ORIGINAL ARTICLE

Localization of mandibular changes in patients with Class II Division 1 malocclusions treated with Twin-block appliances: Finite element scaling analysis

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Thirty mandibular landmarks were digitized from cephalographs of 46 children (prepubertal, ≈10 years old) and 53 adolescents (pubertal, ≈13 years old) to determine mandibular morphological changes in patients with Class II Division 1 malocclusions treated with Twin-block appliances. Procrustes superimposition computed average geometries and an analysis of variance were performed on the cephalographs. Prepubertal pretreatment and ≈13-month–posttreatment profiles and pubertal pretreatment and ≈22-month–posttreatment profiles were statistically different ($P < .002$). In male prepubertal configurations, a color-coded finite element scaling analysis revealed a conspicuous area of positive allometry (≈12%) in the condylar neck and negative allometry (≈17%) at the apex of the coronoid process. For the female prepubertal configuration, local increases in size were discernible in the condylar neck (≈3%) and in the apex of the coronoid process (≈4%). Comparing male pubertal configurations, finite element scaling analysis revealed marked positive allometry (≈27%) in the condylar neck and negative allometry (≈16%) at the apex of the coronoid process. For the female pubertal configurations, local increases in size were noticeable at the condylar neck (≈15%), with negative allometry (≈9%) in the coronoid process. For shape change, all configurations were highly isotropic over the entire mandibular nodal mesh. Therefore, in growing patients treated for Class II Division 1 malocclusions with Twin-block appliances, condylar growth, coronoid process remodeling, and osteogenesis in corpus and dentoalveolar regions may reflect the correction of the underlying skeletal dysmorphology. (Am J Orthod Dentofacial Orthop 2001;119:419-25)

The aim of orthodontic treatment of children with malocclusions is to produce a well-balanced facial profile in addition to an acceptable occlusion. Despite good pretreatment planning and patient selection, facial esthetics may not be ideal, and this may be compounded by relapse after an initially successful course of treatment. Dentofacial orthopedists believe that functional appliances train patients in oral and tongue posture. In the treatment of Class II malocclusion, an early phase of functional appliance treatment is commonly used to simplify subsequent therapy and to optimize the development of the facial skeleton. Unfortunately, the latter expectation enjoys little support in the literature. A prospective trial found no evidence that functional appliances can alter the shape of the mandible.[1] Indeed, a study that compared matched patients from a 2-stage bionator/edgewise regimen and a conventional 1-stage edgewise treatment found that the groups underwent essentially indistinguishable skeletal changes; the early phase of functional treatment conferred no obvious measurable benefits.[2] Similarly, another study reported that the length of the mandible did not increase in young adult patients treated with functional regulator therapy.[3]

When the effects of Fränkel's functional regulator appliance (FR-4) were evaluated cephalometrically in the treatment of anterior open bite, it was found that the growth of the mandible could be changed to an upward and forward direction.[4] Indeed, another study reported that the major skeletal effect of functional regulators was on the mandible.[5] Similarly, it was reported that an increase in mandibular length occurred with tooth- and tissue-borne functional appliances.[6] Likewise, in skeletofacial-matched cases with severe Class II Division 1 malocclusion, Herbst therapy significantly increased mandibular length with sagittal repositioning.[7]

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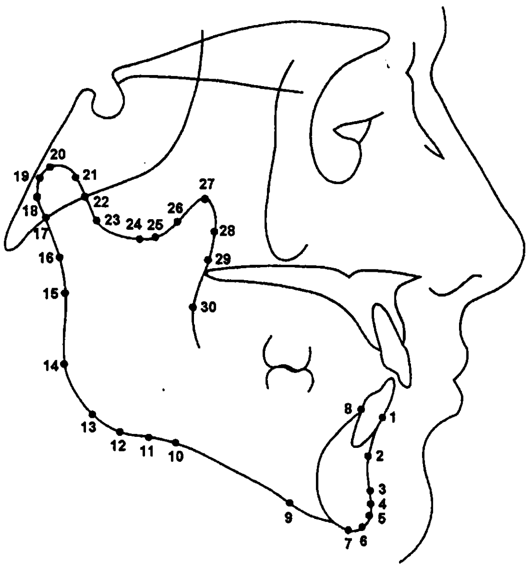

