

Mandibular morphology in subjects with Class III malocclusions: Finite-element morphometry

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The determinants of occlusion, such as interocclusal distance, envelope of motion, chewing stroke, and tooth-to-tooth relationships, vary for different classes of occlusion.¹ The Class III patient undergoes changes in occlusal patterns because occlusal morphology is dictated by mandibular size and length.¹ Therefore, mandibular prognathism may be one feature responsible for Class III malocclusion.² In this respect, Tollaro et al.³ examined children with Class III malocclusion and reported larger mandibular body lengths and forward positioning of the mandible at ages 4, 5, and 6 years. It appears that mandibular form is influenced by genetics, muscular factors, growth, and tooth development.⁴ The secondary cartilage of the mandibular condyle shows intrinsic growth po-

tential,⁵ and this presumably contributes to the development of Class III malocclusions. In addition, differences in velocity and deceleration in growth may account for sexual dimorphism of total mandibular length⁶ as well as the final occlusal pattern. Burdi and Spyropoulos⁷ consider that prenatal growth patterns of the human mandible are complex and that abnormal mandibular shape may be directly associated with altered masseter muscle morphologic features. Therefore, developmental features of the mandibular condylar cartilage are not fully understood, and its morphological contribution to Class III malocclusion remains unclear.

There is a growing realization that conventional osteometric data are of uncertain scientific validity, primarily due to the lack of dissociation be-

Abstract

The absence of physical restraint may be associated with a mandibular allometry that contributes to mandibular prognathism. Cephalographs of 73 prepubertal children of European American descent with untreated Class III malocclusions were traced and eight mandibular landmarks digitized. The resulting eight-noded geometries were normalized, and the mean Class III geometry compared with the equivalent Class I average. Procrustes analysis established statistical difference ($p < 0.05$) between these mean configurations. A color-coded finite-element (FEM) analysis was used to localize differences in morphology. Comparing Class III and normal mandibular configuration for changes in size, FEM revealed positive allometry of the mandibular corpus and around suprmentale (15% increase in size), with reductions (30%) between the incisor alveolus and menton. For changes in shape, mandibular configurations were predominantly isotropic, with the exception of the anisotropic anterior region in the Class III subjects. Incremental growth differences are consistent with the view that the absence of physical restraint is associated with mandibular prognathism.

Key words

Class III • Finite element • Mandible • Morphology • Morphometry

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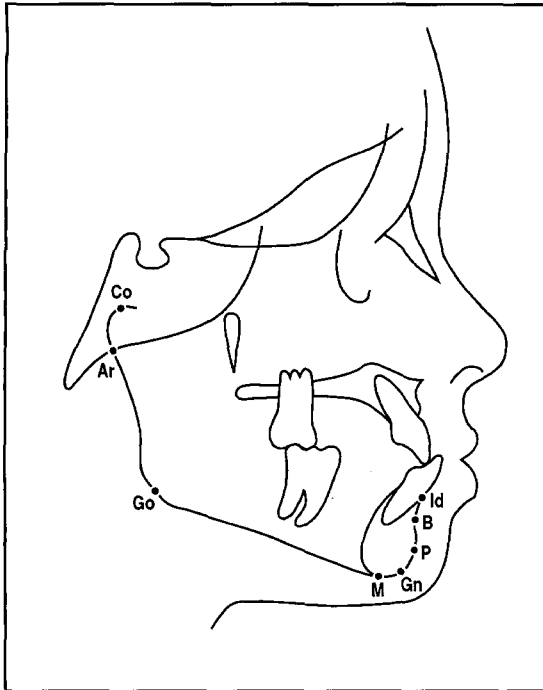


Figure 1A

Figure 1A
Eight mandibular landmarks used in this study superimposed on a cephalographic tracing of a Class III profile. Definitions are found in Table 1.

