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A re-investigation of the relationship between head posture and craniofacial growth

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SUMMARY This investigation was designed to repeat classic studies into the associations between head posture and growth as a single unified study using up-dated methods for gathering and analysing the data. The material comprised the cephalometric radiographs of 59 children (34 males and 25 females) recorded in natural head posture (self-balance position), at the beginning and end of a period of observation during which no treatment was performed (mean age at initial radiograph 11.76 years, mean interval between radiographs 3.52 years).

Correlation analysis (corrected for multiple inference and adjusted for dependency between the variables) showed the strongest associations to be between growth direction of the face and the change in posture. No association was found between growth (direction or magnitude) and pre-observation posture. The most prominent associations were between the change in cranio-cervical posture (CCP) and variables representing the growth directions of the mandible ($r = 0.72$, $P < 0.0001$); anterior maxilla ($r = 0.49$, $P < 0.001$); posterior cranial base ($r = 0.45$, $P < 0.01$); temporomandibular joint ($r = 0.56$, $P < 0.001$); and the change in postural height of the tongue ($r = 0.54$, $P < 0.0001$).

These findings do not support the hypothesis of a causal relationship between initial posture and subsequent facial growth. Instead, they indicate that it is the change in posture that is primarily linked to the growth direction of the face. The patterning of the correlations and the inter-relationships between the main growth variables suggest that this linkage arises from the coordinated changes that occur in the postures of the mandible and tongue. These coordinated postural changes appear to determine the growth direction of the mandible and, at the same time, influence CCP, possibly via an effect on pharyngeal patency.

Introduction

Although a relationship between head posture and craniofacial morphology was suggested by Schwartz (1926) and later by Björk (1955, 1960), the primary evidence for such a relationship and for a causal connection between head posture and facial growth is the series of observational studies conducted by Solow and Tallgren (1976) and Solow and Siersbæk-Nielsen (1986, 1992).

There are, however, several aspects of the design and interpretation of those studies that give cause for concern. For example, no adjustment was made in any of the studies for multiple statistical comparisons (greatly increasing the chance of false positive findings). However, the most troubling aspect is the method (and underlying reasoning) used to establish the crucial conclusion that cranio-cervical posture (CCP) or factors determining posture 'influence the direction of growth of the face' (Solow and Siersbæk-Nielsen, 1992).

While it is generally understood that there are major difficulties in establishing causation from correlation, there are, however, methods for narrowing down or pinpointing possible causation. One such method is 'temporal exclusion' (Sokal and Rohlf, 1995). Simply put, if two events are correlated but occur at different times, the later event cannot have caused the earlier event and thus the direction of causation (if it exists) is for the earlier event to have caused the later event.

This line of reasoning was used by Solow and Siersbæk-Nielsen (1992) to establish that it is posture which influences growth and not the converse, because at the time posture was measured growth had not yet occurred. Although this appears to be a compelling argument, it is not possible to determine the direction of the association between posture and growth from the relative timing of events when the posture was measured only on a single occasion at the start of the study.

The conclusion that posture influences growth is particularly surprising given that the evidence of the mean facial diagrams and individual case analyses presented by Solow and Siersbæk-Nielsen (1986, 1992), points to a different conclusion, namely that a more obvious association appears to exist between growth and post-observation posture than between growth and pre-observation posture. At the very least, this raises the suspicion that growth and posture may not be causally linked in the way that has been claimed.

In an attempt to resolve these uncertainties, it was decided to re-examine the relationship between posture and growth in a single sample but this time examining both pre- and post-observation posture as well as growth and postural changes during the observation period.

In the time since the original studies were performed, there have been major advances in the methods for detecting, gathering, and analysing radiographic data. It was hoped that these and associated advances in the statistical analysis of large correlation matrices would permit a deeper insight into the associations between head posture and growth than was possible in the original studies.

Materials and methods

Design of the study

The study was designed as a longitudinal investigation into the associations between head posture and growth in a group of children. Morphological and postural measurements were gathered from lateral cephalometric radiographs recorded in natural head posture before, and after, a period of observation averaging several years during which no orthodontic treatment was performed. The associations between the postural variables and the changes in the morphological variables (growth) were examined by correlation analysis.

Material

The material comprised paired serial lateral cephalometric radiographs of 59 children (34 males and 25 females) recorded with the subjects seated with the head in the self-balance position as described by Solow and Tallgren (1976) at the beginning and end of a period of observation prior to a decision to commence orthodontic treatment. The radiographs were drawn from the research files of the Eastman Dental Institute, London and were recorded during the 1980s and early 1990s as part of the clinical records of children referred for orthodontic treatment. The subjects were of northern European except for four subjects: three males, one of Chinese origin and two of Indian origin, and one female Afro-Caribbean.

The primary criterion for inclusion in the study was that no treatment had been performed during the period between the recording of the films. However, no subject with known mandibular or craniofacial pathology was included in the sample. To maximize detectability of growth changes (relative to the inherent errors), it was decided to exclude those subjects from the main study where the cephalometric films had been recorded less than 12 months apart. Details of the sample are given in Table 1.

Method

The cephalometric radiographs were converted to digital format using a flatbed scanner (DuoScan HiD, Agfa-Gevaert, Mortsel, Belgium) and the comparisons and measurements carried out by computer. Cephalometric landmarks and the associated postural and morphological variables (Figure 1 and Tables S1 and S2, available as supplementary data in *European Journal of Orthodontics* online) were located and measured directly on the images of pre- and post-observation radiographs—no intervening tracings were used. Variables measured on the pre-observation radiographs are designated by the suffix '-1' and on the post-observation radiograph by the suffix '-2'. The change and the rate of change in these variables between the recording of the two radiographs are indicated by the suffixes '-c' and '-r', respectively.

The assessment of growth changes was made by direct superimposition of the cephalometric images on structures in the anterior cranial base using the method described by Björk and Skieller (1983). For assessment of mandibular growth rotation, the images were superimposed on structural features in the mandible as described by Björk and Skieller (1983) with the additional modifications proposed by Springate (2010).

Although conventional cephalometric angular and linear morphological variables were included in the study (to allow direct comparisons with previous research), they cannot

Table 1 Details of the sample.

Description	Number	Mean (years)	SD (years)	Range (years/degrees)
Number of subjects	59	—	—	—
Males	34	—	—	—
Females	25	—	—	—
Age at pre-observation film	—	11.76	1.90	7.93–15.89
Age at post-observation film	—	15.26	2.23	10.36–18.66
Interval between films	—	3.52	1.52	1.04–7.08
Skeletal Class I	12 (6 males, 6 females)	—	—	—
Skeletal Class II	37 (22 males, 15 females)	—	—	—
Skeletal Class III	10 (6 males, 4 females)	—	—	—
MM planes angle (degrees)				
Low (<25)	16	—	—	10.70–24.40
Average (25–30)	21	—	—	25.30–29.40
High (>30)	22	—	—	30.40–39.70

