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Scientific Section

Finite Element Analysis of the Cranial Base in Subjects with Class III Malocclusion

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Abstract. *The association between cranial base morphology and Class III malocclusion is poorly understood. This study analyses local shape – and size differences in cranial base configurations of Class I and Class III subjects, employing finite element (FEM) analysis. Seventy-three prepubertal European-American children with Class III malocclusion were compared to their counterparts with a normal, Class I molar occlusion. Lateral cephalographs were traced, checked and subdivided into age- and sex-matched groups. Thirteen points on the cranial base were identified and digitized, providing a geometrical cranial base representation. Average cranial geometries were scaled to an equivalent size and a FEM analysis, capable of depicting and quantifying local shape- and size-change, employed to highlight regionalized, morphological differences. While the anterior cranial base was more homogeneous for shape-change, significant, localized anisotropy in the posterior regions of the cranial base and around sella turcica was evident. For size-change, areas of negative allometry were located posteriorly, but dilations in the mid- and anterior cranial base also were apparent. It is concluded that morphological alterations within the petro-occipital complex accompanied by changes in the sphenoidal and ethmoidal regions induce deviation from a normal cranial base configuration to one associated with deficient orthocephalization and an appearance of Class III malocclusion.*

Index words: Class III, Cranial Base, Finite Element, Morphometry, Orthocephalization.

Refereed Paper

Introduction

The morphology of the cranial base is a major factor in establishing the antero-posterior relationship of the upper and lower jaws (Hopkin *et al.*, 1968). Most traditional orthodontic cephalometric studies measure the relationship of the maxilla and mandible to the cranial base, and to each other, but little emphasis has been place on the morphological characteristics of the cranial base itself in Class III malocclusion. In the examination of the aetiology of Class III malocclusion, Battagel (1993) was unable to demonstrate significant differences in cranial base parameters between normal and Class III subjects using tensor analysis. Indeed, Battagel (1994) suggests that Class III malocclusions do not form a single, homogeneous group, and the relationship between the morphology of the cranial base and Class III malocclusion remains tentative.

Class III malocclusion is characterized by several developmental, craniofacial features such as an acute mandibular plane angle, obtuse gonial angle, overdeveloped mandible/underdeveloped maxilla, and a small cranial base angle (Jacobson *et al.*, 1974; Ellis and McNamara, 1984; Sato, 1994). Despite such assertions, Williams and Andersen (1986) suggest that no single morphological trait indicative of potential Class III development can be isolated because of the skeletal heterogeneity of this group of malocclusions. Therefore, although these studies provide useful morphological information, they attempt to characterise global changes in the craniofacial region, rather than regional changes within the cranial base and its relationship with Class III development. Consequently, the number of cranial base landmarks selected often are limited and, as a result of this, differential grown features may not have been captured. Therefore, morphometric analysis utilizing a larger complement of landmarks may provide more precise information regarding the role of the cranial base in the aetiology of Class III malocclusion.

Finite element morphometry (FEM) is one technique that describes morphological alterations with respect to anatomical landmarks (Cheverud *et al.*, 1983; Cheverud and Richtsmeier, 1986; Lozanoff and Diewert, 1986, 1989; Moss *et al.*, 1987; McAlarney *et al.*, 1992; Lozanoff *et al.* 1994; Sameshima and Melnick, 1994). Using this technique,

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change in morphology is viewed as a deformation of an initial geometric configuration, whose boundaries are formed by edges that connect anatomical landmarks, into a final form. Deformation of the initial geometry is depicted graphically as a set of principal tensors (perpendicular stretch/strain extensions defining the degree of deformation) within the initial geometric configuration (reviewed by Richtsmeier *et al.*, 1992). Tensor analysis has been employed previously in studies of cranial base anomalies (e.g. Grayson *et al.*, 1985), as this method allows visualization of the magnitude and direction of the principal tensors (Battagel, 1995). However, while tensor biometrics only determines size- and shape-change at specific landmarks, FEM provides information on deformation within the geometrical configuration and between the defining anatomical landmarks (Cheverud *et al.*, 1983; Lozanoff and Diewert, 1986; Lozanoff *et al.*, 1994).

Although concerns have been expressed regarding FEM (Read and Lestrel, 1986; Bookstein, 1987, 1991), this technique has been applied to numerous problems in craniofacial growth and has contributed much, significant, biological information (Richtsmeier and Lele, 1990; Richtsmeier and Lele, 1990; Richtsmeier *et al.*, 1991, 1993; Diewert *et al.*, 1991; Kohn *et al.*, 1994; Ma and Lozanoff, 1996). Size and shape variables generated with FEM also have been shown to accurately reflect biologically relevant, craniofacial growth data in experimental animal models. For example, Lozanoff and Diewert (1986) showed in an experimental rat sample that principal tensors derived from FEM depict drug-induced craniofacial growth alterations in a predictable fashion. As well, cell growth activities in the murine cranial base correspond to principal extensions in an experimental sample of young postnatal mice (Lozanoff *et al.*, 1993). Therefore, FEM of geometrical configurations of the cranial base in subjects with Class III malocclusion is warranted. This paper aims to provide evidence for the theory that deficient orthocephalization, i.e. failure of sufficient horizontalization in cranial base angulation, is a factor associated with the development of Class III malocclusion. The purpose of this analysis is to test the hypothesis that principal dilations in the cranial base occur using FEM when Class I subjects are compared to Class III subjects with a retrognathic midfacial profile. Differential morphogenesis is implied if this hypothesis is not rejected, and the resultant FEM maps would suggest areas with divergent growth activities leading to further experimental analyses using animal models of Class III malocclusion (Lozanoff *et al.*, 1994). Therefore, application of this methodology in the analysis of cranial base morphology may lead to a more clear understanding of the underlying skeletal mechanisms, such as premature synostosis, responsible for final craniofacial form.