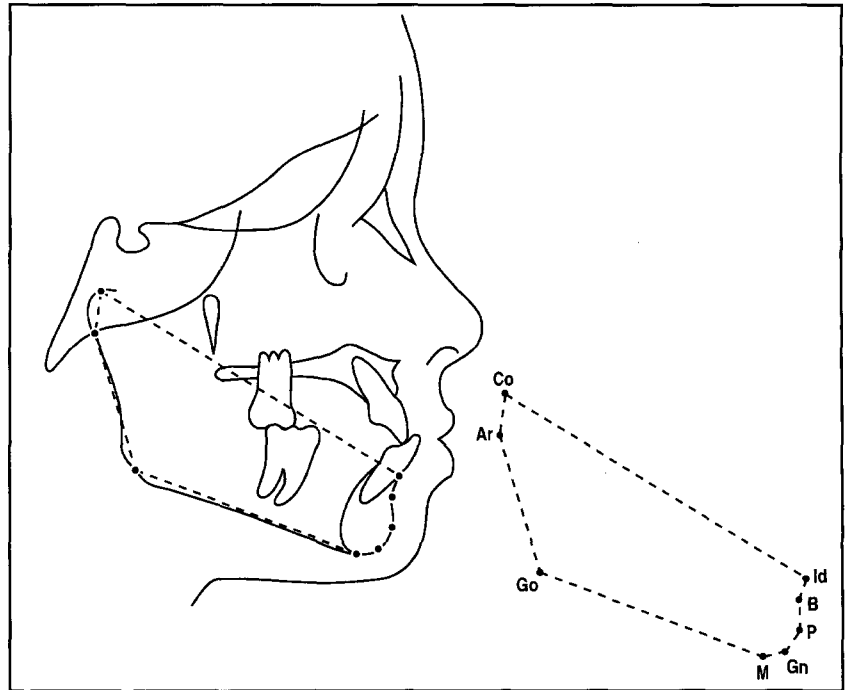


Figure 1B

Figure 1B
Geometry derived from landmarks used for FEM analysis in this study and cephalographic tracing of a Class III profile.

tween size and shape parameters.⁴ It has been shown, however, that finite element analysis (FEM) is well suited for comparisons of form (e.g., Lozanoff and Diewert,⁸ Singh et al.⁹). In the analysis of mandibular form, Corner and Shea¹⁰ used landmark data to provide measures of shape- and size-differences in giant transgenic mice (MT-rGH) using FEM scaling. Moss¹¹ analyzed differences in adult female murine mandibles using FEM because this method overcomes the conceptual and methodologic constraints of both craniometry and cephalometry. Similarly, Cheverud et al.¹² used FEM to uncover significant genetic variation in mandibular size and shape in inbred mice. Therefore, there appears to be a genetic basis for a more forward growing mandible¹³ and this may be associated with the distinctive profile of Class III malocclusions.

However, there is a dearth of studies devoted to the analysis of human mandibular morphology, and few reports in the current literature have employed FEM as the technique of choice in the analysis of the etiology of Class III malocclusions. Therefore, the aim of this study was to apply FEM⁹ to human mandibular configurations and determine local size- and shape-change differences in subjects with normal and Class III malocclusion, and to test the hypothesis that the absence of physical restraint is associated with incremental condylar growth¹⁴ and the concomitant development of mandibular prognathism. Rejection of the null hypothesis will allow the

formulation of therapeutic modalities for the alteration of mandibular form during morphogenesis to achieve a well-balanced facial profile.

Materials and methods

The sample used in this study was derived from a total of 133 children of European-American ancestry between the ages of 5 years and 11 years. A group of 73 subjects with Class III molar occlusion¹⁵ was compared with a group of 60 children with a normal Class I molar relationship. The use of archival radiographs conformed to institutional standards that had been reviewed and approved by an appropriate institutional board at the University of Michigan. The sample included approximately equal numbers of males and females with negative history of airway problems and no obvious vertical skeletal discrepancies. Chronological ages were assumed to match developmental ages, as carpal radiographs were unavailable. The whole sample also was discretizable into age-matched (5, 6, 7, 8, 9, 10, and 11 years) and sex-matched groups for each occlusal type (Class I, Class III).

