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Longitudinal Quantitation of Tooth Displacement in Chinese Adolescents with Normal Occlusion

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Summary: This longitudinal study aims to analyze the different modes of the maxillary and mandibular tooth displacement in subjects, who were aged 12.5–17.5 years (150–210 months), with untreated normal (Class I) occlusion. Longitudinal lateral cephalograms for a set of 10 subjects (7 females and 3 males) at consecutive annual time points were selected and monitored. Data were analyzed on the basis of the superimpositions of serial tracings of lateral cephalograms on stable anterior cranial base, the anatomies of the maxillary and mandibular structures. The horizontal and vertical displacements of the first molar and incisor were assessed by *t*-test. The local and the secondary tooth displacements with growth contributed to the total horizontal and vertical displacements of the molars and incisors of the subjects. In the total tooth displacement, the horizontal growth of maxilla and mandible had the same contribution as the local tooth displacements. The vertical maxillary growth played a smaller role than the local drift, and mandibular remodeling went in a reverse direction with the local tooth drift. The first molars moved more forward than the incisors in the upper and lower arches. Both the upper and lower first molars showed forward tipping. The analysis of tooth displacement may be utilized in making orthodontic treatment plan, including anchorage or torque control.
Key words: tooth movement; growth evaluation; cephalometrics; superimposition

Tooth displacement is a common but immensely important issue, and the core concern in orthodontics. The analysis of tooth changes during craniofacial development can provide a guideline for orthodontics[1]. Orthodontists should be fully aware of the natural changes in tooth locations, orthodontic treatment design, and appliances to be used. Otherwise, undesired results or changes are imminent.

Raymond Begg, a famous Australian orthodontist, emphasized the occurrence of considerable amounts of interproximal and occlusal attrition, which disappeared in modern society because of soft diets and late crowding[2]. In other words, stability of tooth position was not maintained.

Tooth displacement has been extensively studied. Changes in total tooth location include the local part occurring around the periodontal tissues in addition to the left part as the result of bone modeling and remodeling. The "golden" implant method used by Bjork and Skieller *et al*[3–5] nearly provided a differentiation of the components accurately. The "pitchfork" analysis of Lysle[6] also demonstrated this view. These studies focused on the qualitative reaction of outline change of the bony structures and general changes of tooth location or mainly emphasized the comparison of different superimposition. A quantitative research by Baumrind *et al*[7–10] provided a special method for analyzing tooth displacement. However, this method contained other complex and unassured information about tooth changes and was based on the samples with different occlusion conditions and ages.

Superimposition is the indispensable resort for quantifying tooth displacement. Downs, Ricketts, Melson, Broadbent, Efstratiadis, and Baumrind from the American Board of Orthodontics[11–19] all provided their own methods. However, a substantial number of errors may result from the selection of superimposition method because major components of bony structures in craniofacial complex were modified in nearly the entire development process instead of the stable position. Thus, the relationship between tooth and jaw became a complicated issue. Nevertheless, Bjork *et al*[3, 4] provided a golden implant method, and structural anatomy superimposition was concluded as a result.

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Thus, this study aimed to (1) investigate the quantitative tooth displacement in Chinese adolescents aged 12.5–17.5 years with normal occlusion at annual interval, utilizing the superimposition of serial cephalograms; (2) analyze the different parts of the total changes, and (3) link the tooth displacement to the craniofacial development. This study may provide useful information for orthodontists.

1 MATERIALS AND METHODS

The files of the Growth and Development Center of Peking University School and Hospital of Stomatology were used. The serial lateral cephalograms of 901 subjects were available for random selection. The inclusion criteria were as follows: (1) no craniofacial abnormalities or tooth abnormalities in number or eruption; (2) normal skeletal pattern; (3) Class I canine and molar relationship; (4) normal overjet and overbite and no or minimal crowding; (5) acceptable profile and lip-tooth relationship; and (6) no orthodontic treatment or orthopedic surgery. Finally, 10 subjects aged 12.5–17.5 years (12.5 for TP1, 13.5 for TP2, 14.5 for TP3, 15.5 for TP4, 16.5 for TP5, and 17.5 for TP6) from these files were included. The sample demographics and partial detailed information are shown in tables 1 and 2.

