Original Article

Correlation between the cross-sectional morphology of the mandible and the three-dimensional facial skeletal pattern: *A structural equation modeling approach*

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ABSTRACT

Objective: To clarify the relationship between the cross-sectional morphology of the mandible and vertical, transverse, and anteroposterior facial skeletal patterns using statistical shape analysis and structural equation modeling (SEM).

Materials and Methods: We used 150 cone beam computed tomography (CBCT) images to obtain three-dimensional (3D) facial landmarks and cross-sectional images of the mandible. The morphology of the inner and outer cortices of the mandible was analyzed using statistical shape analysis, including generalized Procrustes analysis and principal component analysis (PCA). Factor analysis was performed to determine factors pertaining to the skeletal measurements and shape variations for the inner and outer cortices, following which a structural equation model was constructed.

Results: Using factor analysis, characteristics of the vertical, transverse, and anteroposterior facial skeletal patterns were determined. PCA of the cross-sectional morphology of the mandible revealed 70% of the cumulative proportion by PC1 and PC2 after generalized Procrustes superimpositions. SEM showed complex relationships between the facial skeletal patterns and variations in the cross-sectional morphology of the mandibular cortices. The influence of the transverse factors on the outer cortex as a latent variable was relatively significant ($P = .057$). However, the influence of the vertical factors on the outer and inner cortices was not significant.

Conclusions: The transverse skeletal pattern is associated with the morphology of the outer cortex of the mandible. (*Angle Orthod.* 2019;89:78–86.)

KEY WORDS: Mandible; Cross-section; Skeletal pattern; Shape; Structural equation modeling; Correlation

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INTRODUCTION

An understanding of the cross-sectional morphology of the mandible is important for orthodontic treatment. Performing orthodontic treatment without considering the cortical bone in the apical region can cause iatrogenic damage, because bone is an anatomical limiting factor. Therefore, orthodontic treatment based on an understanding of mandibular morphology can minimize damage to the roots and alveolar bone.[1,2]

Cross-sectional mandibular morphology is affected by the vertical skeletal pattern which, in turn, is influenced by genetic and environmental factors.[3–5] The vertical skeletal pattern interacts with masticatory function and influences the morphology of the mandible.[6,7]

Choi et al. conducted finite element analysis to evaluate the effects of an increase in the vertical skeletal pattern.[8] Several studies have reported that forces are generated in different parts of the mandible, which can result in displacement and deformation of the mandible.[7–9]

Cross-sectional mandibular morphology is related to not only the vertical skeletal pattern but also the anteroposterior and transverse skeletal patterns. A hyperdivergent skeletal pattern has an increased anterior facial height and a decreased facial width; therefore, a long and narrow mandible is observed. In contrast, a hypodivergent skeletal pattern has a decreased anterior facial height and an increased facial width.[10–12] While many studies have reported the relationship between cross-sectional mandibular morphology and a vertical skeletal pattern, few have evaluated the relationship in anteroposterior and transverse skeletal patterns.[13,14]

Three-dimensional (3D) facial skeletal pattern analysis is conducted to investigate the skeletal pattern. Compared with two-dimensional (2D) radiography, 3D computed tomography allows visualization of the entire facial skeleton without using a combination of different cephalometric radiographs. Furthermore, landmarks can be assessed on various cross-sectional images, and errors are minimized.[15]

The cross-sectional morphology of the mandible and its variations are assessed using morphometric analysis, which measures morphological differences and estimates the average shape and morphology quantitatively. The relationship between many factors and the morphological data is analyzed by structural equation modeling (SEM). This technique can verify the hypotheses and evaluate the fitness to examine the effectiveness of the experimental model.[16]

The purpose of this study was to analyze the cross-sectional morphology of the mandible in the first molar region using morphometric analysis and to investigate its relationship with different skeletal patterns using SEM. The specific aims of the study were to (1) determine the relationship between vertical, transverse, and anteroposterior facial skeletal patterns and the cross-sectional shape and morphology of the mandible, (2) evaluate the effects of the cross-sectional morphology of each component using principal component analysis (PCA), and (3) validate the causal relationship between factors using SEM.