Materials and Methods

Seventy-three lateral cephalographs were selected on the basis of Class III molar occlusion from children of European-American descent aged between 5–11 years (Guyer *et al.*, 1986), consisting of approximately 10 subjects per age group. A further 69 cephalographs of untreated subjects with a normal, Class I molar occlusion also were selected (approximately 10 subjects per age group). The chronological age was assumed to match developmental age in this study as carpal radiographs were unavailable. All cephalographs included in the study sample had a negative history of airway problems and no obvious vertical skeletal problems. Deployment of approximately equal numbers of male and female patients permitted the construction of seven age- and sex-matched groups. The magnification of each cephalograph was standardized to 8 per cent. It was presumed that all radiographs were taken from patients exhibiting left-right symmetry and that the central X-ray passed along the transmeatal axis while the teeth were in occlusion. Each cephalograph was traced on frosted acetate film (0·03″ thick) and checked by one investigator (GDS). Thirteen points on the cranial base and midface were identified and digitized (Fig. 1A), employing appropriate software and a digitizing tablet (Numonics Inc., Montgomeryville, PA). The cranial geometry derived from cephalographs of Class III subjects showing the configuration composed of the landmarks used in this study is shown in Fig. 1B. The rationale of selection was that preference was given to landmarks that encompass cranial developmental sites and were located in the mid-sagittal plane where possible (Varjanne and Koski, 1982; Bhatia and Leighton, 1994). Any landmarks that showed a discrepancy of >1 per cent on duplicate digitisation were deemed to be identified unreliably and were excluded from the final analyses.

Average cranial base configurations of Class I subjects were compared to Class III subjects in an age-wise fashion, therefore, seven comparisons were generated for shape- and size-change, respectively. Morphological differences in the cranial base between both subject groups have been briefly described using conventional cephalometric analyses (Guyer *et al.*, 1986; Singh *et al.*, 1997a). All cranial base configurations employed were determined to be significantly different from one another based upon statistical and multivariate analyses (Singh *et al.*, 1997a). The average cranial base configurations were compared using a FEM routine (Lozanoff & Diewert, 1989) that incorporated a spline function algorithm (Bookstein, 1991; Singh *et al.*, 1997b) for interpolating points internal to the anatomical landmark co-ordinates. Therefore, geometrical decomposition (element discretisation) was undertaken on four-noded elements, using 2000 elements per geometry. The software was written in 'C' and implemented on an Amiga 3000. The Class I cranial base configuration was taken as the initial geometry and this was compared to the Class III mean, providing the final geometry for each age grouping. Size-change variables were computed as the product of the principal tensors, while shape-change measures were calculated as the ratio of the greater divided by the lesser principal extension (Lozanoff and Diewert, 1986). Values were computed for at least 2000 points per geometry for graphical display, and although each point within the configuration could be determined, only values at homologous landmarks were tabulated. A log-linear interpolation of the size- and shape-values were used to generate a colour map. These morphologic change measures were then colour-mapped into each Class I cranial base configuration to provide graphical displays of geometrical change for each age-wise comparison. These

