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Midfacial morphology of Koreans with Class III malocclusions investigated with finite-element scaling analysis

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Abstract: The spheno-ethmoidal model of midfacial retrognathia suggests that deficient chondrocytic proliferation in the anterior cranial base is associated with inadequate anterior translation of the midfacial complex resulting, for example, in Class III malocclusions. The purpose of this study was to determine whether the morphology of the midface differed in subjects of diverse ethnic origin exhibiting features associated with Class III malocclusions. Lateral cephalographs of 142 children of Korean or European–American descent aged between 5 and 11 years were compared. The cephalographs were traced and subdivided into seven age- and sex-matched groups. Average geometries, scaled to an equivalent size, were generated using Procrustes superimposition and subjected to analysis of variance (ANOVA). Graphical analysis using a color-coded finite-element scaling analysis (FESA) program was used to localize differences in morphology. Results indicated that the mean Korean and European–American midfacial configurations differed statistically ($P < 0.01$), and this difference was maintained at most, but not all, age-wise comparisons. Comparing Korean and European–American Class III midfacial configurations for local size-change, FESA analysis revealed that while local increases in size were apparent in the posterior palatal regions, the Korean anterior nasal spine regions were generally smaller. For shape-change, the Korean and European–American midfacial configurations were predominantly isotropic. Therefore, heterogeneity in appearance may be influenced by morphological variation of the midfacial complex in subjects of diverse ethnic origin, but features of the anterior cranial base may contribute also to the prevalence and severity of Class III malocclusions in Koreans. Moreover, perturbations in endochondral mechanisms of cranio-mandibular growth, and not maxillary intramembranous methods, may be implicated in the etiology of Class III malocclusions in South East Asians.

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Introduction

The number of individuals seeking orthodontic treatment in South Korea is increasing [Yang, 1995]. Yang [1990], 1995] reported that about half of the patients presenting for orthodontic treatments at Seoul National University Hospital exhibited Class III malocclusions; however, other studies report a lower prevalence of ≈ 16% [Kang and Ryu, 1991]. Nevertheless, it has been noted that individuals with Class III malocclusions are more likely to seek evaluation than those with mandibular deficiencies [Proffit et al., 1990]. In other South East Asians, a higher incidence of Class III malocclusions compared with Caucasians has also been reported [Mak, 1969; Johnson et al., 1978; Woon et al., 1989; Lew et al., 1993; Tang 1994], higher than studies of the prevalence of Class III relationships in the Japanese [Endo, 1971; Susami et al., 1972; Kitai et al., 1989]. Thus, the underlying etiological factors responsible for the prevalence and severity of Class III malocclusions require further probing.

A useful model for the study of midfacial retrusion is the Brachyrrhine (*Br*) mouse that displays a deficient sagittal midfacial growth trajectory [Lozanoff, 1993]. In this mutant, midfacial retrusion is caused in part by growth deficiencies of the posterior (presumptive spheno-ethmoidal) region of the anterior cranial base [Lozanoff et al., 1994], associated with decreased chondrocytic proliferation [Ma and Lozanoff, 1996, 1999] in that region. Therefore, reduction in size or alteration in shape of the anterior cranial base might cause a retrognathic midfacial profile associated with Class III malocclusions in humans. This notion contrasts with previously held views that anterior translation of the midfacial complex is dependent upon nasal septal traction [e.g. Ousterhout and Vargervik, 1987; Moss, 1997]. Support for the spheno-ethmoidal hypothesis is advocated by the finding that the anterior cranial base is shorter in human East Asian populations with Class III malocclusions [Ngan et al., 1997; Park and Lee, 1998; Singh et al., 1999a].

The contribution of the midfacial complex in the development of Class III malocclusions appears to be controversial [Dibbets, 1996]. Lew and Foong [1993] reported normal antero-posterior maxillary position in Chinese adults, while Murata et al. [1990] suggested that skeletal Class III malocclusions are due to a retrusive maxilla in Japanese females. Kim and Lee [1990] reported that in 12-year-old Korean children with Class III malocclusions, $\approx 45\%$ had maxillary orthognathia and $\approx 45\%$ had maxillary retrognathia, among other Class III skeletal features. Baik [1995] reported that after maxillary protraction, the maxilla moved forwards in Korean children treated for anterior crossbite. Similarly, Shanker et al. [1996] found that correction of Class III malocclusions in Chinese children treated with maxillary protraction therapy was due to skeletal maxillary advancement.

