Dentofacial changes following treatment with a fixed functional appliance and their three-dimensional effects on the upper airway

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Background: Proposed skeletal changes achieved by functional appliances (FA) with reference to stable structures (structural method) have received relatively little attention compared to conventional cephalometric measurements (conventional method). Using the two methods, the aims of this study were to (1) determine the skeletal changes as a result of FA treatment; and (2) identify the skeletal changes associated with upper-airway volume and minimum cross-sectional area (MCA).

Methods: Pre- and post-treatment CBCT scans were selected from 73 FA treated children (37 girls and 36 boys; mean age 12.0 years) and 73 children as a control group (matched for chronological age, skeletal age, gender, and mandibular inclination) who received orthodontic treatment using only fixed appliances (no FA). Skeletal, upper-airway volume, and MCA changes were analysed by applying both structural and conventional methods.

Results: The FA group had significant skeletal effects compared with the control group (both methods; $p = 0.04 - p < 0.001$). The horizontal displacement of pogonion (both methods) and the hyoid bone, together with a forward mandibular rotation (structural method), had positive effects on upper-airway volume and MCA ($p < 0.05$).

Conclusions: The horizontal changes in pogonion (both methods) and the hyoid bone, as well as a forward mandibular rotation (structural method), have a strong association with changes in the upper airway. The conventional method underestimates FA treatment effects. These results may influence the management of growing class II patients with compromised upper airways.

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Introduction

Functional appliances (FA) are commonly used as fixed or removable devices for the orthodontic treatment of class II malocclusions.[1] In addition to class II correction, cephalometric studies have shown an association between FA treatment and an increase in the upper airway area, with increased ANB and SNB angles;[2] a posterior mandibular rotation;[3] and an increased vertical growth pattern being negatively associated with airway changes.[4] The limitations of cephalometric imaging, however, suggest that a reliable analysis of the medio-lateral widths, and therefore the volume of the airway, is not possible.[5]

Cone beam computed tomography (CBCT) is an accurate and reliable method of assessing the upper airway in three dimensions (3D)[6] and previous studies have reported the significant effects that a fixed FA has on airway volume and minimum cross-sectional area (MCA).[7,8] Only one study has sought to investigate the association between skeletal and 3D airway changes seen as a result of FA therapy.[9]

Most investigations which have assessed the skeletal effects of FA have used the linear and angular changes between the jaws and a cranial base line as the primary outcome measure (conventional method).[10] However, these common reference points change during growth.[11] Consequently, the reference points are not stable, which introduces potential measurement errors.[11] Using an implant method, Bjork demonstrated stable structures in the cranial base, maxilla, and the mandible, which can be used for superimposition to demonstrate true dental and skeletal changes over time (structural method).[12] Few studies reporting the skeletal effects of FA have used these stable structures to determine treatment changes.[13] Furthermore, no previous studies have investigated the relationship between skeletal and airway changes as a result of FA treatment, using both 3D imaging and the structural method.

By using two different methods, the structural method described by Bjork[12] and the conventional cephalometric method, the aim of the present study was to determine the cephalometric changes following treatment using a fixed FA which are most likely to be associated with upper airway volume and MCA. The null hypothesis was that there was no association between skeletal and airway changes using either measurement method.

Methods

Pre- (T_0) and post-treatment (T_1) CBCT scans were obtained from a database of patients who received orthodontic treatment between 2006 and 2012. Based on a previous study,[8] a power calculation determined that 70 subjects per group would achieve a power of 80% (α = 0.05). Once the inclusion and exclusion criteria had been applied (Table I), the final sample consisted of 73 FA patients treated with a modified Herbst appliance (Hanks Telescoping Herbst, American Orthodontics, Sheboygan, WI, USA), followed by fixed appliances. When clinically indicated, a Hyrax rapid maxillary expansion (RME) device was included in the design of the modified Herbst appliance.