Fig 1. Definitions of homologous mandibular landmarks used during FESA size-change and shape-change analyses. *1,* Infradentale, most anterosuperior point on labial aspect of mandibular alveolus; *2,* supramentale (point B), deepest point on mandibular alveolus; *3,* most superoposterior point on symphysis above pogonion; *4,* pogonion, most anterior point on symphysis; *5,* gnathion, most anteroinferior point on mandibular symphysis; *6,* midpoint of curvature between gnathion and menton; *7,* menton, inferiormost point on mandibular symphysis; *8,* most anterosuperior point on lingual aspect of mandibular alveolus; *9,* point of deepest convexity between menton and antegonial notch on inferior border of mandible; *10,* point of deepest concavity between menton and antegonial notch on inferior border of mandible; *11,* antegonial notch, most superior point of concavity on inferior border of mandible; *12,* inferior gonion, most inferior aspect of gonial curve; *13,* gonion, midpoint at angle of mandible; *14,* superior gonion, most superior aspect of gonial curve; *15,* point of deepest concavity on posterior border of ramus; *16,* point of deepest concavity between posterior border of ramus and articulare; *17,* articulare, posterior intersection of condylar head and posterior cranial base; *18,* most posterior point of condylar head; *19,* most superior point on posterior border of condylar head; *20,* condylion, most superior point on mandibular condyle; *21,* most superior point on anterior border of condylar head; *22,* most anterior point of condylar head; *23,* most anteroinferior point of condylar head on sigmoid curve; *24,* sigmoid notch, most inferior point between condylar head and coronoid process; *25,* most inferior point between sigmoid notch and coronoid process; *26,* most anterosuperior point between sigmoid notch and coronoid process; *27,* apex of coronoid process; *28,* most anterior point on anterior border of ramus; *29,* deepest convexity inferior to apex of coronoid process; *30,* most posterior point on anterior border of ramus.

More recently, it was reported that increased mandibular lengths can be found in 12-year-old patients[8] and adolescents[9] treated with Twin-block appliances (TBA). A similar cephalometric study by Mills and McCulloch[10] indicated that mandibular growth is greater in patients with severe Class II malocclusion, reflecting the finding that an increase in ramus and body length can occur in patients with Class II malocclusion treated with TBA.[11] These studies, however, were unable to localize the effects of TBA on mandibular growth. Indeed, there are remarkably few studies that have used the newer geometric morphometric techniques that have become available for the assessment of allometry (size-related shape change) in patients undergoing orthodontic therapies.[12] Thus, cephalometric studies demonstrate generic mandibular lengthening, but the actual sites of putative mandibular bone growth are not determinable.[9-11] The lateral pterygoid muscle hypothesis states that postural and functional activity of the superior and inferior heads increases after insertion of a functional appliance and stimulates condylar growth. The goals of this retrospective longitudinal study were to test the hypothesis that mandibular form differs in patients treated with TBA and to localize those changes.

MATERIAL AND METHODS

Sample

After consent was obtained, pretreatment lateral cephalographs of 46 consecutive patients (ages 9-11) with Class II Division 1 malocclusions were gathered from an orthodontic practice. Fifty-three cephalographs of untreated patients (ages 12-14) with similar Class II relationships were also obtained. The sample comprised males and females with large overjets and distal occlusions with moderate to severe Class II skeletal relationships. Chronological ages were assumed to match developmental ages in this study because carpal ages were unavailable.

It was presumed that when all radiographs were taken the central x-ray passed along the transmeatal axis while the teeth were in occlusion. The magnification of each film was standardized to 8%. For each lateral cephalograph, the x and y coordinates of 30 homologous mandibular landmarks (Fig 1) were digitized with the use of appropriate software and a digitizing tablet (RMO, Calabascus, Calif). These discrete, maximal, and extremal landmarks encompassed the lateral profile of the mandible and permitted the construction of the mandibular configurations to be studied.