Geometric morphometry of the nasomaxillary complex might help in the elucidation of midfacial morphogenesis, and as yet these techniques have not been undertaken in Korean children with Class III malocclusions. The developmental hypothesis of this study is based upon the notion that decreased cartilaginous growth of the postnatal spheno-ethmoidal region (and thus decreased cellular number in the spheno-ethmoidal synchondrosis) would predict a minimally deformed (generalized isometric) midface when comparing East Asian and European–American children with Class III malocclusions. Therefore, this study tests the hypothesis that the spheno-ethmoidal model of midfacial retrognathia [Lozanoff, 1999] can account for the increased prevalence and heightened severity of the Class III condition in the East Asian child, given the underlying midfacial morphology.

Materials and methods

After obtaining ethical permission, pre-treatment lateral cephalographs of 74 European–American subjects aged between 5 and 11 years with Angle's Class III molar malocclusion were retrieved [Guyer et al., 1986]. A further 71 cephalographs of untreated Korean subjects with a similar Class III molar relationship also were obtained from a Korean orthodontic practice. The total sample included an approximately equal number of age-matched males and females with negative history of airway problems and no obvious vertical skeletal problems. It was presumed that all radiographs were taken from subjects exhibiting left-right symmetry and that the central X-ray passed along the transmeatal axis when the teeth were in occlusion. The magnification of each film was standardized to 8%. The chronological age was assumed to match developmental age in this study, as carpal ages were unavailable.

Each lateral cephalograph was traced on frosted acetate film (0.03″ thick) and checked by one investigator (G.D.S.). Digitization of landmark co-ordinates from cephalographs taped to a light box of uniform brightness was achieved using appropriate software and a digitizing tablet (Numonics Inc., Montgomeryville, PA). Seven homologous midfacial landmarks were identified and digitized (Fig. 1). These landmarks encompassed the lateral profile of the nasomaxillary complex and permitted the construction of the midfacial configurations to be studied. For the x, y co-ordinates of the landmarks, the digitization error was $< 1\%$ on duplicate digitization ($P > 0.05$). Therefore, the landmarks were deemed to be identified reliably and further analyses warranted.

For statistical analysis, a Procrustes method was employed to determine the variance around each landmark and express it as a root-mean square. Therefore, each overall sample was subjected to Procrustes superimposition and each group was represented as a mean and variance. The Procrustes routine was implemented on an Amiga 3000 computer, and an average seven-noded geometry for each age group was determined using a generalized orthogonal Procrustes analysis [Gower, 1975]. Following this method, every object's co-ordinates were translated, rotated and scaled iteratively until the least-squares fit of all configurations was no longer improved. Therefore, all configurations were registered with respect to one another, and as a result of this procedure, geometric midfacial configurations were scaled to equivalent areas, avoiding problems introduced by differences in size. To determine whether midfacial