A pair-matched control group of 73 patients with a class I sagittal jaw (ANB 0-5 degrees[14]) and Angle class I molar relationship were selected to match the FA group for chronological age, skeletal age,[15] gender, mandibular inclination,[14] and the time interval between the pre-treatment and post-treatment scans (Table II). The matched control group underwent non-extraction orthodontic treatment using only fixed appliances (no FA nor other adjunct orthodontic devices) for minor class I malocclusions. The study protocol was approved by the Danish Data Protection Board (ref: SUND-2015-57-0121).

Using a scan time of 8.9 sec, all images were acquired using an iCAT Next Generation CBCT machine (Imaging Sciences International, Hatfield, Pa) at 120 Kv, 5 mA, and a 0.4 mm voxel resolution. Data were processed through Dolphin Imaging Software (version 11.5; Dolphin Imaging and Management Solutions, Chatsworth, Calif.). Images were analysed using a previously validated airway measurement protocol.[16]

The increase in airway volume and MCA associated with fixed FA treatment reported in a previous

Table I. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Orthodontic treatment requiring a fixed FA (Hanks Telescoping Herbst, American Orthodontics, Sheboygan, WI)	Previous orthodontic treatment
Biting in habitual intercuspal position	Movement artifacts
Full unit Angle class II molar relationship pre-treatment and a class I relationship post-treatment	Swallowing during scan acquisition
Class II skeletal base (ANB>5 degrees)	
A non-extraction orthodontic treatment plan	
Pre- and post-treatment CBCT scans with imaging of the cranial base, maxilla, mandible and first four cervical vertebrae and associated airways	
Children between 8 and 15 years of age	

Table II. Differences between the two groups before treatment.

	FA	Control
ANB (degrees)	6.2 (±1.8)	3.2 (±2.1)***
Airway volume (mm^3)	10,442.6 (±3,485.8)	12,169.3 (±4815.3)**
Airway MCA (mm^2)	112.8 (±44.7)	132.5 (±70.5)*
Age (years)	12y, 0m (±1y, 6m)	12y, 0m (±1y, 5m)
Skeletal age (CVMS[12]/number)	1 = 9; 2 = 19; 3 = 33; 4 = 11; 5 = 1	1 = 9; 2 = 19; 3 = 33; 4 = 11; 5 = 1
Gender	M = 36; F = 37	M = 36; F = 37
Time between scans	1y, 11m (±11m)	1y, 11m (±10m)
Mandibular inclination	33.2 (±6.0)	34.9 (±6.1)

*$p < 0.05$; **$p < 0.01$; ***$p < 0.0001$.

study (volume 5,659.18 mm^3; MCA 68.72 mm^2)[8] were compared to evaluate the associations between skeletal and airway changes.

Cephalometric assessment

Pre- and post-treatment craniofacial morphology was digitally assessed on two-dimensional lateral cephalograms generated from the CBCT scans at zero magnification. Cephalometric changes were evaluated by two techniques, the structural and the conventional method. The pre-treatment vertical facial pattern was determined using the angle between the Nasion-Sella Line (NSL) and the mandibular line (ML). The changes in cephalometric points (structural method) and cephalometric angles (conventional method) used to assess the skeletal changes produced by FA are shown in Table III.

Structural method

Stable anatomical structures in the anterior cranial base, maxilla and mandible were used as reference landmarks for analysis of the vertical and sagittal rotational changes in the jaws according to the methodology described by Bjork.[12]

Conventional method

Standard craniofacial measurements were made of the cranial base, maxilla and mandible as detailed by Bjork[14,17] with reference points, lines, and angles defined according to Solow and Tallgren[18] (Figure 1). The pre-and post-treatment measurements were subtracted to find the difference, which therefore identified the cephalometric changes observed between T_0 and T_1.

Both the cephalometric analysis and superimposition of the lateral cephalometric radiographs were conducted using TIOPS (Total Interactive Orthodontic Planning System, Roskilde, Denmark).