Geometric morphometric techniques

For statistical analysis, a Procrustes method was used to determine the variance around each landmark and express it as a root-mean square. Thus, each group was subjected to Procrustes superimposition, and each group was represented as a mean and a variance. The Procrustes routine was implemented on an Amiga 3000 computer (Amiga, Snoqualmie, Wash) and an average 30-noded geometry for each group was determined by using a generalized orthogonal Procrustes analysis.[13] According to this method, every object's coordinates were translated, rotated, and scaled iteratively until the least-squares fit of all configurations was no longer improved. Thus, all configurations were registered with respect to each other, and, as a result of this procedure, geometric mandibular configurations were scaled to equivalent areas and thereby avoided problems introduced by differences in size.

To determine whether prepubertal pretreatment and posttreatment mandibular landmark configurations differed, each pretreatment group mean geometry was compared statistically with the posttreatment group mean geometry with the use of an analysis of variance (ANOVA).[13] For these prepubertal children, the posttreatment cephalographs were taken at the end of active treatment (≈13 months after the start of treatment). Similarly, the pubertal pretreatment and posttreatment mandibular mean geometries were compared statistically. For this adolescent group, the posttreatment cephalographs were taken after ≈22 months of active treatment. The prepubertal and pubertal groups were also divided by sex so that the mean geometries for males and females at each age could be compared. Therefore, 4 comparisons were generated in total:

- pretreatment and posttreatment prepubertal males
- pretreatment and posttreatment prepubertal females
- pretreatment and posttreatment pubertal males
- pretreatment and posttreatment pubertal females

In all instances, the null hypothesis was that the pretreatment and posttreatment means were not significantly different. Residuals and corresponding F values were computed, tabulated, and compared. To demonstrate regions of alteration, a finite element scaling analysis (FESA) was undertaken that incorporated a spline interpolation function.[9] By taking this approach, differences can be described graphically as a size or shape change.[14-17] The FESA software was written in "C" and implemented on an Amiga 3000 computer. The mean pretreatment configuration was taken as the initial geometry and was compared with the corresponding posttreatment 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 principal extension divided by the lesser principal extension. 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 were then color-mapped into each pretreatment configuration to provide graphical displays of geometrical change for the particular comparison.

Table I. Procrustes analysis of mean pretreatment and posttreatment mandibular configurations of subjects treated with TBA

	Prepubertal males	*Prepubertal females*	*Pubertal males*	*Pubertal females*
Residual	0.0001	0.0001	< 0.0001	< 0.0001
F value	3.307	8.048	1.675	2.653
P <	.002	.002	.02	.002

As an independent investigation, conventional composite tracings were completed with the Image Pro (Quick Ceph Systems, San Diego, Calif) to determine pretreatment and posttreatment linear distances for mandibular length (articulare-gnathion), corpus length (gonion-gnathion), and ramus height (articulare-gonion). Thus, in this part of the study, simple cephalometry was used to compare the pretreatment and posttreatment cephalographs of the 4 groups. The purpose of this part of the investigation was to determine whether the results of conventional cephalometry were in agreement with the geometric morphometric techniques used above and to clarify how changes depicted with FESA are associated with Twin-block intervention.

RESULTS

Table I shows the results of the statistical analysis of the mean pretreatment and posttreatment mandibular configurations of patients treated with TBA. For both girls and boys, the ANOVA established statistical differences ($P < .002$) between the mean prepubertal pretreatment and the ≈13-month–posttreatment mandibular configurations. Statistical differences were also significant when comparing the mean male and female pubertal pretreatment and the ≈22-month–posttreatment mandibular profiles ($P < .002$).

Posttreatment changes in prepubertal patients

The differences in morphology in mandibular prepubertal male configurations were localized as a conspicuous area in the condylar neck with a positive allometry (≈12% increase in local size; Fig 2, *A*). In contrast, the apex of the coronoid process and the antegonial notch showed negative allometry (≈17% decrease in local size). The ramus and corpus, however, exhibited positive allometry (≈10%), whereas the symphyseal region indicated a small decrease in size (≈3%).

