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Localisation of deformations of the midfacial complex in subjects with class III malocclusions employing thin-plate spline analysis

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ABSTRACT

This study determines deformations of the midface that contribute to a class III appearance, employing thin-plate spline analysis. A total of 135 lateral cephalographs of prepubertal children of European-American descent with either class III malocclusions or a class I molar occlusion were compared. The cephalographs were traced and checked, and 7 homologous landmarks of the midface were identified and digitised. The data sets were scaled to an equivalent size and subjected to Procrustes analysis. These statistical tests indicated significant differences ($P < 0.05$) between the averaged class I and class III morphologies. Thin-plate spline analysis indicated that both affine and nonaffine transformations contribute towards the total spline for the averaged midfacial configuration. For nonaffine transformations, partial warp 3 had the highest magnitude, indicating the large scale deformations of the midfacial configuration. These deformations affected the palatal landmarks, and were associated with compression of the midfacial complex in the anteroposterior plane predominantly. Partial warp 4 produced some vertical compression of the posterior aspect of the midfacial complex whereas partial warps 1 and 2 indicated localised shape changes of the maxillary alveolus region. Large spatial-scale deformations therefore affect the midfacial complex in an anteroposterior axis, in combination with vertical compression and localised distortions. These deformations may represent a developmental diminution of the palatal complex anteroposteriorly that, allied with vertical shortening of midfacial height posteriorly, results in class III malocclusions with a retrusive midfacial profile.

Key words: Craniofacial growth; dental malocclusion.

INTRODUCTION

Biometry and interest in quantitative shape analysis have a long history (e.g. Thompson, 1917). Currently, there is some concern that in the assessment of facial morphology newer techniques have not been employed fully (Moyers & Bookstein, 1979). The methods of recording and measuring malocclusion include Angle's classification and, although it is probably the most widely used (Tang & Wei, 1993), this method of categorisation is empirically qualitative and does not provide information on the developmental mechanisms by which the observed occlusal relationship has been reached. During secondary palate development in human fetuses, Diewert (1983) noted that growth of the mandible was more rapid than the nasomaxillary complex, but the sagittal position of the maxilla changed with respect to the anterior cranial base. Later, Diewert (1985) demonstrated that facial structures grow predominantly in the sagittal plane prenatally and that the sagittal position of maxilla with respect to the anterior cranial base changes, presumably to enable the attainment of a class I occlusal relationship. These studies suggest that human patterns of maxillary position develop in the late embryonic period and that interference with

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normal growth changes during this early critical period may produce irreversible effects on final facial form (Diewert, 1985).

The functional matrix model has been proposed to account for the predominantly downward and forward pattern of postnatal human craniofacial growth. Accordingly, Moss et al. (1968) suggested a passive role for the septal cartilage in midfacial growth, and Oyen (1982) proposed that masticatory function is an important factor in craniofacial morphogenesis. In the experimental manipulation of animal models, however, Latham et al. (1975) explained the putative role played by the vomer in the growth and support of the upper jaw in the dog. Anteroposterior retardation of upper jaw growth became evident when these animals were subjected to extirpation of the vomer. Such studies lead to the septal-traction model. Mooney & Siegel (1989) proposed that the septal-traction model is in accord with human midfacial growth patterns in contradistinction to earlier suggestions (Moss et al. 1968). In a series of studies on the Brachyrrhine mouse, it has been shown that the role of the cranial base in the aetiology of class III malocclusion resulting in midfacial deficiency cannot be overlooked (Lozanoff, 1993; Lozanoff et al. 1993, 1994; Ma & Lozanoff, 1996; and others). Some doubt has been cast on the association between the Angle's classes and facial morphology recently (Dibbets, 1996). Therefore, a rigorous quantitative analysis of the spatial organisation of size and shape change during class III morphogenesis is warranted.