Table 1 Sample demographics at each time point

Demographics	TP1	TP2	TP3	TP4	TP5	TP6
Sample size	10	10	10	10	10	10
Nominal age/mos	150	162	174	186	198	210
Actual age/mos	155.7±5.20	167.8±6.04	180.1±5.59	195.8±5.94	206.5±5.50	218.8±5.70
Ratio (male/female)	0.3	0.3	0.3	0.3	0.3	0.3

TP, time point; mos, months

Table 2 Gender and dental stage of each individual at each time point

Case	Gender	Dental stage (from TP1–TP6)
1	F	Permanent
2	F	Permanent
3	F	Permanent
4	M	Permanent
5	M	Permanent
6	F	Permanent
7	F	Permanent
8	F	Permanent
9	F	Permanent
10	M	Permanent

TP, time point; F, female; M, male

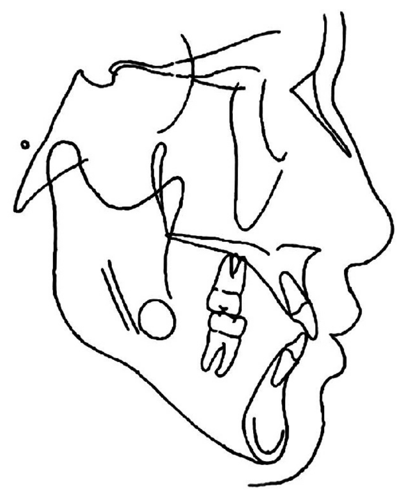

Fig. 1 An example of cephalometric tracing

All the lateral radiographs under standard conditions were obtained in Peking University School and Hospital of Stomatology. The same machine operated by the same practitioner was used.

A preliminary tracing was obtained by one operator. The purpose was to ensure the ability of tracing of landmarks, outlines of maxilla and mandible, and superimposition. Errors were minimized by tracing the serial lateral radiographs three times by the same investigator in an interval of 2–3 weeks. The tracing was checked by second practitioner for the location, outline tracing, and superimposition. An example of cephalometric tracing is shown in fig. 1.

The structural superimposition methods of Bjork[3, 4] based on the stable implant study were referenced in this project. Importantly, we considered the tips of the Johnston method to increase the simplicity and minimize the difficulty caused by the fine details of the 2D cephalograms during superimposition. The "pitchfork" method provided a detailed description of the technical aspects of the analysis, including tracing, superimposition, and the measurement of change.

The superimposition methods are described as follows and a subject example is shown in fig. 2.

1. Cranial base superimposition: the anterior wall of sella turcica, the greater wings of the sphenoid, the cribriform plate, the orbital roofs, and the inner surface of the frontal bone.

2. Maxillary superimposition: best-fit registration on the zygomatic process of the maxilla (right- and left-side average) and on the bony anatomical details superior to the incisors.

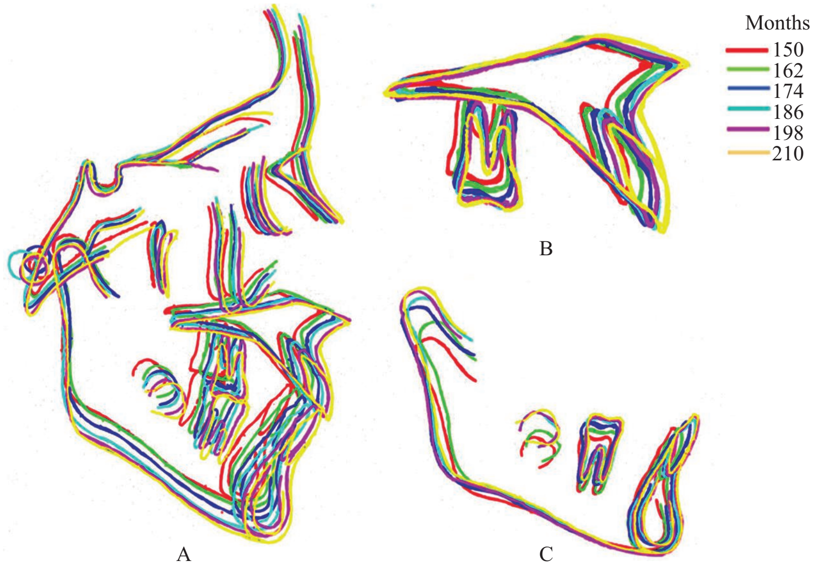

Fig. 2 A subject example of superimposition

A: cranial base superimposition; B: maxillary superimposition; C: mandibular superimposition

3. Mandibular superimposition: mandibular canal, tooth germs (prior to the initiation of root formation), and architecture in the labial aspect of the symphysis.