Reliability

In total, 20 randomly selected airway and skeletal measurements were repeated by the same examiner after 2 weeks. No systematic error was found as assessed by a *t*-test; the method error according to Dahlberg's formula[19] ranged between 0.5 and 2.3%, and reliability according to Houston[20] was 0.94–0.99 for all measurements.

Statistical analysis

The intra- and inter- group changes in cephalometric points between T_0 and T_1 utilising both the conventional and structural measurement methods were evaluated separately using linear mixed effects models which allowed for the longitudinal and nested structure of the data. The data had a nested structure as the FA and control group changes were derived from comparisons of multiple individual pairs.

The fixed part of the models included the cephalometric measurements as dependent variables and the independent variables group and time as well as their interactions. The random effects component of the model included the individual participants nested in their pairs.

Table III. Cephalometric landmarks[19] used to assess FA changes using both the structural and conventional methods (illustrated in Figure 1).

Landmark	Abbreviation	Definition
Reference points		
Sella	S	Centre of the sella turcica
Nasion	N	Most anterior point of the frontonasal suture
A point	A	Most posterior point on the anterior contour of the maxillary alveolar arch
B point	B	Most posterior point on the anterior contour of the mandibular alveolar arch
Pogonion	pg	Most anterior point on the mid-sagittal mandibular symphysis
Gnathion	gn	Most inferior point on the mandibular symphysis
Spinal point	sp	Apex of the anterior nasal spine
Pterygomaxillary	pm	Intersection between the nasal floor and the posterior contour of the maxilla
Basion	ba	Most postero-inferior point on the clivus
Articulare	ar	Intersection of external contour of the cranial base and posterior contour of the condyle
Infradentale	id	Most anterio-superior point on the lower alveolar margin,
Hyoid	hy	Hyoid bone
Reference lines		
Chin line	CL	Tangent to the chin through id
Upper incisor line	IL_s	Axis of the upper central incisor
Lower incisor line	IL_i	Axis of the lower incisor
Mandibular line	ML	Tangent to the lower border of the mandible through gn
Nasal line	NL	Line through sp and pm
Nasion-sella line	NSL	Line through N and S
Ramus line	RL	Tangent to the posterior border of the mandible
Conventional method		
Relation of maxilla to cranial base	SNA	The angle of sella-nasion to A point
Relation of mandible to cranial base	SNPg	The angle of sella-nasion to Pg
Relation of basal part of mandible to the cranial base	SNB	The angle of sella-nasion to B point
Sagittal relationship of the jaws	ANB	The angle of A point to nasion to B point
Inclination of the Maxilla	NSL/NL	Then angle between the nasion-sella line and the nasal line
Mandibular inclination	NSL/ML	Angle between the nasion-sella line and the mandibular line
Vertical jaw relationship	NL/ML	Angle between the nasal line and the mandibular line

For each of the measurement methods, the cephalometric points for which the treatment effect of the FA was statistically significant were included in a backwards stepwise linear regression model ($F < 0.05$) to determine if the changes in the variables revealed an association with previously reported changes in airway volume and MCA in the FA group.[8]

Preliminary analyses for the mixed effects model and linear regressions were performed to ensure that there was no violation of the assumption of normality, linearity, and multicollinearity. A Pearson's correlation coefficient was applied to determine the strength of the association between the changes determined by the structural and conventional

