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Procrustes, Euclidean and cephalometric analyses of the morphology of the mandible in human Class III malocclusions

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Abstract

The role of mandibular phenotype in the development of Class III malocclusion remains unclear. The purpose of this study was to determine whether the form of the mandible differed between prepubertal individuals with Class I and Class III malocclusions. Lateral cephalographs of 73 children of European-American descent aged between 5–11 years with Class III malocclusion were compared to those of 60 counterparts with a normal, Class I molar occlusion. The cephalographs were traced and checked, and eight homologous mandibular landmarks were digitized. Average mandibular geometries, scaled to an equivalent size, were generated using Procrustes superimposition. Euclidean distance matrix analysis (EDMA) was undertaken to corroborate the Procrustes analysis, and bivariate analysis utilizing eight linear and five angular measurements was also performed. Residuals and F-values from Procrustes analysis indicated that mandibular configurations differed statistically for Class I and Class III types. EDMA confirmed that the Class I and Class III geometries were significantly different, revealing that the greatest differences in morphology arose in the anterior-most mandibular regions. As well, most variables showed statistically significant differences when the Class I and Class III mandibular types were compared. When the sample was subdivided into seven age- and sex-matched groups, nearly all age-based comparisons were significantly different. It is concluded that the morphology of the mandible differs in individuals with Class III malocclusions when compared to the normal Class I configuration, and that these alterations may indicate dichotomous postnatal mandibular ontogeny.

Keywords: Malocclusion; Morphometrics; Morphometry

1. Introduction

Craniofacial abnormalities may stem from morphological changes affecting the components of the craniofacial skeleton, including the mandible. For example, the lower border of the mandible is characteristically deformed in the mandibulofacial dysostosis syndrome (Gray et al., 1989). Similarly, a retrusive mandible is identifiable in children with fetal alcohol-like syndromes (Sterling et al., 1987). In less severe craniofacial anomalies, genioplasty of the mandibular symphyseal region may be undertaken to achieve a well-balanced facial profile (Ayoub et al., 1994). In all such cases an appreciation of skeletal jaw relations is warranted. It therefore is pertinent that the growth and form of the mandible be understood fully. The

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Abbreviations: EDMA, Euclidean distance matrix analysis.

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development and morphology of the mandible has been assessed by the application of various methods, such as histology and conventional cephalometry in isolation, but the use of two or more investigative techniques in combination can provide considerably more accurate information (Sarnat, 1986). Indeed, more modern analytical techniques, e.g. elliptical Fourier functions, have been applied to study the boundary outlines of the mandible (Lowe et al., 1994).

An understanding of the aetiology of Class III malocclusion is crucial for its clinical correction (Schatz and Tsimas, 1995). Class III malocclusions appear as a disharmonious relation between the maxilla and mandible. The morphological features of this group of malocclusions are, however, variable and may involve several craniofacial structures, including an acute mandibular-plane angle, an obtuse gonial angle, an overdeveloped mandible/underdeveloped maxilla, and deficient orthocephalization (Jacobson et al., 1974; Ellis and McNamara, 1984; Sato, 1994; Singh et al., 1997a,b,c). The posterior discrepancy is an important aetiological factor in the development of a skeletal Class III malocclusion because it affects the occlusal plane (Sato, 1994). Therefore, the mandible is likely to be involved in the aetiology of Class III malocclusions because it forms the lower third of the facial profile. As most studies do not acknowledge size differences between individuals, the aetiological contribution of variation in homologous landmarks and mandibular variables may not be clear (Battagel, 1993, 1994). Furthermore, statistical assumptions made for clinical data-sets, such as equivalence of variance, may not be valid. Not surprisingly perhaps, Kerr et al. (1994), using an outlining technique, found little difference in mandibular form when comparing a sample of 10-year-old boys with Class III and Class I occlusions.