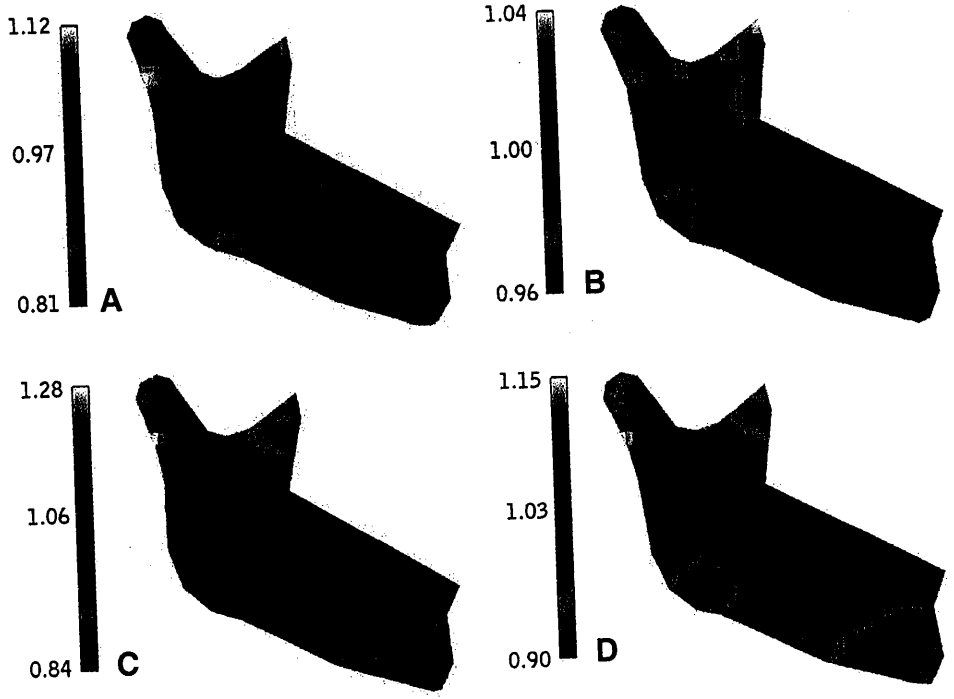

Fig 2. A, Prepubertal male configuration. Condylar neck shows white region, indicating ≈12% increase in local size. Apex of coronoid process and antegonal notch show green regions, indicating ≈17% decrease in local size. Ramus and corpus appear purple, indicating ≈10% increase in local size. Symphyseal region shows red coloration, indicating decrease in local size of ≈3%. **B,** Prepubertal female configuration. Note purple condylar coloration, indicating ≈3% increase in local size. Apex of coronoid process is white, indicating ≈4% increase in local size. Coronoid process and angle of mandible are green/black, indicating ≈5% decrease in local size. Ramus is red/purple, showing increase in size more anteriorly, although red symphyseal region indicates no change in local size. **C,** Pubertal male configuration. Note white/purple area of condylar neck region, indicating increase in size of up to ≈28%. Green coronoid process shows decrease in size of ≈16%. Reddish coloration of angle, ramus, corpus, and symphyseal regions indicates ≈1%-5% increase in size in those regions. **D,** Pubertal female configuration. Note white/purple coloration in condylar neck region, indicating ≈15% increase in local size. Green coloration of coronoid process, angle, and symphyseal regions indicates decrease in local size of ≈9%. Red regions of ramus show little change in size, whereas purple coloration of corpus indicates ≈2% increase in size.

The mandibular prepubertal female configuration (Fig 2, *B)* also showed condylar positive allometry. However, the growth was only ≈3% and not as well localized as that found in the prepubertal male. Instead, the apex of the coronoid process showed positive allometry (≈4%), but there was evidence of a decrease in the size of the coronoid process, as well as at the angle of the mandible (negative allometry ≈5%). Similar to the males, however, the corpus and ramus showed evidence of an anterior increase in size (≈3%), although the symphyseal region was predominantly isometric (no change in local size).