In this study, fiducial lines were created in the cranial base, maxilla, and mandible, and then transferred from one timepoint to the next in each subject's serial cephalograms. The "functional" occlusal plane (FOP) was used as the reference plane for the measurement of tooth displacement. The FOP is the straight line passing through the best-fit occlusal region of the canines, bicuspids, and the first molars regardless of the incisors.

Tooth displacement relative to the anterior cranial base (ACB) (total changes) consists of the local drift (local changes) caused by periodontal tissue remodeling and secondary displacement (secondary changes) that develops as the bones grow. In this article, the data of the first two types of changes were obtained from the superimposition of ACB, maxillary anatomical structures (A/MAX), and mandibular anatomical structures (A/MAND), which have been previously introduced. The initial data of TP1 were the measurements relative to the axes consisting of the FOP line and a line perpendicular to the FOP tangent to the anterior outline of sella. The mesiobuccal cusp and the apex of the first molar were used for measurements, so as the edge and the apex for the central incisor.

In this study SPSS software (version 16.0, SPSS for Windows, SPSS, USA) was used in the statistical analysis. The descriptive statistics, including the means and standard deviations (SD), were calculated for the variables at each timepoint. Independent *t* tests were performed for the evaluation of the intergroup differences in the measurements at each interval and the intergroup differences in the transformation from TP1 to TP2 until TP6. Paired *t* tests and analysis of variance (ANOVA) were also used. The nominal level of significance was set at P>0.05.

2 RESULTS

The horizontal and vertical displacements of the upper and lower first molars and central incisors are shown in tables 3–10 and the statistical analysis is shown in table 11.

Table 3 Horizontal and vertical displacements of the maxillary first molar cusp (means±standard deviations measured referred to the FOP)

U6 cusp stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	1.61±0.72	0.85±0.39	2.01±0.72	1.45±0.39
174 mos	3.00±1.15	1.55±0.62	3.40±1.15	2.15±0.62
186 mos	4.18±1.34	2.22±0.68	4.58±1.34	2.82±0.68
198 mos	4.43±1.35	2.34±0.66	4.83±1.35	2.94±0.66
210 mos	4.43±1.33	2.36±0.65	4.83±1.33	2.96±0.65

U6, upper first molar; mos, months

Table 4 Horizontal and vertical displacements of the maxillary first molar apex (means±standard deviations measured referred to the FOP)

U6 apex stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	1.41±0.71	0.65±0.39	1.81±0.71	1.25±0.39
174 mos	2.80±1.15	1.35±0.62	3.20±1.15	1.95±0.62
186 mos	3.98±1.34	2.02±0.68	4.38±1.34	2.62±0.68
198 mos	4.23±1.35	2.14±0.66	4.63±1.35	2.74±0.66
210 mos	4.23±1.33	2.16±0.65	4.63±1.33	2.76±0.65

U6, upper first molar; mos, months

Table 5 Horizontal and vertical displacements of the maxillary central incisor edge (means±standard deviations measured referred to the FOP)

U1 edge stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	0.91±0.71	0.15±0.39	1.91±0.71	1.25±0.39
174 mos	2.30±1.15	0.85±0.62	3.30±1.15	1.95±0.62
186 mos	3.48±1.34	1.52±0.68	4.48±1.34	2.62±0.68
198 mos	3.73±1.35	1.64±0.66	4.73±1.35	2.74±0.66
210 mos	3.73±1.33	1.6±0.65	4.73±1.33	2.76±0.65

U1, upper central incisor; mos, months

Table 6 Horizontal and vertical displacements of the maxillary central incisor apex (means±standard deviations measured referred to the FOP)

U1 apex stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	0.81±0.72	0.05±0.39	1.61±0.72	1.05±0.39
174 mos	2.20±1.15	0.75±0.62	3.00±1.15	1.75±0.62
186 mos	3.38±1.34	1.42±0.68	4.18±1.34	2.42±0.68
198 mos	3.63±1.35	1.54±0.66	4.43±1.33	2.56±0.65
210 mos	3.63±1.33	1.56±0.65	4.53±1.31	2.66±0.55

