

Multidimensional tooth movement boundaries in the extended aesthetic zone: a cone-beam computed tomography study

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Purpose: To establish tooth movement boundaries in four directions by a novel morphometric analysis of alveolar bone using cone-beam computed tomography (CBCT) images. The aim was to assist clinicians in minimising the occurrence of bone fenestration and dehiscence, thereby facilitating safe and efficient orthodontic treatment.

Methods: CBCT images of 123 male volunteers comprising 55 individuals with hypodivergent vertical skeletal patterns and 68 individuals with normodivergent vertical skeletal patterns and normal occlusions but without a history of previous orthodontic treatment, were analysed. The mesiodistal and labiolingual alveolar bone height (ABH) as well as the labiolingual cancellous bone thickness (CBT) were measured in relation to the maxillary and mandibular anterior teeth and premolars. These parameters were subsequently compared between the different vertical skeletal patterns.

Results: Teeth within the extended aesthetic zone exhibited a limited range of safe movement on the labial aspect across all three root aspects, with 97.6% of the upper lateral incisors and 98.4% of the lower lateral incisors positioned against the labial cortical plate (<0.5 mm). The lingual aspects had significantly more space for tooth movement compared with the labial aspects ($P < 0.05$). The ABH was significantly greater in the hypodivergent group than the normodivergent group involving particular teeth and sites in the maxilla ($P < 0.05$), while no significant difference was noted in the mandible. The hypodivergent group also exhibited thicker cancellous bone on most labial and some lingual aspects.

Conclusions: The findings provided the average tooth movement range in the horizontal and vertical directions within the extended aesthetic zone in male individuals presenting with a normal occlusion. It was concluded that a hypodivergent growth pattern may have a relatively large range of safe tooth movement in the sagittal and vertical directions.

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Introduction

The anatomical morphological structure of the alveolar bone determines the basic limit of tooth movement throughout orthodontic treatment. If

tooth movement exceeds this limit, bone dehiscence and fenestration will occur, especially in cases undergoing retraction or inclination compensation movements.^{1,2} This risk can be prevented during fixed appliance treatment by limiting excessive movements

via regular clinical monitoring. It is more complex for clear aligner treatments, however, as most final target positions are firmly established during the initial design phase. If the root-bone relationship of a patient is not identified early, it is likely to result in dehiscence or fenestration. When considering the acquisition of clear aligner skills, it is vital that clinicians understand alveolar bone morphology in normal healthy individuals and master the basic rules of tooth movement.

Routine two-dimensional radiographs, involving panoramic films or lateral radiographs, are unable to provide significant detail related to tooth roots and alveolar bone. Until the introduction of cone-beam computed tomography (CBCT), it was not possible to identify the root-bone relationship prior to orthodontic therapy. At present, considerable progress has been made in the use of CBCT to determine alveolar bone height (ABH) and thickness.^{3–15} before which previous studies proposed normal values. However, in clinical practice, it is evident that the distance from the root surface to the alveolar bone surface can only be used as an alert threshold instead of providing guidance for designing treatment protocols. When the root of a tooth contacts the interior cortex of the alveolar bone, tooth movement becomes significantly affected. If the root continues to move, the risk of root resorption or bone dehiscence will substantially increase. To date, few previous studies have measured the specific distance between the root surface and the interior cortex of the alveolar bone and therefore, it is hypothesised that this measurement will be more meaningful in guiding the range of possible tooth movement.

In previous research, measurements were often taken at a fixed distance (for example, 3, 6, 9 or 12 mm) from the cemento-enamel junction to act as the reference plane in axial or sagittal views.^{3,16,17} The lack of uniform measurements makes it challenging to perform horizontal comparisons. Furthermore, no previous study has offered a reason explaining why a particular setting was used. To provide greater understanding, it would be helpful to measure the ABH around all anterior and premolar teeth to determine the relationship between specific distances below the cemento-enamel junction (CEJ) and the dental roots.

Earlier studies divided sample patients into groups based on vertical skeletal patterns and examined the correlation between vertical facial characteristics

and alveolar bone morphology.^{8,17} However, to the authors' knowledge, the relationship between cancellous bone thickness (CBT) and ABH have not yet been investigated. Therefore, the primary aim of this study was to identify the normal range of ABH and CBT in maxillary and mandibular anterior and premolar regions. A secondary aim was to investigate the relationship between vertical skeletal patterns and alveolar bone morphology.

Materials and methods

This retrospective cross-sectional study was conducted using CBCT images collected during previous research and was approved by the Stomatological Hospital of the Fourth Military Medical University Ethics Committee (project number: IRB-REV-2015001). The samples were selected according to the following inclusion criteria: (1) male patients who were 18 to 40 years of age; (2) patients who agreed to participate in the research study and provided signed and informed consent; (3) patients who were in good health, with normal development, normal features and who had an aesthetic profile; and (4) patients who had a complete permanent dentition,^{15,18–21} without supernumerary teeth, a Class I skeletal relationship, a dental Class I relationship of the molars and canines, a normal overbite of the anterior and posterior teeth, and crowding of the upper and lower dentitions less than 1 mm. Patients were excluded from the study if they had a cleft lip and/or palate, a history of maxillofacial trauma, previous surgery, orthodontic treatment, or temporomandibular disorders. The sample size was calculated by considering a mean difference of 0.73 mm in alveolar bone thickness and 0.81 mm in ABH between the hypodivergent group and the normodivergent group, as well as a standard deviation of 1.38 mm in alveolar bone thickness and 1.45 mm in ABH (based on data from a previous pilot study), with a significance level of 5% and a test power of 80%. A minimum of 54 CBCT scans for hypodivergent patterns and 67 CBCT scans for normodivergent patterns were deemed necessary for each group. The sample included the CBCT scans of 123 individuals (mean age, 23.5 ± 3.7 years) and were divided into a hypodivergent group ($n = 55$) and a normodivergent group ($n = 68$).