Our purpose now was to test the hypothesis that mandibular morphology differs between individuals with Class I and Class III malocclusions, and to localize the source of any mandibular heterogeneity. Such mandibular morphological differences could include an acute mandibular plane angle, an obtuse gonial angle, or an overdeveloped mandible (Singh et al., 1997d) *inter alia*. By employing morphometric techniques that normalize (size-correct) geometric areas (Procrustes superimposition) and take account of inequality of variance (EDMA; Lele and Cole, 1996), it might be possible to eliminate the effects introduced by size differences between individuals. Furthermore, comparisons of unscaled (size-incorporated) data, using conventional cephalometric analysis, were undertaken, in an attempt to localize sites where changes in mandibular form can be identified, and to specify features particularly associated with the characteristic phenotype of the Class III mandible.

2. Materials and methods

The samples used were derived from a total of 133 children of European-American descent between the ages of 5–11 years. After obtaining appropriate consent, the use of archival radiographs conformed to institutional standards that had been reviewed and approved by an ethical committee at the University of Michigan, USA. Seventy-three individuals with a Class III molar occlusion (Guyer et al., 1986) were compared to 60 children with a normal, Class I molar relation. The total sample included an approximately equal number of males and females, who all had no history of airway problems and no obvious vertical skeletal discrepancies (Sato, 1994). The total sample comprised seven age-matched (5, 6, 7, 8, 9, 10, 11 years) and sex-matched groups for each occlusal type (Class I, Class III). Chronological age was assumed to match developmental age as carpal radiographs were not available.

The magnification of each lateral cephalograph was standardized to an 8% enlargement factor. It was assumed 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 lateral cephalograph was traced on to frosted acetate film (0.03″ thick) and checked by one investigator (GDS). To increase the reliability of the landmarks selected, cephalographs were taped to a light box of uniform brightness in a darkened room and the landmarks digitized by using a cross-wire cursor. Eight homologous mandibular landmarks were identified and digitized (Fig. 1; Table 1) with appropriate software and a digitizing table (Numonics Inc., Montgomeryville, PA). These landmarks showed a discrepancy of $<1\%$ in their x, y coordinates on duplicate digitiation and were deemed to be reliably identified.

To determine whether mandibular landmark configurations differed between the two occlusal types independently of the clinical diagnosis, a Procrustes routine was implemented on an Amiga 3000 computer. An average 8-node geometry for each occlusal group was determined using a generalized orthogonal Procrustes analysis (Gower, 1975; Rohlf and Slice, 1990; Singh et al., 1997a). Following this method, every object's coordinates were translated, rotated and scaled iteratively until the least-squares fit of all configurations was no longer improved. Therefore, all configurations were scaled to an equivalent size and registered with respect to one another. Each Class I group-mean geometry was also compared statistically to the age-matched Class III group average by analysis of variance (Gower, 1975). In each case, the null hypothesis was that the Class I mean was not significantly different from the Class III average. The residuals and corresponding F-values resulting from

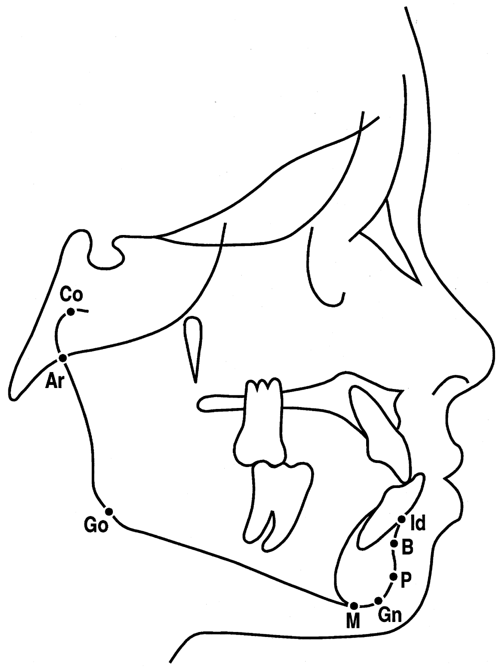

Fig. 1. Eight mandibular landmarks used in this study superimposed on a cephalographic tracing of a Class III profile. The definition of each homologous landmark is found in Table 1.

the analysis described above were computed, tabulated and compared.