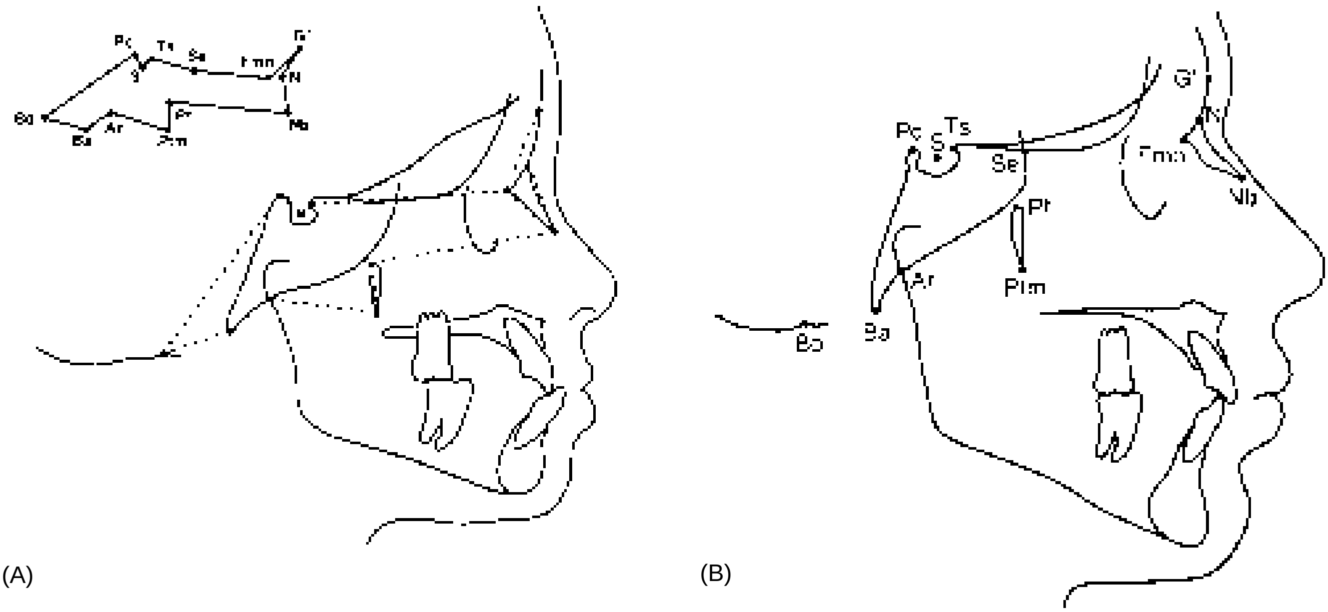


FIG. 1 (A) Tracing derived from cephalograph of Class I subject, showing the position of the thirteen landmarks used to define the cranial base in this study. (B) Cranial geometry derived from cephalograph of Class III subject, showing the configuration derived from the 13 landmarks used in this study. Definitions of cranial landmarks and variables employed

Ar	Articulare (intersection of the condyle and the posterior cranial base)
Ba	Basion (lowest point on the anterior border of foramen magnum)
Bo	Bolton point (highest point behind the occipital condyle)
Fnm	Frontonasomaxillary suture
Gl	Glabella (most prominent point on the frontal bone)
Pc	Posterior clinoid process (most superior point)
N	Nasion (most anterior point on frontonasal suture)
Nb	Tip of nasal bone
Pt	Rickett's point (postero-superior point on outline of pterygomaxillary fissure)
Ptm	Pterygo-maxillare (most inferior point on outline of pterygomaxillary fissure)
S	Sella (centre of sella turcica)
Se	Sphenoidale (intersection of the greater wings of the sphenoid and the anterior cranial base).
Ts	Tuberculum sellae (most anterior point of sella turcica).

Cranial linear variables	Cranial angular variables
S–N	N–S–Ba
S–Ba	N–S–Ar
N–Se	N–Se–S
S–Se	N–Pc–Bo
Pc–Bo	Gl–N–Nb

plots were inspected visually to determine those regions exhibiting changes in morphology.

Results

Graphic displays of average cranial base configurations of Class I and Class III subjects were generated using the FEM routine. The size- and shape-changes were viewed as colour maps. These colour changes were examined to determine localized changes in morphology. Conventional cephalometric analyses have previously provided quantitative information with statistical verification (e.g. Guyer *et al.*, 1986; Singh *et al.*, 1997a), and although the results reported in this study are qualitative in nature, our findings compare favourably with those obtained using traditional cephalometrics.

Comparing the Class I and Class III cranial base configurations in the 5-year-old group, the shape-change is characterized by a high degree of anisotropy (i.e. non-homogeneous shape-change) in the posterior region of the cranial base. Therefore, the shape-change detected has directionality (observed to be predominantly in the horizontal plane in this particular region). Generally, anisotropy was highest in the region of the Bolton point (85 per cent: Table 1) and decreased in the postero-anterior axis (Figure 2A). For the body of the sphenoid and anterior cranial base regions, less anisotropy (i.e. shape-change more homogeneous in all directions) is evident. Therefore, the 5-year-old group Class III cranial base is

TABLE 1 *Shape changes derived from products of principal extensions at homologous landmarks of normal and Class III cranial base morphologies*

Age	Bo	Ba	Pc	S	Ts	Se	Fnm	N	Gl	Nb	Ptm	Pt	Ar
05	1·847	1·291	1·378	1·382	1·324	1·025	1·067	1·015	1·047	1·054	1·102	1·019	1·012
06	1·509	1·056	1·142	1·133	1·078	1·161	1·013	1·150	1·078	1·100	1·021	1·043	1·031
07	1·678	1·172	1·222	1·217	1·158	1·028	1·119	1·053	1·095	1·115	1·224	1·119	1·042
08	2·304	1·520	1·198	1·062	1·085	1·048	1·154	1·117	1·040	1·060	1·055	1·044	1·214
09	1·494	1·195	1·102	1·155	1·093	1·061	1·126	1·184	1·065	1·105	1·072	1·003	1·075
10	1·554	1·195	1·062	1·052	1·080	1·071	1·188	1·183	1·206	1·082	1·175	1·103	1·046
11	1·531	1·106	1·115	1·127	1·101	1·016	1·213	1·286	1·319	1·071	1·216	1·124	1·006

TABLE 2 *Size changes derived from ratios of principal extensions at homologous landmarks of normal and Class III cranial base morphologies*