Posttreatment changes in pubertal patients

For the pubertal males, the mandibular configuration showed a marked area of positive allometry (≈27%) localized in the condylar neck region (Fig 2, *C)*. In contrast, the coronoid process showed negative allometry (≈16%). The angle, ramus, corpus, and symphyseal regions showed positive allometry (≈1%-5%).

The mandibular pubertal female configuration (Fig 2, *D)* showed a similar area of positive allometry (≈15%) in the condylar neck region. In contrast, the coronoid process, gonial angle, and symphyseal regions showed negative allometry (≈9%). The ramus, however, was isometric, and the corpus showed some positive allometry (≈2%).

For shape change, all mandibular configurations studied were highly isotropic over the entire mandibular nodal mesh (Fig 3, *A-D)* with little evidence of anisotropy (directionality of shape change).

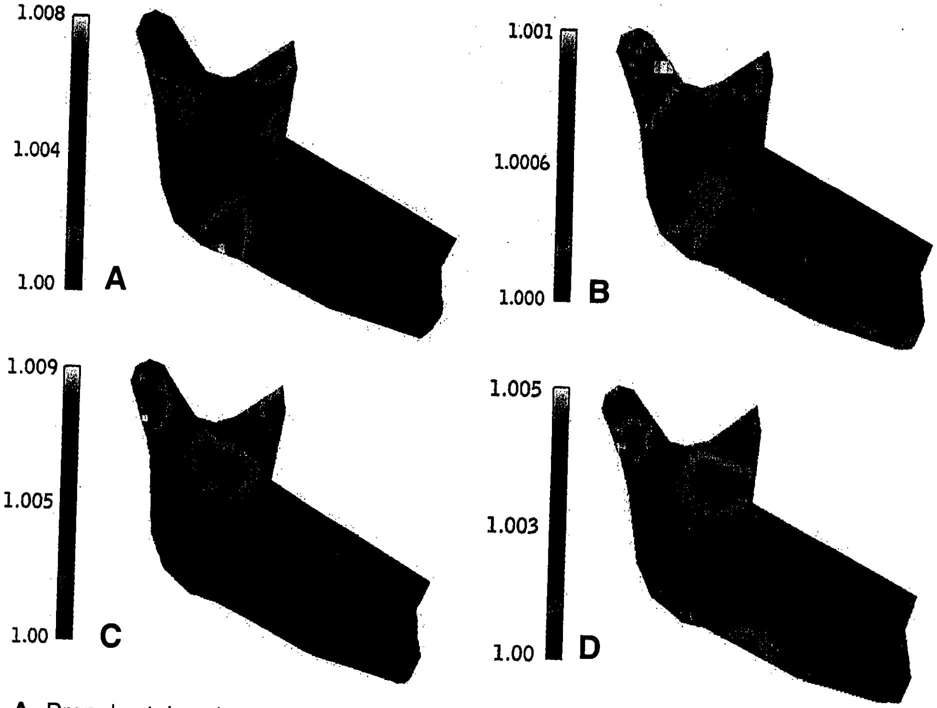

Fig 3. A, Prepubertal male configuration. For shape change, mandibular configuration is highly isotropic over entire mandibular nodal mesh. Minor anisotropy present at antegonal notch. **B,** Prepubertal female configuration. For shape change, mandibular configuration is highly isotropic over entire mandibular nodal mesh. Minor anisotropy present in condylar region. **C,** Pubertal male configuration. For shape change, mandibular configuration is highly isotropic over entire mandibular nodal mesh. Minor anisotropy present in condylar region. **D,** Pubertal female configuration. For shape change, mandibular configuration is highly isotropic over entire mandibular nodal mesh. Minor anisotropy present in condylar region, similar to pubertal male configuration.

For the conventional analysis, the parameter for mandibular length (articulare–gnathion) increased overall by ≈5 mm, from 110.8 mm to 116.2 mm, after treatment. Similarly, the corpus length (gonion–gnathion) increased by ≈3 mm, from 71.5 mm to 74.6 mm. In concordance, the ramus height (articulare–gonion) increased by ≈3 mm, from 45.5 mm to 48.8 mm.