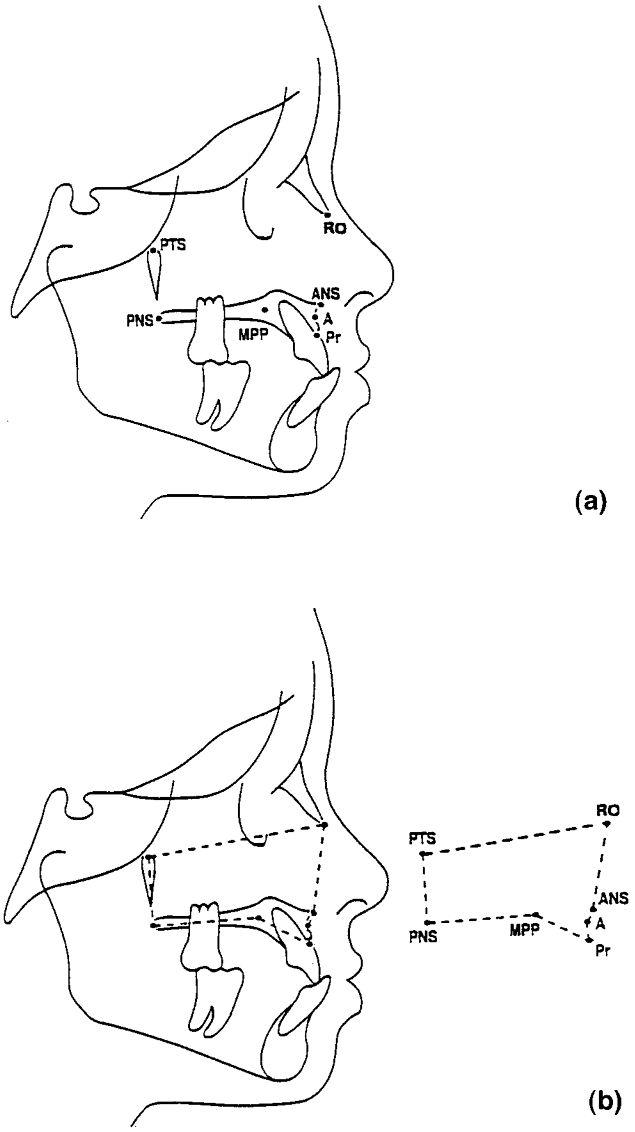

Fig. 1. **a:** Homologous landmarks employed for the construction of a seven-noded geometry to define the midfacial complex.

A	Subspinale:	Point of maximum concavity inferior to the anterior nasal spine on maxillary alveolus
ANS	Anterior nasal spine:	Anterior-most point on anterior nasal spine
MPP	Midpalatal point:	Midpoint between outlines of the nasal and oral palatal surfaces
RO	Rhinion:	Inferior-most point on tip of nasal bone
PNS	Posterior nasal spine:	Posterior-most point on posterior nasal spine
Pr	Prosthion:	Antero-inferior point of maxillary incisor alveolus
PTS	Pterygoid point:	Superior-most point on outline of pterygoid fissure

b: Midfacial geometry derived from the seven homologous landmarks employed superimposed on a tracing of a Class III cephalograph, and shown separately. A: subspinale, ANS: anterior nasal spine, MPP: midpalatal point, RO: rhinion, PNS: posterior nasal spine, Pr: prosthion, PTS: pterygoid point.

landmark configurations differed between the two ethnic types and at each age interval, each European–American group mean geometry was compared statistically with the age-matched Korean group average geometry using analysis of variance (ANOVA) [Gower, 1975]. In each instance, the null hypothesis was that the European–American mean was not significantly different from the Korean average. Residuals and corresponding F-values were computed, tabulated and compared.

In order to demonstrate sources of heterogeneic midfacial morphology, a FESA analysis was undertaken that incorporated a spline interpolation function [Bookstein, 1991]. Based on this approach, differences can be described graphically as a size- and/or shape-change [e.g. Singh et al., 1997a,b, 1998a, 1999a]. The FESA software was written in "C" and implemented on an Amiga 3000 computer. The overall mean European–American configuration was taken as the initial geometry, and this configuration was compared with the overall Korean mean. Size-change variables were computed as the product of the principal extensions, while shape-change measures were calculated as the ratio of the greater divided by the lesser principal extension. The mean geometries at each age interval were also compared (≈ 10 subjects per group; ≈ 5 males, ≈ 5 females per group). Therefore, eight comparisons were generated in total, and deformation values were computed for at least 2000 points per geometry for graphical display. A log-linear interpolation of the size- and shape-values was used to generate a color map. These form-change measures then were color-mapped into each European–American configuration to provide graphical displays of geometrical change for the overall and each age-wise comparison.

Results

Table 1 shows the residuals from the overall Procrustes analysis and those at each age when compared using an F distribution. Statistically significant differences between the European–American and Korean midfacial configurations occurred at $P < 0.01$ for the total sample. When the total sample was decomposed over seven age intervals, the comparisons maintained statistical significance at all age groups tested, except at age 11 years. Thus, comparing the mean midfacial configurations, the European–American configuration was found to be significantly different from the Korean counterpart, and this difference pre-

TABLE 1. Procrustes analysis of mean midfacial configurations of European-American and Korean Class III subjects

Age (years)	5	6	7	8	9	10	11	Total
Residual	0.003	0.0001	0.0021	0.0006	0.0024	0.0013	0.0011	0.0011
F-value	2.51	1.07	2.38	0.93	3.37	1.19	0.67	3.12
$P<$	0.001	0.01	0.001	0.05	0.05	0.01	NS	0.01

When the total sample is decomposed into age seven groups, nearly all groups maintain statistical significance.

sumably arises partly due to size-change and partly due to shape-change.