Age	Bo	Ba	Pc	S	Ts	Se	Fnm	N	Gl	Nb	Ptm	Pt	Ar
05	0·492	0·654	1·227	1·247	1·314	1·139	1·260	1·246	1·071	1·057	1·061	1·170	0·945
06	0·605	0·884	0·892	1·076	1·075	1·083	1·898	1·492	1·142	1·307	0·977	0·990	0·985
07	0·555	0·803	0·959	1·097	1·082	1·011	1·357	1·265	1·019	1·045	0·936	0·961	0·995
08	0·592	0·940	1·146	1·230	1·232	1·157	1·092	1·101	1·041	1·027	1·064	1·075	1·070
09	0·648	0·749	1·065	1·129	1·136	1·170	1·543	1·395	1·019	1·198	1·010	1·052	0·978
10	0·578	0·767	1·117	1·306	1·339	1·122	1·050	1·013	0·737	0·941	1·012	1·127	0·957
11	0·606	0·791	1·063	1·170	1·101	1·136	1·254	1·358	1·253	0·991	0·944	1·082	0·907

attained, at least in part, by variation in the direction of shape-change, particularly in the posterior regions of the cranial base.

Comparing the Class I and Class III cranial base configurations in the 5-year-old group for size-change, the body of the sphenoid and the frontonosomaxillary region exhibit positive allometry (i.e. they show a relative increase in size related to change in shape). Therefore, the attainment of a Class III cranial base configuration is associated with a relative increase in size anteriorly in the 5-year-old group. The intervening regions, however, have values that hover around the 1.0 level, indicating isometry (i.e. no differences in size related to change in shape) when comparing the Class I and Class III cranial base configurations in the 5-year-old group. In contrast, the posterior cranial base has a gradient of negative allometry (i.e. it shows a relative decrease in size related to shape-change) in the antero-posterior axis. The negative allometry is highest at the region of the Bolton point (51 per cent: Table 2), decreasing between basion and articulare (Figure 3A). Therefore, the posterior-most region of the cranial base configuration in the 5-year-old Class III subjects is some 50% smaller in relative size compared to the Class I subjects at this particular location.

For the 6-year-old group, the posterior cranial base is the most anisotropic (Bolton point: 51 per cent; Table 1) with a decreasing gradient through the posterior cranial base up to dorsum sellae, similar to the 5-year-old group (Fig. 2B). However, whereas the sphenoidal region is less anisotropic, the anterior cranial base expresses more heterogeneity in shape-change, except in the frontomaxillary suture region. For size changes, negative allometry is evident in the posterior cranial base (Bolton point: 61 per cent; Table 2), but a gradient in the body of the sphenoid and anterior cranial base is not evident (Fig. 3B). In contrast, there is minor, relative increase in the region of the sphenoidal air sinus, but the frontonasal region shows a strong positive allometry with its epicentre located at the frontonasomaxillary suture (90 per cent; Table 2).

For the 7-year-old group, the posterior cranial base is the most anisotropic (Bolton point: 68 per cent; Table 1) with a gradient through to the clivus, similar to the 5- and 6-year-old groups (Fig. 2C). However, while the sphenoidal complex is moderately anisotropic, the anterior cranial base shows little heterogeneity in shape-change, except for the vicinity of the frontomaxillary suture. For size changes, negative allometry is evident in the posterior cranial base (Bolton point: 45 per cent; Table 2). There is, however, a relative increase in the region of the sphenoidal air sinus (Fig. 3C), and the anterior-most region of the cranial base shows positive allometry (36 per cent at the frontonasomaxillary suture; Table 2) with some negative allometry evident in the intervening areas.

For the 8-year-old group, the posterior cranial base is the most anisotropic of all the age groups tested. However, the gradient of anisotropy traverses further through the clivus than the 5–7 year-olds, ending between articulare and the sphenoidal region (Fig. 2D). The mid- and anterior cranial base show few changes. For size changes, negative allometry is apparent for the extreme posterior cranial base (40 per cent at Bolton point; Table 2), quickly diminishing by the dorsum sellae (Fig. 3D). In contrast, there is a positive allometry in the body of the sphenoidal region, but the anterior cranial base is more isometric.

For the 9-year-old group, the posterior cranial base is the most anisotropic (49 per cent at Bolton point; Table 1). The gradient traverses further through the clivus, similar to the 8-year-old group (Fig. 2E). However, the mid- and anterior cranial base also demonstrate some minor anisotropy. For size changes, negative allometry is evident for the posterior cranial base (35 per cent at Bolton point; Table 2) with a gradient through to the body of the sphenoid (Fig. 3E). In contrast to a relative increase in the sphenoidal region, the anterior cranial base is more positively allometric with its epicentre located at the frontonasomaxillary suture (54 per cent; Table 2).

For the 10-year-old group, the posterior cranial base is the most anisotropic (55 per cent at Bolton point; Table 1)