MATERIALS AND METHODS

Samples

In total, 150 patients (56 male, 94 female; mean age: 23.74 ± 5.52 years) who visited the Department of Orthodontics at Pusan National University Dental Hospital between May 2010 and January 2017 were included in this study. Cone beam computed tomography (CBCT) images were used to analyze the craniofacial structures and cross-sectional mandibular morphology. Patients with systemic disease or a history of trauma or surgery were excluded. This study was reviewed and approved by the institutional review board of Pusan National University Dental Hospital (PNUDH-2017-035).

CBCT Protocol and Image Analysis

All patients were scanned using CBCT (Zenith3D; Vatech Co, Seoul, Korea) under the following conditions: 90 kVp; 10 mA; scan time, 24 seconds; voxel size, 0.3 mm; field of view, 20 × 19 cm. 3D imaging software (InVivo; Anatomage Inc, San Jose, Calif) was used to evaluate the facial skeletal pattern and cross-sectional shape of the mandible.

The Frankfort horizontal (FH) plane and midsagittal reference (MSR) plane were selected as the 3D horizontal and vertical reference planes, respectively, for skeletal measurements. The MSR plane was perpendicular to the FH plane, passing through nasion and sella. Nasion was set as the origin (0,0,0). The size of cross-sectional mandibular images may be affected by the mandibular angle since shorter images are obtained for patients with a steep mandibular angle when the base of the mandible is parallel to the floor.[17] After the CBCT image was reoriented using the mandibular plane (menton and gonion), the image of the mandibular cross-section was measured. The obtained images passed through the center of the left and right mandibular first molar furcation.

Measurement of Craniofacial Morphology

The definition of landmarks on the 3D images is shown in Table 1. Each landmark was measured on

Table 1. Definition of the Landmarks Used in This Study

Landmarks	Definition
S (sella)	Midpoint of the pituitary fossa in the sagittal plane
N (nasion)	Midpoint of the frontonasal suture in the frontal plane
Ba (basion)	Anteroinferior margin of the foramen magnum
A (point A)	Deepest point on the anterior outline of the maxilla between supradental and anterior nasal spine in the sagittal plane
B (point B)	Deepest point on the anterior outline of the mandible between infradental and pogonion in the sagittal plane
Or (orbitale)	Lowest point on the inferior rim of the orbit
Po (porion)	Most superior point on the external auditory meatus
FZ (frontozygomatic point)	Intersection of the frontozygomatic suture and the inner rim of the orbit in the frontal plane
ZA (zygomatic arch)	Most lateral aspect of the zygomatic arch
J (jugal point)	Deepest midpoint of left jugal process of maxilla
Co (condylion)	Most posterosuperior point of mandibular condyle
Go (gonion)	Point on the inferoposterior outline of the mandible at which the surface turns from the inferior border into the posterior border in the sagittal plane
Ag (antegonion)	Lateral inferior margin of antegonial protuberances at antegonial notch
Pg (pogonion)	Most anterior point on the mandibular chin area in the sagittal plane
Gn (gnathion)	Midpoint between Pg and Me on the surface of mandibular chin in the sagittal plane
Me (menton)	Most inferior point on the mandibular chin area in the sagittal plan

sagittal, horizontal, and frontal multiplanar reformation images for increased accuracy.

Craniofacial skeletal morphology was measured in the vertical, transverse, and anteroposterior dimensions (Table 2). The vertical facial height was divided into anterior and posterior components. The former was determined using the total and upper facial heights, whereas the latter was determined using the posterior and lower facial heights.

The left and right orbits, zygomatic bones, and mandibular segments were included in measurements of the transverse facial width. The interocular distance was determined as the distance between the left and right orbits and the distance between FZs. The mandibular width was set as the intercondylar distance and the distance between the left and right segments of the mandibular body.

The anteroposterior length was measured using the length of the cranial base, maxilla, and mandible in the sagittal plane. The length of the cranial base was divided into anterior and posterior lengths. The maxillary length was the distance between ANS and PNS. The mandibular length was the distance between Go and menton.

