ORIGINAL ARTICLE

# *Shape-coordinate analysis of skeletal changes induced by rapid maxillary expansion and facial mask therapy*

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The aim of this study was to evaluate maxillary and mandibular shape/size changes by means of Bookstein's shape-coordinate and tensor analysis in children with Class III malocclusions treated with rapid maxillary expansion and a facial mask in order to define optimum timing of intervention for this type of therapy. The treated group (46 subjects, 26 females and 20 males) was divided into two subgroups according to the stage of dentitional development. The early-treated group consisted of 23 subjects treated in the early mixed dentition (mean age at Time 1, 6 years 9 months ± 7 months); the late-treated group included 23 subjects treated in the late mixed dentition (mean age at Time 1, 10 years 3 months ± 1 year). The mean treatment period was about 11 months. The control group (32 subjects with untreated Class III malocclusion, 18 females and 14 males) also was divided into two subgroups (an early control group, 17 subjects in the early mixed dentition, and a late control group, 15 subjects in the late mixed dentition). Maxillary triangles (point T, the most superior point of the anterior wall of sella turcica, point FMN, the fronto-maxillary-nasal suture, and point A) and mandibular triangles (point Condylion, point Gonion, and point Pogonion) were digitized on cephalograms in both groups at Time 1 and Time 2. Combined facial mask and rapid maxillary expansion therapy produced a significant enhancement of the forward growth of the maxilla and significantly more upward and forward direction of growth of the mandibular condyle (leading to smaller increments in mandibular total length, Co-Pg) in the early-treated group when compared with controls and to the late-treated group. Both maxillary size and mandibular size were significantly affected by treatment in the early mixed dentition. The results of this study indicate that orthopedic treatment of Class III malocclusion induces favorable size and shape changes both in the maxilla and mandible, and that this combined treatment approach is more effective in the early mixed dentition than in the late mixed dentition. (Am J Orthod Dentofacial Orthop 1998;114: 418-26)

New descriptive methods of shape changes in craniofacial structures have been developed and implemented as major improvements when compared with conventional cephalometrics.[1-4] Among these methods, Bookstein's innovations have been used to investigate shape modifications related both to facial growth and to treatment.[4-8]

In particular, Bookstein[5] recently conceived a powerful morphometric tool to describe shape changes in any number of landmarks by analysis of shape-coordinate variables, which represent the shape of a triangle of landmarks in a manner completely independent of size. When a set of triangles is scaled so that the separation between one pair of landmarks is held constant, then the triangle may be considered to have been constructed with both of those landmarks fixed in position. In this way, the information about the shape of the original triangle is encoded in the only aspect of the data that remains free to vary, ie, the location of the third landmark. The Cartesian coordinates of that landmark (in the "shape space") are called shape coordinates of the original triangle. After statistical computations (ie, average of changes in groups and their comparisons) proceed with shape coordinates, findings are given biological interpretations by means of tensor analysis.

Shape-coordinate analysis can be supplemented by a separate measure of changes in size that may be correlated or uncorrelated with effects on shape. The size variable is uncorrelated with all shape-coordinates, and hence all ratios of homologously measured lengths, are "centroid size" (ie, the root-summed-squared set of interlandmark distances).[5]

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The aim of the present study was to evaluate both maxillary and mandibular shape/size changes in children with Class III malocclusions treated with rapid maxillary expansion (RME) and facial mask therapy by means of two coordinate-free biometric methods (Bookstein's shape-coordinate analysis and tensor analysis), in order to substantiate the modus operandi of maxillary protraction in the correction of skeletal Class III malocclusion in the mixed dentition with respect to the timing of treatment onset.

## SUBJECTS AND METHODS

### Treatment Group

Forty-six subjects (26 females and 20 males) were selected for the treatment group (TG) on the basis of inclusionary criteria. Patients were included if they were of European-American ancestry, if they presented for treatment in the mixed dentition, and if they had the following Class III occlusal signs: anterior cross-bite, Class III deciduous or permanent canine relationship, and mesial step deciduous molar relationship or Class III permanent molar relationship.[9] Further, in order to be included in the study, the patient had to have a pretreatment Wits appraisal ≥ –2 mm. Cephalograms were taken at the following time periods: pretreatment ($T_1$) and posttreatment ($T_2$). Generally, there was a 1 or 2 month period between the pretreatment ($T_1$) cephalogram and the actual start of treatment. The posttreatment ($T_2$) film was taken within 1 month of discontinuation of facial mask wear and removal of the expander. The mean age of the treated group at $T_1$ was 8 years 6 months ± 1 year 11 months, and at $T_2$ was 9 years 5 months ± 1 year 10 months. The mean treatment period was 11 months ± 4 months.