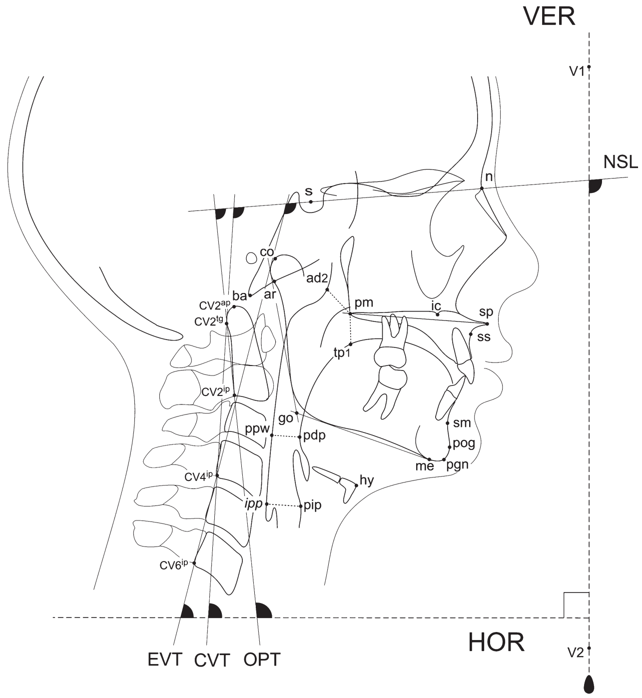


Figure 1 The definitions of the cephalometric reference points, lines, and angles employed in the study are those of Solow and Tallgren (1976) with the exception of EVT, 'incisive canal point' (ic) and the additional points on the outline of the tongue and pharynx. These were defined as follows: EVT, the line through cv4ip and cv6ip; ic, the mid-point at the confluence of the cortical contours of the nasal floor forming the superior foramen of the incisive canal; tp1, the point on the outline of the dorsum of the tongue where it is intersected by a perpendicular from pm; pdp, the most posterior point on the dorsum of the tongue where it forms the anterior wall of the pharynx; ppw, the point on the posterior wall of the oropharynx where it is intersected by a line perpendicular to the long axis of the pharynx passing through pdp; ipp, the point on the posterior pharyngeal wall at the level of the laryngo-pharyngeal junction; pip, the point on the anterior pharyngeal wall at the level of the laryngo-pharyngeal junction. On the post-observation radiograph, the line NSL′ was defined in relation to its location on the pre-observation film as described by Björk and Skieller (1983).

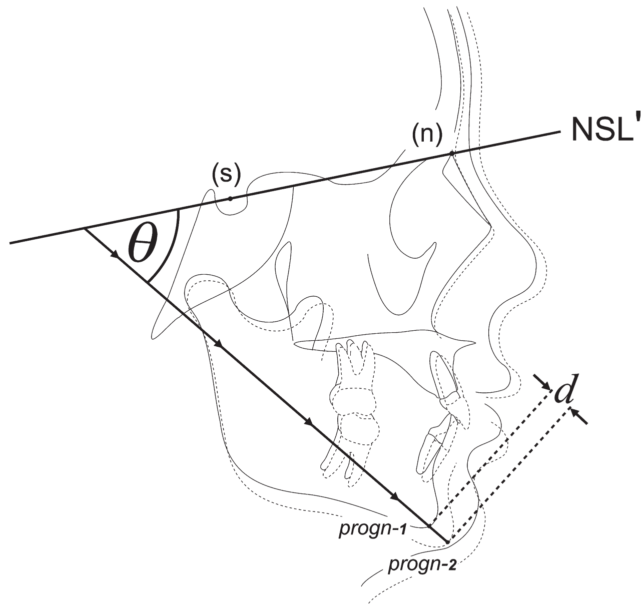


Figure 2 Diagram illustrating the construction of a vector for the assessment of the direction and magnitude of sagittal growth. The system of sagittal growth vectors allows measurement of both the direction and magnitude of skeletal growth (or displacement) at cephalometric landmarks throughout the face and cranial base. The method of measurement for the growth vector at prognathion is shown schematically. Pre- and post-observation radiographs were superimposed on structural details in the anterior cranial base; the nasion-sella line (NSL) on the pre-observation radiograph was used as the reference for the direction component (θ) of the vector between earlier (progn-1) and later (progn-2) locations of proganthion; and the magnitude component of the vector (d) was measured along the line of the vector (progn-1 to progn-2) and corrected for magnification.

provide an accurate indication of the direction or magnitude of facial skeletal growth. Consequently, an additional series of measurements was made to assess the sagittal growth vectors (growth direction and growth magnitude) at selected landmarks in the cranial and facial skeleton (Figure 2).

To further enhance the sensitivity of the assessment of growth changes, computer-based image enhancement was carried out to improve the visibility of fine bony details and skeletal contours. This was achieved by equalizing the brightness and contrast of each pair of serial images and then applying a mid-blue tone to the middle and maximum optical densities of each image. This tonal alteration maximizes the psychometric perceptibility of fine details but does not alter the spatial characteristics of the images (Pratt, 2007).

Statistical methods

Correlation analysis was used to assess the strength of the relationship between the postural and morphological variables. The correlations were assessed using Pearson's (product-moment) correlation (r). However, where the requirements for its use were not met, as indicated by non-normality in either variable, or where obvious outliers were present in the samples, the robust alternative of Spearman's rank correlation coefficient (r_s) was used instead. Although outliers can be identified and removed from the samples using standard criteria, a decision was taken that the study data would be presented complete and without adjustment.

Although correlation analysis is the method of choice for assessing the degree of association between biological variables that are examined observationally (Sokal and Rohlf, 1995), this method of analysis suffers from two main problems that complicate the interpretation of the findings: spurious correlation and the uncertainties associated with multiple comparisons and simultaneous inference from the elements of a large correlation matrix.

Spurious correlation, caused by the inclusion of identical random errors in the variables to be correlated, can lead to large but otherwise entirely false correlations (Blomqvist, 1977; Andersen, 1990). To prevent this, independent measurements were made for posture and morphology; and separate superimpositions were performed for postural and morphological growth changes. In addition, all cephalometric landmarks and cephalometric planes were located and recorded separately and, as far as possible, independently on each occasion that a measurement was made involving the landmark or plane. To this extent, the random errors involved in location and measurement were not shared by any of the morphological or postural variables.

The second problem is that even where no correlation truly exists, on average, 5 per cent of the correlations will appear to be statistically significant at the $P \leq 0.05$ by chance alone and where the matrix involves hundreds or thousands of correlations, many of the apparently significant results will be false positives.

To overcome this difficulty, a correction must be applied to the critical values (thresholds) used for the acceptance of statistical significance. Where all the correlations are statistically independent, a simple Bonferroni correction can be used. However, where the variables are correlated among themselves and therefore statistically dependent (as in this type of cephalometric study) an adjustment is required to account for this (Shaffer, 2006). The resulting dependency-adjusted Bonferroni correction was calculated as described by Garcia (2004) using the average absolute correlation between the variables.

Error of the method

Three separate error studies were undertaken to examine the precision of the measurement of the conventional cephalometric linear and angular variables; the errors involved in the measurement of growth changes; and the errors involved in registering the postural variables.

The first two assessments of error were made by replicating measurements on the original radiographs for 25 cases selected randomly from the main study. The third error study (registering postural variables) was performed on replicated radiographs. That is, those pairs of films excluded from the main study because the interval between the recording of the films was less than 1 year. From this group, 12 pairs of cephalometric radiographs were selected, with a mean interval between films of 3.4 months [standard deviation (SD) 2.2 months].