TpsUtil64 and tpsDIG software (http://life.bio.sunysb.edu/morph/soft-utility.html) were used for measurements, and landmarks were marked along the inner and outer borders of the mandibular cortex, which were determined using 23 landmarks on the cross-sectional mandibular images. The landmarks were determined to be where the highest points of the inner and outer cortices intersected with the buccal and lingual alveolar ridges. The landmark on the buccal alveolar ridge was called L1 and the landmark on the lingual alveolar ridge was called L2. Twenty-one semilandmarks were also

Table 2. Definition of the Measurements Recorded in This Study

Dimension	Measurement	Definition
Vertical	N-Me (total face height)	Distance between N and Me
	N-ANS (upper face height)	Distance between N and ANS
	S-Go (posterior face height)	Distance between Co and Go
	Co-Go (ramus length)	Distance between Co and Go
Transverse	Or-Or	Distance between the right and the left Or
	FZ-FZ	Distance between the right and the left FZ
	ZA-ZA	Distance between the right and the left ZA
	Co-Co	Distance between the right and the left Co
	Go-Go	Distance between the right and the left Go
	Ag-Ag	Distance between the right and the left Ag
Anteroposterior	S-N (anterior cranial base)	Distance between S and N
	Ba-N (cranial base)	Distance between Ba and N
	ANS-PNS (maxillary base)	Distance between ANS and PNS
	Go-Gn (mandibular body)	Distance between Go and Gn
	S-A	Distance between S and A
	S-B	Distance between S and B

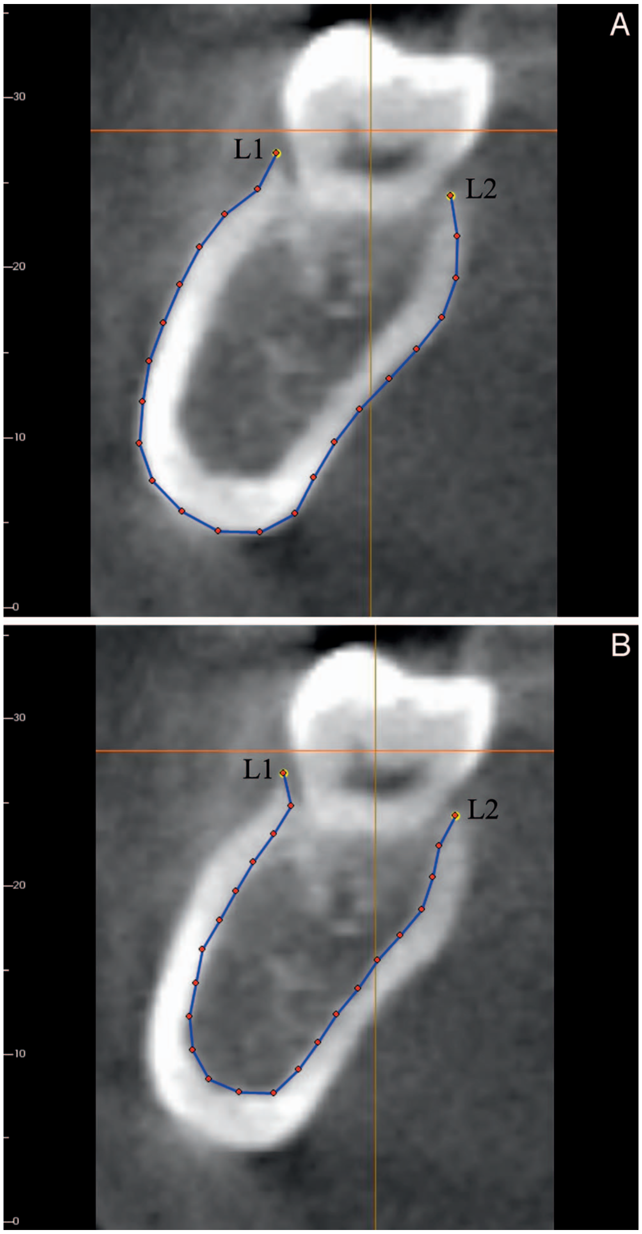

Figure 1. Landmarks marked on cross-sectional images of the mandible**.** Cross-sectional computed tomography (CT) reconstructions with fixed landmarks (yellow; L1 and L2, buccal and lingual alveolar bone crest) and semilandmarks (red). (A) Outer contour of the cortex in the first molar region. (B) Inner contour of the cortex in the first molar region.

marked on the mandibular cortex, leaving out the buccal and lingual alveolar ridges. The representative landmark of the cortex was located and repositioned to maintain approximately the same distance[18] (Figure 1).