The TG was divided into two subgroups according to the stage of dentitional development. The early-treated group (ETG) comprised 23 subjects treated in the early mixed dentition (erupting permanent incisors and/or first permanent molars); the late-treated group (LTG) included 23 subjects treated in the late mixed dentition (erupting permanent canines and/or premolars). The mean age of ETG was 6 years 9 months ± 7 months at $T_1$ and 7 years 9 months ± 7 months at $T_2$, with a mean ETG treatment period of 1 year ± 5 months. The mean age of LTG was 10 years 3 months ± 1 year at $T_1$ and 11 years 1 months ± 1 year at $T_2$, resulting in a mean LTG treatment period of 10 months ± 3 months.

### Control Sample

Thirty-two subjects (18 females and 14 males) with untreated Class III malocclusion were selected from the files of the Department of Orthodontics of the University of Florence to comprise the control group (CG). This sample was used as a comparison group as it matched the treated group as to race, stage of dental development, Class III occlusal and skeletal signs, and gender distribution. The mean age of the control group was 7 years 11 months ± 1 year 11 months at $T_1$ and 9 years 9 months ± 2 years at $T_2$. The mean observation period without treatment was 1 year 10 months ± 1 year.

The control group also was divided into two subgroups according to dentitional phase. The early-control group (ECG) included 17 subjects in the early mixed dentition (as defined previously); the late-control group (LCG) comprised 15 subjects in the late mixed dentition. The mean age of ECG was 6 years 5 months ± 8 months at $T_1$ and 8 years 4 months ± 1 year and 2 months at $T_2$, resulting in an average observation period of 1 year 11 months ± 1 year. The mean age of LCG was 9 years 6 months ± 1 year 6 months at $T_1$ and 11 years 4 months ± 1 year 6 months at $T_2$, with a mean observation period of LCG of 1 year 8 months ± 10 months.

The two cephalograms from each subject in both the treatment and control groups were taken with the use of a standardized protocol on the same radiographic unit, and the enlargement factors were similar among units (about 7.5% to 8%); thus no correction was made for enlargement in the analysis of the films. Dental casts of all patients also were analyzed to assess the stage of dentitional development.

### Treatment Protocol

The components of orthopedic facial mask therapy in the treated group included a facial mask,[10] a bonded maxillary acrylic splint expander with vestibular hooks, and heavy elastics.[11,12] In patients with maxillary transverse deficiency, the midline expansion screw of the RME was activated once per day until the desired change in the transverse dimension was achieved (the lingual cusps of the upper posterior teeth approximating the buccal cusps of the lower posterior teeth). In instances in which no transverse change was necessary, the maxillary splint still was activated, usually once a day for 1 week to 10 days to disrupt the circumaxillary sutural system.

At the time of delivery of the facial mask, bilateral $^3/_8$-in, 8-oz elastics typically were used for the first 1 to 2 weeks of treatment to ease the adjustment of the patient to the appliance. The force generated then was increased by using $^1/_2$-in, 14-oz elastics, and finally $^5/_{16}$-in, 14-oz elastics. The direction of elastic traction was forward and downward from the hooks on the RME to the adjustable crossbar of the facial mask, so that the

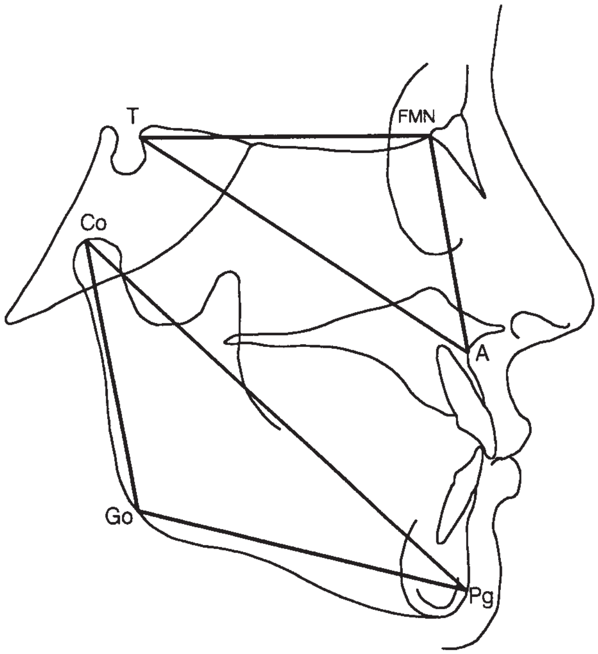

**Fig 1.** Maxillary and mandibular cephalometric triangles.

elastics did not interfere with the function of the lips. The patients were instructed to wear the facial mask on a full-time basis except during meals, although the actual amount of appliance wear was variable.

### Construction of Maxillary and Mandibular Triangles

The landmarks were digitized directly on the radiographs with a Numonics digitizing tablet (Numonics 2210, Numonics, Lansdale, Pa). Maxillary and mandibular triangles for each subject were constructed with the aid of digitizing software (Viewbox 1.8, as described by Halazonetis[13]).