Due to concerns expressed by Lele (1993) about the robustness of Procrustes analysis, and the likelihood of inequality of the variance–covariance matrices of the samples, the occlusal types were also compared using EDMA (Lele and Cole, 1996). This is a coordinate-free, statistical procedure for the comparison of two forms using all possible linear distances between homologous landmarks. Form matrices are constructed for the numerator and denominator configurations. EDMA compares these matrices and the form-difference matrix generated thus allows determination of the way the two shapes differ. It identifies those linear distances that are the most and least different among the forms being compared (Lele and Richtsmeier, 1991; Ayoub et al., 1994). EDMA has been successfully employed in several biological and clinical studies (e.g., Lele and Richtsmeier, 1991; Ayoub et al., 1994, 1995). By using a new EDMA procedure (Lele and Cole, 1996), the assumption of equality of variance–covariance matrices is bypassed. Therefore, distances between each of the eight homologous landmarks were calculated and EDMA matrices formed for the Class I and Class III configurations. The corresponding linear distances were compared and statistical significance of form difference was tested by the non-parametric bootstrap method (Lele and Richtsmeier, 1991; Lele and Cole, 1996).

Finally, eight linear distances (mm) between coordinates were calculated (Table 1) as well as five selected mandibular angles (°). By employing bivariate statistical analysis (paired *t*-tests), the battery of linear and angular variables delineated was analysed. This part of the study enabled comparison of the baseline data with previous studies that were restricted to conventional cephalometric analysis.

Table 1
Definitions of mandibular homologous landmarks and variables

Co	Condylion (superior-most point on mandibular condyle)
Ar	Articulare (intersection of dorsal contour of condylar head and posterior cranial base)
Go	Gonion (mid-point at angle of mandible)
M	Menton (inferior-most point on mandibular symphysis)
Gn	Gnathion (most anteroinferior point on mandibular symphysis)
P	Pogonion (anterior-most point on mandibular symphysis)
B	Supramentale (point B: deepest point on mandibular alveolus)
Id	Infradentale (most anterosuperior point on mandibular alveolus)
Linear distances (mm)	Angular measurements (°)
Co–Gn	Co–Gn–B
Gn–B	Co–Go–Gn
Co–Go	Ar–Go–M
Go–Gn	Id–Gn–Go
Ar–Go	Id–M–Go
G–M	Id–Gn
Id–M	

Table 2
Procrustes analysis comparing normal (Class I) and prognathic mandibular (Class III) indivuals; TM compares the total Class I and Class III mandibular samples

Age	Residual	*F*-value	Significance
05	0.00038	1.0093	$p < 0.01$
06	0.00101	2.2508	$p < 0.001$
07	0.00044	1.4321	$p < 0.001$
08	0.00008	0.3077	N.S.
09	0.00036	1.6401	$p < 0.001$
10	0.00032	1.2394	$p < 0.001$
11	0.00053	1.4582	$p < 0.001$
TM		4.706	$p < 0.001$

3. Results

Residuals computed from the Procrustes analysis for the two occlusal types were tabulated and compared using an *F*-distribution (Table 2). For the overall comparison [Total Mandible (TM); Table 2], there was a statistically significant difference between the mean Class I and Class III mandibular configurations ($p < 0.001$). When the total Class III sample was decomposed into seven age- and sex-matched groups and compared to the equivalent Class I subgroups, the mandibular configurations were also significantly different ($p < 0.001$) for all age-based comparisons (age 5 years; $p < 0.01$) except for age 8 years (no statistical difference).

With EDMA (Lele and Cole, 1996), comparison of the total sample demonstrated a statistical significance ($p < 0.01$) between the two occlusal types. The form matrix signified that a shape difference existed between the two occlusal forms, and that the greatest differences in morphology arose in the anterior mandibular regions (Table 3). For example, a form difference for P–B of 0.83 and 0.92 for Gn–B indicated an increase in size between pogonion and supramentale, and between gnathion and supramentale, for the Class III configuration. Other symphyseal distances exhibited an increase, with the M–P form difference at 1.14, while the M–Gn form difference rose to 1.26, demonstrating an increased size in the mental region for the Class I configuration. In contrast, the variables that spanned the mandible, such as Id–Co and Gn–Co, showed remarkable uniformity (Table 3), suggesting that for these there was little difference between the two configurations. Generally, size and shape change were more apparent in the symphyseal region when the two occlusal types were compared.