In each error study, the measurement procedure used in the main study was repeated and the values were then combined with those from the main study to form duplicate pairs. The random errors were assessed as the SD of the differences between the duplicate pairs of measurements. In addition, the mean differences between the duplicate measurements were examined using one-sample *t*-tests to check for systematic differences.

Three variables exhibited statistically significant systematic differences between the duplicate measurements (OPT/HOR, mean difference = 0.7 degrees, $P < 0.05$; NSL/EVT, mean difference = −1.4 degrees, $P < 0.05$; CVT/HOR, mean difference = 1.1 degrees, $P < 0.05$). This number of significant results (at the $P \leq 0.05$ level) is almost exactly what would be expected by chance alone (3/58 = 0.052). The method errors (random error) are given in Tables 2, 3, and 4.

Table 2 Method errors for the postural variables.

Code No.		Symbol	Random error (degrees)
Pre- and post-observation posture			
066	017	NSL/OPT	0.8
061	018	NSL/CVT	1.0
062	019	NSL/EVT	1.1
063	020	NSL/VERT	1.0
067	021	OPT/HOR	1.2
068	022	CVT/HOR	1.5
069	023	EVT/HOR	1.8
005	001	NL/VERT	1.0
006	002	ML/VERT	0.8
007	003	NSL/NL	0.6
008	004	NSL/ML	0.6
Postural change (during observation)			
092	—	NSL'/OPT-c	1.6
096	—	NSL'/CVT-c	1.2
095	—	NSL'/EVT-c	1.8
097	—	NSL'/VERT-c	0.9
098	—	OPT/HOR-c	1.0
099	—	CVT/HOR-c	1.5
100	—	EVT/HOR-c	1.5

$n = 25$, except for those variables involving EVT, for which $n = 24$. The method errors for pre- and post-observation posture were derived from repeated measurements on the same radiographs and therefore do not take into account the variability of posture itself.

Results

In presenting the results, no attempt has been made to distinguish between males and females nor to subdivide the data to provide age-specific descriptions of growth, posture, or postural change.

Although the data are based on the 59 subjects included in the study, it was not possible to register the infero-posterior tangent point of C6 on the pre-observation radiographs of three subjects and in the post-observation radiographs of five subjects; for three subjects, the point was not visible in either radiograph. Variables involving this reference point are based on the registrations from the remaining subjects. All other variables are based on registrations from all 59 subjects.

Correlation analyses

The results for the correlation analyses are presented graphically as a rectangular matrix (Figures 3 and 4) where each column represents a postural variable and each row a growth variable. To simplify interpretation, the matrix has been segmented vertically into classes of postural variables (pre-observation, post-observation, and postural change) and horizontally into anatomical regions to allow patterns of significant associations to be more easily visualized.

Figure 3 shows the distributions of the correlations among the postural and growth variables. Only those correlations that reached or exceeded the $P \leq 0.05$ threshold before correction for multiple inference are shown. This provides a highly permissive (and incorrect) view of the statistical significance of the results but it does permit easier comparison with the results of previous studies in which no appropriate correction was applied for multiple inference. These uncorrected results are presented without further commentary.

Figure 4 shows those cells where the correlation reached or exceeded the $\hat{P} \leq 0.05$ (the dependency-adjusted Bonferroni threshold; $r_{(n = 59)} = 0.408$). In comparison with the situation shown in Figure 3, once the corrections for multiple inference and dependency were applied, very few of the correlations were truly statistically significant. Surprisingly, and in contrast to the study of Solow and Siersbæk-Nielsen (1992), none of the correlations involving pre-observation posture reached significance at the $\hat{P} \leq 0.05$ level. Statistically significant correlations were found, however, between post-observation posture and growth and between postural change and growth.

The statistically significant correlations were more numerous between postural change and growth (.46) than between post-observation posture and growth (.15). This difference was highly statistically significant ($\chi^2 = 15.754$, 1 df, $P < 0.001$). In addition, the highest absolute correlations were found in the columns representing the change in CCP as measured from the cranial end of the cervical spine (NSL′/CVT-c and NSL′/OPT-c). There was also a clear gradient of increasing strength of the associations from the lowest to the highest level on the cervical spine (from EVT/HOR to CVT/HOR to OPT/HOR) at which CCP was calculated.

The relationship between posture and growth was greatest for the change in CCP and the morphological variables representing the postural height of the tongue ($r = 0.54$, $\hat{P} < 0.0001$); the direction and magnitude of mandibular growth rotation ($r = 0.64$, $\hat{P} < 0.0001$); and the variables representing the growth directions of the mandible ($r = 0.72$, $\hat{P} < 0.0001$), anterior maxilla ($r = 0.49$, $\hat{P} < 0.001$), posterior cranial base (PCB; $r = 0.45$, $\hat{P} < 0.01$), temporomandibular joint (TMJ; $r = 0.56$, $\hat{P} < 0.001$), and the hyoid bone ($r = 0.43$, $\hat{P} < 0.05$).

The change in CCP was associated with a series of changes in the face and PCB, which might be described as ‘total facial rotation’. These associations are most easily visualized by examining the mean facial diagrams for subjects drawn from the extremes of the range of postural change shown in Figure 5. As can be seen, a decrease in CCP was associated with anteriorly directed growth throughout the face and PCB, and a raised tongue position; while an increase in CCP was seen in association with a downward direction of jaw growth and posteriorly directed growth of the PCB and TMJ, and a lowered posture of the tongue.

Table 3 Method errors for the main growth vectors.