Thin-plate spline analysis (TPS) is a geometric morphometric technique that expresses the differences between 2 configurations as a continuous deformation, using regression functions in which homologous landmarks are matched exactly between the 2 forms, explicitly to minimise the bending energy (Richtsmeier et al. 1992). Bending energy can be thought of as the energy that would be required to bend an infinitely thin metal plate over one set of landmarks so that the height over each landmark is equal to the coordinates of the corresponding point in the other form. The specific interpolation function is a mathematical expression for the deformation of theoretically idealised thin metal plates (Bookstein, 1989, 1991). These properties enable the construction of transformation grids such as those associated with Thompson (1917).

The deformation can be decomposed into a series of geometric components; affine and nonaffine changes. The affine transformations correspond to changes due to size difference, rotation and uniform shape change. The nonaffine changes correspond to nonuniform or local deformation; each component is a weighted combination of landmark displacements. Moreover, if the objects are 2-dimensional, these nonaffine changes can be inspected visually for biological interpretations (Richtsmeier et al. 1992). The nonaffine changes can be decomposed further into a series of more localised components represented by partial warps, components corresponding to deformations at different geometric scales. The number of these partial warps is 3 fewer than the number of landmarks (Bookstein, 1989, 1991; Swiderski, 1993; Singh et al. 1997*a*). The most global components are combinations that represent transformations affecting the entire form. The other components represent a series of transformations affecting progressively smaller regions, down to highly localised changes affecting the immediate vicinity of a few closely spaced landmarks (Swiderski, 1993).

The mode of each partial warp is determined by the configuration of landmarks in the starting form and represents the mode of relative landmark displacements for shape changes at that scale of localisation. These modal forms are called the principal warps; eigenvectors of the bending energy matrix (Bookstein, 1989, 1991). Therefore, the contribution of change at the scale of a particular principal warp to the realised landmark displacements in the x, y plane is expressed as a vector; the partial warp, i.e. the multipliers of the eigenvectors (the thin-plate spline weighted sums of the principal warps) are the partial warps. Eigenvalues are interpreted at an inverse index to the scale of the corresponding principal warp; more energy is required to bend the thin-plate between closely spaced landmarks. Therefore, eigenvalues are inversely related to the spatial scale of the feature; high eigenvalues are associated with highly localised features and high bending energy. As magnitude is a measure of how important a principal warp is for fitting the second form, partial warps with large magnitudes are interpreted as making the most difference (Zelditch et al. 1992, 1993). For these partial warps, the bending energy is the product of the magnitude of the warp and its eigenvalue (Bookstein 1989, 1991). Thus, principal warps are geometric terms in which morphological differences can be described, and partial warps are the values assigned to them (Swiderski, 1993).

Singh et al. (1997*a*) previously employed TPS in the examination of the role of the cranial base and the mandible (Singh et al. 1997*b*) in the aetiology of class III malocclusions. The overall aim of this study is to provide evidence for the theory that deficient anteroposterior elongation of the midface, presumably due to premature synostosis or deficient sutural proliferation, is associated with the development of class III malocclusions. Therefore, the specific objectives of this investigation were to undertake TPS analysis of midfacial morphology, to localise primary morphological sites, and to assess their contributions to the appearance of a class III facial profile. This paper will test the hypothesis that representation of the pattern of midfacial deformation associated with class III malocclusions is feasible using TPS.

MATERIAL AND METHODS

A total of 135 lateral cephalographs of untreated prepubertal European-American patients with either class III molar malocclusions (Guyer et al. 1986) or normal class I molar occlusions were retrieved. The group with class III malocclusions consisted of 74 subjects (age 5 y: 5 females, 4 males; age 6: 3 females, 4 males; age 7: 5 females, 5 males, age 8: 5 females, 5 males; age 9: 10 females, 7 males; age 10: 5 females, 6 males, age 11: 5 females, 5 males). The group with class I occlusions consisted of 61 subjects (age 5: 5 females, 5 males; age 6: 3 females, 4 males; age 7: 3 females, 4 males; age 8: 5 females, 4 males; age 9: 5 females, 4 males; age 10: 5 females, 4 males; age 11: 5 females, 5 males). Therefore, the sample included an approximately equal number of male and female patients of the same ethnic group, with a negative history of airway problems, and no obvious vertical skeletal problems.