Using FESA to compare the overall European–American and Korean midfacial configurations for size-change graphically, FESA revealed that a localized area of positive allometry was discernible for the Korean configuration with its epicenter between the posterior nasal spine and midpalatal region (Fig. 2a; $\approx 9\%$ increase in size). Conversely, a region of negative allometry was localized with an epicenter between the anterior nasal spine and subspinale. A decrease in size of $\approx 15\%$ was evident in that region (Fig. 2a). For shape-change, the overall Korean Class III midfacial nodal mesh was predominantly isotropic, with evidence of anisotropy restricted to areas in the anterior-most regions of the midfacial configuration (Fig. 3a). For specific nodes, size-change and shape-change values are summarized in Table 2.

Decomposition of the sample into the seven age- and sex-matched groups revealed that a similar pattern of size-change was discernible at ages 5–11 years (Fig. 2b–h). The Korean posterior palatal region showed an increased size at ages 5–7 and 10–11 years (5–23%), while it was largely isometric (invariant with respect to local size-change) in the other two age groups. Similarly, for all age groups (Fig. 2b–h), the Korean anterior nasal spine region exhibited a negative allometry (≈ 7–35% decrease in size), although the epicenter of the diminution varied in its location for the 5 year olds. Perhaps not surprisingly, shape-changes in the 5–11-year-old age groups were remarkably similar (Fig. 3b–h). The majority of the configurations was isotropic, with evidence of anisotropy localized between an area extending from the maxillary incisor alveolus over the anterior-most part of the midfacial configuration.

Discussion

For the analysis of landmark data, geometric morphometric techniques, such as thin-plate spline analysis [Lynch et al., 1996; Singh et al., 1997c], have been employed. While these techniques are appropriate in the rigorous analysis of shape- and size-change, each methodology has inherent weaknesses as well as advantages. For example, Lele [1991] has commented on the use Procrustes superimpositions and, although the deployment of Euclidean distance matrix analysis has been advocated, its co-ordinate-system invariance introduces graphical difficulties [Cole and Richtsmeier, 1998]. Similarly, Ferrario et al. [1997] have employed Fourier analysis of mandibular outlines to compute cosine and sine coefficients of harmonics, but earlier Richtsmeier and Cheverud [1986] and Lozanoff and Diewert [1986, 1989] noted that decomposition of morphological integration is possible also using FESA. Although the strains represent measures of morphological deformation, it was assumed that they reflect localized cell/extracellular matrix growth activities. Therefore, the application of FESA was warranted in this study when computing the color-coded configurations.

Orthodontic, dentofacial orthopedic and surgical treatments, either in isolation or combination, may be employed in the treatment of patients with Class III malocclusions that exhibit midfacial retrusion [Bell and Jacobs, 1980; Baik et al., 1995]. As the maxilla forms much of the midfacial complex, the midfacial abnormality may be directly associated with maxillary hypoplasia, maxillary retrognathia (retroposition), or a combination of the two. It is also thought that soft tissues may inhibit anterior translation of the midface [Yang, 1996; Singh et al., 1999b]. Thus, by removing abnormal muscle forces, patients with Class III malocclusions due to maxillary retrusion without mandibular prognathism can be successfully treated with the Frankel regulator appliance [Yang, 1996; Kocadereli, 1998]. Indeed, in cases of midfacial dysmorphology such as orofacial clefting, the use of maxillary-midfacial distraction osteogenesis has been employed [Cohen et al., 1997; Talisman et al., 1997]. The controversy, however, over a passive or active role for the circumoral musculature in the development of Class III malocclusions remains unresolved [Singh et al., 1999c].