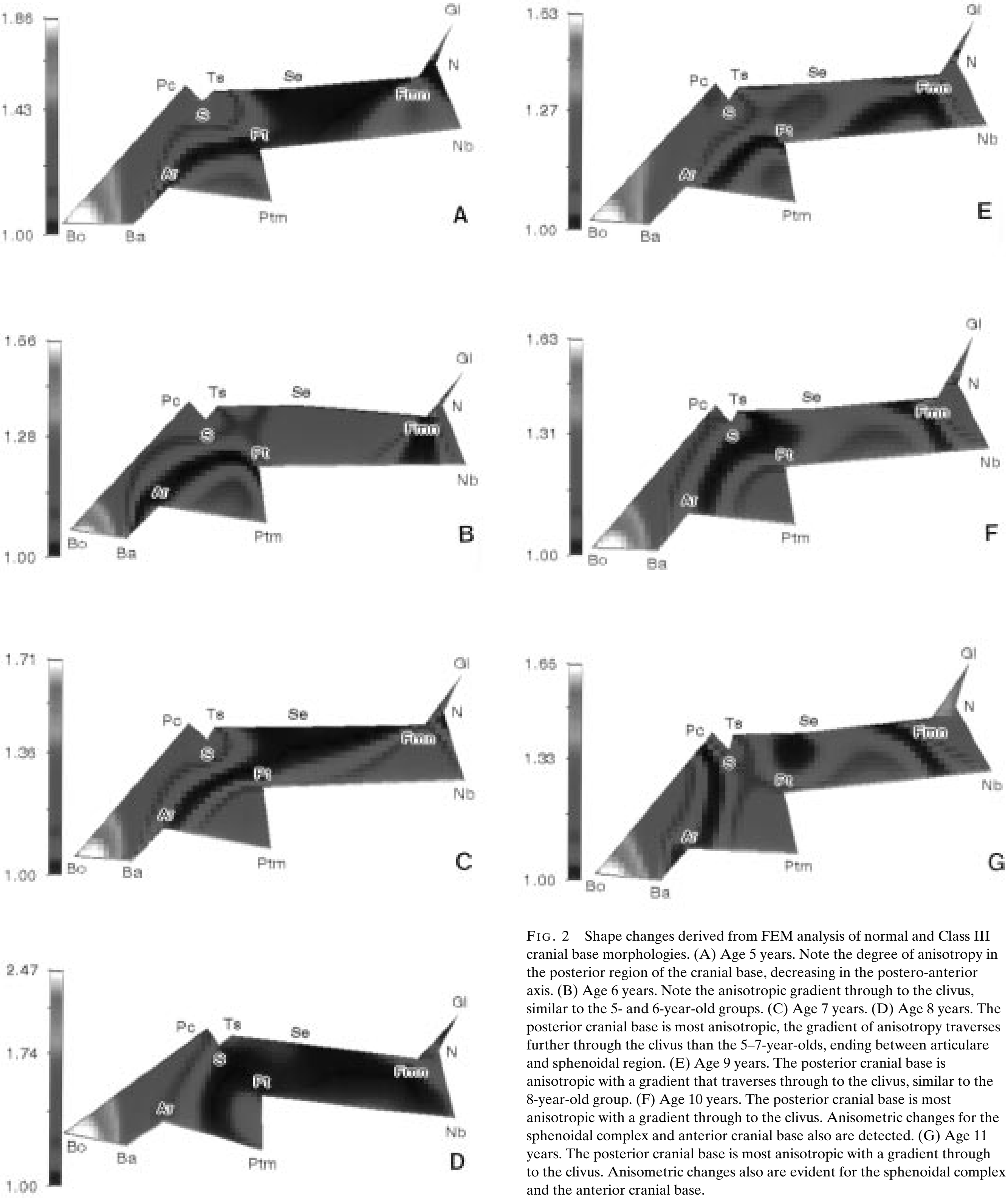
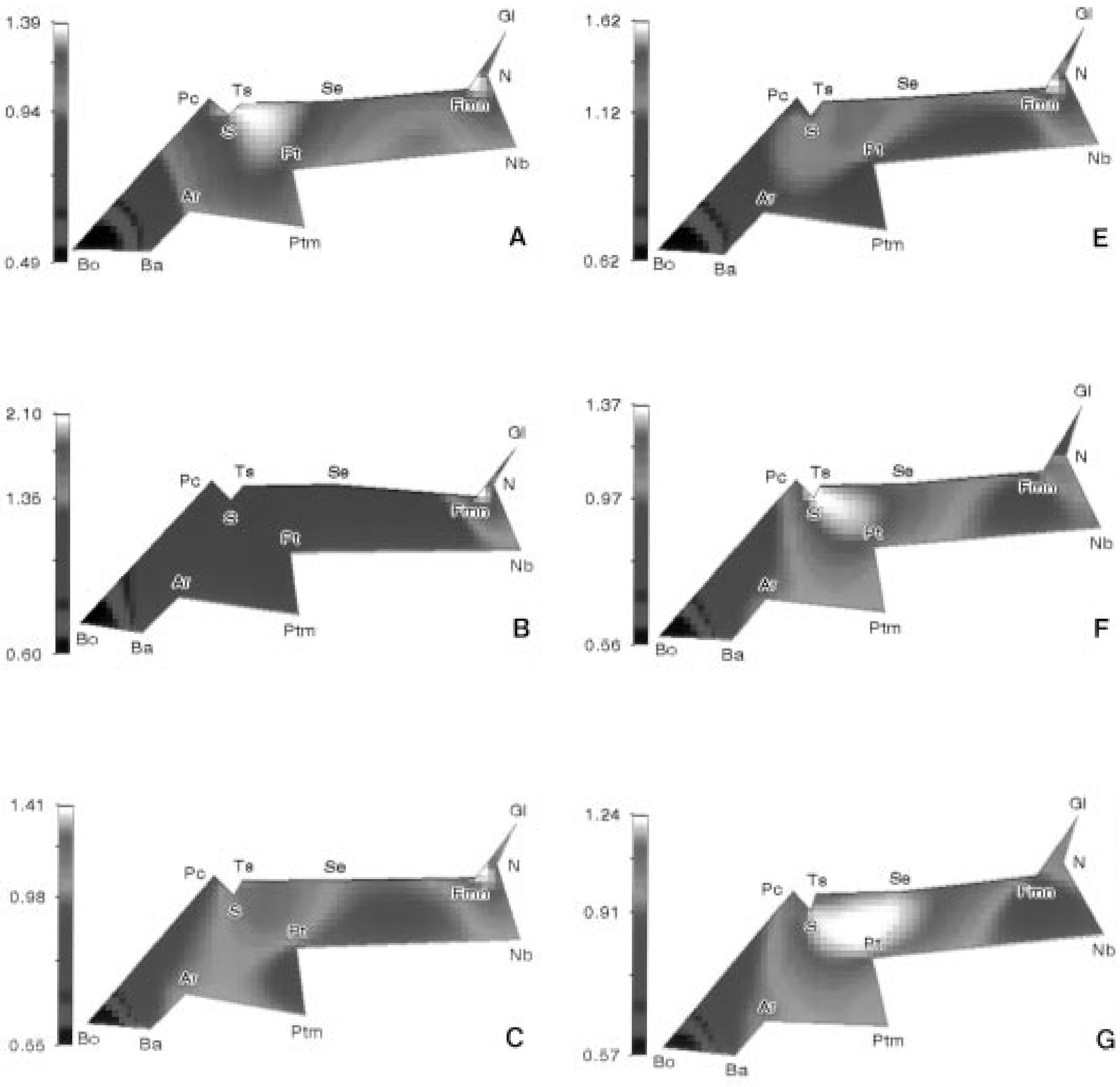