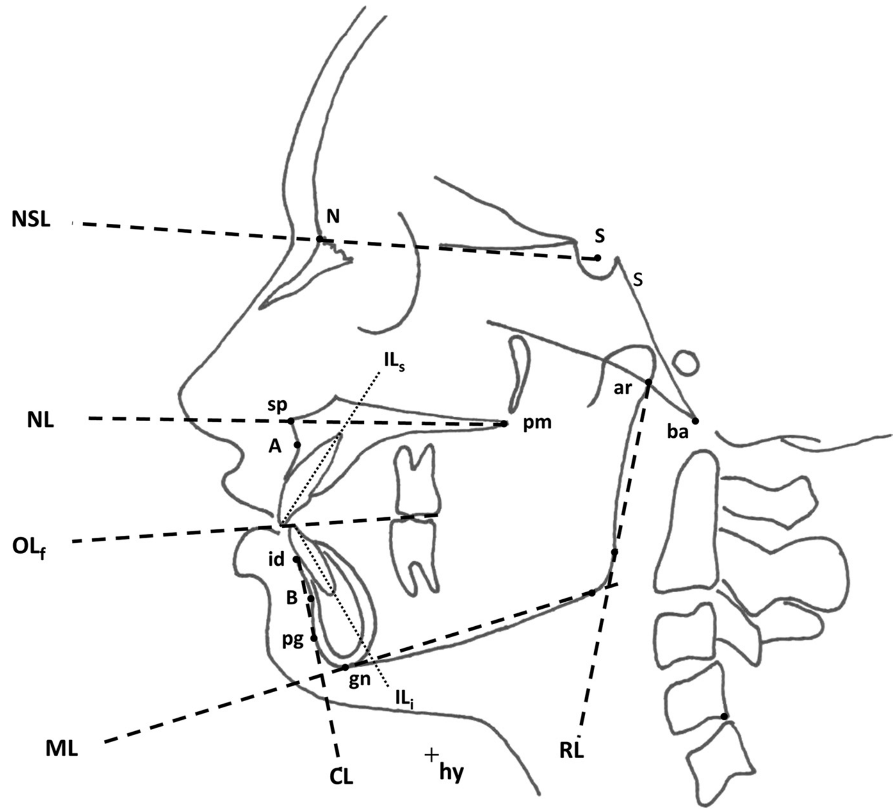

Figure 1. Reference points and lines used according to Solow and Tallgren[18] (Table III).

methods. Statistical analysis was carried out using Stata version 15 (StataCorp LLC, College Station, TX) and the level of significance set at $p < 0.05$.

Results

The structural method revealed significant differences in the amount and direction of the changes in A-point ($p = 0.03 - p = 0.45$), B-point ($p < 0.001 - p = 0.02$), pogonion ($p < 0.001 - p = 0.04$), and the hyoid bone ($p = 0.01 - p = 0.39$) in the FA group when compared with the control group (Table II, Figures 2 and 3). The results of the stepwise linear regression model analysing the relationship between the skeletal changes observed by the structural method (Table IV) and the changes in the airway volume and MCA showed that, for each millimeter advancement in the sagittal plane at pogonion, an increase of 615.3 mm^3 ($p < 0.001$) and 7.5 mm^2 ($p = 0.005$) on airway volume and MCA, respectively, could be expected and each millimeter advancement of the hyoid bone would have an expected increase of 500.4 mm^3 ($p < 0.001$) and 5.9 mm^2 ($p < 0.001$), respectively. For each degree of mandibular forward rotation, airway volume and MCA increased 584.4 mm^3 ($p = 0.03$) and 4.4 mm^2 ($p = 0.01$), respectively (Table V). For all mixed models, the random part of the model had a significant effect ($p < 0.001$), indicating that the individual variation was significant.

The conventional method identified significant changes in B-point (SNB) and pogonion (SNPg) in the sagittal plane (Table VI); however, there was no statistically significant effect of the FA on the mandibular line (ML) when compared with the control group (+0.22^0; $p = 0.7$; 95% CI −0.95–1.40). The results of the stepwise linear regression model analysing the relationship between cephalometric changes (Table VI) and changes in the airway volume and MCA showed that, for each degree reduction in SNPg, an increase of 544.9 mm^3 ($p = 0.01$) and 6.7 mm^2 ($p = 0.03$) on airway volume and MCA, respectively, could be expected. There was no association found between changes in SNB and changes in the airway.