Results of the bivariate tests carried out on the total sample and age subgroups of the two occlusal types are presented in Table 4. Bivariate analysis of the total sample indicated that the mandibular-body length of 75.9 mm (Go–Gn) was greater in the Class III sample than in the normal sample (73.9 mm) ($p < 0.005$). Similarly, the mandibular-body length of 71.7 mm (Go–M) was greater in the Class III occlusal type than in the normal sample (68.4 mm) ($p < 0.005$). Despite these findings, there were no differences in panmandibular length (Co–Gn) when normal and Class III types were tested. These findings reflect the EDMA results reported above.

The ramus height of 54.0 mm (Co–Go) was shorter in the total Class III sample than in the total normal sample (55.9 mm) ($p < 0.005$). Similarly, the ramus height of 42.7 mm (Ar–Go) was shorter in the Class III sample than in the normal sample (45.8 mm) ($p < 0.005$). In contrast, the supramentale length (Gn–B) was longer in the Class III group (19.2 mm) than in the normal group (17.6 mm) ($p < 0.001$). However, there was no difference in symphyseal heights as indicated by the variables Id–Gn or Id–M. These results further corroborate the EDMA findings.

For mandibular angles, angle Ar–Go–M was slightly more acute in the total Class III sample (133°) than in the total normal group (135°) ($p < 0.05$), but no statistical differences for angle Co–Gn–B or angle Co–Go–Gn were found when the two occlusal types were tested. However, the symphyseal angle (Id–M–Go) was somewhat more acute in the Class III sample (84°) than in the normal sample (87°) ($p < 0.05$) but no statistical difference in mental angle (Id–Gn–Go) was detected. Therefore, the combination of morphometric and cephalometric analyses showed good corroboration. Moreover, that the mandibular configurations analysed are distinctly different appears to emerge from morphological differences noticeable in the anterior-most region of the Class III mandible.

4. Discussion

Mandibular prognathism, commonly associated with Class III malocclusions, is a facial disharmony for which individuals frequently seek treatment (Capelozza et al., 1996). In view of the heterogeneity of this class of malocclusions, we here defined a Class III occlusal type on the molar relation (Guyer et al., 1986). Although other studies have adopted classifications based on cephalometric analysis (e.g. Enlow et al., 1969), ANB angle (Hashim and Sarhan, 1993), incisor relations (Battagel, 1994), or deciduous canine relations (Tollaro et al., 1996), the present selection criterion was supported when tested independently of the clinical diagnosis using Procrustes analysis. Similarly, growth of the mandible can be described by the use of anthropometry, vital stains, histology, and serial roentgenography sometimes in combination with radiopaque implants (Bjork, 1968; Sarnat, 1986). Each approach has advantages and inherent disadvantages

Table 3
EDMA with the total normal (Class I) sample of individuals as numerator and the total prognathic mandibular sample of indiviuals (Class III) as denominator