DISCUSSION

Lack of geometric rigor in the analysis of landmark data can be addressed by techniques such as thin-plate spline analysis.[18-19] Although these techniques provide rigorous assessment of shape- and-size change, the presentation of findings as eigenvalues, partial warps, and bending energies might not be entirely appropriate for the clinician. Others have used Fourier analysis of mandibular outlines to compute cosine and sine coefficients of the harmonics, but graphical outputs might be preferable for ease of interpretation.[20] The use of Euclidean distance matrix analysis has also been advocated but its coordinate system invariance introduces graphical difficulties.[21] It has also been found that decomposition of morphological integration is possible with the use of FESA,[22-23] and this has been attempted in earlier studies.[14-17,24] Indeed, opinion is emerging that the FESA strains may represent localized proliferation of cells or extracellular matrix (ECM), as indicated by stereological parameters such as cell size and ECM volume in the anterior cranial base of mice. Thus, although the strains represent measures of morphological deformation, it is assumed that they might reflect localized cell and ECM growth activities and, although specific growth activities are not measured directly, the localized strain values are assumed to reflect such activities. Consequently, the application of FESA is warranted in this study, even though it is acknowledged that the color-coded configurations generated were based on a combination of discrete, maximal, and extremal landmarks encompassing the lateral profile of the mandible. Despite these drawbacks, the aim of this study was to localize differences in mandibular morphology in patients treated with TBA, and meaningful hypotheses relating to mandibular growth and development during TBA therapy were obtained.

The putative advantage of TBA therapy is that, in addition to producing an acceptable occlusal rehabilitation, it produces better facial esthetics—presumably well-balanced facial profiles with an absence of disharmonious facial features. Thus, it appears that TBA can deliver a high degree of satisfaction to both clinicians and patients.[25] The Twin-block is a versatile and effective appliance in the correction of Class II malocclusion because its main purpose is to advance the mandible and correct moderate to severe overjets.[26,27] Despite these claims, there have been remarkably few morphometric assessments of this mode of treatment. Therefore, the specific goal of this study was to apply FESA to retrospective age-, sex-, and ethnically matched data sets of patients treated with TBA and to determine if differences in mandibular form are demonstrable.

The concept of "growth guidance" of the mandibular complex has been investigated to some extent. For example, a histological study in young adult monkeys fitted with functional protrusive appliances concluded that adaptive capability might still be present in the temporomandibular joint of young adults.[28] A later study that investigated the effect of protrusive appliances in juvenile Rhesus monkeys reported that significant condylar growth occurred along with an overall increase in mandibular length.[29] The results of our study concur with those findings, as we noted positive allometry in the condylar region that presumably equates with condylar growth. In another study, both conventional and geometric analyses were used to evaluate adaptations in patients treated with the functional regulator of Fränkel.[30] This study found that the principal skeletal effect was anteroinferior advancement of the mandible, which produced increases in mandibular length and vertical face height.

Our findings also correspond with earlier conventional findings,[26-27] as positive allometry was noted in the mandibular corpus. Nevertheless, other areas showing positive allometry, such as the posterosuperior area of the ramus, the midregion of the corpus, and the dentoalveolar process, are not related to muscle insertions. Indeed, areas exhibiting isometry and negative allometry may be related to muscle attachment. Specifically, negative allometry at the gonial angle and the antegonial notch relates to the attachments of the masseter muscle, whereas isometry extends over its area of insertion on the ascending ramus. Similarly, areas of negative allometry on the coronoid process relate to the insertion of the tendon of the temporalis muscle. The area of the mental protuberance and the symphysis exhibit a negative allometry that may be associated with the insertion of the mentalis muscle. In the pubertal male, however, no negative allometry is observed in the ramus, gonial angle, or the symphysis, but these areas appear to be isometric during a period of rapid growth. In contrast, the distal aspect of the condylar neck consistently showed positive allometry at all stages examined, in line with the lateral pterygoid hypothesis.[31] In normal growth, significant bony remodeling is necessary in this area to maintain the shape of the mandibular ramus to compensate for distal condylar extension, vertical extension of the ramus, and thickening of the posterior border of the ramus.[32] The high degree of isotropy over the entire nodal mesh in the analysis of mandibular shape confirms that a similar remodeling process could occur during functional protraction to maintain the shape of the mandible.