FIG. 2 Shape changes derived from FEM analysis of normal and Class III cranial base morphologies. (A) Age 5 years. Note the degree of anisotropy in the posterior region of the cranial base, decreasing in the postero-anterior axis. (B) Age 6 years. Note the anisotropic gradient through to the clivus, similar to the 5- and 6-year-old groups. (C) Age 7 years. (D) Age 8 years. The posterior cranial base is most anisotropic, the gradient of anisotropy traverses further through the clivus than the 5–7-year-olds, ending between articulare and sphenoidal region. (E) Age 9 years. The posterior cranial base is anisotropic with a gradient that traverses through to the clivus, similar to the 8-year-old group. (F) Age 10 years. The posterior cranial base is most anisotropic with a gradient through to the clivus. Anisometric changes for the sphenoidal complex and anterior cranial base also are detected. (G) Age 11 years. The posterior cranial base is most anisotropic with a gradient through to the clivus. Anisometric changes also are evident for the sphenoidal complex and the anterior cranial base.

with a gradient through to the clivus (Fig. 2F). Some anisometric changes for the sphenoidal complex are also detected (18 per cent at Ptm; Table 1). The anterior cranial base also demonstrates anisometry; 19 per cent at Fnm and 21 per cent at glabella (Table 1). For size changes, negative allometry is evident for the posterior cranial base (42 per cent at Bolton point; Table 2) with a gradient of relative increase through the body of the sphenoid (Fig. 3F) where there is a more positive allometry (31 per cent at sella; Table 2). The anterior cranial base is more isometric, but



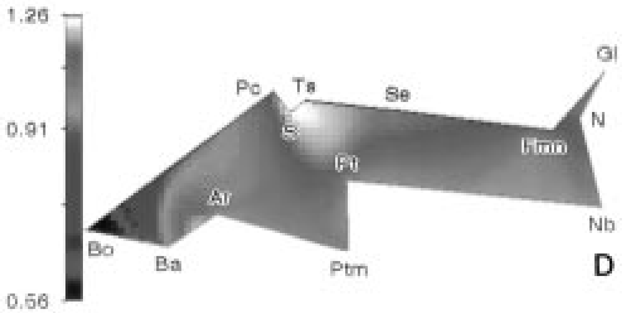


FIG. 3 Size changes derived from FEM analysis of normal and Class III cranial base morphologies. (A) Age 5 years. Note gradient of negative allometry in the antero-posterior plane, decreasing between basion and articulare. (B) Age 6 years. Note the negative allometry in the posterior cranial base. (C) Age 7 years. Note negative allometry is evident in the posterior cranial region. There is a relative increase in the region of the sphenoidal air sinus, and the anterior-most region of the cranial base shows positive allometry. (D) Age 8 years. Negative allometry is apparent in the extreme posterior cranial region, but diminishing towards the dorsum sellae. (E) Age 9 years. Negative allometry is evident for the posterior cranial with a gradient through to the body of the sphenoid. (F) Age 10 years. Negative allometry is evident for the posterior cranial base with a gradient of relative increase through to the body of the sphenoid. The anterior cranial base is more isometric, but shows some negative allometry. (G) Age 11 years. Negative allometry is evident for the posterior cranial base with a gradient through to the sphenoidal region. Note the positive allometry located in the body of the sphenoid.

also shows some negative allometry in the region of the frontomaxillary suture.