U1, upper central incisor; mos, months

Table 7 Horizontal and vertical displacements of the mandibular first molar cusp (means±standard deviations measured referred to the FOP)

L6 cusp stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	1.70±0.69	0.90±0.38	2.10±0.69	–1.4±0.38
174 mos	2.58±1.08	1.31±0.59	2.98±1.08	–1.81±0.59
186 mos	4.23±1.71	2.25±0.79	4.63+1.71	–2.75±0.79
198 mos	4.68±1.69	2.46±0.81	5.08±1.69	–2.96±0.81
210 mos	4.82±1.65	2.58±0.82	5.22±1.65	–3.08±0.82

L6, lower first molar; mos, months

Table 8 Horizontal and vertical displacements of the mandibular first molar apex (means±standard deviations measured referred to the FOP)

L6 apex stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	1.40±0.69	0.60±0.38	1.80±0.69	–1.10±0.38
174 mos	2.28±1.08	1.01±0.59	2.68±1.08	–1.51±0.59
186 mos	3.93±1.71	1.95±0.79	4.33±1.71	–2.45±0.79
198 mos	4.38±1.69	2.16±0.81	4.78±1.69	–2.66±0.81
210 mos	4.52±1.65	2.28±0.82	4.92±1.65	–2.78±0.82

L6, lower first molar; mos, months

Table 9 Horizontal and vertical displacements of the mandibular central incisor edge (means±standard deviations measured referred to the FOP)

L1 edge stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	0.40±0.69	–0.40±0.38	1.8±0.69	–1.5±0.38
174 mos	1.28±1.08	0.01±0.59	2.68±1.08	–1.91±0.59
186 mos	2.93±1.71	0.95±0.79	4.33±1.71	–2.85±0.79
198 mos	3.38±1.69	1.16±0.81	4.78±1.69	–3.06±0.81
210 mos	3.52±1.65	1.28±0.82	4.92±1.65	–3.18±0.82

L1, lower central incisor; mos, months

Table 10 Horizontal and vertical displacements of the mandibular central incisor apex (means±standard deviations measured referred to the FOP)

L1 apex stage	Horizontal		Vertical	
	Total change	Local change	Total change	Local change
162 mos	0.70±0.69	–0.20±0.38	1.50±0.69	–1.30±0.38
174 mos	1.58±1.08	0.21±0.59	2.38±1.08	–1.71±0.59
186 mos	3.23±1.71	1.15±0.79	4.03±1.71	–2.65±0.79
198 mos	3.68±1.69	1.36±0.81	4.48±1.69	–2.86±0.81
210 mos	3.82±1.65	1.48±0.82	4.62±1.65	–2.98±0.82

L1, lower central incisor; mos, months

Table 11 Statistical analysis of total and local displacements of the molars and incisors

Tooth site	TP2–TP1 TP3–TP1	TP3–TP1 TP4–TP1	TP4–TP1 TP5–TP1	TP5–TP1 TP6–TP1
U6				
Total	<0.01	<0.01	0.03	>0.05
Local	<0.01	<0.01	<0.01	>0.05
L6				
Total	<0.01	<0.01	0.01	0.03
Local	<0.01	<0.01	0.02	0.03
U1				
Total	<0.01	<0.01	0.03	>0.05
Local	<0.01	<0.01	<0.01	>0.05
L1				
Total	<0.01	<0.01	0.01	0.03
Local	<0.01	<0.01	0.02	0.03

2.1 Maxillary Tooth Displacement

2.1.1 Molar Crown (1) Horizontally, the total and the local mesial drifts of the upper first molar were 4.43 and 2.36 mm, respectively, and the local changes accounted for 54%. Vertically, downward changes were 4.83 and 2.96 mm, respectively, and the local changes accounted for 61%. Hence, vertical change was slightly larger than the horizontal change. (2) The mesial displacement at the first three intervals increased remarkably, but the molar crown maintained a relatively stable location from TP4 to TP6. Only a minimal amount of local remodeling was left, that is, the maxilla growth was minimal from TP4 to TP6. (3) Meanwhile, the mean values of males showed more forward and downward changes than those of females.