The magnification of each lateral cephalograph used in this study was standardized to an 8% enlargement factor. 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). To increase the reli-

Table 1
Definitions of mandibular homologous landmarks

Co	Condylion (superiormost point on mandibular condyle)
Ar	Articulare (posterior intersection of condylar head and posterior cranial base)
Go	Gonion (midpoint at angle of mandible)
M	Menton (inferiormost point on mandibular symphysis)
Gn	Gnathion (most anteroinferior point on mandibular symphysis)
P	Pogonion (anteriormost point on mandibular symphysis)
B	Supramentale (Point B: deepest point on mandibular alveolus)
Id	Infradentale (most anterosuperior point on mandibular alveolus)

ability of the landmarks selected, cephalographs were taped to a light box of uniform brightness and digitization of landmarks was achieved in a darkened room using a cross-wires cursor. Eight homologous landmarks on the mandible were identified and digitized (Figure 1, Table 1), employing appropriate software and a digitizing table (Numonics Inc, Montgomeryville, Pa). These landmarks showed a discrepancy of <1% on duplicate digitization and were deemed to be reliably identified.

A generalized orthogonal Procrustes routine¹⁶ implemented on an Amiga 3000 computer was employed to generate a normalized Class I group mean geometry. 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.¹⁷ Therefore, all configurations were scaled to an equivalent size and registered with respect to one another. The Class I group mean geometry was compared statistically with the Class III group average geometry using an analysis of variance.¹⁸ In each case, the null hypothesis was that the Class I mean was not significantly different from the Class III average. Therefore, the Procrustes analysis¹⁵ was necessary to provide a measure of discrimination between the two occlusal groups independent of the clinical diagnosis. Residuals and corresponding *F*-values were computed, tabulated, and compared. In addition, the total sample was decomposed into seven age groups and scaled mean eight-node geometries for each

of the seven age groups were determined using the Procrustes analysis.^{15,16} Procrustes analysis was employed in order to determine whether mandibular landmark configurations differed between occlusal types at each age interval.

In order to localize differences in mandibular morphology and to identify the areas of greatest deformation, qualitative graphical FEM analysis was undertaken. For this analysis, the scaled overall average configuration generated with the Procrustes analysis for each occlusal type (Class I, Class III) was compared. After decomposition into age groups (5, 6, 7, 8, 9, 10, 11 years), the mean landmark configuration for each age group was also used to characterize alterations. In this study, the Class I average was taken as the initial geometry and the Class III configuration was the final geometry. Size-change variables were calculated as the product of principal extensions,^{8,9} whereas shape-change variables were calculated as the ratio of principal extensions.^{8,9} These values were calculated for at least 2000 points per geometry and were used to generate a color map using a log-linear scale. Areas of greatest or least change were characterized qualitatively, noting deformation based on the graphical display. Size- and shape-change values were tabulated at the location of anatomical mandibular landmarks for the normal and Class III groups. The FEM methodology followed that of Lozanoff and Diewert⁸ and Singh et al.⁹

Results

Procrustes analysis

Residuals and corresponding *F*-values derived from the initial Procrustes analysis indicated that the mean Class I and Class III mandibular configurations differed significantly (Table 2). Similarly, all but one of the seven age groups tested returned statistical differences for normal and Class III comparisons (Table 2).

Graphical analysis

Comparing mean normal and Class III mandibular configurations for size-change (Table 3), FEM analysis revealed that there were local increases in size of the mandibular corpus between gonion and menton of approximately 14% (Figure 2A). In contrast, between gonion and condylion, a reduction in size of the ramus of approximately 8% was detected. Around supramentale, a local increase in size of approximately 15% was noted, but this expansion was accompanied by a reduction in size in the incisor alveolus and menton regions in the Class III subjects. For shape-change (Table 3), the man-

Table 2
Procrustes analysis comparing normal (Class I) and prognathic (Class III) mandibular subjects. TM compares the total Class I and Class III sample

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	$p < 0.001$

Table 3
FEM size- and shape-change values at the location of anatomical mandibular landmarks for the average normal (Class I) and prognathic (Class III) mandibular configurations. Note the largest size-changes appear to be localized in the symphyseal region

Landmark	Co	Ar	Go	M	Gn	P	B	ld
Size	0.997	0.997	0.969	0.835	0.734	0.921	1.029	0.807
Shape	1.001	1.001	1.000	1.006	1.004	1.005	1.006	1.005