The magnification of each film was standardised to an 8 % enlargement factor. 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 inch thick) and checked by one investigator (GDS). Digitisation of landmark coordinates from cephalographs taped to a light box of uniform brightness was achieved using appropriate software and a digitising tablet (Numonics Inc., Montgomeryville, PA). Seven homologous midfacial landmarks were digitised (Fig. 1*a*). Any landmarks that demonstrated a discrepancy of $> 1\%$ for each x, y coordinate on duplicate digitisation would be deemed to be identified unreliably and would be excluded from the final analyses. For the analysis of geometric transformation from a class I to a class III configuration, the scaled, mean midfacial morphologies for normal and class III forms were employed (Fig. 1*b*).

The class I and class III samples were tested for statistical difference under the assumption of equivalence of variance (Procrustes analysis; Goodall, 1991; Singh et al. 1997*c*). These tests would indicate

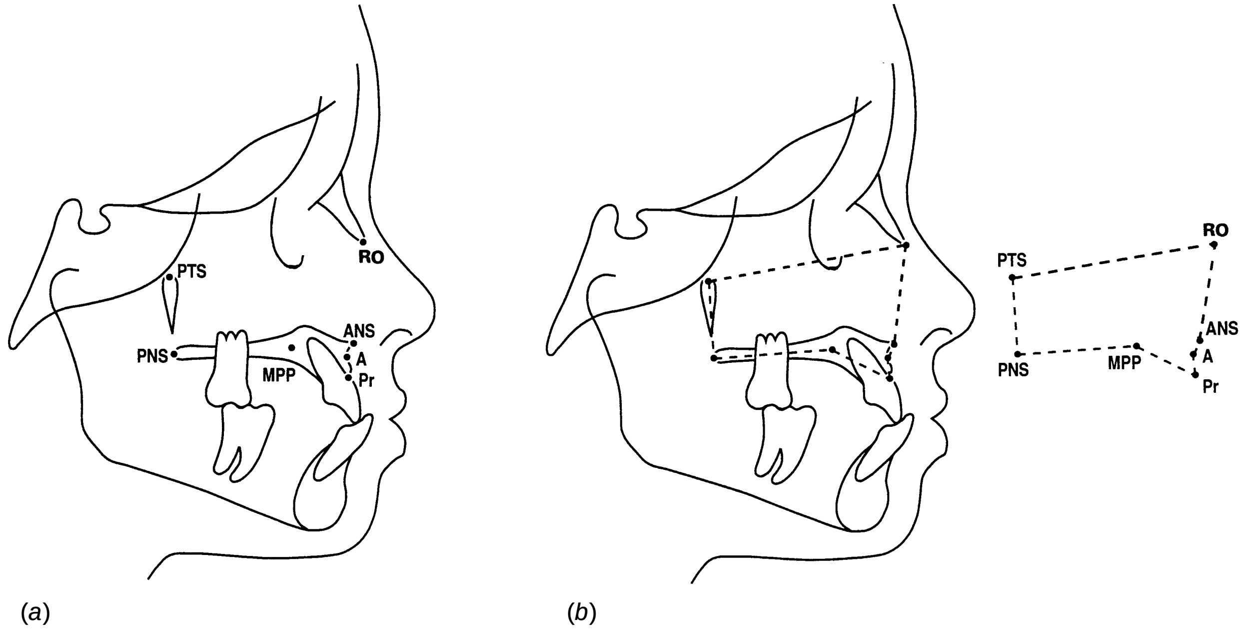

Fig. 1. (*a*) Homologous landmarks employed for the construction of a seven-noded geometry to define the midfacial complex. A, subspinale: point of maximum concavity inferior to the anterior nasal spine on maxillary alveolus; ANS, anterior nasal spine: anterior-most point on anterior nasal spine; MPP, 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: anteroinferior point of maxillary incisor alveolus; PTS, pterygoid point: superior-most point on outline of pterygoid fissure. (*b*) Midfacial geometry derived from the 7 homologous landmarks employed superimposed on a tracing of a class III cephalograph, and shown separately.