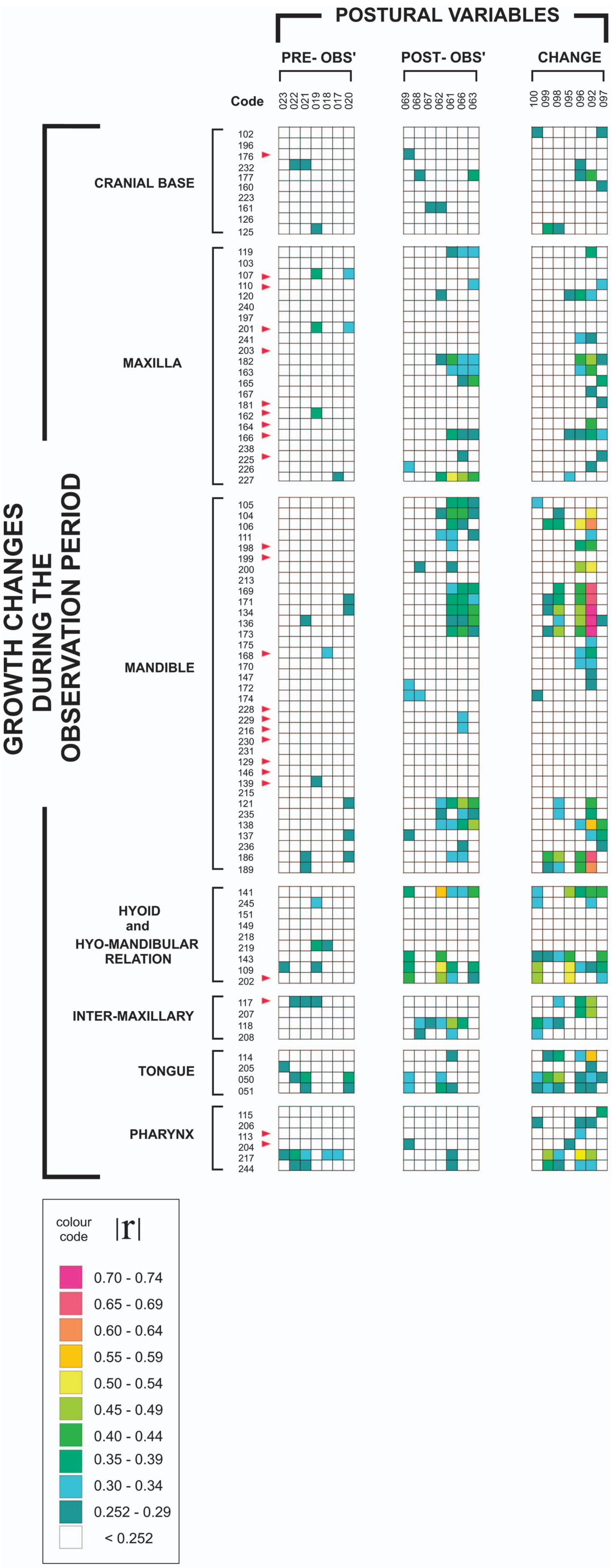
Code No.	Symbol	Random error (degrees or mm)
Growth vectors variables		
160	*n* magnitude	0.7
161	*n* direction	8.2
137	ar magnitude	1.1
138	ar direction	7.7
176	ba magnitude	0.8
177	ba direction	12.5
164	pm magnitude	1.1
165	pm direction	9.3
181	ic magnitude	0.8
182	ic direction	6.2
162	sp magnitude	1.0
163	sp direction	5.2
166	ss magnitude	0.9
167	ss direction	9.5
147	pgn magnitude	0.8
134	pgn direction (ACB)	4.2
136	pgn direction (ML)	4.4
168	sm magnitude	0.9
169	sm direction	5.0
170	pog magnitude	1.0
171	pog direction	6.0
172	me magnitude	1.0
173	me direction	7.1
174	go magnitude	2.3
175	go direction	6.7
146	co magnitude	1.7
129	co direction (ACB)	6.7
139	co direction (Ram)	6.8
149	hy magnitude	2.0
141	hy direction (ACB)	6.8
245	hy direction (ML)	7.4
151	hy-vert magnitude	2.1
186	Mandibular rotation	1.2

$n = 25$.

Table 4 Reproducibility of the postural variables.

Code No.		Symbol	Random error (degrees)
Pre- and post-observation posture			
066	017	NSL/OPT	3.9
061	018	NSL/CVT	2.7
062	019	NSL/EVT	4.3
063	020	NSL/VERT	3.7
067	021	OPT/HOR	3.2
068	022	CVT/HOR	3.5
069	023	EVT/HOR	4.3

$n = 12$. The method errors were derived from repeat radiographs and consequently they take into account the variability of posture over time (average interval 3.4 months).



The specific morphological and postural variables indicated by the 3-digit numerical codes are given in Tables 2 and 3.

Correlations between variables of the same class

Although this study focused primarily on the associations between growth and posture, it was also of interest to examine some of the relationships between similar variables, i.e. the associations between postural and growth variables.

The relationships between nine pairs of variables were examined with particular reference to the growth changes in two anatomical regions: the anterior mandible and maxilla, and the tongue. The selection of these variables was made *post hoc* after the results of the main study became known. That is, they were selected with the specific aim of aiding the interpretation of the results from the main study.

Because these pairs of variables were selected (but without prior knowledge of the presence or absence of a meaningful correlation), they did not form part of an exhaustive survey of all possible associations using a classic correlation matrix. Consequently, although the statistical significance of the observationally determined correlation coefficients could not be accurately assessed using the unadjusted (univariate) probability, it was felt unnecessary to adjust the probabilities to the same extent as in the main study. However, the degree to which these additional isolated comparisons should influence the threshold(s) for statistical significance is open to question. Because of this uncertainty, both the unadjusted probability and the dependency-adjusted Bonferroni probability were calculated for each pair of variables examined in this way.

The results of these additional correlations between variables of the same type given in Table 5 revealed several points of interest. First, there was a close relationship between time-varying changes in the vertical position of the tongue (tongue posture) and the sagittal depth of the oropharynx, and, related to this, the anterior wall of the oropharynx (formed by the most infero-posterior part of the dorsum of the tongue) tended to move posteriorly (relative to the posterior edge of the mandibular ramus) as the postural position of the tongue was lowered. The converse occurred as the postural position of the tongue rose. Second, there were significant correlations between changes in tongue position and the magnitude (and direction) of mandibular growth rotation and mandibular growth direction measured at the symphysis.

Figure 3 Correlation matrix illustrating the distribution of the correlations between the postural and growth variables examined in the study. The matrix has been segmented vertically into the three postural classes and horizontally into seven anatomical regions to allow significant associations to be easily visualized. Each element of the matrix is represented by a square cell which is colour-coded to indicate the absolute magnitude of correlation coefficients greater than $|r|_{(n\,=\,59)} = 0.252$ (the critical level for statistical significance at $P < 0.05$ without correction for multiple inference). This presentation of the data allows comparison with previous studies where no appropriate correction was applied for multiple inference. The figure was constructed using Pearson's product-moment correlation coefficients except for those variables with non-normal distributions (indicated by a red arrow). For these cases, Spearman correlation coefficient was used.