In addition, dysmorphologies of the maxilla have been implicated in the development of Class

III malocclusions. In a caprine study, Weinzweig et al. [1999] demonstrated maxillary hypoplasia and subsequent midfacial retrusion resulting in a Class III jaw relationship associated with cleft palate. Weinzweig et al. [1999] suggest that in mammals with cleft palate, midfacial dysmorphology is unrelated to post-operative scarring, and that the Class III relationship may be precipitated by abnormal maxillary growth. This notion is supported by the work of Wood et al. [1997] on children, and that of Denny and Bonawitz [1994] who consider that human orofacial clefting is an abnormality of the entire maxilla, with deficient midfacial projection producing a Class III malocclusion. Further evidence for the lack of anterior translation of the midface comes from the study of

Fig. 2.

Linton [1998], who reported that in Korean children with orofacial clefting, the sella-nasion-subspinale (SNA) angle was smaller than in non-cleft children. Therefore, maxillary hypoplasia needs to be considered in the etiology Class III malocclusions.

In previous cephalometric studies of midfacial heterogeneity, the antero-posterior midfacial length was found to be shorter in Korean children [Park and Lee, 1998; Singh et al., 1998b]. This foreshortening might be due to soft tissue influences or maxillary hypoplasia as alluded to above. Nevertheless, using geometric methodology such as Euclidean distance matrix analysis, the antero-posterior diminution appears to depend upon the anterior component of the hard palate being longer in European–Americans because their posterior palatal component was found to be shorter than that of their Korean counterparts [Singh et al., 1998b]. Confirmation of these localized differences between Korean and European–American children noted in this study might aid in the understanding of the contribution of maxillary ontogeny in the etiology of Class III malocclusions. It appears that developmental compensation is a feature of antero-posterior maxillo-mandibular growth, presumably instigated in a fashion similar to the hypothesis of medio-lateral developmental stability and fluctuating asymmetry. Given that in the attainment of a Class I skeletal relationship, a site for proliferative activities might be the transverse palatine suture, the finding that up to age 10 years, all Korean midfacial configurations were statistically smaller than the European–American counterparts supports the claim that the compensation is insufficient. By age 11 years, however, catch-up growth removes the morphological difference; nevertheless a Class III profile is still seen. Therefore, a developmental mechanism external to the midfacial complex might be implicated in these instances.

Recent studies [Park and Lee, 1998; Singh et al., 1999a] suggest that the anterior cranial base is shorter in Korean children with Class III malocclusions, supporting the spheno-ethmoidal hypothesis of midfacial translation [Lozanoff, 1999]. The idea that the source of midfacial retrognathia could be within the anterior cranial base is supported by studies in the *Br* mouse mutant that displays midfacial retrusion [Ma and Lozanoff, 1996]. These studies provide evidence that chondrocytic proliferation is the underlying biological mechanism, and cellular studies [Ma and Lozanoff, 1999] are beginning to bear out this notion, at least in the *Br* mouse. However, the *Br* mice studied thus far are in the prenatal or early postnatal stages and there is still a lot of cartilage in the cranial base. This is not the case with young postnatal children.

In human studies, Spaeth and Krugelstein [1996] have indicated that the spheno-ethmoidal complex shows rapid development during the first

TABLE 2. FEM analysis comparing Korean and European–American Class III midfacial nodal values for size- and shape-change

Size-change						
PTS	Ro	ANS	MPP	PNS	A	Pr
1.031	0.954	0.856	1.068	1.070	0.922	0.942
Shape-change						
PTS	Ro	ANS	MPP	PNS	A	Pr
1.000	1.001	1.015	1.001	1.001	1.008	1.007