whether statistically significant differences were demonstrable for the sample independently of the clinical diagnosis. Hence, further geometric and graphical analysis using TPS analysis would be warranted. Midfacial configurations of the mean forms were subjected to TPS using appropriate software (Rohlf, 1996). Each total spline was decomposed into affine and nonaffine components. The affine transformation describes the uniform component of change that has no bending energy. The nonaffine component, however, was decomposed further into partial warps, the magnitude representing the importance of the partial warp to the total fit. Deformations of the midface were interpreted on this basis. The terms used in this paper are in accord with the NATO ASI Series (Slice et al. 1996).

RESULTS

On duplicate digitisation, errors in the range of 0.08–0.2% for individual landmarks were recorded. Therefore, no landmarks were excluded and all 7 homologous landmarks were deemed to be identified reliably. As Bookstein (1996) recommended a sample size 4 times as large as the number of landmarks, all 135 subjects were included. Initial Procrustes results based upon the average class I and class III 7-noded geometries, scaled to an equivalent size, indicated that the overall mean configurations were statistically different ($P < 0.05$). Further graphical analysis was therefore undertaken employing TPS.

Figure 2 shows the mean midfacial configuration of the class I morphology derived from the 61 class I subjects in untransformed space. The pattern of deformation of the transformation grid to attain a class III configuration starting from the class I mean (the total spline; Fig. 3) showed evidence of vertical compression of the configuration between PTS and PNS. Anteroposterior compression in the PNS-MPP axis was also noted. In contrast, anteroposterior elongation between MPP and ANS was accompanied by an indication of apparent vertical elongation between RO and Pr.

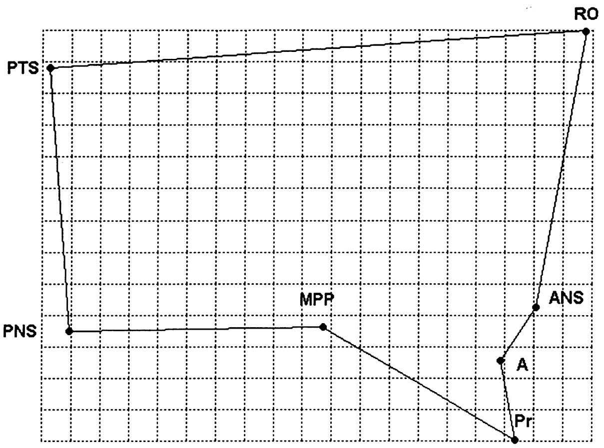

Fig. 2. The mean midfacial configuration of the class I morphology derived from the 61 class I subjects in untransformed space.

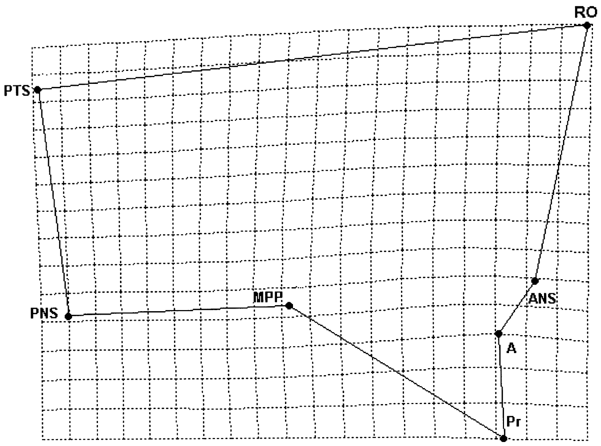

Fig. 3. The total spline demonstrating the pattern of deformation of the transformation grid to attain a class III configuration starting from the class I mean. There is vertical compression of the configuration between PTs and PNS with anteroposterior compression in the PNS-MPP axis. Anteroposterior elongation between MPP and ANS accompanied by apparent vertical elongation between RO and Pr is discernible.