Discussion

Much of the cephalometric research into the effects of orthodontic appliances on the airway has limitations due to the inability of cephalometric imaging to reliably assess mesio-lateral dimensions.[21] Using CBCT

A

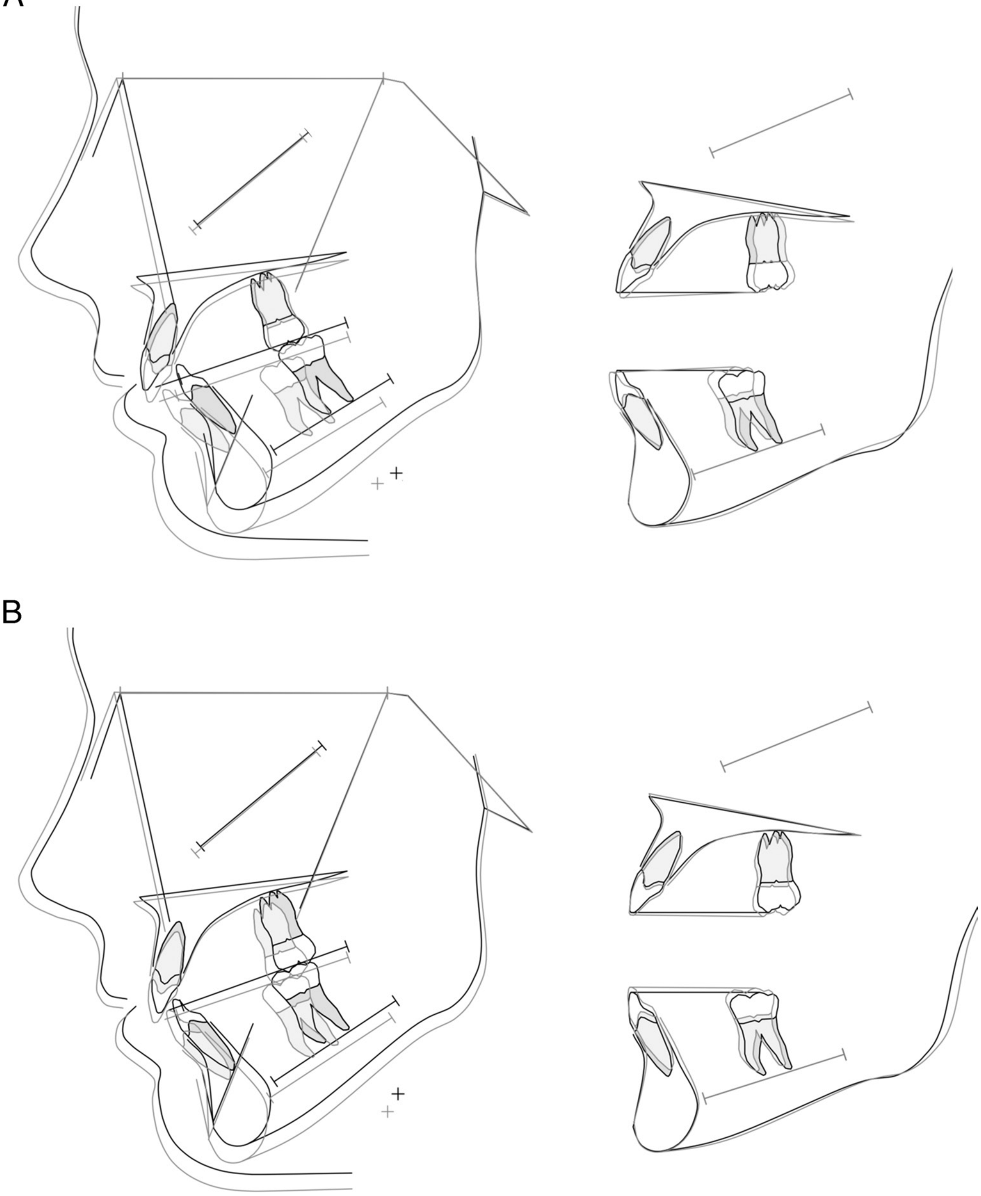

Figure 2. Mean cephalometric changes in (A) the FA and (B) control groups using the structural method (+ denotes hyoid bone).

imaging, the present study was able to analyse the effects of skeletal changes on the three-dimensional airway changes, as a result of treatment using a FA.