Figure 2
Graphical displays of size-changes derived from FEM analysis
A (top left): Combined age groups of Class I and Class III geometries. Note local increases in size of the mandibular corpus between gonion and menton and around supramentale. Some localized reductions in size are also detectable.
B: The pattern for the 5-year-old group is similar to that of the combined group, except there is less reduction in size in the menton region.
C: In the 6-year-old group, changes include corpus stretch and ramal diminution, with both positive and negative allometry visible in the symphyseal region.
D: The 7-year-old group demonstrates an almost isometric ramus, but similar patterns of corpus lengthening and positive symphyseal allometry are evident.
E (top right): The 8-year-old group shows some ramus diminution but, unlike any of the other age groups, positive allometry in the infradental region.
F: The 9-year-old group displays positive allometry in both ramus and corpus regions. Similar changes in the symphyseal region as other age groups were found.
G: The 10-year-old group shows negative allometry, but the symphyseal changes are similar to those of the other age groups.
H: The 11-year old group demonstrates corpus lengthening, ramus shortening, and symphyseal changes comparable to most other age groups.

dibular configurations were predominantly homogeneous except in the symphyseal regions between infradentale and pogonion, where anisotropic changes were evident. These localized differences in the incisor alveolus region and pogonion were notable for the Class III subjects (Figure 3A).

Decomposition of the sample into the seven age- and sex-matched groups revealed that, at age 5 years, a similar pattern of size-change emerged, although less reduction in size in the mental region was noted for the Class III subjects (Figure 2B). Similarly, the 6-year-old group (Figure 2C) exhibited corpus stretch and ramal diminution with both positive and negative allometry visible in the symphyseal region. The 7-year-old group (Figure 2D) demonstrated an almost isometric ramus, but similar patterns of corpus lengthening and positive symphyseal allometry were evident. In contrast, the 8-year-old group (Figure 2E) showed some ramus diminution but a positive allometry in the infradental region, unlike any of the other age subgroups.

The 9-year-old group (Figure 2F) exhibited positive allometry in both ramus and corpus regions, but changes in the symphyseal region similar to other age groups were found. The 10-year old group (Figure 2G) showed the largest negative allometry for the ramus (a diminution in size by some 15%) but the symphyseal changes were similar to those of the other age subgroups. Finally, the 11-year-old group (Figure 2H) demonstrated corpus lengthening, ramus shortening, and symphyseal changes comparable to most other age subgroups.

For shape-change, the 5- to 7-year-old groups were similar (Figures 3B-D). The majority of the mandibular configurations were isotropic, with evidence of anisotropy restricted to the symphyseal regions. However, while the 8-year-old group (Figure 3E) exhibited an anisotropic condylar region, the 9-year-old group (Figure 3F) displayed isotropy in that region as well as in the incisor alveolus region. The 10-year-old group (Figure 3G) was the most isotropic, exhibiting minor anisotropy of about 0.5%. Finally, the 11-year-old group (Figure 3H) demonstrated homogeneity in mandibular shape-change with anisotropy restricted to the alveolar and supramentale regions.

It appears that the combination of a longer mandibular corpus and shorter ramus, allied with changes in mandibular and symphyseal angles, distinguish the Class III morphology from the normal mandible. Moreover, these morphological differences are predominantly local-