For the 11-year-old group, the posterior cranial base is the most anisotropic (53 per cent at Bolton point; Table 1) with a gradient through to the clivus (Fig. 2G). Some anisometric changes also are evident for the sphenoidal complex (22 per cent for the pterygoid plates; Table 1). The anterior cranial base also is anisometric; 29 per cent at nasion and 32 per cent at glabella (Table 1). For size changes, negative allometry is evident for the posterior cranial base (40 per cent at Bolton point; Table 2) with a gradient through to the sphenoidal region (Fig. 3G). In contrast to a positive allometry detected with its epicentre located in the body of the sphenoid, there is a relative decrease in size in the frontomaxillary suture region.

In overall terms, anisometry was most pronounced in the posterior-most region of the cranial base (i.e. non-homogeneous shape-change, producing changes in morphology in this region) with the anterior- and mid-cranial regions exhibiting moderate to low levels of shape-change, respectively. For size-change, negative allometry was evident in the posterior-most region of the cranial base (i.e. decrease in size that produces changes in morphology in this region). However, the mid-cranial regions exhibited moderate levels of positive allometry (i.e. increase in size that produces changes in morphology), particularly in the vicinity of the body of the sphenoid, with similar magnitudes of size-change in the anterior region of the cranial base.

Discussion

Due to intrinsic constraints of conventional cephalometrics, newer and more appropriate methods of craniofacial growth analysis are desirable (Moyers and Bookstein, 1979; Moss *et al.*, 1986 a,b; Battagel, 1993, 1994, 1995). FEM represents one technique, among others, useful for the analysis of anatomical changes resulting from growth (Rohlf and Marcus, 1993). However, traditional cephalometrics can still provide clinically-useful, quantitative information. Therefore, statistical analyses of cephalometric parameters (Guyer *et al.*, 1986), and corroborative multivariate techniques (Singh *et al.*, 1997a), was performed to show that the cranial landmark configurations of Class I subjects employed in this study were significantly different from the Class III geometries for all age groups tested (Table 3). Specifically, these conventional analyses showed that linear and angular measures involving basion and Bolton point contributed significantly to the differences between Class I and Class III geometries (Guyer *et al.*, 1986; Singh *et al.*, 1997a). Therefore, the maps of changes in morphology between Class I and Class III cranial base geometries generated in this FEM analysis are in agreement with the descriptions of anatomical change depicted by statistical analyses alone. However, the FEM analysis provides greater resolution, enabling graphic and numerical information to be more easily visualized and interpreted.

In this study, we compared Class I and Class III cranial base configurations. For all age groups studied, the posterior cranial base was the most anisotropic, showing a spectrum of colour representing a decreasing gradient in the magnitude of shape-change through to the clivus. Invariably, Bolton point was the most affected landmark in the antero-posterior axis. Significantly, these large anisotropic changes always were associated with spatial diminution in this region in the Class III subject. Hoyte (1991) provides support for the contention that developmental mechanisms occur in the petro-occipital complex to account for such changes in the age range studied, specifically elongation of the posterior cranial fossa. However, the non-homogeneous nature of anatomical structures in the vicinity of the foramen magnum could preclude this conclusion as the foramen magnum has achieved most of its length by 5 years of age (Hoyte, 1991). Alternatively, the outcome of this morphogenetic patterning accords with the hypothesis of Ellis and McNamara (1984) that a decreased angulation between the anterior and posterior cranial base (i.e. alteration of saddle angle) invariably is a feature of the Class III cranial base. The resulting prognathic face, characterized by shortening and angular bending of the cranial base, and a diminished angle between the cranial base and mandibular ramus (Ellis and McNamara, 1984), provides an indication of apparent cranial kyphosis associated with the appearance of a Class III facial morphology.

In contrast to the findings for the posterior-most components of the occipito-sphenoidal complex, the body of the sphenoid behaved differently. In nearly all age groups studied, the directionality of shape changes was more isotropic. Moreover, the body of the sphenoid increased in size in a region enclosing the sphenoidal air sinuses. Dolan (1982) suggests that pneumatization of the sinuses continues until the age of 12 years, when they reach nearly adult size. This radiographic contention, although

TABLE 3 *The* F *values derived from Procrustes analysis indicate statistical differences at all ages groups, except age 7 which marginally failed. Hotelling's* T^2 *indicates statistical differences for either Linear or Angular parameters, if not both, at most age groups*

Age	Procrustes		Hotelling's T^2			
		Significance (*P*)	Linear	Significance (*P*)	Angular	Significance (*P*)
05	4·512	<0·05	88·15	<0·05	42·46	<0·05
06	1·756	<0·05	21·06	N.S.	31·06	<0·05
07	1·432	N.S.	32·36	<0·05	5·64	N.S.
08	3·353	<0·05	96·89	<0·05	206·04	<0·05
09	3·795	<0·05	46·34	<0·05	28·67	<0·05
10	1·482	<0·05	21·75	<0·05	8·91	N.S.
11	1·870	<0·05	10·71	N.S.	30·09	<0·05