All volunteers underwent craniomaxillofacial scans using the same CBCT machine (KaVo 3D eXam

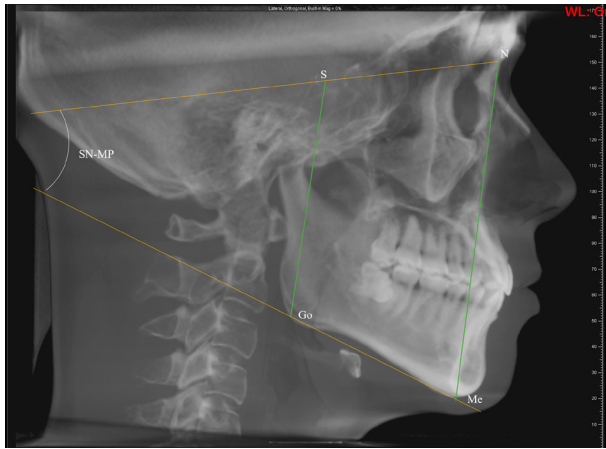


Figure 1. The cephalometric measurements used in this study. (1) SN-MP; (2) S-Go/N-Me (a/b).

cone beam CT, Kavo Corporation, Hatfield, USA) and using the following scanning parameters: the tube voltage was 120 kV, the tube current was 5mA, the field size was 23 cm × 17 cm, the spatial resolution was 0.3 mm, and the exposure time was 3.0 s. The reconstructed results were saved in DICOM version 3.0 format for subsequent analysis. The volunteers were asked to adopt a relaxed sitting position, with their lips closed naturally, and with their eyes looking straight ahead. This ensured that the orbital-ear plane was parallel to the ground and that the intercusp position was maintained. To avoid compression and deformation of the soft tissue of the chin, the chin bracket was removed during CBCT scanning, and head position was fixed by frontal banding.

The cephalometric indicators used for dividing the different vertical skeletal patterns are shown in Figure 1: (1) SN-MP (29°–40°, normal; <29°, low-angle), (2) SGo-NMe (62–65%, normal; >65%, low-angle). Axial, coronal, and sagittal orientation planes

were constructed using specific rules for the accurate positioning of a given tooth and the interdental region prior to measurement (Figure 2). For anterior teeth and the premolar regions, the long axis of the tooth was defined as the line between the cusp (or the midpoint of the incisal margin) and the root tip. To identify a horizontal plane, a parallel line was constructed from an orange marker line tangent to the corresponding dental arch on the labial and buccal side of the target tooth which then identified a point of intersection between the orange marker line and a green marker line as the centre point of the root section. Subsequently, the sagittal and coronal planes were adjusted to pass through the long axis of the tooth. For the molar areas, the long axis of the crown and the long axis of the root (especially the terminal third of the root) often form an angle. Considering the specific research aim, and based on previous studies,²² the long axis of the root was used to replace the long axis of the tooth, that is, through the centre point of the furcation and the apical point of the root. In the case of curved roots, the long axis of the root was defined as the central axis of the root beyond the curved portion. As the buccal cortical bone of the molar area gradually thickened from anterior to posterior, it was not appropriate for the tangent line to be used as a basis for measurement in posterior areas. The orange marker line in the molar area was defined as passing through the long axis of the root and parallel to the long axis of the alveolar ridge which passed through the canine to the second molar. The sagittal and coronal planes were then adjusted to each pass through the long axis of the root.

The cancellous bone thickness (CBT) was measured in the sagittal plane at three positions on the labial, buccal and lingual aspects of the tooth (Figure 3).



Figure 2. (A) Axial plane; (B) Sagittal plane; (C) Coronal plane.

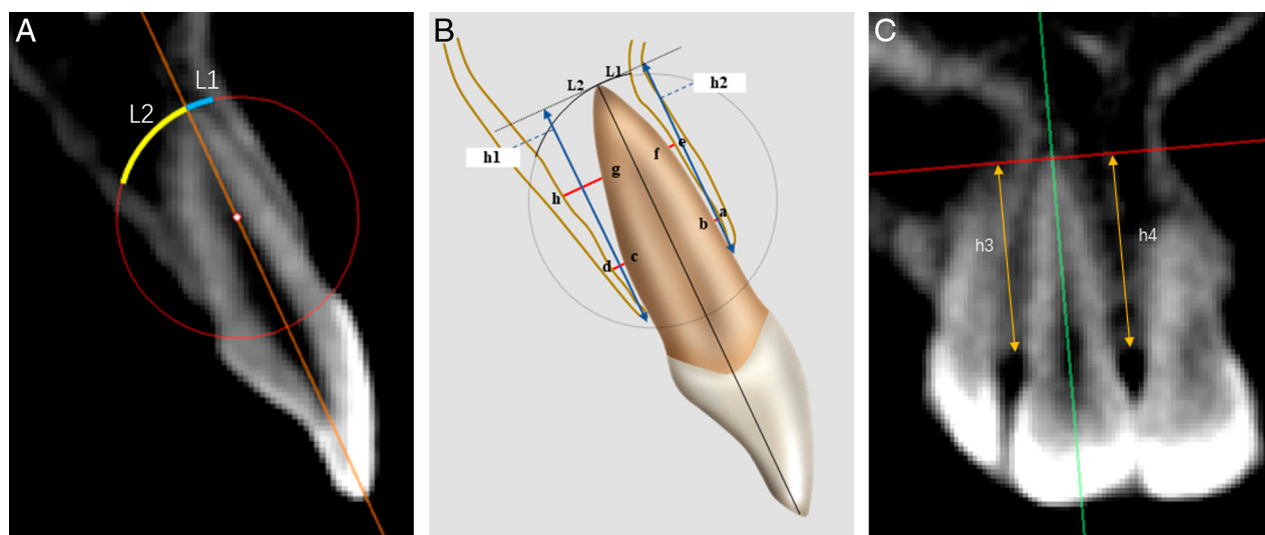


Figure 3. (A) Measurements at the apex section of the anterior teeth; (B) A schematic diagram showing measurements in the sagittal plane: (a, b) labial CBT at the 1/3 root section (close to the CEJ); (c, d) lingual CBT at the 1/3 root section (close to the CEJ); (e, f) labial CBT at the 2/3 root section; (g, h) lingual CBT at the 2/3 root section; arc L1: labial CBT at apex section; arc L2: lingual CBT at apex section; h1: lingual ABH; h2: labial ABH. (C) Measurements in the coronal plane. h3: distal ABH; h4: mesial ABH. CBT, cancellous bone thickness; ABH, alveolar bone height.