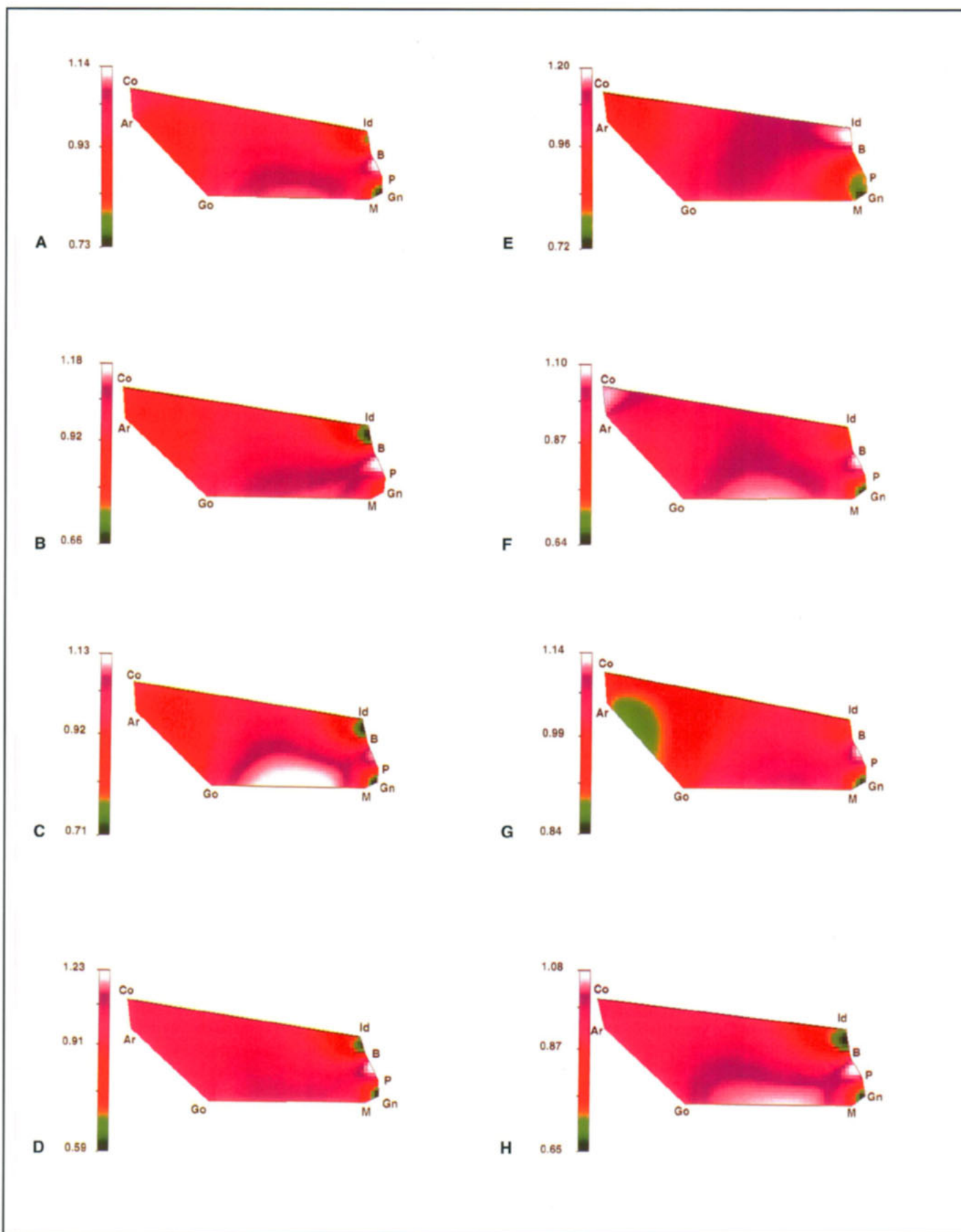


Figure 2A-H

ized anteriorly and may have a bearing on the prognathic mandibular profile associated with Class III malocclusions.

Discussion

For the orthodontic management of mandibular prognathism, it would aid the clinician to know whether Class III malocclusion is caused by variations in mandibular position or mandibular morphology, or a combination of the two.¹⁹ In the investigation of these factors, large longitudinal samples may be better than cross-sectional samples, but serial cephalographs of the subjects in this study were not available. Therefore, although age- and sex-matched groups were employed, the use of mean, cross-sectional Class I and Class III forms may not be optimal because the averages may show biological variation. Most previous studies, however, do not allow for size differences between individuals. This oversight may confound results and account for some of the difficulties encountered when investigating the etiology of Class III malocclusions. To avoid these problems, the mandibular forms were normalized prior to graphical FEM analysis in the present study. Class III malocclusions can be defined in different ways, including, for example, on the basis of cephalometric analyses, incisor relationships,²⁰ or molar relationships.¹⁵ Only the latter definition was adopted in this study. Nevertheless, a random nature of selection is a fundamentally important assumption in the analysis of variance, and this principle was complied with despite the limited

size of the cross-sectional samples.