Table. *Contribution of each partial warp towards the total spline**

Partial warp	Eigenvalue	Energy × 10^4	Magnitude × 10^5
1	43.94	8.34	1.90
2	7.67	0.68	0.89
3	3.81	9.84	25.80
4	2.08	3.41	16.34

Note that when the mean normal (class I occlusion) configuration is transformed into a class III malocclusion the deformation indicates that partial warp 3 has the highest magnitude, making the largest contribution.

When the total spline for the overall configuration (Fig. 3) was decomposed into partial warps, the pattern of deformation was confirmed. Partial warp 3 had the highest magnitude (Table; Fig. 4*c*), indicating large-scale deformations compressing the transformation grid between PNS and MPP accompanied by posterior displacement of the anterior maxillary alveolus. Partial warp 4 largely was responsible for the vertical compression of the configuration posteriorly (Table; Fig. 4*d*). In contrast, partial warp 1 had the highest eigenvalue and a high bending energy (Table; Fig. 4*a*), indicating localised shape changes of the anterior maxillary alveolar region with supero-

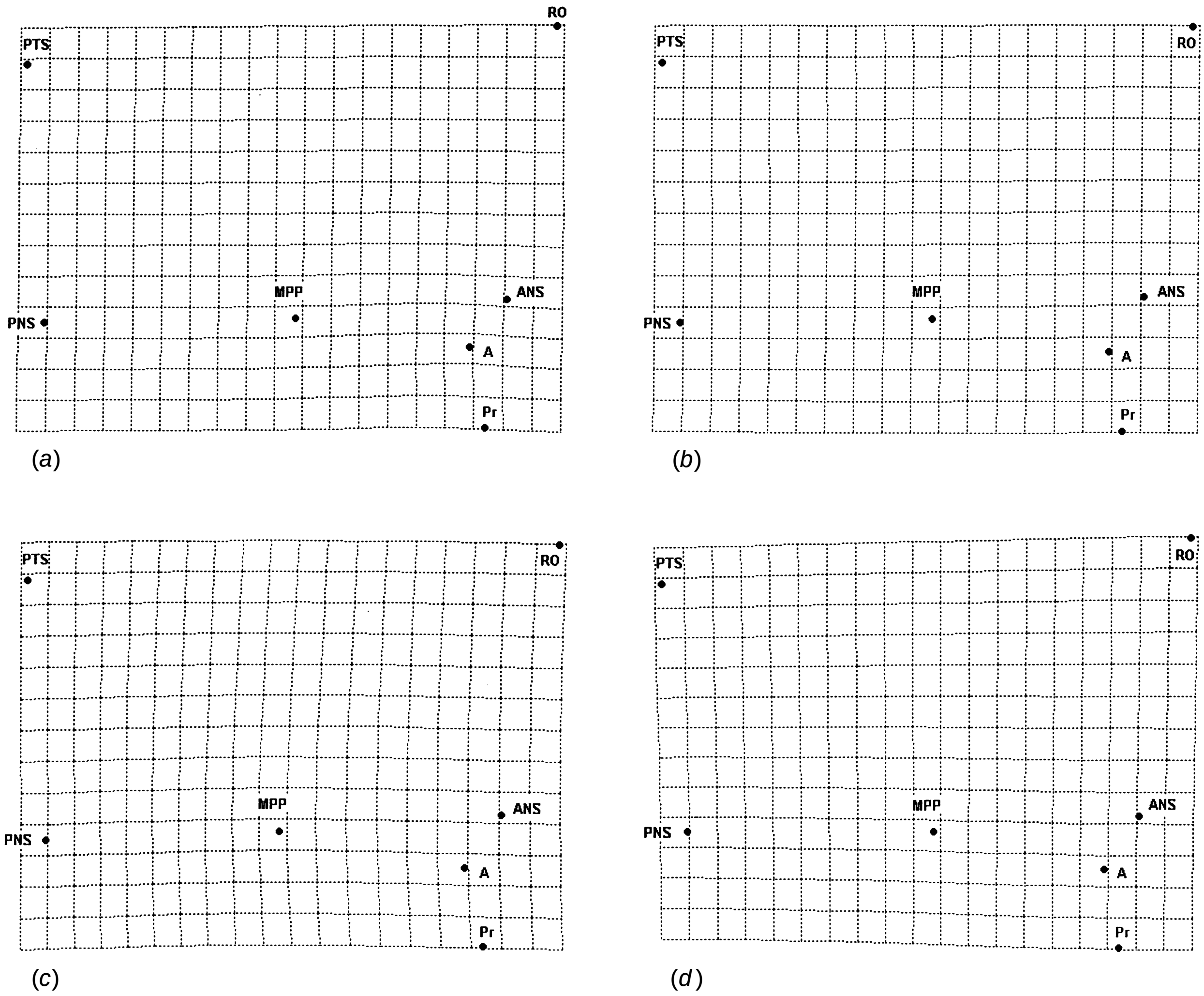

Fig. 4. Partial warps obtained when the total spline of the overall transformation was decomposed. (*a*) Partial warp 1. This indicates localised shape changes of the anterior maxillary alveolar region with superoposterior displacement of the landmarks in that vicinity. It has the highest eigenvalue and a high bending energy (Table). (*b*) Partial warp 2. This demonstrates anteroinferior deformation of the maxillary alveolus region. (*c*) Partial warp 3. Indicates large-scale deformations compressing the transformation grid between PNS and MPP accompanied by posterior displacement of the anterior maxillary alveolus. This partial warp had the highest magnitude (Table) and thus made the greatest contribution in transforming the mean class I geometry to a class III configuration. (*d*) Partial warp 4. Demonstrates vertical compression of the configuration posteriorly. It has a relatively high magnitude (Table).