Form matrix for numerator sample:								
M	0.000							
Gn	0.046	0.000						
P	0.081	0.048	0.000					
B	0.146	0.129	0.083	0.000				
Id	0.215	0.199	0.152	0.070	0.000			
Co	0.814	0.842	0.824	0.768	0.742	0.000		
Ar	0.773	0.805	0.792	0.743	0.724	0.090	0.000	
Go	0.499	0.540	0.542	0.521	0.532	0.408	0.334	0.000
Form matrix for denominator sample:								
M	0.000							
Gn	0.037	0.000						
P	0.071	0.043	0.000					
B	0.155	0.140	0.100	0.000				
Id	0.215	0.200	0.159	0.061	0.000			
Co	0.819	0.840	0.827	0.761	0.741	0.000		
Ar	0.771	0.794	0.785	0.728	0.716	0.093	0.000	
Go	0.523	0.554	0.558	0.534	0.546	0.394	0.312	0.000
Form difference matrix (sorted):								
P	B	0.831						
Gn	B	0.919						
M	B	0.944						
M	Go	0.954						
P	Id	0.956						
Co	Ar	0.969						
P	Go	0.971						
Gn	Go	0.974						
Id	Go	0.974						
B	Go	0.976						
M	Co	0.993						
Gn	Id	0.993						
P	Co	0.997						
M	Id	1.000						
Id	Co	1.000						
Gn	Co	1.002						
M	Ar	1.003						
P	Ar	1.009						
B	Co	1.010						
Id	Ar	1.012						
Gn	Ar	1.013						
B	Ar	1.020						
Co	Go	1.036						
B	Id	1.158						
Ar	Go	1.072						
Gn	P	1.119						
M	P	1.141						
M	Gn	1.259						

Probability that the forms are the same: $p < 0.01$.

but newer methods, e.g. elliptical Fourier analysis (Lowe et al., 1994) are preferable, owing to the intrinsic deficiencies of conventional cephalometric analyses (Grayson et al., 1985).

We used a Procrustes analysis (Singh et al., 1997a), the advantage of which is that all configurations are scaled to an equivalent size and registered with respect to one another. The disadvantages of Procrustes analysis (e.g., its reliance upon the assumptions of equality of variance and normality of distribution) have been discussed by Lele (1993). Kerr and Ford (1991) assessed homogeneity of variance in 10-year-old boys and reported that the linear dimensions that demonstrated the greatest variability included mandibular-

Table 4
Bivariate statistical tests on linear and angular variables of normal (Class I) and prognathic mandibular (Class III) individuals

Age	*n*	Co–Gn	Gn–B	∠Co–Gn–B	Co–Go	Go–Gn	∠Co–Go–Gn	Ar–Go	Go–M	∠Ar–Go–M	Id–Gn	∠Id–Gn–Go	Id–M	∠Id–M–Go
Class I														
05	10	106.7	17.7	53.93	56.3	72.8	125.72	46.0	67.2	136.71	28.4	78.30	30.2	87.82
06	7	105.7	17.2	58.42	55.1	72.3	126.39	47.4	66.7	136.61	26.2	79.67	28.3	89.71
07	7	107.8	18.3	51.24	56.4	73.5	126.45	45.8	67.7	136.74	27.4	74.86	28.9	85.32
08	9	106.5	18.1	50.47	54.9	75.2	123.40	44.6	70.2	133.74	27.1	77.75	29.8	86.08
09	9	106.9	17.5	48.81	56.0	75.0	122.58	46.1	69.3	132.90	27.0	76.10	29.7	85.82
10	9	106.9	17.6	49.08	56.6	74.8	121.94	46.1	68.9	132.78	26.1	76.88	28.4	87.68
11	9	107.8	17.1	48.56	56.1	73.8	126.49	44.8	68.7	136.93	28.5	73.90	31.5	84.71
TM1	60	106.9	17.6	51.49	55.9	73.9	124.70	45.8	68.4	135.21	27.2	77.23	29.5	86.72
Std		0.70	0.04	3.57	0.70	01.1	2.00	0.90	1.20	1.96	0.90	2.00	1.10	1.75
Class III														
05	9	106.2	20.3	56.05	53.8	74.6	125.47	43.3	70.2	135.26	28.5	78.88	30.6	85.93
06	7	106.1	19.7	55.20	52.6	76.0	124.74	41.3	72.1	134.13	28.4	79.16	30.4	85.51
07	10	106.4	20.1	53.73	54.3	75.1	124.14	43.3	71.0	133.82	26.7	78.78	28.8	85.84
08	10	106.8	19.0	50.20	55.2	76.0	122.04	43.6	71.6	131.01	27.8	78.22	29.9	85.53
09	17	107.1	18.8	48.31	53.7	76.1	124.86	42.2	72.2	134.45	27.3	74.93	29.3	81.61
10	10	106.8	18.7	49.15	53.7	76.8	122.91	42.5	71.9	132.00	27.1	76.72	29.3	85.29
11	10	107.1	17.9	47.99	54.6	76.5	122.82	42.9	72.8	131.37	26.3	74.65	28.4	81.27
TM3	73	106.6	19.2	51.64	54.0	75.9	123.85	42.7	71.7	133.15	27.4	77.38	29.5	84.46
Std		0.40	0.80	3.39	0.80	0.80	1.28	0.80	0.80	1.67	0.90	1.91	0.80	2.05
Significance		N.S.	$p < 0.01$	N.S.	$p < 0.01$	$p < 0.01$	N.S.	$p < 0.01$	$p < 0.01$	$p < 0.05$	N.S.	N.S.	N.S.	$p < 0.05$