Previous investigations of craniofacial growth and morphology have been either purely descriptive or have involved the use of cephalometric points, lines, and angles; neither method has given an entirely clear picture of the changes that occur.²¹ Sameshima and Melnick²² addressed this issue using color-coded finite-element triangles, and Battagel²⁰ employed tensor analysis, as graphical representation seems to facilitate interpretation of cephalometric data. Bookstein²³ argued, however, against the use of descriptive FEM for actual configurations of more than three landmarks; one of the problems he cited was the choice of triangles. However, others have shown that the reliability of pooled data is satisfactory for intergroup FEM comparison.²⁴ For morphometric analysis, scaled data are preferentially employed as they permit decomposition of shape- and size-influences at the local level. Such decomposition should allow formulation of developmental algorithms that account for any changes observed. Although FEM is neither a statistical nor a quantitative analytical technique, these deficiencies were avoided by undertaking Procrustes analysis at the outset. Alternative techniques in which analysis is not limited to pre-assigned triangles, e.g., thin-plate spline analysis,²⁵ are subjects of a further study;²⁶ and although the current examination is limited to two-dimensional analysis, it compares favorably with both conventional and morphometric studies. Therefore, in the present study, detailed, localized changes in the size and shape of normal and Class III mandibular configurations were assessed using finite-element analysis.⁹

The morphometric findings of this study are in accord with those of Lavelle,²⁷ whose medial axis transformation study demonstrated that, in 12- to 15-year-old females, mandibular shape was less variable than size. In their conventional analysis, Williams and Andersen²⁸ noted that mandibular prognathism was partly the result of an increase in mandibular length, as did Guyer et al.¹⁵ Similarly, Miyajima et al.²⁹ also reported an increased pan-mandibular length (Co-Gn) in a large sample of untreated Class III Japanese females. Nevertheless, Sato³⁰ supported Dietrich's³¹ view, that forward positioning of the mandible due to anterior displacement of the glenoid fossa is also an important etiologic factor in the development of Class III malocclusions.

In the present study, it appears that the combination of a longer mandibular corpus and shorter ramus, allied with acute mandibular and symphyseal angles, distinguishes a Class III man-

Figure 3
FEM graphical display of shape-change derived from FEM analysis.
A (top left): Combined age groups of Class I and Class III geometries show that mandibular configuration is predominantly homogeneous except in the symphyseal regions between infradentale and pogonion, where anisotropic changes are evident.
B: The shape-change in 5-year-old age group is similar to that of the combined group. The majority of the mandibular configuration is isotropic, with evidence of anisotropy restricted to the symphyseal region.
C: In the 6-year-old group, the majority of the shape-change is isotropic, with evidence of anisotropy restricted to the symphyseal region.
D: Change in the 7-year-old group is similar to that of the combined groups. The majority of the mandibular configuration is isotropic, with evidence of anisotropy in the symphyseal region.
E (top right): The 8-year-old group exhibits an anisometric condylar region, with some anisotropy evident anteriorly.
F: The 9-year-old group displays isometry in the condylar and incisor alveolus regions, with evidence of anisotropy in the symphyseal region.
G: The 10-year-old group is the most isotropic, exhibiting only minor anisotropy of about 0.5% around supramentale.
H: The 11-year-old group demonstrates homogeneity in mandibular shape-change with anisotropy restricted to the alveolar and supramentale regions.