The skeletal effects of functional appliances assessed by the conventional and structural methods have been studied extensively[22] and the skeletal changes found in the present study are similar to those previously reported.[23–25] The conventional method showed a significant difference in mandibular changes in the sagittal plane (SNB and SNPg) but not in the vertical plane (NSL/ML), when the FA and control groups were compared.

Using the structural method, the present study found that there was a significant effect of a FA on the maxilla at A-point when compared with the control group. There were also significant mandibular skeletal changes when the two groups were compared. B-point and pogonion in the FA group showed greater horizontal and vertical displacement compared with the control group, with the greatest effect seen in the vertical plane. Furthermore, the mandible showed a small but significant forward rotation and the hyoid bone also showed significantly greater horizontal displacement when the two groups were compared.

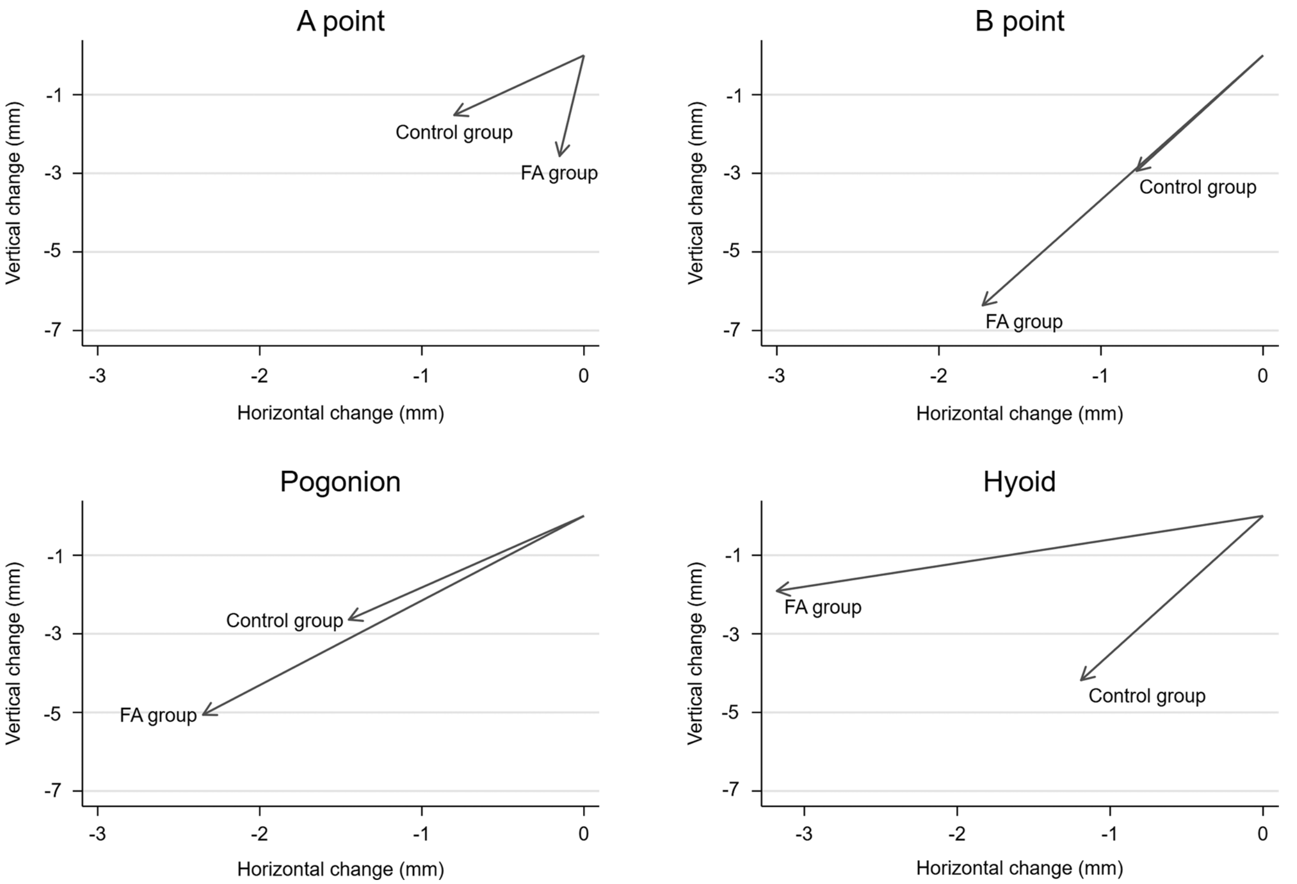

Figure 3. Illustration of the significant skeletal changes (structural method) in the maxilla and mandible of the FA group when compared with the control group.

The significant skeletal changes found using the conventional and structural methods in the present study were evaluated against FA associated airway changes previously reported.[8] The conventional method determined a significant association between a reduction in the SNPg angle and positive changes in the upper airway volume and MCA. The structural method identified a horizontal anterior change in pogonion and the hyoid bone, as well as a forward rotation of the mandible all of which were associated with a positive change in airway volume and MCA. Previous studies have also found a more posterior position of the hyoid bone[26] and pogonion[27] are associated with more severe symptoms of obstructive sleep apnoea (OSA). This is likely due to the intricate relationship between the mandible, hyoid bone, and upper airway, which are interconnected through various soft tissue attachments.[28]