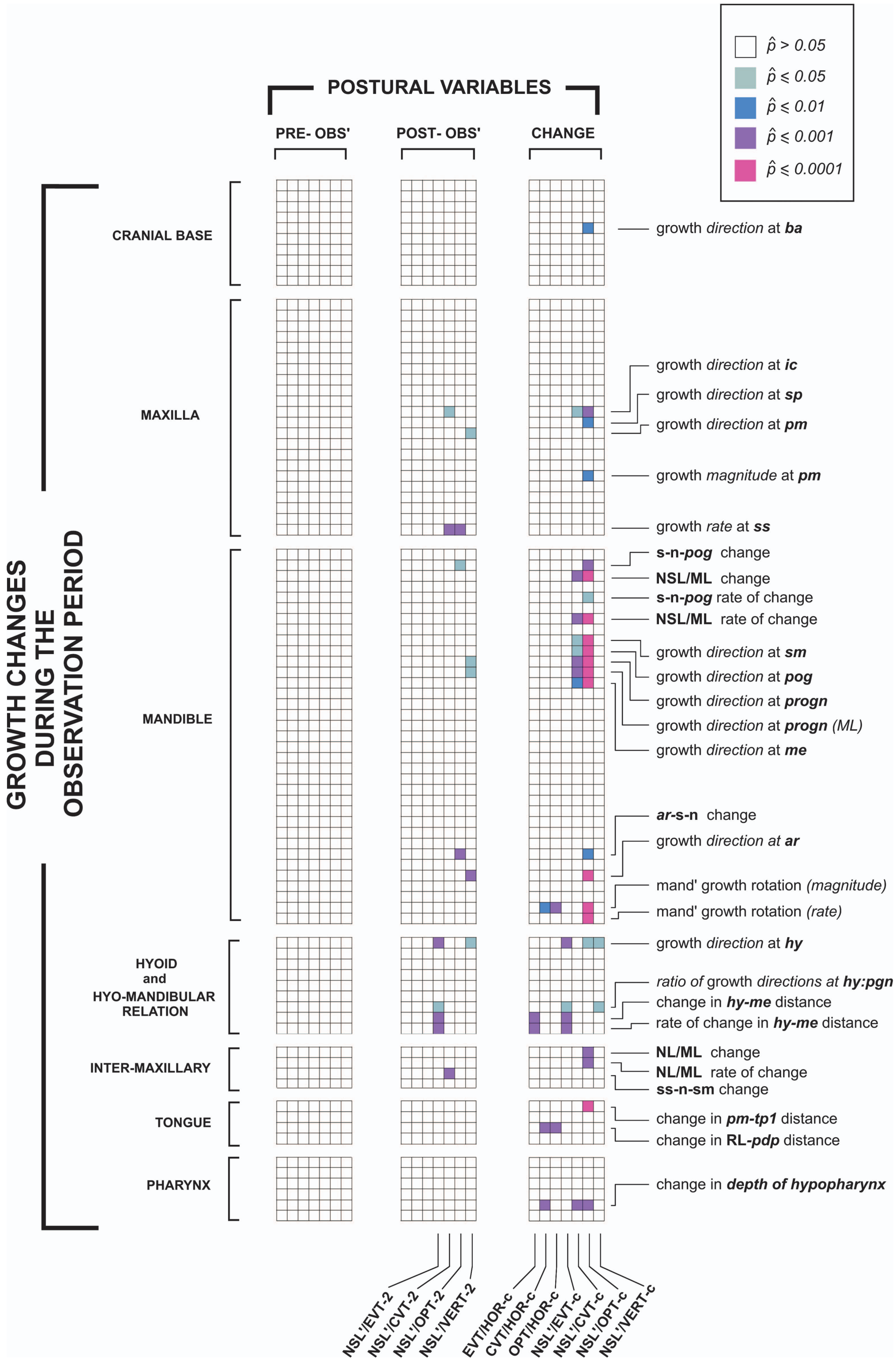


Figure 4 Correlation matrix for posture and growth showing the location of significant associations after correction for multiple inference. This figure reproduces the matrix shown in Figure 3 but shows only those cells where the correlation coefficients reached or exceeded $|r|_{(n\,=\,59)} = 0.408$ (the critical level for statistical significance at the dependency-adjusted Bonferroni probability, $\widehat{P} < 0.05$). The cells are colour-coded to indicate the probability associated with each correlation. The postural and growth variables involved in these statistically significant correlations are indicated beneath and to the right hand side of the matrix, respectively. The numerical values of these significant correlations are given in the Appendix (available as supplementary data in *European Journal of Orthodontics* online).

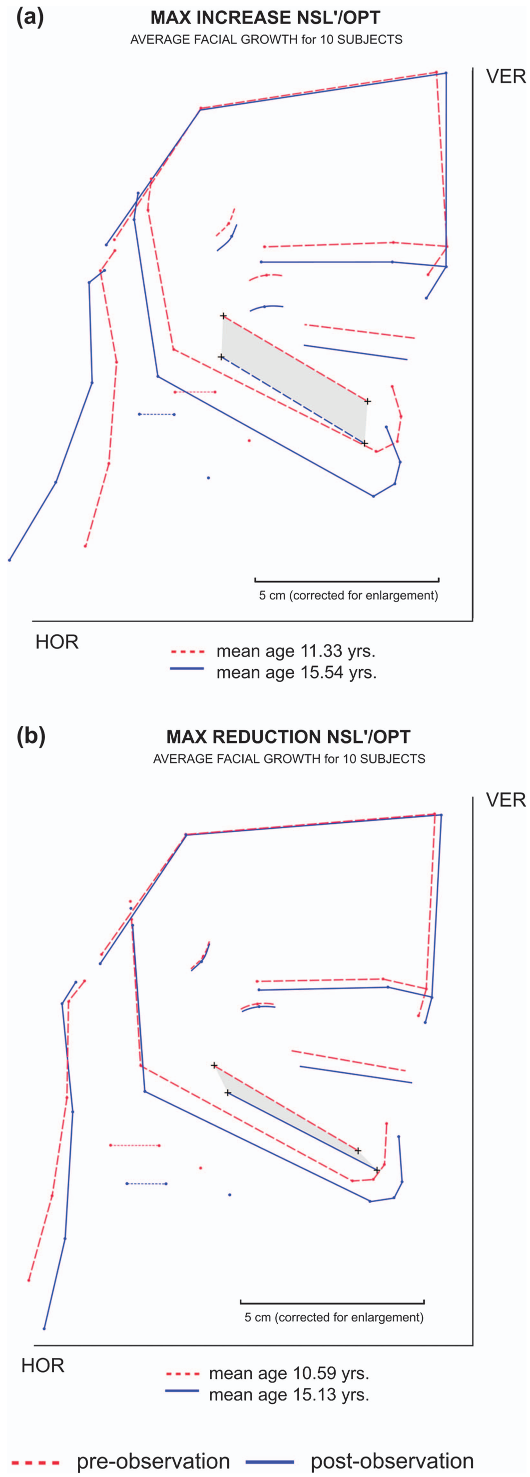


Figure 5 Mean facial diagrams illustrating the average sagittal changes at 25 skeletal and soft tissue landmarks for the 10 subjects with (a) the largest increase in cranio-cervical angulation (mean = +11.2 degrees); (b) the largest reduction in cranio-cervical angulation (mean = −10.4 degrees). Note the differences in the directions of growth at the anterior landmarks in the mandible and maxilla, and the differences in mandibular rotation evident in the shaded areas between the two positions of the (arbitrary) corpus reference lines. The diagrams are orientated at the average cranio-vertical angulation recorded from the pre-observation radiographs of the 10 subjects used in each illustration.

Similarly, there was a moderately strong correlation between the directions and magnitudes of growth measured at the mandibular symphysis and anterior of the maxilla, and between mandibular growth rotation and mandibular growth direction measured at the symphysis.

No meaningful association could be found between the change in CCP (NSL′/OPT-c) and its pre- or post-observation value.

Discussion

This investigation was designed to repeat the classic studies of Solow and Siersbæk-Nielsen (1986, 1992) as a single unified study to examine the correlations between growth and head posture. Additional examinations, not found in the original studies, were also made of post-observation posture and of the postural changes of the tongue, pharynx, and hyoid.

In the time since the original studies were performed, there have been major advances in detecting and analysing radiographic data, which were applied in the present research. Efforts were also made to enhance the sensitivity of the assessment of growth changes by employing growth vectors (as well as conventional cephalometric angular measurements) and by referencing all changes to stable structures in the anterior cranial base rather than cephalometric planes based on changeable anatomical contours. In addition, care was taken to avoid spurious and false-positive correlations resulting from dependency between the variables and from failures to account for multiple statistical inference.

Before the study was undertaken, it was expected that significant correlations would occur between the two main postural classes (pre- and post-observation posture) and the changes in morphology (growth) but that no clear unequivocal picture would emerge on whether growth followed posture or posture followed growth.

What was actually found was very different and totally unexpected. Namely, that the highest absolute correlations, and by far the greatest number of significant correlations, occurred between the variables representing growth and those representing postural change; that there were very few significant correlations between growth and post-observation posture; and, perhaps most surprisingly, that not a single correlation between any measure of pre-observation posture and subsequent growth reached significance at the dependency-adjusted Bonferroni threshold ($\hat{P} < 0.05$).