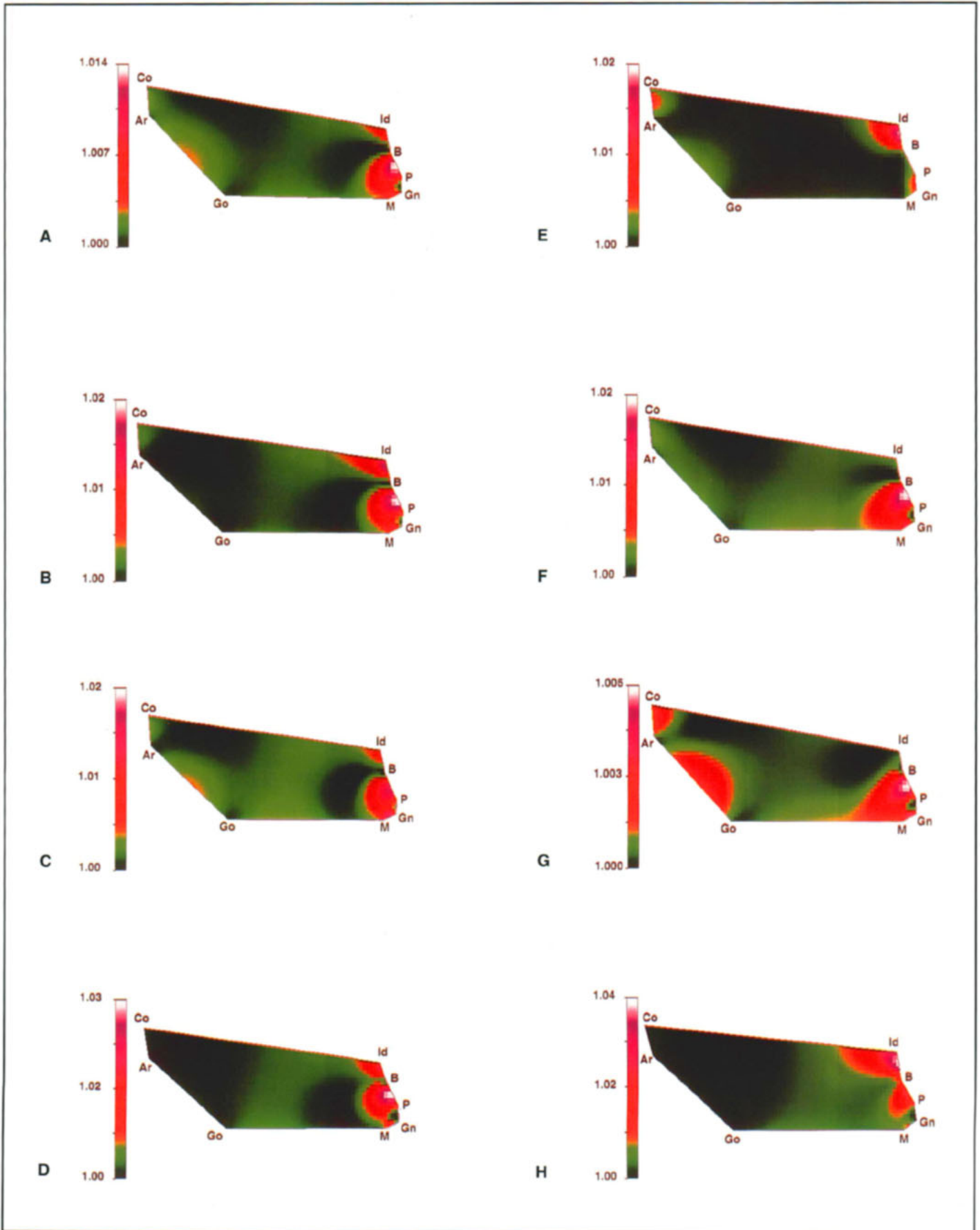


Figure 3A-H

dible from a normal one. Using finite element analysis, it has been demonstrated that differences between Class I and Class III mandibular configurations are due to local uniform size increases that give rise to a significant change in mandibular morphology when overall size is removed. Therefore, there is a size-related form change and, in this case, an increase in size (positive allometry). That these morphological differences localize at the anterior extremity of the mandible may have a bearing upon the mandibular prognathic appearance associated with Class III malocclusions. These morphometric findings lend support to a developmental hypothesis of incremental condylar growth and mandibular allometry. With concomitant remodeling³² and the absence of physical restraint, these developmental patterns may be associated with the emergence of mandibular prognathism.^{13,15}