Two planes perpendicular to the long axis of the tooth (or the root) and past the root apex and the CEJ were used as the starting plane and the end plane, respectively. The long axis was equally divided into three sections, the 1/3 root section (close to the CEJ), the 2/3 root section (close to the root apex), and the root apex section. The cancellous thickness of the labial, buccal and lingual alveolar bone was defined as the distance from the root surface to the interior side of the cortical bone. Previous research on alveolar bone morphology has predominantly focused on the bone mass for an immediate implant.³ Such measurement standards are still used when studying orthodontic movement, which does not conform to the biomechanical law of tooth movement. Therefore, in the present study, the measurement method described previously by Pei and Sadek^{18,23} was adopted, which intercepted different measurement planes according to the length of the root instead of the absolute distance below the cemento-enamel junction (CEJ).

Tipping movements tend to occur in anterior teeth during orthodontic treatment. Given this, it was assumed that a tooth tilts around its centre of rotation, which was defined as the midpoint of the root when measuring the root apex section of the central incisors, lateral incisors and canines in both arches. The length of the arch between the

intersection point of the labial or lingual interior cortical bone and the apical point was defined as the CBT at the root apex section.^{11,24}

Subsequently, the mesiodistal and labiolingual ABH were measured in the sagittal and coronal views, respectively (Figure 3). The height of the alveolar bone was defined as the distance from the alveolar crest to the reference plane which passed through the apical point and was perpendicular to the long axis of the tooth (or root).^{19,25} All image data were measured by one orthodontist with more than 3 years of practice experience. Twenty samples were randomly selected for re-measurement by the same observer after an interval of one month.

Statistical analysis

Data analysis was performed using SPSS for Windows version 27.0 (SPSS Inc., Chicago, IL, USA). The reliability of intra-rater measurements was determined by repeating them twice after a one-month interval and analysed using the intraclass correlation coefficient. The Kolmogorov-Smirnov test was used to assess the normality probability distribution of mean outcome measurements. Variables that did not follow a normal distribution were described by quartiles. The remaining variables were described by the 95% reference value range

Table I. Maxillary cancellous alveolar bone thickness after merging the left and right teeth

	Labial			Lingual		
	LA_1	LA_2	LA_3	LL_1	LL_2	LL_3
Central incisor	0 (0)*	0 (0)*	0.93 (1.55)*	1.16 (0.91)	2.99 (1.43)	6.29 ± 3.36
Lateral incisor	0 (0)*	0 (0)*	0 (1.29)*	0.87 (0.79)	2.53 (1.63)	5.60 ± 2.93
Canine	0 (0)*	0 (0)*	0 (1.38)*	1.4 (1.59)	4.28 ± 3.40	8.15 ± 3.59
First premolar	0 (0.76)*	0 (0.74)*	1.11 (1.55)*	0.70 (1.06)	1.8 (1.46)	6.16 ± 4.90
Second premolar	1.28 (1.08)*	1.38 (0.99)*	2.5 (1.73)*	1.04 (1.26)	2.38 (1.82)	6.85 ± 5.64

Data are given as "median (P75-P50)" in non-normal distribution or "mean±SD" in normal distribution. LA_1 (LL_1): 1/3 root section (close to the CEJ); LA_2(LL_2): 2/3 root section (close to the root apex); LA_3 (LL_3): root apex section.

*Significant differences between the labial alveolar bone thickness (LA) and lingual alveolar bone thickness (LL) in the same tooth position and the same section, when evaluated by the paired t test (normal distribution) or Wilcoxon's signed rank test (non-normal distribution) ($p < 0.05$).

Table II. Mandibular cancellous alveolar bone thickness after merging the left and right teeth

	Labial			Lingual		
	LA_1	LA_2	LA_3	LL_1	LL_2	LL_3
Central incisor	0 (0)*	0 (0.64)*	2.19 (1.1)	0 (0)	0.68 (1.01)	2.22 (1.17)
Lateral incisor	0 (0)*	0 (0)*	2.18 ± 1.84*	0 (0.53)	0.82 (1.16)	2.53 (1.16)
Canine	0 (0)*	0 (0.73)*	2.78 ± 2.20*	0.65 (0.96)	1.4 (1.1)	4.02 ± 2.80
First premolar	0 (0)*	0.38 (0.8)*	2.38 ± 1.97*	0.59 (0.95)	2.18 ± 1.98	4.53 ± 2.77
Second premolar	0 (0.62)*	0.86 (0.53)*	2.71 ± 2.04*	0.93 (0.97)	2.67 ± 2.27	4.79 ± 2.92

Data are given as "median (P75-P50)" in non-normal distribution or "mean±SD" in normal distribution. LA_1 (LL_1): 1/3 root section (close to the CEJ); LA_2(LL_2): 2/3 root section (close to the root apex); LA_3 (LL_3): root apex section.

*Significant differences between the labial alveolar bone thickness (LA) and lingual alveolar bone thickness (LL) in the same tooth position and the same section, when evaluated by the paired t test (normal distribution) or Wilcoxon's signed rank test (non-normal distribution) ($p < 0.05$).

(±1.96 mm). Paired t-tests (for data with a normal distribution) or Wilcoxon's signed rank tests (for data with a non-normal distribution) were applied to compare parameters on the left and right sides. If there was no significant difference between the two groups of samples, they were combined for further analysis. An independent sample t-test (for data with a normal distribution) or Mann-Whitney U test (for data with a non-normal distribution) were performed on the ABH and CBT of the hypodivergent or normodivergent groups with a significance level α of 0.05.

Results

The intraclass correlation values of each index were greater than 0.9, thus indicating that the measurement results had high repeatability. According to the

Kolmogorov–Smirnov test, the variables with statistical significance greater than 0.05 were described by the 95% reference value range (±1.96). Variables with a significance of less than 0.05 were described by quartiles (P50, P75-P25) (Tables I–IV).