Consequently, the results of the present study do not coincide with those reported by Solow and Siersbæk-Nielsen (1992), who found significant correlations between pre-observation posture (particularly CCP) and the direction of subsequent jaw growth.

The absence of a significant correlation between pre-observation posture and the direction of subsequent mandibular growth has also been reported by Huggare and

Table 5 Additional correlations outside the posture-growth matrix: correlations between variables of the same class.

Variable 1	Variable 2	Correlation coefficient	Probability, *P*	
			Unadjusted	Bonferroni
Postural variables				
NSL'/OPT-c	NSL/OPT-1	$r = -0.233$	>0.05 ns	—
NSL'/OPT-c	NSL'/OPT-2	$r = -0.061$	>0.05 ns	—
Growth variables				
ic direction	progn direction	$r_s = 0.651$	<0.0001	<0.0001
ic magnitude	progn magnitude	$r_s = 0.528$	<0.0001	<0.001
mand rot-c	progn direction	$r = 0.699$	<0.0001	<0.0001
mand rot-c	pm-t1-c	$r = 0.565$	<0.0001	<0.0001
progn direction	pm-t1-c	$r = 0.508$	<0.0001	<0.001
RL-pdp-c	pm-t1-c	$r_s = 0.373$	<0.01	<0.05
RL-pdp-c	CVT/HOR-c	$r_s = -0.443$	<0.001	<0.05

$n = 59$.

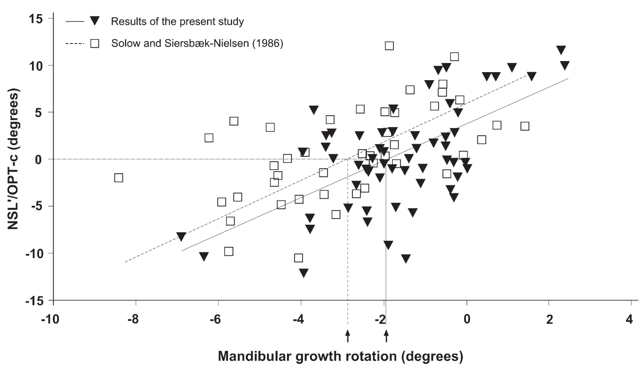


Figure 6 Comparison of the relationship between the changes in cranio-cervical posture (CCP) and mandibular growth rotation in the present study and that found by Solow and Siersbæk-Nielsen (1986). The data from Solow and Siersbæk-Nielsen (1986) has been plotted against the corresponding data from the present study. The distribution of the data points is very similar for the two studies and there is an almost identical range for the change in CCP. Least-squares lines of best-fit constructed on the data sets also reveal an almost parallel orientation of the two distributions. In both studies, a zero mean change in CCP was associated with an average forward (−ve) rotation of the mandible of approximately 2 degrees.

Cooke (1994) in the only other study that examined this relationship in untreated children. They found non-significant correlations of $r = 0.10$ for males ($n = 20$) and $r = 0.09$ for females ($n = 16$) between the initial CCP (NSL/OPT) and the direction of subsequent mandibular growth measured at prognathion over intervals of between 2 and 5 years. The corresponding correlation found in the present study for both genders combined was $r = -0.09$ ($\hat{P} > 0.05$, ns).

Despite the lack of correspondence between the results of the present study and those of Solow and Siersbæk-Nielsen (1992), there are, however, some clear similarities with the findings reported by Solow and Siersbæk-Nielsen (1986). The most conspicuous finding of that study and one of the more striking findings of the present research was the association between the change in CCP and mandibular growth rotation. The similarity of the findings of the two studies is particularly striking when plotted graphically, as shown in Figure 6.

The most informative aspects of the current study are, however, in the findings for the additional growth variables not examined by Solow and Siersbæk-Nielsen (1986, 1992), that is, for the directional components of the skeletal growth vectors and the changes in the locations of the soft tissue landmarks for the tongue and pharynx. In each case, the strongest associations occurred with the variables representing postural change rather than initial posture as previously suggested (Solow and Siersbæk-Nielsen, 1992; Solow 1992). While this does not entirely rule out an effect of soft tissue stretching on facial growth, it does contradict the more general 'soft tissue stretching hypothesis' (Solow and Kreiborg, 1977).

Although the primary associations in this study involve variables representing postural change, there were 15 statistically significant correlations involving variables representing post-observation posture. In all but two cases, these significant correlations arose in combination with growth variables where the absolute correlation with postural change was moderately high but the correlation with pre-observation posture was very close to zero. This strongly suggests that they have arisen by 'mathematical coupling' (Archie, 1981) between post-observation posture and postural change. That is, because post-observation posture is the arithmetic sum of pre-observation posture and postural change, the correlation with post-observation posture will 'incorporate' the correlation with postural change. This coupling only becomes evident, however, where the correlation with pre-observation posture is numerically close to zero.

For 13 of the 15 significant correlations, the average absolute correlation with pre-observation posture was −0.002. Thus, it appears very likely that the majority of the significant correlations with post-observation posture have a mathematical, rather than a biological, origin. Consequently, the biological linkage between growth and posture appears limited to the variables expressing the change in posture.

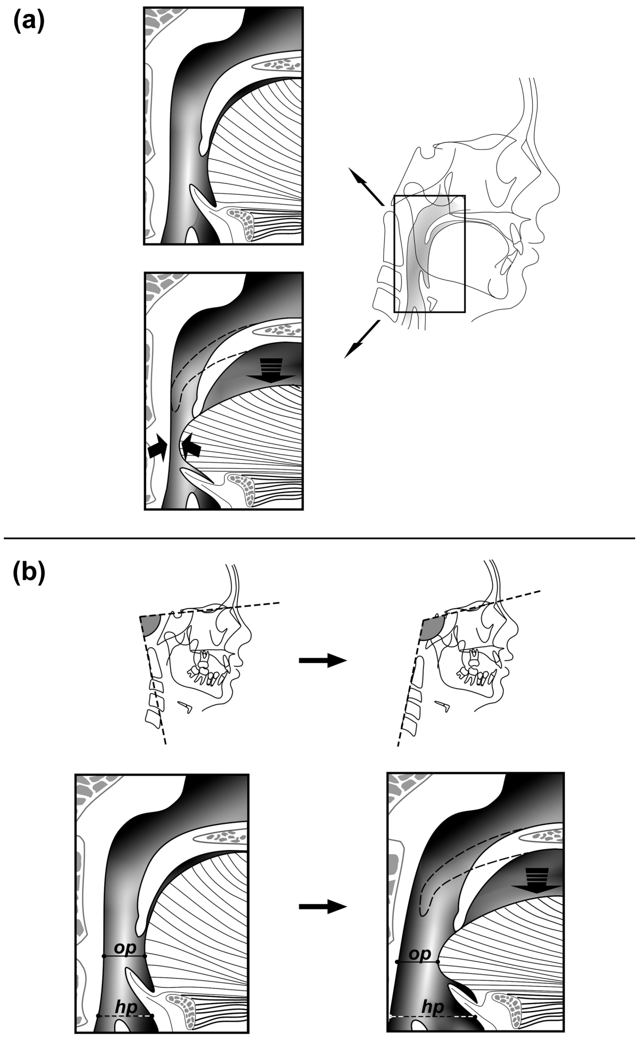


Figure 7 Diagram showing the hypothetical mechanism linking the change in tongue posture to the change in cranio-cervical posture. (a) If the tongue is lowered within the mouth, the most postero-inferior part of the dorsum bulges into the pharynx, narrowing the space between the anterior and posterior walls of the pharynx—potentially blocking the pharyngeal airway at the base of the tongue. (b) If the lowered posture of the tongue is maintained, a compensatory relative backward movement of the posterior pharyngeal wall is required to reopen the airway. This is achieved by either tilting and lifting the cranium (and mandible) away from the spine or by altering the horizontal inclination of the cervical spine, or a combination of both. Note that while this maintains the sagittal depth of the oropharyngeal airway (op) it enlarges the hypopharyngeal airway (hp).