Fig. 2. Comparison of European–American and Korean midfacial configurations for size-change. **a:** Overall comparison. In the posterior palatal region between PNS and MPP, an increase in size of ≈ 9% is evident. The anterior part of the midfacial configuration, however, shows little change in size (isometry) but ≈ 15% decrease in size is visible further anteriorly, particularly localized near the anterior nasal spine region. **b:** Age 5 years. Between PNS and MPP, an increase in size of ≈ 20% is visible. Most of the mid-region of the configuration shows isometry but the antero-superior region shows ≈ 7% decrease in size. **c:** Age 6 years. In the posterior half of the configuration an increase in size of ≈ 9% is seen. While the anterior half of the configuration shows some isometry, the anterior nasal spine region, however, shows a decrease in size (≈ 23%). **d:** Age 7 years. An increase in size of ≈ 23% is seen extending across the posterior region of the configuration between PNS and MPP. The anterior half, in contrast, is predominantly isometric, while the anterior-most region shows a ≈ 15% decrease in size. **e:** Age 8 years. The midfacial configuration appears to be largely isometric. Between MPP and Pr an increase in size of ≈ 14% is localizable. Similar to the other groups, the anterior nasal spine shows a ≈ 15% decrease in size. **f:** Age 9 years. Similar to the 9-year-old configuration, the midfacial nodal mesh appears to be predominantly isometric. Between MPP and Pr an increase in size of ≈ 12% is noticeable, and similar to the other groups, the anterior nasal spine shows a ≈ 7% decrease in size. **g:** Age 10 years. The posterior half of the configuration shows an increase in size of ≈ 10%. In contrast, the anterior half of the configuration shows isometry, but the anterior-most region shows a decrease in size (≈ 12%). **h:** Age 11 years. In the posterior half of the configuration an increase in size of ≈ 5% is seen. While the anterior half also shows some increase in size, the anterior nasal spine region, however, exhibits a decrease in size (≈ 33%).

decade, in line with findings reported in this study. Indeed, Cohen et al. [1985] suggest that growth in length of the anterior cranial base takes place primarily by adaptation at the spheno-ethmoidal synchondrosis. We surmise that developmental aberrations could affect the spheno-ethmoidal, inter-sphenoidal and spheno-frontal synchondroses that are still undergoing endochondral ossification within the anterior cranial base. Therefore, deficient chondrogenesis i.e. decreased chondrocytic number/proliferation, or premature fusion i.e. early synostosis/maturation in the anterior cranial base synchondroses of South East Asian children emerge as hypotheses that might explain small overall anterior cranial base size resulting in failure of sufficient anterior midface translation associated with Class III malocclusions.