No other three-dimensional studies evaluating the association between longitudinal skeletal and airway changes of FA compared with a control group, using either the conventional or structural methods, could be found.[29] A previous cross-sectional study compared the airway volumes in different patients presenting with various skeletal patterns prior to treatment and found that, for every degree that the ANB angle increased, the airway volume could be expected to reduce by 453 mm^3.[30] While this cross-sectional study compared different individuals with different skeletal patterns, the present longitudinal study showed that a horizontal change in the position of pogonion and the hyoid bone is a good predictor of airway change in that individual over time.

The mandibular changes identified by the structural and conventional methods differed. Although there was a significant correlation between the two methods in the sagittal plane, no significant skeletal effect of the FA was detected in the vertical plane by using the conventional method. In contrast, a significant vertical effect was detected using the structural method. Using changes in cephalometric angles without reference to stable landmarks may therefore underestimate the skeletal effects of FA in the vertical plane.

Table IV. Linear mixed effect modeling analysis for the significant differences in skeletal changes over time between FA and control groups determined by the superimposition on stable structures according to Bjork (structural method).[11]

	Group	Horizontal change (mm)	*p* value	(95% CI)	Vertical change (mm)	*p* value	(95% CI)	Total change (mm)	*p* value	(95% CI)
Maxilla										
A point	Control	0.8	0.001	(0.32–1.25)	1.52	0.001	(0.85–2.19)	1.67	0.001	(1.16–2.18)
	FA effect	−0.65	0.04	(−0.02–−1.30)	+1.04	0.03	(0.11–1.98)	+0.27	0.45	(−0.43–0.98)
Mandible										
B point	Control	0.78	0.01	(0.19–1.36)	2.94	<0.001	(2.25–3.62)	3.00	<0.001	(2.38–3.63)
	FA effect	+0.95	0.02	(0.14–1.76)	+3.42	<0.001	(2.47–4.38)	+3.52	<0.001	(2.66–4.39)
Pogonion	Control	1.45	<0.001	(0.82–2.08)	2.64	<0.001	(1.82–3.46)	3.02	<0.001	(2.26–3.78)
	FA effect	+0.90	0.04	(0.03–1.78)	+2.42	<0.001	(1.28–3.56)	+2.62	<0.001	(1.57–3.67)
Hyoid	Control	1.19	0.27	(−0.94–3.33)	4.18	0.02	(0.69–7.68)	4.34	0.02	(3.86–5.39)
	FA effect	+1.99	0.01	(0.46–3.52)	−2.27	0.36	(−2.61–7.17)	−0.63	0.39	(−2.7–1.74)