The linear distances are in mm and the angles (∠) in degrees (°). TM1 is the total Class I sample and TM3 is the total Class III sample. Std is the standard deviation.

body length and total mandibular length. Indeed, Kerr et al. (1994), using an outlining technique, found mandibular form and size to be similar when comparing a sample of 10-year-old boys with Class III and Class I occlusions. Therefore, the inequality of the variance–covariance matrix is fundamentally important within a biological population, and this principle was reconciled by confirming the findings with a new analytical technique (EDMA; Lele and Cole, 1996) that bypasses these assumptions, and takes into account the limited size of cross-sectional samples. EDMA is, however, unable to provide a graphical display to illustrate changes in form. In a previous study (Singh et al., 1997d), thin-plate spline analysis was employed for graphical display. Therefore, in the present study conventional cephalometric analysis was also undertaken to demonstrate how the baseline data compared with those of some earlier studies.

It has long been held that mandibular form is influenced by genetics (Festing, 1974) and various extrinsic factors such as muscle development (Avis, 1959), growth (Walker and Kowalski, 1972), and tooth eruption (Dempster et al., 1963). Lavelle (1985) believes mandibular form to be essentially plastic in nature due to continuous remodelling. Presumably a characteristic, genetically inherited mandibular morphology is established very early on in ontogeny, and demonstrable in early childhood (Tollaro et al., 1996). This is the pattern that was discovered when the combined Class III sample was decomposed into seven age- and sex-matched groups and compared to the equivalent Class I group; the mandibular configurations were significantly different ($p < 0.01$) in nearly all the age-based comparisons. Therefore, form difference is a dominant feature of the Class III mandible, and this is developmental in origin (Burdi and Spyropoulos, 1978; Malinowski, 1983; Goret-Nicaise and Dhem, 1984; Trenouth, 1985; Tollaro et al., 1994), establishing a premise of mandibular morphological diversity between normal and Class III phenotypes. It is likely that these statistical differences arise from localized changes in mandibular form that, in turn, reflect heterogeneic mandibular ontogeny.

To localize more precisely the regional differences in Class I and Class III mandibular form, the normalized Class I and Class III configurations were subjected to EDMA, which revealed that the greatest differences in mandibular morphology arise in the symphyseal region. Generally, these form differences indicated an increase in size in the symphyseal region in the Class III case, but the M–Gn form difference rose to 1.26, demonstrating a decreased size in the Class III mental region. Although size and shape changes were apparent in the symphyseal region, the panmandibular variables such as Id–Co showed remarkable uniformity, suggesting that there is no noticeable form change when normal and Class III mandibles are compared for this particular linear distance. That the morphological distinction appears to localize anteriorly is perhaps not surprising, in view of the prominent mental region associated with the prognathic mandibular profile. On the other hand, one could argue that the results merely reflect the fact that most of the landmark data were concentrated in the symphyseal region. Nevertheless, it is conceivable that continuous mandibular remodelling (Lavelle, 1985) could summate developmental changes occurring elsewhere, for example the condylar region, so that they appear to be most prominent at the anterior symphyseal region. This hypothesis was not tested here but using more landmarks in different regions of the mandible would have allowed such testing. Nevertheless, our findings are in accord with the principle that the growing mandibular ramus undergoes remodelling to give rise to the body of the mandible during postnatal ontogeny (Bjork, 1955; Sarnat, 1986).