The coordination between growth direction and the change in posture

In an attempt to understand the relationship between growth direction and the change in posture, it was decided to examine more closely the inter-relationships and associations between the growth features involved in the most conspicuous correlations with the postural change. Analysis of the patterning of these associations suggests that coordination between these growth features is centred on the development of the mandible. The same conclusion was reached by Solow (1992) and Solow and Sandham (2002) concerning the relationship between posture and changes in craniofacial morphology. However, the additional associations examined in this study also reveal several points of correspondence with the known functional relationships between the mandible, pharynx, and tongue.

The change in postural height of the tongue and sagittal depth of the pharynx

The posture of the tongue has been viewed as an important link between the patency of the pharynx and natural head posture (Hellsing, 1989; Behlfelt *et al.*, 1990). Opdebeeck *et al.* (1978) suggested a mechanism by which this link might operate. They commented that the diameter of the pharyngeal airway is narrowest at the base of the tongue and encroachment of the airway will occur here first in subjects with 'long face syndrome'. As a consequence, they suggested that a backward rotation of the cervical spine combined with hyperextension of the head could be a mechanism to restore the pharyngeal space at the base of the tongue.

A systematic demonstration of this effect has not been made, but Shelton and Bosma (1962) have shown that extension of the head generally leads to an increase in the antero-posterior diameter of the oropharynx even where this is accompanied by flexion of the cervical spine, and Hellsing (1989) demonstrated a statistically significant increase in the sagittal depth of the pharynx at the levels of the C2 and C4 cervical vertebra which accompanies a 20 degree extension of the head from its postural position.

A statistically significant positive correlation was found in the present study between CCP change and the sagittal depth of the hypopharynx (C4) but not at the level of the oropharynx (C2 and posterior inferior dorsum of the tongue). This lack of correlation is surprising given that the points of measurement were just 2 cm apart. It seems likely, therefore, that something structurally different occurs at the base of the tongue when the change in cranio-cervical angulation occurs posturally rather than being consciously induced in a laboratory study.

What appears to be happening in the present sample is that the posturally induced change in cranio-cervical angulation is accompanied by a positional change in the intra-oral height of the tongue. Although it is not possible to establish a cause-and-effect relationship from these data, there are functional reasons for believing that it is the change in tongue posture that leads to the change in cranio-cervical angulation. That is, because as the tongue is mainly composed of incompressible visco-elastic tissue (Sicher and Dubrul, 1988) which is constrained laterally by the body of the mandible, any downward displacement of the tongue will be accompanied by a redistribution of its bulk either anteriorly between the lips or posteriorly into the pharynx. In normal function, gross protrusion of the tongue through the lips does not occur so redistribution of the mass of the tongue will most likely cause the tongue to bulge into the pharynx. Such a relationship, although quite weak, was found in the present sample