The ABH of each tooth position followed a normal distribution; however, most of the alveolar bone thicknesses did not conform to the normal distribution. The lingual CBT was greater than labial CBT in both the upper and lower arches; all differences were statistically significant ($P < 0.05$) except for the apical section of the lower central incisor. In the normal occlusion samples reported by Rong et al.,⁷ 98.5% of the upper anterior teeth were closer to the labial alveolar bone. In the subjects with a normal occlusion, almost all of the anterior and premolar teeth were close to the labial cortical bone

Table III. Maxillary alveolar bone height after merging the left and right teeth

	LA_h	LL_h	M_h	D_h
Central incisor	10.22 ± 3.48*	10.51 ± 3.34	12.59 ± 3.76	12.29 ± 3.57
Lateral incisor	11.04 ± 2.86	10.90 ± 2.98	12.82 ± 3.04	12.15 ± 2.97
Canine	13.78 ± 4.19*	14.48 ± 4.32	16.41 ± 4.16	14.73 ± 3.67
First premolar	10.03 ± 3.59*	10.53 ± 3.52	11.75 ± 3.77	11.51 ± 3.36
Second premolar	10.36 ± 4.01	10.33 ± 4.22	11.68 ± 4.13	10.48 ± 4.39

Data are given as "mean±SD".

* $p < 0.05$ for labial alveolar bone height (LA) and lingual alveolar bone height (LL) in the same tooth position.

D_h, the distal alveolar bone height; LA_h, the labial alveolar bone height; LL_h, the lingual alveolar bone height; M_h, the mesial alveolar bone height.

Table IV. Mandibular alveolar bone height after merging the left and right teeth

	LA_h	LL_h	M_h	D_h
Central incisor	9.72 ± 2.95*	9.34 ± 2.60	10.84 ± 2.44	10.83 ± 2.44
Lateral incisor	10.88 ± 3.42*	10.37 ± 3.41	11.98 ± 2.73	11.65 ± 2.65
Canine	13.18 ± 4.76*	13.68 ± 4.27	15.45 ± 4.25	14.31 ± 4.19
First premolar	12.26 ± 3.87	12.37 ± 3.63	12.88 ± 3.29	12.55 ± 3.30
Second premolar	12.10 ± 4.03	12.11 ± 3.89	12.78 ± 3.93	12.33 ± 3.77

Data are given as "mean±SD".

* $p < 0.05$ for labial alveolar bone height (LA) and lingual alveolar bone height (LL) in the same tooth position.

D_h, the distal alveolar bone height; LA_h, the labial alveolar bone height; LL_h, the lingual alveolar bone height; M_h, the mesial alveolar bone height.

in the bimaxillary alveolus, and the thickness of the labial alveolar bone of the anterior teeth was skewed closer to zero. The skewed data from each group were merged with 0.5 mm as the group distance and a composite percentage bar plot is shown in Figure 4.

The ABHs of the maxillary teeth in the hypodivergent group were higher than those in the normodivergent group for particular teeth and sites ($P < 0.05$) (Table V). There were no significant differences identified in the mandibular arch. The labial CBT in the apex sections in the hypodivergent group were higher than those in the normodivergent group in both arches ($P < 0.05$) (Table VI).

Discussion

"Cortical bone anchorage" is often referred to in orthodontic clinical practice and was used by Ricketts and other scholars in "Bioprogressive Therapy"²⁶ to describe effective physiological tooth movement, and was first mentioned by Yangxi Chen²⁷ in China. If a tooth position requires change, it will often need

to be relocated from the dense cortical bone into vascular cancellous bone to promote both movement and tissue remodelling. Conversely, when anchorage is needed, the root should be pressed against the adjacent dense cortical bone.

Since most initial research on alveolar bone morphology was conducted by implantologists who aimed to assess bone mass for immediate implant placement and to prevent bone dehiscence and fenestration during orthodontic treatment,³ the measurement of alveolar bone thickness encompassed both the lateral cortical bone and cancellous bone surrounding the root. However, when clinicians analyse the relationship between the root and bone by CBCT, in addition to a risk assessment of bone dehiscence and fenestration, the distance from the root to the cortical bone is the point of common concern. The issue is related to the limitations and difficulty of orthodontic tooth movement, and even the control of anchorage.^{27,28} When designing a clear aligner plan, only the crown data are available without the limitations imposed by the root and the alveolar

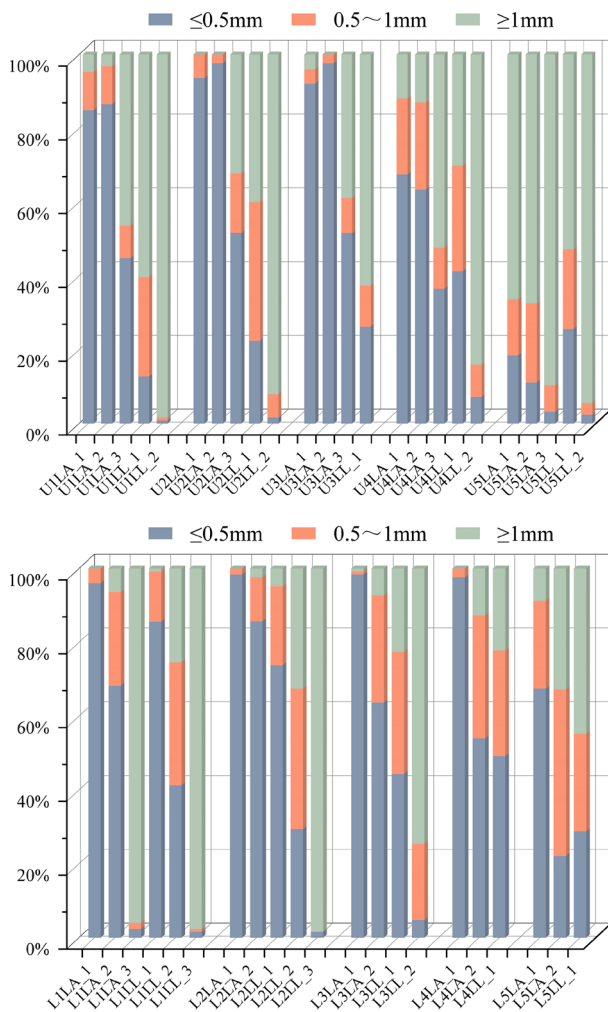


Figure 4. Distribution of cancellous bone thickness in the maxillary/mandibular alveolar bone. U: upper jaws; L: lower jaws; 1: central incisors; 2: lateral incisors; 3: canine teeth; 4: first premolar teeth; 5: second premolar teeth; LA_1: labial cancellous bone thickness at the 1/3 root section (close to the CEJ) of central incisors; LA_2: labial cancellous bone thickness at the 2/3 root section; LA_3: labial cancellous bone thickness at root apex; LL_1: lingual cancellous bone thickness at the 1/3 root section (close to the CEJ); LL_2: lingual cancellous bone thickness at the 2/3 root section; LL_3: lingual cancellous bone thickness at root apex.