Analysis

Exploratory factor analysis based on PCA was performed for evaluation of facial skeletal variations in the 150 participants. The facial landmarks were divided into three groups based on the vertical, transverse, and anteroposterior planes. Factors were extracted from each group to account for the cumulative proportion of variance, which was explained to be 70%. The contribution of each factor was used to score that factor, and two factors were retained. After varimax rotation, the factor loadings were extracted to understand the relationship between factor and variable using eigenvector, and the landmark with significant interpretation was selected.

Generalized Procrustes analysis was performed to estimate the mean cross-sectional shape of the mandible. PCA was performed to determine individual morphological variations in the mandibular cross-section for comparison of its mean shape. Two principal components (PCs) were extracted to obtain 70% of the cumulative proportion of the cross-sectional shape variance explained and the PC score for these components was determined using the observation score for the cross-sectional shape variance.

SEM was used to analyze the effects of vertical, transverse, and anteroposterior skeletal variables on the mandibular cross-section. Confirmatory factor analysis (CFA) was performed to extract five latent variables using PC on the inner and outer mandibular cortices and skeletal variables. A path diagram was used to visualize the research hypothesis in the SEM and allow a comprehensive understanding of the entire model. The fitness of the model was determined with consideration of the errors within SEM itself.

RESULTS

Factor analysis was conducted to determine the observed variables measured for facial morphology and two primary factors were extracted for each variable (Table 3). Each first-order factor was marked as Transverse 1 and 2, Vertical 1 and 2, and Anteroposterior 1 and 2. FZ-FZ, Co-Co, ZA-ZA, and Or-Or were effective factors for Transverse 1, while J-J, Go-Go, and Ag-Ag were effective factors for Transverse 2. CFA was performed based on these results for the extraction of secondary factors, latent variables of the transverse factor. The same analysis was used for Vertical 1 and 2 and Anteroposterior 1 and 2. The effective factors were determined as S-Go (posterior facial height) and Co-Go (ramus length) for Vertical 1 and N-Me (total facial height) and N-ANS (upper facial height) for Vertical 2. Likewise, the effective factors for Anteroposterior 1 were determined as S-N (anterior cranial base), Ba-N (posterior cranial base), ANS-PNS (maxillary base), and S-A, whereas those for Anteroposterior 2 were determined as S-B and Go-Gn (mandibular body length). The secondary

Table 3. Factor Analysis for the Skeletal Measurements

	Labels	Factor 1	Factor 2	Latent	Proportion
Transverse					
FZ-FZ	T1	0.8690	0.2961	Transverse 1	0.4713
Co-Co	T4	0.6840	0.3549		
ZA-ZA	T2	0.8091	0.4263		
Or-Or	T7	0.8635	−0.1089		
J-J	T3	0.0152	0.8395	Transverse 2	0.2676
Go-Go	T5	0.5884	0.5866		
Ag-Ag	T6	0.5739	0.6457		
Vertical					
S-Go	V4	0.9222	0.3013	Vertical 1	0.4504
Co-Go	V5	0.9037	0.3442		
N-Me	V1	0.2476	0.9153	Vertical 2	0.4622
N-ANS	V2	0.3472	0.8687		
Anteroposterior					
S-N	D1	0.8510	0.3151	Anteroposterior 1	0.4426
Ba-N	D3	0.8508	0.2380		
ANS-PNS	D4	0.7762	0.1681		
S-A	D6	0.6800	0.5410		
S-B	D7	0.2426	0.9267	Anteroposterior 2	0.3510
Go-Gn	D5	0.2896	0.8777		

factors were extracted for each primary factor, Vertical 1 and 2, and Anteroposterior 1 and 2 (Figure 2).