Allometry equates change in shape with changes in size, whereas anisotropy is viewed as one aspect of affine changes that can produce a change in shape. In the analysis of mandibular allometry presented, nearly all nodal values hovered below the 1.0 value, indicating that Class III configurations are actually smaller in size. Yet, in the intervening areas, the values were >1.0, indicating local size increases. But the variation from 1.0 at nodes is somewhat misleading as it is very small (i.e., 0.997 at condylion). Presumably, such nodal consistency indicates the highly isotropic nature of the change at the nodes, confirmed by no or very low levels of shape change (1.000 to 1.006). Therefore, one conclusion could be developmental compensation. It appears that functional matrices (soft tissues, muscle attachments, etc.) maintain nodal positioning despite absolute increases in size elsewhere (e.g., in the body of the mandible) as in these intervening areas the values were >1.0, indicating local increases in size. Therefore, the Class III mandibles are absolutely larger than the Class I case (positive allometry); this has been achieved largely through uniform stretch (incremental growth). This supposition is confirmed by the uniform nature of the shape-change (poorly anisotropic). These findings support a developmental hypothesis of condylar hyperplasia with concomitant remodeling^{4,12,32} and are in accord with the view that Class I and Class III mandibles exhibit similar developmental mechanisms with changes in local trajectories¹² leading to morphological dimorphism in the absence of physical restraints.

Goret-Nicaise and Dhem³³ reported that during normal development, endochondral ossification occurred in the condylar cartilage and that the

fetal mandibular body entails woven bone formation along Meckel's cartilage. They also found mineralized tissue different from calcified cartilage ("chondroid") in the mandibular symphysis in pre- and postnatal human mandibles. Anisotropic changes were particularly well localized in the symphyseal region in our study, and these changes were allied with an acute mandibular symphyseal angle in the Class III subject. Heterogeneous shape-change during symphyseal maturation and remodeling of the mandible itself could be partially responsible for the characteristic prognathic Class III mandibular profile.¹³

Given the plastic nature of mandibular growth and development, it is feasible to suggest that orthodontic therapies may modulate prognathic mandibular growth patterns. Growth attenuation is likely, because the condylar cartilage cannot grow against intermittent or continuous forces.¹⁴ For example, Mimura and Deguchi³⁵ reported that chin cup therapy changed the direction of mandibular ramus growth, while the condylar heads bent forward. Similarly, de Alba³⁶ reported that mandibular growth was attenuated, giving less mandibular growth, and the condyles repositioned. These treatment-induced changes were accompanied by retruded incisors and molars that were redirected distally. In another study, Tollaro et al.³⁷ induced changes therapeutically in the growth direction of the condyles and compensated for excessive mandibular growth. But Vego¹³ negated the idea that Class III traction simply repositions the condyle within the fossa; it is likely that the observed changes include remodeling of the mandible itself.¹³ Kerr and Ten Have³⁸ suggested that overclosure may be significant also. Nevertheless, the present study supports the view that, in the absence of physical restraint, incremental growth appears to be associated with mandibular prognathism.

In summary, anteroposterior elongation of the mandibular body incorporated within the Class III configuration is demonstrable using FEM. It appears that mandibular allometry is a developmental feature associated with the emergence of Class III malocclusions in the absence of physical restraints, such as orthodontic appliances. Furthermore, we are able to localize these changes in the corpus and symphyseal regions, and determine that the change in mandibular morphology is not so much one of overall shape-change, but rather size-change. The clinical significance of this study is that mandibular prognathism can be precipitated by the growth patterns of the prepubertal Class III mandible.

Moreover, early diagnosis is crucial³⁹ if orthodontic growth attenuation of the Class III patient is to be attempted to establish a more favorable craniofacial growth pattern, because the presence of mechanical pressure can limit the growth of the young, actively growing condyle.^{13,14} Our findings reflect the earlier view of Cheverud et al.,¹² that morphological differences between normal and Class III mandibles arise because of variations in the local size of regions relative to contiguous regions. Contributions of other craniofacial components require delineation, however. Malinowski⁴⁰ suggested that the cranial base is important for increase in length and breadth of the mandible, and Singh et al.^{9,16,25} commented on the significance of cranial base in Class III malocclusions. Further studies will focus on other craniofacial regions, including the midface and soft tissues, to determine the overall patterning of the retruded midfacial appearance.

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