bone. Therefore, it is easy to consider that a given tooth could continue to move even when contacting the cortex. This can eventually lead to impeded tooth movement or bone cracking or fenestration. Therefore, it is necessary to use normal cancellous bone thickness as a guide when considering tooth movements and be aware of influences based on other craniofacial characters such as vertical skeletal patterns.

This is the first study to investigate the trabecular thickness between the root and internal bone cortex,

as well as ABH in four directions of the anterior and premolar teeth. The present analysis showed that in cases of normal occlusion, the roots of the maxillary anterior teeth and the premolars (except for the second premolar) were sited very close to the labial cortical bone, while the lingual root aspects had more space in which to move; the canine had the most space to move towards the lingual. Therefore, it may be inferred that the premolar region allows a small range of buccal movement during arch expansion and arch adjustment; however, the upper anterior area creates difficulty with regard to labial tooth movement. These conditions are, however, relatively safe in cases involving extraction and retraction. The distance at the upper third of the lateral incisor root was the smallest, and therefore needs to be carefully considered along with the alveolar bone thicknesses of the lower anterior teeth on both the labial and lingual aspects which are generally narrow.

The selection of measurement planes is a distinguishing factor between orthodontists and implantologists in studies of alveolar bone morphology, yet all tended to reach a consistent conclusion. In a previous study, Jun-Beom Park et al.¹⁻⁴ selected regions at 3 mm and 5 mm from the CEJ and at the root apex as measurement planes. Analysis revealed that most labial bony wall thicknesses of the upper and lower anterior teeth and premolars were less than 2 mm, and some were less than 1 mm. It is worth noting that all of Park's studies measured the thickness of the entire bony plate; however, in the present study, the thickness of the cancellous bone was measured. The trends observed in the current research are consistent with those described by Park et al. and complement each other.

The measurement methods for ABH can be generally divided into three types. The first is to measure the height from the cemento-enamel junction to the alveolar crest,^{20,29} the second is to measure the height from the alveolar crest to the bottom of the basal bone (palatine bone or mandibular base),^{18,21,25} and the third is to measure the height from the alveolar crest to the apical plane.¹⁹ From a clinical perspective, the first method is primarily utilised for evaluating appropriate periodontal support; the second method is mainly employed to investigate the correlation between base bone morphology and facial shape as well as anterior occlusal overlap; while the third method, employed in the present study, served

Table V. Alveolar bone height of the maxilla and mandible of individuals with different vertical skeletal patterns

Measurement	Alveolar bone height			Measurement	Alveolar bone height		
	Hypodivergent	Normodivergent	P-value		Hypodivergent	Normodivergent	P-value
U1LA_h	10.49 ± 1.73	9.95 ± 1.84	0.099	L1LA_h	9.88 ± 1.55	9.49 ± 1.41	0.148
U1LL_h	10.64 ± 1.65	10.36 ± 1.76	0.373	L1LL_h	9.41 ± 1.38	9.18 ± 1.21	0.315
U1M_h	12.64 ± 2.11	12.53 ± 1.76	0.741	L1M_h	10.83 ± 1.35	10.80 ± 1.13	0.914
U1D_h	12.43 ± 1.89	12.13 ± 1.78	0.363	L1D_h	10.83 ± 1.30	10.77 ± 1.17	0.772
U2LA_h	11.33 ± 1.41	10.78 ± 1.43	0.035*	L2LA_h	11.04 ± 1.53	10.67 ± 1.89	0.228
U2LL_h	11.19 ± 1.56	10.67 ± 1.41	0.059	L2LL_h	10.51 ± 1.70	10.18 ± 1.69	0.297
U2M_h	13.07 ± 1.58	12.65 ± 1.49	0.132	L2M_h	12.03 ± 1.59	11.89 ± 1.11	0.581
U2D_h	12.47 ± 1.57	11.87 ± 1.40	0.028*	L2D_h	11.75 ± 1.55	11.52 ± 1.03	0.338
U3LA_h	14.19 ± 2.13	13.35 ± 2.12	0.031*	L3LA_h	13.39 ± 2.29	12.97 ± 2.52	0.337
U3LL_h	14.87 ± 2.15	14.05 ± 2.25	0.042*	L3LL_h	13.70 ± 2.28	13.65 ± 2.09	0.900
U3M_h	16.70 ± 2.09	16.05 ± 2.15	0.095	L3M_h	15.43 ± 2.13	15.49 ± 2.20	0.891
U3D_h	14.85 ± 1.78	14.53 ± 1.94	0.350	L3D_h	14.26 ± 2.04	14.39 ± 2.17	0.746
U4LA_h	10.23 ± 1.91	9.72 ± 1.71	0.121	L4LA_h	12.31 ± 2.11	12.16 ± 1.79	0.676
U4LL_h	10.47 ± 1.86	10.53 ± 1.75	0.850	L4LL_h	12.60 ± 2.01	12.06 ± 1.63	0.107
U4M_h	11.89 ± 1.81	11.51 ± 2.06	0.279	L4M_h	13.02 ± 1.79	12.63 ± 1.52	0.207
U4D_h	11.69 ± 1.82	11.24 ± 1.61	0.154	L4D_h	12.77 ± 1.74	12.22 ± 1.57	0.067
U5LA_h	10.71 ± 2.02	9.82 ± 1.94	0.015*	L5LA_h	12.19 ± 2.29	11.88 ± 1.72	0.404
U5LL_h	10.68 ± 2.12	9.85 ± 2.14	0.034*	L5LL_h	12.18 ± 2.10	11.97 ± 1.85	0.564
U5M_h	11.93 ± 2.28	11.29 ± 1.89	0.092	L5M_h	12.77 ± 1.94	12.64 ± 2.05	0.716
U5D_h	10.68 ± 2.53	10.13 ± 1.88	0.176	L5D_h	12.35 ± 1.85	12.22 ± 2.00	0.717

*P<0.05.