2.1.2 Molar Apex (1) The total and the local mesial displacements of apex in horizontal and vertical directions were similar to but smaller than the crown at 4.23 and 2.16 mm, and 4.63 and 2.76 mm, respectively. This difference resulted in forward tipping of the first molar. (2) The changes were also larger at the first three intervals than the interval from TP4 to TP5 then to TP6. (3) The mean values of males showed more forward and downward changes than those of females.

2.1.3 Central Incisor Edge and Apex (1) The amount of displacement of incisors was smaller than the first molar, with total 0.7 mm difference in the horizontal axe, which was almost similar to vertical changes. (2) The changes in the edge and the apex had almost equal values, indicating that the inclination of incisors remained almost consistent throughout the six TPs.

2.2 Mandibular Tooth Displacement

2.2.1 Molar Crown The total and the local mesial displacements in horizontal direction were 4.82 and 2.58 mm, respectively, and local changes accounted for 53%. (2) Vertically, changes were 5.22 and −3.08 mm, respectively, with downward total change relative to cranial base, whereas ascension relative to the periodontium tissue occurred.

2.2.2 Molar Apex The total and the local mesial displacements of apex in horizontal and vertical directions were similar to but smaller than the crown, 4.52 and 2.28 mm, and 4.92 and −2.78 mm, respectively. This difference resulted in the forward tipping of the first molar.

2.2.3 Central Incisor Edge and Apex (1) For the total changes, the lower incisor showed considerably smaller mesial displacement than the first molar (the total difference was 1.3 mm). (2) The apex went 0.2 mm mesially more than the edge, and the edge showed a lingual drift tendency. Thus, the angle of incisors moved backward or lingually. (3) The tendency of changing was similar to the upper incisor vertically.

The results above are consistent with the rationale of the craniofacial development and tooth eruption. The tooth erupts in a downward and forward direction for maxilla and upward and forward direction for mandible. Meanwhile, the modeling, remodeling, and rotation of mandibular border and ramus occur during the growth process, whereas the maxilla goes forward and downward without excessive rotation in subjects with normal occlusion.

3 DISCUSSION

In this study, we provided several points of importance. We specifically analyzed the results of maxillary and mandibular tooth changes in detail, linking to the craniofacial development and considering the clinical indications.

The analysis of tooth displacement, especially the different parts, is extremely essential for the orthodontists to formulate treatment design and determine the need of using certain appliances such as extraoral force, the applied magnitude, and the prolonged time[20], all of which are crucial to the synthetic effect of neutral development and treatment.

Many files of samples had been used for longitudinal research, including the study materials of McNamara *et al*[21] in the University of Michigan Growth Study. However, the types of Class Ⅰ, Ⅱ, and Ⅲ occlusion conditions of wide extent coexist in the whole process of these studies. To investigate the normal tooth displacement and analyze the relationship between tooth and jaw, we used the materials in the Development Center of Peking University School and Hospital of Stomatology. Of all the 901 subjects, 10 who had available six consecutive lateral cephalograms from 12.5–17.5 years old were finally enrolled.

3.1 Tooth Displacement and Craniofacial Development

According to the data acquired in the above tables, the horizontal tooth local displacement accounted for approximately 50% of the total changes, and vertical local movement accounted for 60%, conforming to the finding of Bjork's[3] implant study, which states that the general local part was half of the total. The ratio explained that both tooth and jaw underwent horizontal and vertical displacement during the modification process of the craniofacial complex. The maxilla and mandible generally moved downward and forward during craniofacial growth. At the same time, the teeth generally erupted and moved mesially and occlusally. Thus this differential growth of upper and lower jaw combined with the compensatory teeth and dentoalveolar movements maintained the relatively stable pattern of occlusion during growth and development. The annual values of changing indicated that the tooth itself changed in periodontium, simultaneously the modification of bony structures occurred in an interacting way. Besides, the statistical analysis showed the comparison for the first three intervals had significant differences and the last one showed no significant difference for upper molars and incisors. However the lower first molars and incisors maintained the difference for each interval. This result might indicate us the mandible development and lower tooth displacement ended later than the maxilla and upper arch.

Disregarding the sagittal displacement, the lower teeth moved downward relative to the ACB and changed upward relative to the stable bony structures when comparing the data in 'V' rows[22]. Hence, the growth of ramus resulted from condyle masks the self-eruption of the lower arch[23]. However, the maxillary tooth eruption together with lower ones compensated the bone modification. Thus, no excessive forward development but appropriate mesial drift of mandible occurred, as well as the forward rotation caused by the vertical difference.