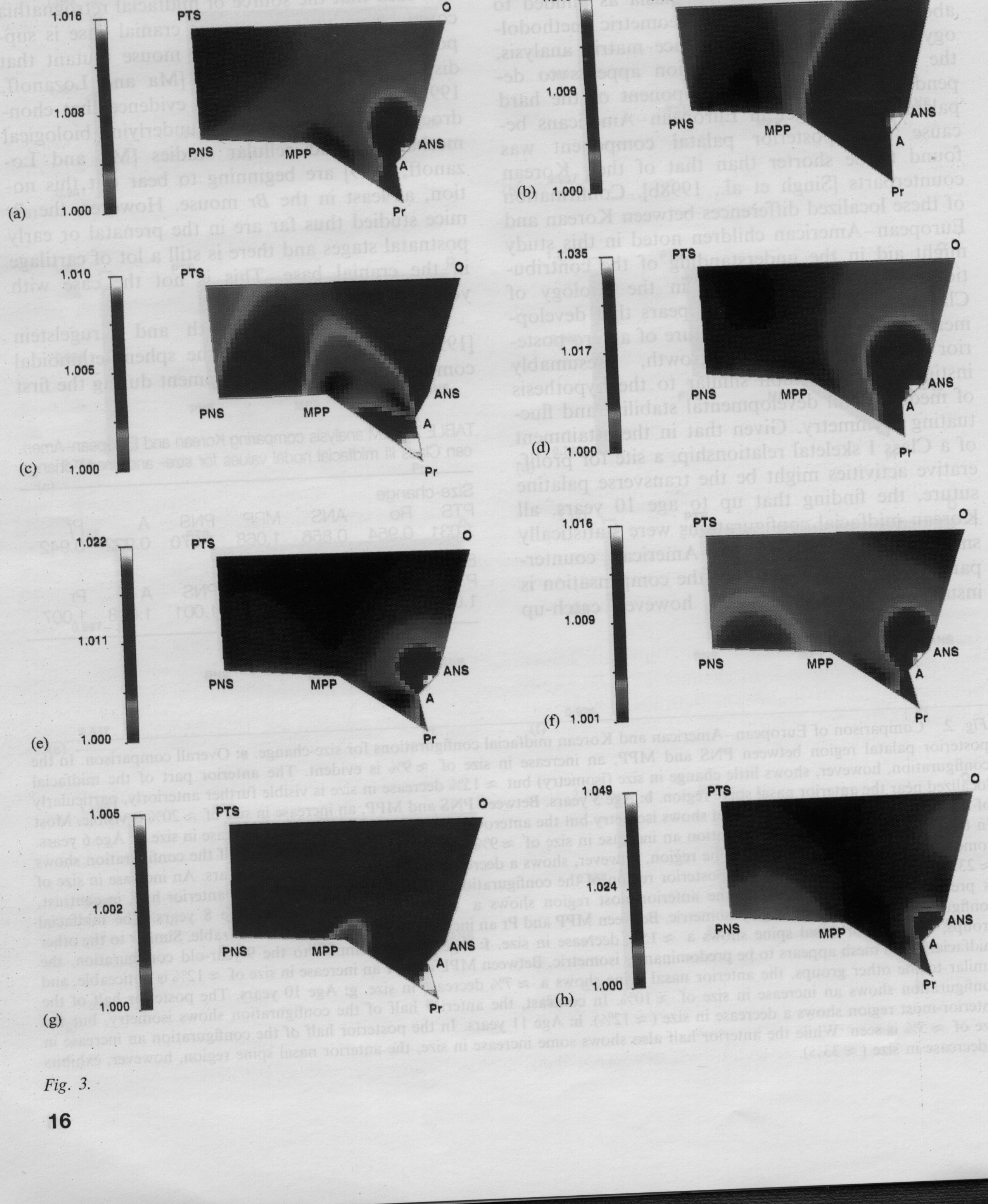

Fig. 3.

It has also been reported that the incidence of Class III malocclusion is significantly greater in Korean sub-populations at $\approx 49\%$ [Yang, 1990], but now decreasing, presumably due to a more representative population profile [Yang, 1995]. Nevertheless, it can be hypothesized that an anterior cranial base deficiency, due to decreased chondrocytic proliferation, results in deficient anterior translation of the midface, and despite developmental compensation mechanisms, the maxillary complex remains retruded. This notion is based upon the findings of this study that indicate midfacial isometry and isotropy. Thus, the midface is largely isometric and as it has not markedly changed in size and shape, the failure of anterior translation might be attributable to cranial base allometry.

As well as an increased prevalence in the South East Asian child, however, the severity of Class III malocclusions may also be increased; 74% requiring orthognathic surgery in one study [Baik et al., 1995]. Although the developmental mechanism(s) for this remain obscure as yet, it can be postulated that perturbations of endochondral mechanisms of cranio-mandibular growth, and not maxillary intramembranous methods, may be implicated in the etiology of Class III malocclusions in South East Asians. This notion lays a foundation for the search within the South East Asian genome for genes associated with cartilage proliferation, resulting in a skeletal pattern characterized by anterior cranial base foreshortening, midfacial retrognathia and concomitant mandibular prognathism.

Acknowledgments

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Fig. 3. Comparison of European–American and Korean midfacial configurations for shape-change. **a:** Overall comparison. The vast majority of the configuration is isotropic, with low levels of anisotropy restricted to a small, localized area extending from the anterior nasal spine to the maxillary incisor alveolus region. **b:** Age 5 years. The posterior half of the configuration shows isotropy predominantly, although low levels of anisotropy are discernible in the anterior half, affecting the anterior nasal spine region. **c:** Age 6 years. While most of the configuration is isotropic, low levels of anisotropy are restricted to a small, localized area of the maxillary incisor alveolus region. **d:** Age 7 years. Anisotropy is restricted to a small, localized area of the anterior nasal spine region, but the vast majority of the configuration is isotropic. **e:** Age 8 years. Similar to the 7 year olds, low levels of anisotropy are discernible in the anterior-most part of the anterior nasal spine region. The remainder of the configuration, however, is isotropic. **f:** Age 9 years. Anisotropy is restricted to a small, localized area extending from the anterior nasal spine to the maxillary incisor alveolus region. While low levels of anisotropy are discernible, most of the configuration is isotropic. **g:** Age 10 years. Despite appearing different in coloration, the majority of the configuration is isotropic (red). Some anisotropy is discernible, restricted to a small, localized area of the maxillary incisor alveolus region. **h:** Age 11 years. Similar to the 8 year olds, low levels of anisotropy are discernible in the anterior-most part of the anterior nasal spine and maxillary incisor alveolus regions. The remainder of the configuration, however, is predominantly isotropic.

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