1, central incisors; 2, lateral incisors; 3, canine teeth; 4, first premolar teeth; 5, second premolar teeth; D_h, distal alveolar bone height of the tooth; L, lower jaws; LA_h, labial alveolar bone height of the tooth; LL_h, lingual alveolar bone height of the tooth; M_h, mesial alveolar bone height of the tooth; U, upper jaws.

predominantly to assess the centre of resistance in orthodontic tooth movement, thereby aiding orthodontists in selecting an optimal force system.²² In a study employing the same measurements, Casanova-Sarmiento, observed ABHs that were comparatively lower than the present findings.¹⁹ Chen et al. employed similar research methods as the current study but differed in that root length was measured from the cemento-enamel junction rather than the alveolar crest without imposing restrictions on the occlusion. The findings were approximately 1 to 3 mm greater than those of the present study, which is consistent with the distance between the enamel-bone boundary and the alveolar crest.¹⁵

The current methods for finding the centre of tooth resistance include a finite-element analysis, an electrical resistance strain gauge method, a

laser reflection measurement, laser holography, or photoelasticity. The finite element analysis method of previous studies only established the position and shape of alveolar bone by simulating along the curvature of the cemento-enamel junction (CEJ) at a distance of 1 mm below³⁰ or according to a standardised tooth model,^{30,31} without considering the actual anatomical characteristics of the tooth-alveolar bone complex. The current finite element model set the tooth and alveolar bone as rigid structures, and established the periodontal ligament as the key entity for instantaneous tooth movement.³² As the source of resistance for tooth movement, the setting of ABH is crucial. Using multidimensional data of the normal occlusion population in the present study will identify significant clinical implications in determining the centre of resistance and selecting the appropriate type of tooth movement.

Table VI. Cancellous bone thickness of the maxilla and mandible of individuals with different vertical skeletal patterns

Measurement	Alveolar bone thickness		
	Hypodivergent	Normodivergent	P-value
U1LA_3	1.10 (1.61)	0.51 (1.45)	0.031*
U2LA_3	0.93 (1.66)	0.00 (0.89)	0.001*
U3LA_3	1.03 (1.58)	0.00 (0.99)	0.001*
U4LA_3	1.33 (1.22)	0.00 (1.31)	0.000*
U5LA_3	2.73 (1.55)	2.1 (1.49)	0.000*
U1LL_3	6.60±1.91	5.97±1.49	0.047*
U2LL_3	5.66±1.52	5.57±1.50	0.734
U3LL_3	8.62±1.85	7.70±1.76	0.006*
U4LL_3	6.67±2.54	5.57±2.40	0.015*
U5LL_3	7.35±3.15	6.16±2.43	0.021*
L1LA_3	2.32 (1.35)	1.99 (0.91)	0.015*
L2LA_3	2.48±0.98	1.87±0.80	0.000*
L3LA_3	3.17±1.11	2.44±0.97	0.000*
L4LA_3	2.69±1.01	2.10±0.92	0.001*
L5LA_3	2.92±1.23	2.50±0.93	0.028*
L1LL_3	2.48 (1.27)	2.04 (0.98)	0.011*
L2LL_3	2.69 (1.33)	2.44 (1.23)	0.168
L3LL_3	4.07±1.32	4.00±1.56	0.154
L4LL_3	4.53±1.31	4.57±1.41	0.872
L5LL_3	4.67±1.46	4.90±1.50	0.392

*P<0.05.

1, central incisors; 2, lateral incisors; 3, canine teeth; 4, first premolar teeth; 5, second premolar teeth; L, lower jaws; LA_3, labial cancellous bone thickness at root apex; LL_3, lingual cancellous bone thickness at root apex; U, upper jaws.

The alveolar bone thickness compared to different growth pattern groups has been considered in past studies. Following a detailed literature review, the conclusions are summarised in Table VII.^{15,18–21} Despite different reference sections and specific measurements, researchers have agreed that the alveolar bone thickness over the root apex sections were greater in the hypodivergent patient groups compared with the normodivergent groups. In the present study, the comparisons between the hypodivergent group and the normodivergent group showed that in certain regions in the maxilla, the ABH in the hypodivergent group was significantly greater than that in the normodivergent group and the CBT on the labial side as well as some sites on the lingual side was greater in the hypodivergent patient group than the normodivergent group. The findings of the current study validate the

presence of a similar principle in cancellous bone and suggest its potential as a supplement to these studies. This difference may be related to bite force in which the force of individuals with a hypodivergent growth pattern is typically greater than an individual with a high mandibular plane angle growth pattern. This may lead to an increase in ABH to accommodate the greater bite force. No such relationship exists in the mandible which may be due to the ability of the mandible to change its position through joint rotation, or because a greater number of factors influence the development of the mandible. Based on the greater labial cancellous bone thickness in the hypodivergent group, there is a larger safe space for tipping movements to correct dental overlap or to compensate for skeletal discrepancies in clinical practice. Additionally, due to the increased ABH in the aesthetic areas of the

Table VII. Comparison of alveolar bone thickness between two prevalent vertical skeletal patterns in individuals with normal occlusion with existing literature

	Region	Section	Classification	n	P-value (Labial/Lingual)
Gaffuri ^[29]	Incisors & Canines	Apex	Normodivergent	10	NS
			Hypodivergent	10	
Dalaie ^[17]	Central incisors	9mm [#]	Normodivergent	\	U: NS / NS
			Hypodivergent	\	L: Hpo>N* / Hpo<N*
Casanova-Sarmiento ^[19]	Mandibular central incisors	Apex	Normodivergent	44	Hpo>N***
			Hypodivergent	48	
Sadek ^[18]	All teeth	Apex	Normodivergent	17	U2: NS / Hpo>N*
					U3: NS / Hpo>N**
			Hypodivergent	15	L4: Hpo>N** / NS
					else: NS
Li ^[33]	Incisors & canines	5mm [#]	Normodivergent	46	U1: NS / NS
					U2: NS / Hpo>N*
					U3: NS / Hpo>N*
			Hypodivergent	45	L1: Hpo>N* / Hpo>N***
					L2: NS / Hpo>N***
					L3: NS / Hpo>N**

All studies except Sadek measured the distance of the whole alveolar bone thickness (cortical bone+ cancellous bone). Sadek measured the cortical bone thickness alone in his research.