not specific to the sphenoidal air sinus alone, generally accords with the phenomenon that we have observed using an entirely different approach. However, our findings indicate that the Class I sphenoidal body is smaller than that of the Class III. Dolan (1982) affirms the morphological reports of Latham (1972), that the mid-sagittal length of the body of the sphenoid increases in the antero-posterior axis. We suggest that this tendency appears to be more extensive for the Class III individual. However, while Hoyte (1991) attributes this phenomenon to the spheno-occipital synchondrosis, augmentation of growth by concomitant pneumatization also is likely. Hoyte (1975) also reported that, in addition to an antero-posterior sequence of basicranial maturation, the hypophyseal fossa drifts caudally up to 14 years of age. We found that sella turcica behaved in an intermediate fashion when compared to the posterior- and anterior-most regions of the sphenoidal complex. Therefore, although expansion of the sphenoidal body influences the final position of contiguous structures such as sella turcica and the anterior cranial base, the relatively small magnitude of these changes appears to be unable to compensate for the larger scale of change in the posterior-most regions of the cranial base associated with the Class III morphology.

Our findings also indicate that the final form of the anterior cranial base is modulated by changes at the frontonasomaxillary suture. For the earlier ages groups, an increase in spatial size was evident, but isometry and relative decrease were more noticeable for the older age groups. Melsen (1974) reports that growth at the spheno-ethmoidal and spheno-frontal sutures ceases at seven years of age, but that continued growth of the anterior cranial base still is necessary. While some early studies suggest that increase in thickness in the region of nasion is accounted for by enlargement of the frontal air sinus (Björk, 1955; Scott, 1958), we contend that elongation of the anterior cranial base is also augmented by spatial increases at the frontonasomaxillary suture, particularly up to age nine years. Our conclusion is similar to that of Hoyte (1975) who found that virtually all sagittal increase of the anterior cranial base, except increasing frontal bone thickness, is completed by seven years of age. It also is likely that growth processes at frontonasomaxillary suture affect the position of the maxilla. Björk and Skieller (1976) noted variability in the direction of maxillary growth, while Melsen and Melsen (1982) reported significant activity in the pterygomaxillary suture. We found that anisometric changes were evident only for the pterygoid plates of the sphenoidal complex at age 11 years. Therefore, it appears that the Class III cranial base emerges from a combination of spatial diminution at the frontonasomaxillary region allied with uniformity of the pterygo-maxillary complex. Taken together, these findings could be responsible for the characteristic maxillary position and alignment observed in Class III malocclusion.

It has been reported that postnatal changes in shape of the craniofacial skeleton include an increased cranial base angle (Moss & Greenberg, 1955; Melsen & Melsen, 1980), although this may be insignificant in the first postnatal year (Brodie, 1955; Knott, 1971; Riolo *et al.*, 1974). For Class III malocclusion, cephalometric studies suggest that the decreased angulation between the anterior and posterior cranial bases (i.e. alteration of saddle angle) displaces the temporomandibular joint forwards, resulting in a prognathic facial profile (Moss 1955; Hopkin, 1961; James, 1963; Houston, 1967; Ellis & McNamara, 1984). Our morphometric studies indicate that the biological basis for the anterior displacement of the mandible lies within the posterior cranial base, presumably coinciding with early cessation of growth activities within the petro-spheno-occipital complex. That premature synostosis is responsible for deficient orthocephalisation i.e. insufficient horizontalization of the cranial base angle, in Class III malocclusion remains a distinct possibility, and it is likely that the consequent shortening of the posterior cranial base (Björk, 1955; Hoyte, 1991) may be a primary factor in the aetiology of Class III malocclusion based on these analyses.

Although the relationship of the cranial base to the maxillo-mandibular complex is of particular interest, we did not include either mandibular or maxillary morphometry in this particular study, and since developmental compensation remains a possibility, this analysis is under current investigation. Similarly, the changes between adjacent age groups in Class I and Class III populations would provide information on the growth pattern of the cranial base, and this comparison is planned as a future study. It should be noted that FEM, as with any other morphometric technique, attempts to numerically characterise biological phenomena. It can be used only to generate hypotheses regarding underlying developmental mechanisms, but these hypotheses must be tested experimentally. Results from this morphometric analysis suggest that midfacial retrusion is due, in part, to growth deficiencies in the posterior-most region of the cranial base or precocious maturation of the normal antero-posterior sequence of basicranial development associated with deficient orthocephalisation. Similar morphological changes in the cranial base were identified in the Brachyrrhine (Br) mouse mutant, which displays severe midfacial retrognathia (Lozanoff, 1993; Lozanoff *et al.*, 1994; Ma and Lozanoff, 1996). Therefore, future work will also employ the Br model in order to determine the cellular and molecular deficiencies within the cranial base.

Conclusions

1. FEM analysis is capable of depicting and quantifying local shape- and size-changes that highlight regionalized, morphological differences between Class I and Class III cranial base configurations.
2. Comparing Class I and Class III cranial base configurations using FEM for shape-change, the anterior base appears to be less heterogeneic, while sella turcica and the posterior cranial base show significant, localized anisotropy.
3. Comparing Class I and Class III cranial base configurations using FEM for size-change, dilations within the anterior cranial base and sella turcica are apparent while areas of negative allometry are located within the posterior cranial base.
4. The morphological alterations within the petro-occipital complex accompanied by changes in the sphenoidal and ethmoidal regions induce deviation from a normal cranial base configuration to one associated with deficient orthocephalization and the appearance of Class III malocclusion.

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