The results of PCA for the cross-sectional morphology of the left and right inner and outer cortices are shown in Table 4 and Figures 3 and 4. PCA yielded over 70% of the cumulative proportion of variance explained. As shown in Figures 3 and 4, PC1 (Principal component 1) had increased vertical height and decreased upper third and lower third widths at −3SD and decreased vertical height and increased upper third and lower third widths at +3SD compared with the average morphology. PC2 (Principal component 2) had a decreased middle third width at −3SD and an increased middle third width at +3SD compared with the average morphology. There was no noticeable change in height of PC2. Each PC was scored using

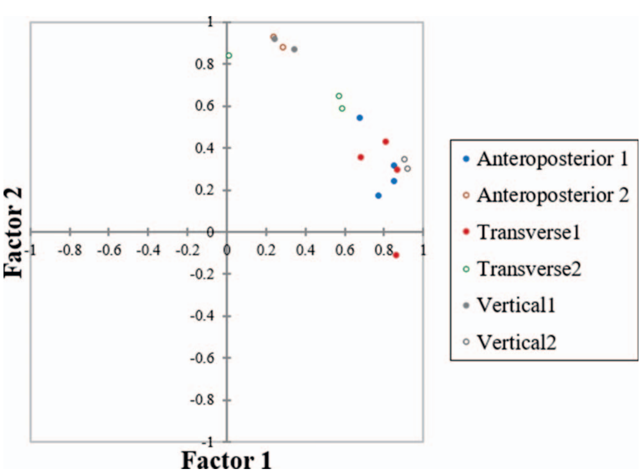

Figure 2. Score-loading biplots of factors 1 and 2 at the Anteroposterior 1 and 2, Transverse 1 and 2, and Vertical 1 and 2.

the observed value of the cross-sectional morphological variance. After the primary factor was extracted using PC with a high correlation coefficient value, the latent variable representing the inner and outer cortex variable was extracted.

SEM and model fitness for the latent variables were determined (Figure 5). SEM, proposed in Figure 5, was used to determine the effects of the skeletal latent variables on the inner and outer cortex latent variables. *P* values for the transverse, vertical, and anteroposterior latent variables on the inner cortex latent variables were 0.92, 0.678, and 0.107, and *P* values for the outer cortex latent variables were 0.057, 0.644, and 0.101, respectively. The effect of the transverse latent variable on outer cortex latent variable was not statistically significant but was relatively significant ($P = .057$) compared with other extracted variables. However, the effect of the vertical latent variable on the inner cortex latent variable ($P = .678$) and outer cortex latent variable ($P = .644$) showed no significant differences. Evaluation criteria for model fitness included the comparative fit index (CFI), relative fit index (RFI), normal fit index (NFI), and root mean square error of approximation (RMSEA). CFI, RFI, and NFI were ≤0.9, whereas RMSEA was ≥0.05.

DISCUSSION

The purpose of this study was to analyze the relationship between the cross-sectional morphology of the mandible and the facial skeletal pattern using SEM. Most previous studies suggested that the vertical facial skeletal pattern was correlated with the horizontal skeletal pattern. Wagner et al. reported that the vertical skeletal pattern may affect the transverse