It appears, therefore, that functional therapies may involve the following: developmental modulations at the condylar cartilage (a concept that cannot be investigated directly on patients),[31] epigenetic remodeling of the ramus and corpus, and osteogenic deposition that extends from the corpus of the mandible into the dentoalveolar areas. The importance of the latter factor relates to vertical adjustments of the occlusion, presumably in response to the observed increases in ramus height. Indeed, a comparison of condylar, ramus, and corpus allometry at the prepubertal and pubertal stages suggests that corpus growth makes a more significant contribution in prepubertal subjects than in pubertal subjects. This difference may reflect the natural process of bony remodeling that occurs in the corpus and dentoalveolar areas during the transition from mixed to permanent dentition. As might be expected, the contribution of condylar growth and remodeling in the ramus appears to increase during the pubertal stage.

In summary, we have attempted to model regions of proliferative growth and remodeling with the use of FESA. Presumably, localization of the size increase in the condylar neck region relates to chondrocytic proliferation in the growing patient, and, perhaps not surprisingly, the degree of cartilaginous enlargement was greater in adolescents compared with that in prepubertal children. These geometric changes might reflect increased activity of the lateral pterygoid muscle and subsequent condylar growth that correlates with observed increases in mandibular length in patients treated with TBA.[31] The morphology of the glenoid fossa, however, was not assessed in this particular study, and any translatory changes of the mandible require determination by undertaking a similar study of the maxillary and soft tissue matrices in patients treated with TBA.

CONCLUSIONS

- Localization of growth in the condylar neck with concomitant remodeling of the coronoid process may reflect the correction of mandibular form achieved with TBA.

- TBA therapy may involve developmental modulations at the condylar cartilage, remodeling of the ramus and corpus, and osteogenic deposition in dentoalveolar regions.