Conventional bivariate tests indicated that the mandibular-body lengths Go–Gn and Go–M were greater in the Class III sample than the normal sample ($p < 0.005$). Guyer et al. (1986) found that the corpus length Go–Gn varied between 68.4 mm at age 5–7 years and 76.8 mm at age 11–13 years, while Jacobson et al. (1974) reported corpus lengths of 81.5 mm in boys and 77.6 mm in girls with Class III malocclusion. The present findings are in accord with previous studies, including those on the deciduous Class III mandible (Tollaro et al., 1994). The lack of size correction may, however, obfuscate findings; no statistical difference in the panmandibular length Co–Gn was found when the normal and Class III types were tested. The ramus heights Go–Co and Ar–Go were, however, lower in the Class III sample than in the normal sample ($p < 0.005$). It was also found that the ramus height Go–Co was similar to that calculated from the reports of both Jacobson et al. (1974) and Guyer et al. (1986) for mandibular prognathic children. Therefore, the baseline data for corpus lengths and ramus heights are in good agreement with those of other studies, and corroborate the morphological differences noted for the Class III mandible, using EDMA on normalized forms.

For mandibular angles, Tollaro et al. (1996) reported a mean Class III angle Ar–Go–M of 130° in 5.5–6.5-year-old children, and Battagel (1993) an angle of 132° in 12-year old, stable Class III children. Our Class III sample provided an Ar–Go–M angle of 133°, in good agreement with other Class III subpopulations, and statistically more acute than the 135° for the normal group ($p < 0.05$). Similarly, Jacobson et al. (1974) reported a gonial angle of 128° and this compares favourably with the statistically different Class III sample (approx. 124°). However, we found no statistical differences for angle Co–Gn–B or angle Co–Go–Gn when the two occlusal types were tested. Therefore, the present data for mandibular angles are in good agreement with those of previous studies and attest to statistical differences for the Class III mandible.

In the symphyseal region, the supramentale length Gn–B was greater in the Class III group than the normal group ($p < 0.001$), but no difference in symphyseal heights was elicited, as indicated by the variables Id–Gn or Id–M. In contrast, the symphyseal angle Id–M–Go was more acute in the Class III sample (84°) than the normal sample (87°) ($p < 0.05$), but no statistical difference in mental angle Id–Gn–Go was detectable. Therefore, cephalometric analysis in the symphyseal region does not reveal striking dissimilarities when unscaled Class I and Class III phenotypes are compared, and supports the use of the morphometric analyses described above. The use of EDMA (Lele and Cole, 1996) on size-scaled data represents a novel development in the application of morphometric techniques. The favourable results of this form-determination analysis reveal symphyseal localization of morphological diversity.

Although conventional cephalometry remains the foundation for the clinical diagnosis of Class III malocclusions, our study utilized newer morphometric procedures including Procrustes superimposition and EDMA (Lele and Cole, 1996). As a result of these procedures, geometric configurations of anatomical landmarks scaled to equivalent areas avoided problems introduced by differences in size, avoided registration on any individual node, and accounted for relatively small sample sizes as well as potential inequalities of variance–covariance matrices. The morphometric techniques provide statistical descriptions which can be used to hypothesize developmental mechanisms that may account for the phenotypic differences noted. Other work has been directed at graphical analyses such as thin-plate spline (Singh et al., 1997b,d) and tensor analysis (Singh et al., 1997c, 1998) so that the changes in mandibular morphology noted for Class III malocclusion may be more easily visualized. In this way it might be possible to identify growth stages when abnormal changes in mandibular form are most pronounced. From a clinical perspective, it might be important to target these periods for corrective procedures and therefore stave off radical intervention later in development when such morphological abnormalities are fully expressed. Therefore, predictive regionalized mandibular ontogeny may aid the clinician in the management of Class III orthodontic patients.

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