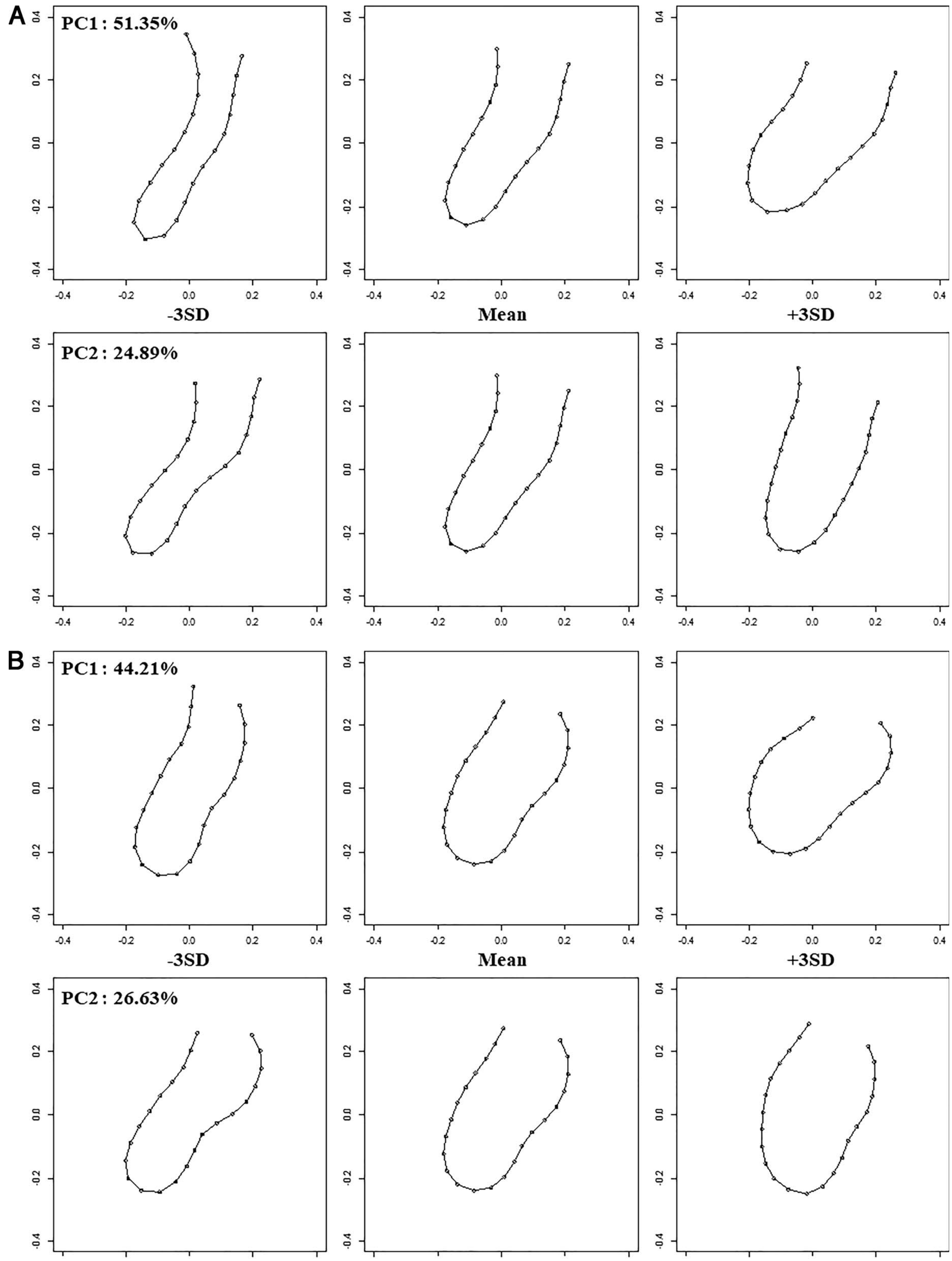

Figure 3. Principal component analyses (PCA) of the mandibular left first molar region (PC1 and PC2), with three standard deviations. (A) Inner cortex in the mandibular left first molar region. (B) Outer cortex in the mandibular left first molar region.