One exception is the lower incisor not exhibiting the rule because of the mandibular modification caused by the condyle's forward and upward modeling[24], as well as the rotation occurring during the growth. Thus, the incisor displacement was never determined by a single factor.

3.2 Molar Changes

The data of the molar displacement from tables 3, 4, 7 and 8 could be consulted for analysis. Through the difference of crown and apex displacement, both the average total drift relative to ACB and the local displacement relative to anatomical structures were observed to yield forward tipping of the first molars. This result conformed to the research of Baumrind[7, 8].

Maxillary modification is simple and clear that it moves in a forward and downward direction with bone resorption and deposition on the surfaces. The path of tooth eruption was also set along similar direction. Thus, the tipping of upper first molars was expected due to the collaboration of these two resorts. However, the mandible was not linked to the nasomaxillary complex. The appeared displacing effect of lower molars relative to cranial base is based on the growth of condyle, the rotation of mandible, the surface remodeling, and the alveolar changes. Thus, the theory of occlusal force of the posterior tooth is only an influencing factor to the adaption of the tip angle.

3.3 Incisor Changes

According to the incisors' data, crown and apex movements in the upper arch almost have equal values, and the apex had slightly more mesial drift than the crown in the lower incisor, or rather, a tendency of lingual tipping of lower incisors. No remarkable changes of incisor long axes occurred, possibly related to the lip-and-tongue function that tends to maintain the relationship of the incisors of subjects with normal occlusion. Meanwhile, mandibular rotation might be the cause of the minimal lingual tipping of lower incisors. During the jaw growth and development, the spontaneously forward and upward modeling of condyle contrasted to the corpus produced a forward rotation of the mandible and greater increases in posterior facial height than in lower anterior facial height. Thus the mandibular growth and simultaneous rotation could cause few changes of lower incisors. However, no definite causes existed to induce the changes. Moreover, the individuals with different skeletal or arch patterns could present various situations of manifestation. Clinically, the overbite and overjet of these subjects were relatively consistent, maintaining the normal occlusion at the initial TP.

3.4 Late Crowding

When comparing the molars data with the incisor data, we could conclude that first molars moved forward with a larger amount than the incisors in both upper and lower arches. We did not check the clinical features of these subjects, but this phenomenon might explain the general late crowding with the decrease of arch lengths. Hence, these quantitative data indicate a qualitatively common phenomenon.

Raymond Begg proposed long ago the “attrition occlusion” theory[2]. He suggested that the normal attrition disappears in modern society as a result of soft diets. Thus, he advised that tooth extraction should be applied in orthodontic treatment without using the extraoral force to move molars backward to release space, thereby addressing the crowding problem. Another contribution to the late crowding[25] may be the slight lingual tipping movement of incisors caused by the jaw rotation.

3.5 Jaw Rotation

We mentioned this point at the last part of this article not only because of its complication but also the wide extent of relation to almost all of the above issues proposed. Bjork proposed that in subjects with normal occlusion, forward rotation of the mandible[26–28] mainly occurs at a center of incisors, despite other types of rotation. All the data analyses above can explain this type of rotation, including the upright of lower first molar, minimal mesial drift and lingual tipping of lower incisors, and late crowding[29].

This article does not emphasize a single factor influencing the quantitative data of measurements. Consideration of the whole body is the most important. This study aimed to deeply analyze the relationship of teeth and craniofacial complex, based on the quantitative measurements obtained through landmarks for identification, tracing, and superimposition.

4 CONCLUSIONS

1. For the subjects aged 12.5–17.5 years, the extents of horizontal and vertical displacement of molars and incisors were found. Both the local and secondary tooth displacement contributed to the total changes.
2. The horizontal tooth local displacement accounted for approximately 50% of the total changes and the vertical local movement for 60%.
3. First molars moved forward with a larger amount than the incisors in both upper and lower arches.
4. Upper and lower first molars showed forward tipping relative to maxillary and mandibular anatomy.
5. The long axes of the incisors had no remarkable change, except the minimal mesial drift and the lingual tipping of the lower incisors.

Conflict of Interest Statement

The authors declare that there were no conflicts of interests regarding the publication of this article.

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