[#]9mm/5mm distance from the cemento-enamel junction.

*P<0.05; **P<0.01; ***P<0.001.

Hpo, Hypodivergent group; L, the lower jaw; N, Normodivergent group; NS, No statistically significant differences; U, the upper jaw.

maxillary anterior teeth within the hypodivergent group, a larger additional force couple to offset this greater moment of force than the normodivergent patients may be required.

There are limitations to the present research that require consideration. Due to the selection criteria, the study lacks a female sample to provide balance with the selected males. In a follow-up study, it is planned to investigate the morphological characteristics of alveolar bone in females. While tooth movement is facilitated within cancellous bone, movement in the cortical bone can be reduced in clinical practice and require more force and a greater control of anchorage. In addition, there naturally exists a discrepancy between CBCT and physical measurements. In a study evaluating the precision of CBCT in detecting bone fenestration and cracking, researchers discovered that even with a voxel value as low as 0.125 mm, the obtained measurements did not

align consistently with the actual conditions.³⁴ Some studies have shown that there were no significant differences in root measurement accuracy within the range of 0.2 to 0.4 mm.^{35–37} Under the premise of ensuring accuracy and for ethical reasons, a smaller voxel size should be used for scanning³⁸ and therefore, more sophisticated protocols may be required for assessing these exceedingly minute distances.

Conclusions

The present research established reference values for the thickness and height of alveolar bone in the anterior and premolar teeth of individuals with a normal occlusion and provided a foundation for finite element studies and other investigations. Most of the anterior and premolar teeth in the bimaxillary alveolar bone were observed to be closely adjacent to the labial cortical plate, while hypodivergent groups exhibited a comparatively larger safe space for root

labial tipping movements. Additionally, achieving bodily movement would require a greater additional force couple due to the higher ABH seen in the hypodivergent group.

Conflict of interest

The authors declare that there is no conflict of interest.

Author contributions

RY Zhang: Project development, Manuscript writing; LY Li: Data acquisition, Data analysis; ZY Lu: Data collection; ZX Song, XY Fan, JN Xu, X Zhang: Data analysis; ZL Jin, YN Ma: Conception and design. The author(s) read and approved the final manuscript.

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Ethical approval

The study was designed under the Declaration of Helsinki, approved by the Stomatological Hospital of Fourth Military Medical University Ethics Committee (project number: IRB-REV-2015001), and all methods were carried out in accordance with relevant guidelines and regulations. No subjects were under 18/illiterate/dead. Written informed consent was obtained from all subjects.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Data availability

All data are available upon request from the corresponding author.

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References

1. Kalaitzoglou ME, Lambrianidis T. Understanding root fenestration: a systematic scoping review of prevalence and clinical factors. *Aust Endod J*. 2023; 49:428–43.
2. Guo Z, Zhang R, Guo C, Li X, Jin Z, Liu Q. A retrospective study of alveolar bone remodelling after anterior retraction in orthodontic tooth extraction cases with clear aligners and fixed appliances. *Orthod Craniofac Res*. 2023. [Epub ahead of print]
3. Jin SH, Park JB, Kim N, Park S, Kim KJ, Kim Y. Analysis of alveolar bone morphology of the maxillary central and lateral incisors with normal occlusion. *J Periodontol Implant Sci*. 2012; 42:173–8.
4. Lee JE, Jung CY, Kim Y, Kook YA, Ko Y, Park JB. Analysis of alveolar bone morphology of the maxillary central and lateral incisors with normal occlusion. *Med Kaunas Lith*. 2019; 55:565.
5. Lee JE, Lee YJ, Jin SH, Kim Y, Kook YA, Ko Y. Topographic analysis of the mandibular symphysis in a normal occlusion population using cone-beam computed tomography. *Exp Ther Med*. 2015; 10:2150–6.
6. Park JB, Lee JE, Kim K, Yoo JT, Kim Y, Kook YA. The thickness of alveolar bone at the mandibular canine and premolar teeth in normal occlusion. *J Craniofac Surg*. 2014; 25:1115–9.
7. Tao R, Niu L. Investigation of sagittal root position in relation to the anterior maxillary alveolar bone: a cone-beam CT study in 300 cases with normal occlusion. *Chin J Stomatol*. 2017; 52:631–6.
8. Han M, Wang R yang, Liu H, Zhu X juan, Wei F lan, Lv T. Association between mandibular posterior alveolar morphology and growth pattern in a Chinese population with normal occlusion. *J Zhejiang Univ Sci B*. 2013; 14:25–32.
9. Srebrzyńska-Witek A, Koszowski R, Różyło-Kalinowska I. Relationship between anterior mandibular bone thickness and the angulation of incisors and canines-a CBCT study. *Clin Oral Investig*. 2018; 22:1567–78.
10. Schneider S, Gandhi V, Upadhyay M, Allareddy V, Tadinada A, Yadav S. Sex-, growth pattern-, and growth status-related variability in maxillary and mandibular buccal cortical thickness and density. *Korean J Orthod*. 2020; 50:108–19.
11. Baysal A, Ucar FI, Buyuk SK, Ozer T, Uysal T. Alveolar bone thickness and lower incisor position in skeletal Class I and Class II malocclusions assessed with cone-beam computed tomography. *Korean J Orthod*. 2013; 43:134–40.
12. Lee S, Hwang S, Jang W, Choi YJ, Chung CJ, Kim KH. Assessment of lower incisor alveolar bone width using cone-beam computed tomography images in skeletal Class III adults of different vertical patterns. *Korean J Orthod*. 2018; 48:349–56.
13. Hourfar J, Bister D, Lisson JA, Goldbecher C, Ludwig B. Vestibulo-Oral inclination of maxillary and mandibular canines and bicuspid - a CBCT investigation. *Head Face Med*. 2016; 12:22.
14. Sadek MM, Sabet NE, Hassan IT. Three-dimensional mapping of cortical bone thickness in subjects with different vertical facial dimensions. *Prog Orthod*. 2016; 17:32.
15. Chen Y, Dai Y, Yan Z, You Y, Wu B, Lu B. Morphological analysis of anterior permanent dentition in a Chinese population using cone-beam computed tomography. *Head Face Med*. 2023; 19:12.
16. Sendyk M, de Paiva JB, Abrão J, Rino Neto J. Correlation between buccolingual tooth inclination and alveolar bone thickness in