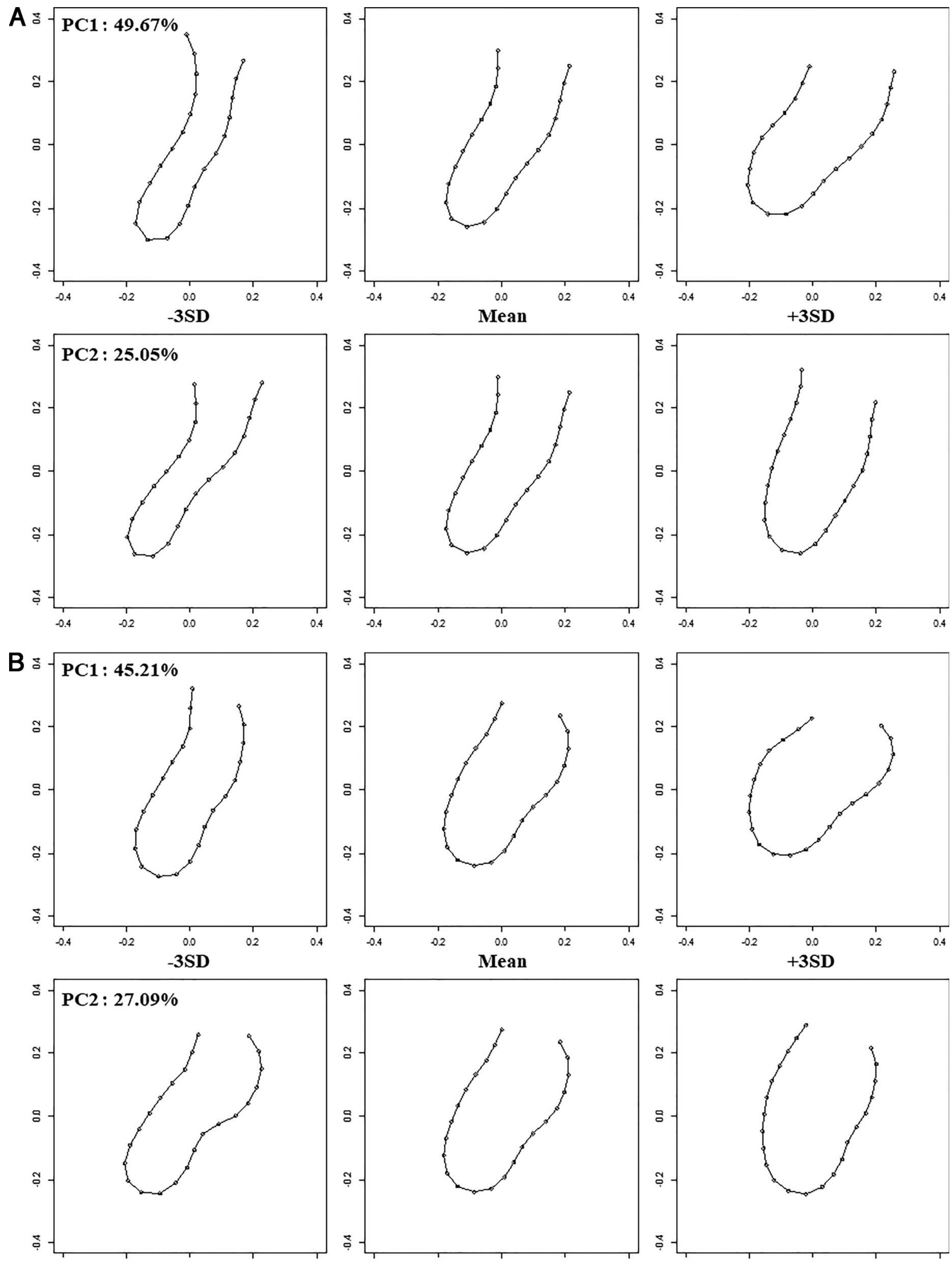

Figure 4. Principal component analyses (PCAs) of the mandibular right first molar region (PC1 and PC2), with three standard deviations. (A) Inner cortex in the mandibular right first molar region. (B) Outer cortex in the mandibular right first molar region.

Table 4. Cumulative Proportion Derived From Principal Component Analysis (PCA) of the Mandibular Cortex

	Inner Cortex		Outer Cortex	
	Mandibular Right	Mandibular Left	Mandibular Right	Mandibular Left
PC1	0.4967	0.5135	0.4421	0.4521
PC2	0.7472	0.7624	0.7084	0.7229

growth of the maxilla and mandible.[13] Hebsy et al. reported a difference in the width of the maxilla and mandible according to the vertical facial skeletal pattern.[19]

Statistical shape analysis was performed and meaningful PCs extracted. PC1 was used to represent the widths of the upper and lower thirds of the mean shape, and the vertical height of the mean shape. PC2 was used to explain changes in the width of the middle third. In other words, the base of the mandible and the morphology of the outer cortex affects thickness. The shape of the mandibular base and the buccal cortical bone tended to be thicker than the inner cortex, as suggested previously by Masumoto et al.[20]

Correlation between the variables obtained from the SEM explained the effect of skeletal factors on the morphology of the mandibular cortices. In this study, the effect of the transverse variable on the cross-sectional morphology of the mandible was relatively significant from the SEM. The transverse variable was more closely related to the outer cortex variable than other extracted variables. This meant that there was a relationship between the transverse skeletal pattern and the morphology of the outer mandibular cortex. However, the effect of the vertical variable on cross-sectional mandibular morphology showed no significant differences.