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REFERENCES

1. Nelson C, Harkness M, Herbison P. Mandibular changes during functional appliance treatment. Am J Orthod Dentofacial Orthop 1993;104:153-61.
2. Livieratos FA, Johnston LE Jr. A comparison of one-stage and two-stage nonextraction alternatives in matched Class II samples. Am J Orthod Dentofacial Orthop 1995;108:118-31.
3. McNamara JA Jr. Dentofacial adaptations in adult patients following functional regulator therapy. Am J Orthod 1984;85:57-71.
4. Erbay E, Ugur T, Ulgen M. The effects of Frankel's function regulator (FR-4) therapy on the treatment of Angle Class I skeletal anterior open bite malocclusion. Am J Orthod Dentofacial Orthop 1995;108:9-21.
5. Kerr WJ, TenHave TR, McNamara JA Jr. A comparison of skeletal and dental changes produced by function regulators (FR-2 and FR-3). Eur J Orthod 1989;11:235-42.
6. McNamara JA Jr, Howe RP, Dischinger TG. A comparison of the Herbst and Frankel appliances in the treatment of Class II malocclusion. Am J Orthod Dentofacial Orthop 1990;98:134-44.
7. Sidhu MS, Kharbanda OP, Sidhu SS. Cephalometric analysis of changes produced by a modified Herbst appliance in the treatment of Class II Division 1 malocclusion. Br J Orthod 1995;22:1-12.
8. Lund DI, Sandler PJ. The effects of Twin Blocks: a prospective controlled study. Am J Orthod Dentofacial Orthop 1998;113:104-10.
9. Illing HM, Morris DO, Lee RT. A prospective evaluation of Bass, Bionator and Twin Block appliances. Part I—The hard tissues. Eur J Orthod 1998;20:501-16.
10. Mills CM, McCulloch KJ. Treatment effects of the twin block appliance: a cephalometric study. Am J Orthod Dentofacial Orthop 1998;114:15-24.
11. Stangl DP. A cephalometric analysis of six Twin Block patients. A study of mandibular (body and ramus) growth and development. Funct Orthod 1997;14:4-6,8-14,17-9.
12. Bookstein FL. Morphometric tools for landmark data. Cambridge: Cambridge University Press; 1991.
13. Gower JC. Generalised Procrustes analysis. Psychometrika 1975;40:33-51.
14. Singh GD, McNamara JA Jr, Lozanoff S. Finite element analysis of the cranial base in subjects with Class III malocclusion. Br J Orthod 1997;24:103-12.
15. Singh GD, McNamara JA Jr, Lozanoff S. Finite element morphometry of the midfacial complex in subjects with Angle's Class III malocclusions. J Craniofac Genet Dev Biol 1997; 17:112-20.
16. Singh GD, McNamara JA Jr, Lozanoff S. Mandibular morphology in subjects with Angle's Class III malocclusion: finite-element morphometry. Angle Orthod 1998;68:409-18.
17. Singh GD, McNamara JA Jr, Lozanoff S. Finite-element morphometry of soft tissue morphology in subjects with untreated Class III malocclusions. Angle Orthod 1999;69:235-44.
18. Lynch JM, Wood CG, Luboga SA. Geometric morphometrics in primatology: craniofacial variation in Homo sapiens and Pan troglodytes. Folia Primatol (Basel)1996;67:15-39.
19. Singh GD, McNamara JA Jr, Lozanoff S. Soft tissue thin-plate spline analysis of pre-pubertal Korean and European-Americans with untreated Angle's Class III malocclusions. J Craniofac Genet Dev Biol 1999;19:94-101.
20. Ferrario VF, Sforza C, Poggio CE, Colombo A, Cova M. Effect of growth and development on cephalometric shapes in orthodontic patients: a Fourier analysis. Eur J Orthod 1997; 19:669-80.
21. Cole TM, Richtsmeier JT. A simple method for visualization of influential landmarks when using Euclidean distance matrix analysis. Am J Phys Anthropol 1998;107:273-83.
22. Richtsmeier JT, Cheverud JM. Finite element scaling analysis of human craniofacial growth. J Craniofac Genet Dev Biol 1986; 6:289-323.
23. Lozanoff S, Diewert VM. Measuring histological form change with finite element methods. Am J Anat 1986;177:187-201.
24. Sameshima GT, Melnick M. Finite element-based cephalometric analysis. Angle Orthod 1994;64:343-50.
25. Clark WJ. Twin block functional therapy: applications in dentofacial orthopaedics. London: Mosby-Wolfe; 1995.
26. Clark WJ. The twin block traction technique. Eur J Orthod 1982;4:129-38.
27. Clark WJ. The twin block technique. A functional orthopedic appliance system. Am J Orthod Dentofacial Orthop 1988;93:1-18.
28. McNamara JA Jr, Hinton RJ, Hoffman DL. Histologic analysis of temporomandibular joint adaptation to protrusive function in young adult rhesus monkeys (*Macaca mulatta*). Am J Orthod 1982;82:288-98.
29. McNamara JA Jr, Bryan FA. Long-term mandibular adaptations to protrusive function: an experimental study in *Macaca mulatta*. Am J Orthod Dentofacial Orthop 1987;92:98-108.
30. McNamara JA Jr, Bookstein FL, Shaughnessy TG. Skeletal and dental changes following functional regulator therapy on class II patients. Am J Orthod 1985;88:91-110.
31. Yamin-Lacouture C, Woodside DG, Sectakof PA, Sessle BJ. The action of three types of functional appliances on the activity of the masticatory muscles. Am J Orthod Dentofacial Orthop 1997;112:560-72.
32. Moyers RE, Enlow DH. Growth of the craniofacial skeleton. In: Moyers RE, editor. Handbook of Orthodontics. Chicago: Year Book Medical Publishers; 1988. p. 60-7.