posterior displacement of the landmarks in that vicinity. Partial warp 2 (Table; Fig. 4*b*) demonstrated anteroinferior deformation of the maxillary alveolus region.

Graphical analysis of the midfacial complex using TPS therefore demonstrated a pattern of large spatial-scale deformation affecting the posterior regions of the midfacial configuration, in combination with localised deformations of the maxillary alveolus anteriorly in order to attain a class III morphology.

DISCUSSION

There are several methods available for the comparison of deformations and transformations of landmark data derived from medical and other imaging techniques (Brown, 1992; Rohlf & Marcus, 1993; Singh et al. 1997*a–d*). Wood & Lynch (1996) regard some geometric morphometric methods such as finite element scaling analysis (FESA) and euclidean distance matrix analysis (EDMA) as being relatively complicated. FESA employs sets of landmarks to form elements of small closed regions defining the shape-space, but different partitioning of the specimen in some instances can provide rather different patterns of deformation (Marcus & Corti, 1996). Similarly, EDMA is not based on Kendall's (1984, 1985) shape-space, and it has been suggested that EDMA can have arbitrarily low statistical efficiency in some applications (Marcus & Corti, 1996). In this study, therefore, TPS (Bookstein, 1989, 1991) was employed which enabled image transformation, and highlighted regions of midfacial dissimilarity. Because of the variation in human anatomy, nonlinear methods such as TPS are relevant and can prove to be very powerful (Little & Mardia, 1996; Singh et al. 1997*a–d*).