Many studies have focused on the correlation between the vertical skeletal pattern and the cross-sectional morphology of the mandible. Swasty et al. reported that patients with a long face had a long and narrow mandible, whereas patients with a short face had a short and wide mandible.[17] Kohakura et al. also reported that the mandibular cross-section was wide in patients with a short face.[14] Tsunori et al. found that the cortical bone of the mandible in patients with a short face was thicker because of thicker masticatory muscles.[21] The thickness of the cortical bone in the mandible is adapted to tolerate functional loads and morphological changes.[6,21,22] Therefore, morphological differences according to the facial skeletal pattern affect the cortical bone of the mandible.

The results of this study were different from those of previous studies that investigated the relationship between the mandible and the vertical skeletal pattern only. In this study, the overall effect of the skeletal

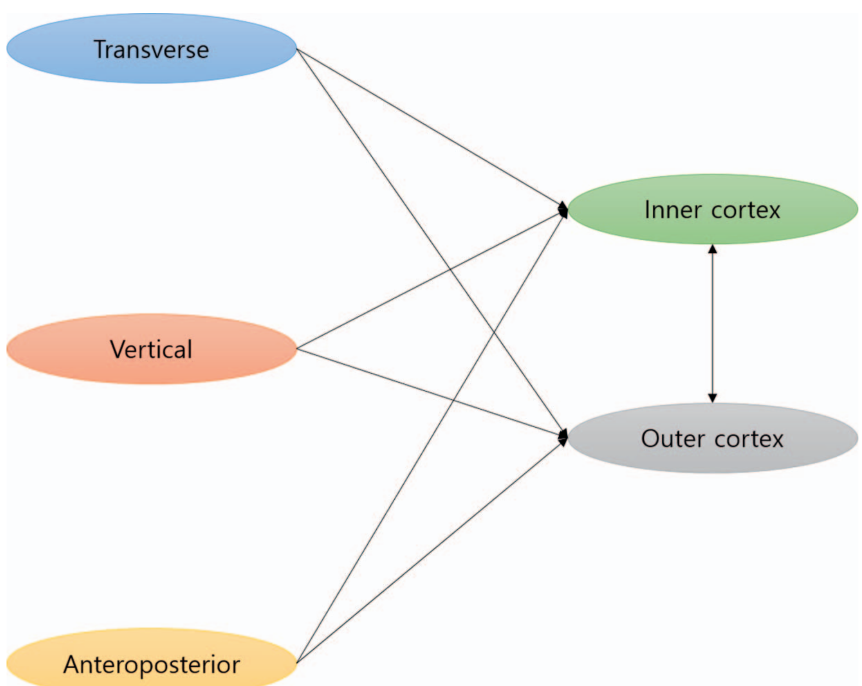

Figure 5. Structural equation model for skeletal measurements and morphology of the mandibular cortex. (Arrows show correlation between variables; left column: skeletal variables; right column: variables of mandibular cortices.)

pattern on the morphology of the mandibular cross-section was evaluated, and the results can be used to aid in orthodontic treatment planning.

In orthodontic treatment, the results of this study may be applicable to microimplant fixation and root resorption during orthodontic tooth movement. Predicting the morphology of bone is needed to place orthodontic microimplants successfully[23] and to accomplish tooth movement without root resorption.[1,2] To orthodontists, the results could be used to evaluate the morphology of the mandible and therefore help make treatment planning decisions.

CONCLUSIONS

- A structural equation model was devised using the variables obtained from statistical shape analysis for cross-sectional mandibular morphology and from facial skeletal measurements obtained using CBCT images.
- The results suggest that cross-sectional mandibular morphology was associated with facial skeletal pattern and that the morphology of the inner and outer mandibular cortices was associated with the transverse facial skeletal pattern.

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