These findings are supported by previous studies by Bjork,[11] which have shown that cephalometric points sella (S) and nasion (N) are not stable. Nasion is displaced downwards or upwards and Sella is displaced downwards and backwards during pubertal growth. As the conventional method relies on a line drawn between these unstable points (S-N line) as a reference for disclosing skeletal effects, changes in the unstable S-N line over time may result in the underestimation of the skeletal effects of FA in the vertical plane when this method is applied.

Despite different observations of the skeletal changes achieved with FA, both structural and conventional methods found anterior repositioning of the mandible was associated with a positive change in the airway. In addition, the structural method showed an anterior repositioning of the hyoid bone, as well as a forward mandibular rotation, have a positive association with the changes in airway dimensions. These findings may assist in predicting airway changes in lateral cephalometric radiographs in which accurate airway measurement is difficult, in contrast to assessing skeletal changes, which can be more accurately performed.

There are identified limitations to the present study. Previous cephalometric research has been able to use untreated patients from historical cephalometric growth studies[31] as a control group; however, a comparable control sample with three-dimensional imaging does not exist. Therefore, it was not possible to use untreated class II patients as a control group. A further limitation was that body mass index (BMI) was not controlled for as these data were not collected as part of standard orthodontic records.

In addition, it was also possible that the fixed appliances and RME used as part of the FA treatment may have induced cephalometric and, consequently, airway changes. However, an earlier study[32] using similar airway boundaries showed that RME has minimal effects on the upper airway. Furthermore, although an additional study[33] showed the significant skeletal effects of fixed appliances in the treatment of class II malocclusions, the fixed appliances were augmented with extra oral traction and class II elastics.

Conclusion

Horizontal changes in pogonion and the hyoid bone identified by the structural and conventional

Table V. Stepwise backward linear regression model showing skeletal changes (structural method) with significant effects on changes in airway volume and MCA.

	Coefficient	SE	*p* value	(95% CI)	*F*	R^2
Volume change						
Intercept	7093.4	594.9	<0.001	(5,904.7–8,282.0)	($p < 0.001$)	0.51
Hyoid sagittal change (mm)	500.4	66.4	<0.001	(367.3–633.4)		
Pogonion sagittal change (mm)	615.3	146.1	<0.001	(323.0–907.6)		
Mandibular forward rotation (°)	584.4	256.9	0.027	(68.2–1,100.5)		
MCA change						
Intercept	102.5	16.2	<0.001	70.1–134.8	($p < 0.001$)	0.35
Hyoid sagittal change	5.9	1.2	<0.001	(3.5–8.3)		
Pogonion sagittal change	7.5	2.5	0.005	(2.3–12.5)		
Mandibular forward rotation (°)	4.4	1.67	0.011	(1.0–7.7)		

Table VI. Linear mixed effect modeling analysis for the significant T_0–T_1 differences in pre- and post-treatment cephalometric measurements between FA and control groups (conventional method).

Angle	Group	Change (°)	*p* value	(95% CI)
Mandible				
SNB	Control	0.03	0.85	(–0.31–0.38)
	FA effect	+0.95	<0.001	(0.46–1.43)
SNPg	Control	0.35	0.04	(0.02–0.68)
	FA effect	+0.59	0.01	(0.12–1.05)

cephalometric methods, as well as a forward mandibular rotation identified by the structural method, have a strong association with changes in the upper airway. However, there was significant individual variation in the skeletal and airway responses to treatment using a FA.

Conflict of interest

The authors declare no conflict of interest.

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