Human and animal studies (e.g. Diewert, 1983, 1985; Mooney & Siegel, 1986; Lozanoff, 1993; Lozanoff et al. 1993, 1994; Tollaro et al. 1994) suggest that midfacial profiles are established early in development and are maintained postnatally. It has also been suggested that sutures of the midface, in particular the transverse palatine suture, may be important in the bony development of the palate during growth (King & Scheiderman, 1993; Njio & Kjaer, 1993). In this current study, large-spatial deformations associated with partial warp 3 were localised. These deformations affected the posterior regions of the midfacial configuration in the vicinity of PNS and MPP. The effect of these deformations appears to be foreshortening of the palatomaxillary complex with size diminution. It is conceivable that deficient sutural proliferation at the transverse palatal suture encompassed by these landmarks may have the effect of reducing the posterior palatal length, with concomitant midfacial retrusion visualised anteriorly on the facial profile. Alternatively, premature synostosis at sutural sites of the posterior configuration such as the pterygomaxillary suture may produce a similarly apparent growth anomaly. The midpalatal point, however, is a notoriously weak landmark. Nevertheless, its usefulness here is that it provides a homologous landmark that encompasses the transverse palatine suture posteriorly and the premaxillary-maxillary suture anteriorly, significant sites for midfacial growth.

In humans, anterior nasal spine size correlates with the timing of premaxillary–maxillary sutural fusion that may have implications for midfacial growth (Mooney & Siegel, 1991). Burdi et al. (1988) demonstrated that the central portion of the postnatal facial T-zone has a clearly recognisable prenatal antecedent as early as the 9th week of fetal life. Therefore, there appears to be a developmental relationship between premaxillary–maxillary suture patency and anterior nasal spine morphology, in accord with the hypothesis of septal-mediated traction of midfacial growth. In this current study, partial warp 1 appeared to affect ANS. Localised deformations and displacement of the anterior maxillary alveolus as well as anteroinferior elongation between MPP and ANS were evident. Therefore, while the posterior regions of the palatomaxillary complex appear to undergo retrusive changes, the anterior maxillary alveolus and contiguous structures appear to undergo anteroinferior displacements, presumably in association with developmental changes in the vicinity of the premaxillary–maxillary suture.

In our present investigation it appears that there is some support for the concept of compensatory growth. Mooney et al. (1992) reported that with rigid fixation, shortened premaxillary lengths, altered palatocranial base angles and class III malocclusions similar to congenital abnormalities were found, but later compensatory growth was evident. Therefore, with respect to the palatomaxillary complex, developmental disturbances in the posterior growth sites might be compensated for by changes occurring in the anterior aspect of the configuration. The extent of the anterior sutural response may vary, however, and might be insufficient in some instances to make good the deficit in anteroposterior growth. In other cases, eruption of the maxillary incisor teeth may effectively lock the sagittal position of the maxillary alveolus such that growth response occurs in an anteroinferior direction due to functional constraints. Support for this notion stems from the work of Ostyn et al. (1996) who indicated the role of interdigitation upon sagittal growth of the maxillomandibular complex. Nevertheless, deficient orthocephalisation of the cranial base (Singh et al. 1997*c*) and anteroposterior elongation of the mandibular corpus (Singh et al. 1997*b*) may overcome any midfacial developmental compensation, resulting in class III malocclusions.

Description of craniofacial shape change from cephalographs is a difficult notion as conventional cephalometry is fundamentally deficient in its application to systematic shape change (Bookstein, 1983). In an attempt to overcome lack of geometric rigour thin-plate spline analysis was employed, utilising landmark data. This method has been able to localise large-spatial scale deformations that shorten the anteroposterior dimensions of the palatomaxillary complex in conjunction with distortions of landmarks that encompass the maxillary alveolus. Presumably, these deformations reflect developmental mechanisms during the formation of class III malocclusions that are typically associated with midfacial retrusion. Homologous landmarks, however, contain no information about their immediate vicinity but landmarks often lie on boundaries between objects, and curvature and rate of change of direction may be elicited from such data. Bookstein & Green (1993, 1994) have developed an Edgel technique that incorporates this extra information at landmarks. Further, TPS in 3 dimensions is available and requires the use of 3 splines, as opposed to 2 in 2 dimensions to define the deformation. These techniques will form the basis of further studies to hypothesise developmental mechanisms in the investigation of morphological diversity in midfacial appearance.

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