119:401–5.
10. Proff P, Will F, Bokan I, Fanghänel J, Gedrange T. Cranial base features in skeletal Class III patients. *Angle Orthod* 2008;78: 433–9.
11. Chin A, Perry S, Liao C, Yang Y. The relationship between the cranial base and jaw base in a Chinese population. *Head Face Med* 2014;10:31.
12. Enlow DH, Moyers RE, Merow WW. *Handbook of Facial Growth*. WB Saunders Company, 1982.
13. Silveira BT, Fernandes KS, Trivino T, Dos Santos LYF, de Freitas CF. Assessment of the relationship between size, shape and volume of the sella turcica in class II and III patients prior to orthognathic surgery. *Surg Radiol Anat* 2020;42:577–82.
14. Akay G, Eren I, Karadag O, Gungor K. Three-dimensional assessment of the sella turcica: comparison between cleft lip and palate patients and skeletal malocclusion classes. *Surg Radiol Anat* 2020;42:977–83.
15. Chou ST, Chen CM, Chen PH, Lin YC, Tseng YC. The left and right differences in sella turcica bridging between sex analyzed by cone-beam computed tomography. *J Dent Sci* 2023;18:220–8.
16. Chang HP, Liu PH, Tseng YC, Yang YH, Pan CY, Chou ST. Morphometric analysis of the cranial base in Asians. *Odontology* 2014;102:81–8.
17. Alhazmi N, Almihbash A, Alrusaini S, et al. The association between cranial base and maxillomandibular sagittal and transverse relationship: a CBCT Study. *Appl Sci* 2022;12:9199.
18. Gong A, Li J, Wang Z, et al. Cranial base characteristics in anteroposterior malocclusions: a meta-analysis. *Angle Orthod* 2016;86:668–80.
19. Isaza J, Díaz CA, Bedoya JF, Monsalve T, Botella MC. Assessment of sex from endocranial cavity using volume-rendered CT scans in a sample from Medellín, Colombia. *Forensic Sci Int* 2014;234. 186.e1-e10.
20. Jhamb T, AlSulaiman A, Parsi G, Will L, Motro M. Three-dimensional morphometric analysis of anterior cranial base in growing patients. *Am J Orthod Dentofacial Orthop* 2023 (in press).
21. Ford E. Growth of the human cranial base. *Am J Orthod* 1958; 44:498–506.
22. Melsen B. The cranial base: the postnatal development of the cranial base studied histologically on human autopsy material. *Acta Odontol Scand* 1974;32:9–126.
23. Sgouros S, Natarajan K, Hockley A, Goldin J, Wake M. Skull base growth in childhood. *Pediatr Neurosurg* 1999;31:259–68.
24. Sakran A, Khan MA, Altaf FMN, et al. A morphometric study of the sella turcica; gender effect. *Int J Anat Res* 2015;3: 927–34.
25. Gkantidis N, Halazonetis DJ. Morphological integration between the cranial base and the face in children and adults. *J Anat* 2011;218:426–38.
26. Lagravère MO, Gordon JM, Flores-Mir C, Carey J, Heo G, Major PW. Cranial base foramen location accuracy and reliability in cone-beam computerized tomography. *Am J Orthod Dentofacial Orthop* 2011;139:e203–10.
27. Rebato E, Susanne C, Chiarelli B. *Para comprender la antropología biológica: Verbo Divino Navarra*. España, 2005.
28. Gapert R, Black S, Last J. Test of age-related variation in the craniometry of the adult human foramen magnum region: implications for sex determination methods. *Forensic Sci Med Pathol* 2013;9:478–88.
29. Catalina-Herrera C. Study of the anatomic metric values of the foramen magnum and its relation to sex. *Cells Tissues Organs* 1987;130:344–7.
30. Gapert R, Black S, Last J. Sex determination from the foramen magnum: discriminant function analysis in an eighteenth and nineteenth century British sample. *Int J Leg Med* 2009;123: 25–33.
31. Olszewski R, Zech F, Cosnard G, Nicolas V, Macq B, Reychler H. Three-dimensional computed tomography cephalometric craniofacial analysis: experimental validation in vitro. *Int J Oral Maxillofac Surg* 2007;36:828–33.
32. Bulsara KR, Leveque JC, Gray L, Fukushima T, Friedman AH, Villavicencio AT. Three-dimensional computed tomographic analysis of the relationship between the arcuate eminence and the superior semicircular canal. *Neurosurgery* 2006;59. ONS7-12; discussion ONS7.