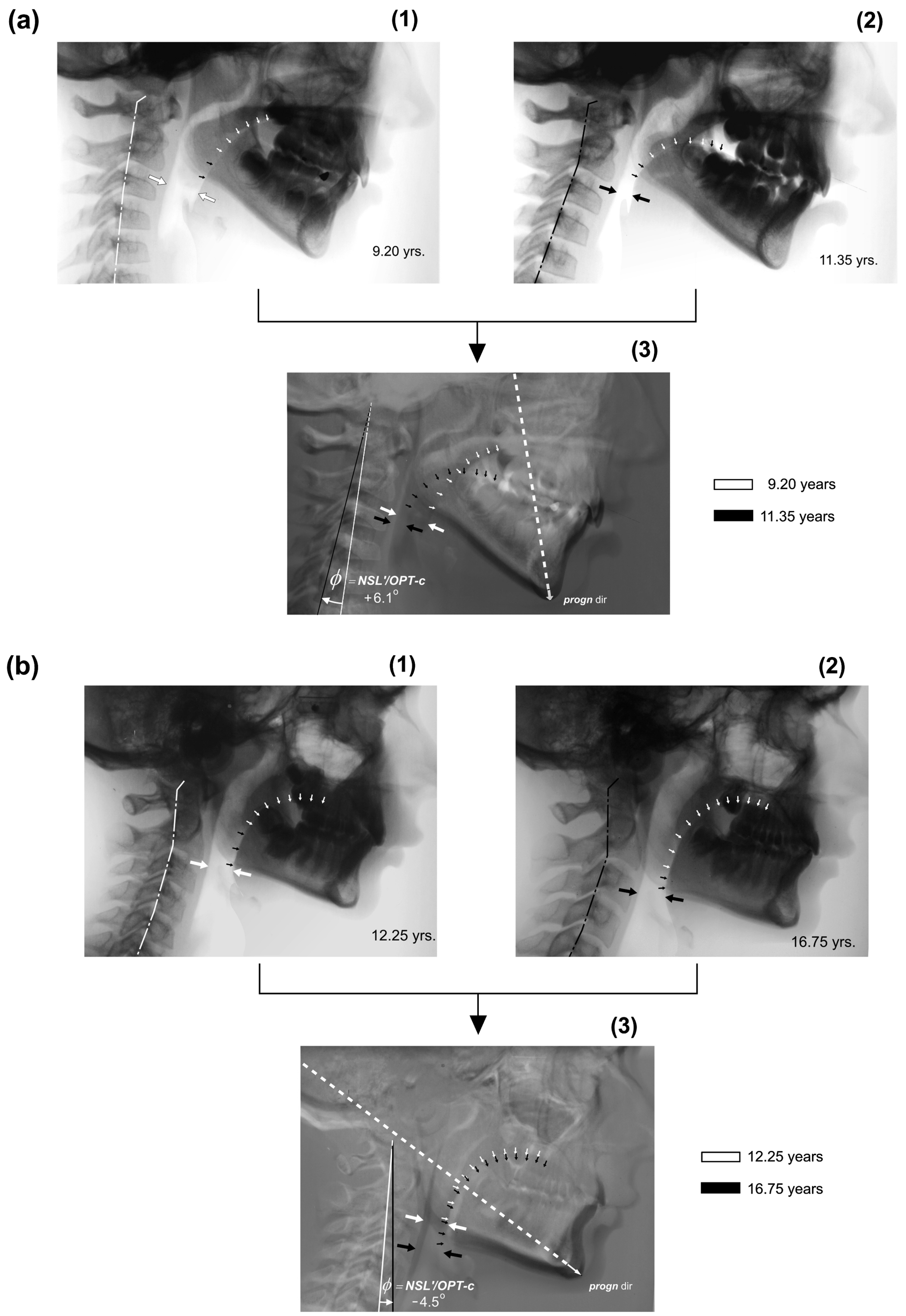


Figure 8 The illustrations show the (1) pre- and (2) post-observation relationships between cranio-cervical posture (CCP) and tongue posture in two subjects from the study with different mandibular growth directions. The images have been tonally reversed to improve the visibility of the soft tissues. In each illustration, the outline of the tongue is indicated by a series of small arrows and the antero-posterior (sagittal) pharyngeal depth at the base of the tongue by large arrows. The contour of the cervical spine is indicated by the dashed cephalometric line, cv2ap-cv2tg-cv2ip-cv4ip-cv6ip. For each subject, illustration (3) shows the images (1) and (2) superimposed on stable structures in the anterior cranial base using image-subtraction (one negative: white; one positive: black) to permit easier recognition of the changes over the observation period. The change in CCP, NSL'/OPT, is indicated by the angle, θ; and the mandibular growth direction measured at prognathion (progn dir) is shown by the thick dashed white line. As can be seen, in (a) the increase in NSL'/OPT (= 6.1 degrees) is associated with a lowered (postero-inferior) position of the tongue; and a vertical, rather than horizontal direction of mandibular growth; while in (b) the decrease in NSL'/OPT (= −4.5 degrees) is associated with a raised (antero-superior) position of the tongue; and a horizontal, rather than vertical direction of mandibular growth.

(r_s= 0.373, $P < 0.01$). However, the weakness of the observed association ($R^2 = 0.14$) is almost certainly related to the difficulty in finding a suitable 'stable' reference from which the pharyngeal changes of the tongue could be measured.

As the tongue attempts to bulge into the pharynx, it potentially compromises the orophayngeal airway necessitating a change in cervical or CCP to restore and maintain the pharyngeal airway at this level, as suggested by Opdebeeck *et al.* (1978). Such an association was observed in the current sample but the main postural element of the relationship was the change in cervical inclination rather than cranio-cervical angulation.

Taking both features together—the change in postural height of the tongue leading to potential changes in the patency of the oropharynx and the compensatory alteration in cervico-horizontal inclination and cranio-cervical angulation—provides a plausible mechanism linking the change in tongue posture to the change in CCP. The proposed mechanism is shown diagrammatically in Figure 7.

A possible mechanism linking postural change and growth direction of the mandible

It is known that the mandible is a motor reference for the position of the tongue–hyoid–larynx column (Bosma, 1963) and that the tongue and mandible are posturally linked in normal respiration (Fish, 1962; Cleall, 1972; Lowe, 1981). This link and the associated postural regulation are only lost if both the nasal and oral routes of respiration are eliminated, as in the tracheotomized child (Cleall, 1972; Storey and Kenny, 1989). Thus, the habitual posture of the tongue and the 'rest position' of the mandible generally change together so that postural lowering of the tongue is accompanied by movement of the mandible away from the cranium (Janský and Holík, 1957; Fish, 1962; Hellsing *et al.*, 1986). It also seems probable that postural lowering of the mandible beyond the habitual position will lead to a change in posture of the tongue as hypothesized by Daly *et al.* (1982). Consequently, postural movement of the tongue away from the palate will be accompanied by postural movement of the mandible away from the cranium. If the mandible is maintained in this new postural position then, by growth of the condyle and vertical alveolar development, this new position of the mandible will be made 'permanent' just a few millimetres below the intercuspal position. In this way, the growth direction of the mandible measured at the chin will simply reflect the difference between the original and new postural positions of the chin.

The radiographs used in this study were recorded with the teeth in occlusion and not with the mandible in its postural or 'rest position'. It has not been possible, therefore, to confirm this relationship in the present sample. Nevertheless, from the temporal and anatomical patterning of the correlations and from the known linkage between mandibular and lingual posture, it appears likely that the association between the change in CCP and mandibular growth direction results from a coordinated change in the postures of the mandible and tongue. This coordinated change in posture determines both the direction of subsequent mandibular growth and also triggers a compensatory alteration in CCP probably via the reflex control of the pharyngeal airway at the base of the tongue.

Examples of the association between mandibular growth direction and changes in CCP and tongue posture are shown in Figure 8.

Control of the growth direction and growth magnitude of the maxilla

The hypothetical mechanism linking mandibulo-lingual postural changes with changes in CCP and growth direction of the mandible, also needs to explain the close association between mandibular and maxillary growth directions ($r = 0.624$, $P < 0.0001$) and growth magnitudes ($r = 0.626$, $P < 0.0001$) found in this study. Whether this apparently close growth linkage could be provided by postural changes in the mandible (altering the freeway space) and the accompanying changes in tongue posture (altering the contact between the tongue and the anterior palate) is uncertain. However, if the proposed mechanism is correct, then the significant correlation between the growth magnitudes of the two jaws, and not just their directions of growth, may indicate that the antero-posterior jaw relationship is under a degree of environmental control, and this has important clinical implications.

'Total facial rotation' and growth direction of the PCB

One of the more unexpected findings of the present study was the existence of a rotational pattern of facial growth accompanying changes in CCP. This pattern of facial growth was originally reported in a cross-sectional study comparing short and long-face syndromes by Opdebeeck *et al.* (1978). The present longitudinal study confirms the existence of this rotational arrangement as a true longitudinal pattern of growth involving the displacement of the cervical spine and soft tissues of the pharynx and tongue as well as growth changes in the jaws and PCB. It also demonstrates that these rotational patterns occur in growing children with relatively normal facial proportions and not just in those at the extremes of the range of face height, as can be seen in Figure 5.

This rotational pattern of growth in the cranial base and facial bones should not, however, be seen as a classical growth rotation in which a 'stable' core of bone rotates during growth, as documented by Björk (1955). Although some of the rotational pattern is probably related to 'true' growth rotation of the mandible and maxilla, much of the rotational pattern appears to be displacement of the facial bones and adjustments of moveable articulations (in the cervical spine).

Interestingly, the difference in the growth direction at basion between the two extremes of cranio-cervical postural change indicates that the caudal end of the PCB follows the general growth direction of the posterior maxilla (pm) but with a much lower magnitude of growth. This seems to indicate that where CCP continues to increase, two morphological features may ultimately develop: the cranial base will become flatter, as is often seen in subjects with high mandibular plane inclination and 'long-faces' and the depth of the bony pharynx (ba-pm) will reduce, perhaps hindering nasal respiration in cases of otherwise mild nasopharyngeal obstruction.

The nature of the present study does not allow insight into the causes of the differences in growth direction at basion. Nevertheless, it is unlikely to be a direct effect of the change in posture of the mandible and tongue. It could possibly be due to the postural relationship between the upper cervical spine and the basilar part of the occipital bone, but it remains for future studies to clarify this point.

Conclusions

This study has revealed a series of associations between the change in CCP and the direction of the accompanying growth of the skeletal components of the face and cranial base and changes in the postural height of the tongue.

Analysis of the patterning of these associations and the inter-relationships between the main growth features linked to the change in posture indicate several points of correspondence with the known functional relationships between the mandible, pharynx, and tongue. These findings suggest that the association between the change in posture and growth direction of the face most likely arises from the coordinated postural behaviour of the mandible and tongue which determines the growth direction of the mandible and, at the same time, influences cranio-cervical angulation, probably via the reflex control of the pharyngeal airway at the base of the tongue.

Supplementary material

Tables 2 and 3 can be accessed as supplementary data at European Journal of Orthodontics online.

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