- subjects with Class III dentofacial deformities. *Am J Orthod Dentofac Orthop.* 2017; 152:66–79.
17. Dalaie K, Hajimiresmail YS, Safi Y, Baghban AA, Behnaz M, Rafsanjan KT. Correlation of alveolar bone thickness and central incisor inclination in skeletal Class I and II malocclusions with different vertical skeletal patterns: A CBCT study. *Am J Orthod Dentofacial Orthop.* 2023; 164:537–44.
 18. Sadek MM, Sabet NE, Hassan IT. Alveolar bone mapping in subjects with different vertical facial dimensions. *Eur J Orthod.* 2015; 37:194–201.
 19. Casanova-Sarmiento JA, Arriola-Guillén LE, Ruíz-Mora GA, Rodríguez-Cárdenas YA, Aliaga-Del Castillo A. Comparison of anterior mandibular alveolar thickness and height in young adults with different sagittal and vertical skeletal relationships: a CBCT Study. *Int Orthod.* 2020;18:79–88.
 20. Dong F, Huan J, Zhiyong L. Evaluation of the accuracy of alveolar bone height measurement in vitro by cone beam computed tomography. *West China J Stomatol.* 2012; 30: 603.
 21. Klinge A, Al-Okshi A, Becktor J, Lindh C. A rater agreement study on measurements in cross-sectional CBCT images exploring the association between alveolar bone morphology and craniofacial height. *Oral Radiol.* 2021; 37:573–84.
 22. Chen J, Bai D. Research progress on root position measurement methods in orthodontic treatment using cone beam CT. *J Prevention Treatment Stomatol Dis.* 2022; 30:740–5.
 23. Pei J, Jin Z. A study of alveolar bone structure around incisors in adult patients with Class I bimaxillary protrusion. *J Pract Stomatol.* 2013; 29:398–402.
 24. Yamada C, Kitai N, Kakimoto N, Murakami S, Furukawa S, Takada K. Spatial relationships between the mandibular central incisor and associated alveolar bone in adults with mandibular prognathism. *Angle Orthod.* 2007; 77:766–72.
 25. Guerino P, Marquezan M, Mezomo MB, Antunes KT, Grehs RA, Ferrazzo VA. Tomographic evaluation of the lower incisor's bone limits in mandibular symphysis of orthodontically untreated adults. *BioMed Res Int.* 2017; 2017:9103749.
 26. Ricketts RM. Bioprogressive therapy as an answer to orthodontic needs: I. *Am J Orthod.* 1976; 70:241–68.
 27. Chen Y. Theory and application of cortical anchorage. *Chin J Stomatol.* 1993; 28:379–81.
 28. Royston P, Altman DG, Sauerbrei W. Dichotomizing continuous predictors in multiple regression: a bad idea. *Stat Med.* 2006; 25:127–41.
 29. Gaffuri F, Cossellu G, Maspero C, Lanteri V, Ugolini A, Rasperini G. Correlation between facial growth patterns and cortical bone thickness assessed with cone-beam computed tomography in young adult untreated patients. *Saudi Dent. J.* 2021; 33:161–7.
 30. Jo AR, Mo SS, Lee KJ, Sung SJ, Chun YS. Finite-element analysis of the center of resistance of the mandibular dentition. *Korean J Orthod.* 2017; 47:21–30.
 31. Oh MB, Mo SS, Hwang CJ, Chung C, Kang JM, Lee KJ. The 3-dimensional zone of the center of resistance of the mandibular posterior teeth segment. *Am J Orthod Dentofacial Orthop.* 2019; 156:365–74.
 32. Luu B, Cronauer EA, Gandhi V, Kaplan J, Pierce DM, Upadhyay M. A finite element approach for locating the center of resistance of maxillary teeth. *J Vis Exp.* 2020;158:e60746.
 33. Li B, Li J, Wang H, Xie X, Wen J, Li H. Relationship between different skeletal facial types and anterior alveolar bone thickness with cone-beam computed tomography in an Asian population. *Ann Trans Med.* 2022;10:956.
 34. Patcas R, Müller L, Ullrich O, Peltomäki T. Accuracy of cone-beam computed tomography at different resolutions assessed on the bony covering of the mandibular anterior teeth. *Am J Orthod Dentofac Orthop.* 2012; 141:41–50.
 35. Özer SY. Detection of vertical root fractures by using cone beam computed tomography with variable voxel sizes in an in vitro model. *J Endod.* 2011; 37:75–9.
 36. Damstra J, Fourie Z, Huddleston Slater JJR, Ren Y. Accuracy of linear measurements from cone-beam computed tomography-derived surface models of different voxel sizes. *Am J Orthod Dentofacial Orthop.* 2010; 137:16.e1–6.
 37. Liedke GS, da Silveira HED, da Silveira HLD, Dutra V, de Figueiredo JAP. Influence of voxel size in the diagnostic ability of cone beam tomography to evaluate simulated external root resorption. *J Endod.* 2009; 35:233–5.
 38. Spin-Neto R, Gotfredsen E, Wenzel A. Impact of voxel size variation on CBCT-based diagnostic outcome in dentistry: a systematic review. *J Digit Imaging.* 2013; 26:813–20.