The maxillary triangle was constructed with the following landmarks: Point T (the most superior point of the anterior wall of the sella turcica at the junction with tuberculum sellae, as described by Viazis[14]); point FMN (fronto-maxillary-nasal suture, according to Riolo et al[15]); and Downs' point A (Fig 1). The mandibular triangle was constructed by joining point Co (Condylion), point Go (Gonion), and point Pg (Pogonion) (Fig 1). The method error for these measurements is reported elsewhere.[16]

### Shape-coordinate Analysis

The segment from point T to point FMN and the segment from Gonion to Pogonion were chosen as baselines for maxillary and mandibular triangles, respectively. The two baselines were positioned in a Cartesian coordinate system so that one extremity (point T or point Go) corresponded to the origin (0.0) and the other extremity (point FMN or point Pg) was located at point (1.0), one unit to the right along the X-axis. After this transformation of the original triangles into "shape-coordinate space," shape coordinates for the third point (point A or point Co) in both treated and control groups were computed in a conventional statistical package (SPSS for Windows, ver. 6.1.3). The procedure was repeated for both triangles in both groups at $T_2$. Because of the homogeneity of treated and control groups (both in the early and late samples) as to age at $T_1$ and at $T_2$, type of malocclusion, craniofacial pattern at $T_1$, gender distribution, and observation period, the comparison between groups was performed on the annualized mean differences between $T_2$ and $T_1$ for the values of the third point.

All shape changes in shape space can be visualized as vectors connecting individual starting points ($T_1$) and ending points ($T_2$). A graphic reduction to a common starting point with a statistical distribution of ending points is possible. A vector representing mean shape change in each group of observations (treated and untreated groups) will originate from a common starting point. The vector difference between these two mean vectors (connecting the ending points of the two mean vectors) expresses the mean difference in shape change between the two groups. An adequate statistical method for comparison of vectors is Hotelling's $T^2$ test.

Shape changes in the ETG were contrasted with those in the ECG. Similarly, the changes in the LTG were compared with those in the LCG. In addition, the changes in ETG were compared with those in LTG to evaluate the effect of different treatment timing on treatment effects. Finally, the changes in ECG were compared with those in LCG to assess any significant growth differences between the two developmental phases that could account for differences between ETG and LTG.

### Centroid Size Analysis

Centroid size was measured both on maxillary and mandibular triangles in the treated and untreated groups. Centroid size was calculated as the root sum of squares of the sides of both maxillary and mandibular triangles. Size changes between $T_1$ and $T_2$ in the treated and control groups were compared by *t* test ($P < .05$).

### Tensor Analysis

Tensors for the mean shape change of triangles in each group were constructed according to the geometric method proposed by Bookstein in 1982.[4] Software (Viewbox, 1.8[13]) performed the geometric construction and calculated the strain along each principal axis. Changes expressed increments/decrements as annualized percentages of initial length ($T_1$) separately in the treated and untreated groups. This procedure allowed for a biologic interpretation of the shape changes that have been determined by shape-coordinate analysis. The interpretation was given according to a useful schematic representation provided by Bookstein.[5] Further, the "mean treatment effects," computed as the contrast of changes between the treated and untreated groups, are displayed in the same way.

## RESULTS

The results of the comparison between the treated and untreated groups (ETG vs ECG; LTG vs LCG) and between the early and late groups (ETG vs LTG; ECG vs LCG) for the annualized mean shape-coordinate differences between $T_2$ and $T_1$ are graphically displayed in Figs 2 to 9.

### Comparison Between ETG and ECG

In the maxillary triangle, shape comparison (early treatment effect) can be described as a mean vector difference pointing upward and forward in relation to the T-FMN baseline (Fig 2). The groups differed significantly ($P < .001$) in this change of shape-coordinates, as indicated by Hotelling's $T^2$ test. Tensor analysis of the early treatment effect in the maxilla identified a direction of greatest rate of change (–5.63% /12 months) bisecting the angle T-FMN-A, and a direction of least rate of change (4.33%/12 months) oriented about 5° clockwise of line T-A (Fig 2). These findings mean that early treatment induces an opening of the angle T-FMN-A with a forward and upward displacement of point A.

As for the mandibular triangle, the mean vector difference (early treatment effect) is expressed as a movement of Condylion in an upward and forward direction relative to the baseline Go-Pg. Hotelling's $T^2$ test indicated that these results were very significant ($P < .001$; Fig 3). Tensor analysis of the early treatment effect on the mandible showed a direction of greatest rate of change (–3.01%/12 months) oriented 5° counterclockwise relative to Co-Pg and a direction of least rate of change (2.18%/12 months) nearly bisecting the gonial angle (Co-Go-Pg; Fig 3). Consequently early treatment induced a closure of the gonial angle and a concomitant "shrinkage" of the mandibular triangle along the direction of total mandibular length (Co-Pg).

Change in centroid size from $T_1$ to $T_2$ differed significantly between early treated and control groups, both for the maxillary triangle (3.64 ± 1.29 for ETG and 1.65 ± 0.98 for ECG; $P < .001$) and for the mandibular triangle (2.55 ± 1.77 for ETG and 5.81 ± 2.67 for ECG; $P < .001$).

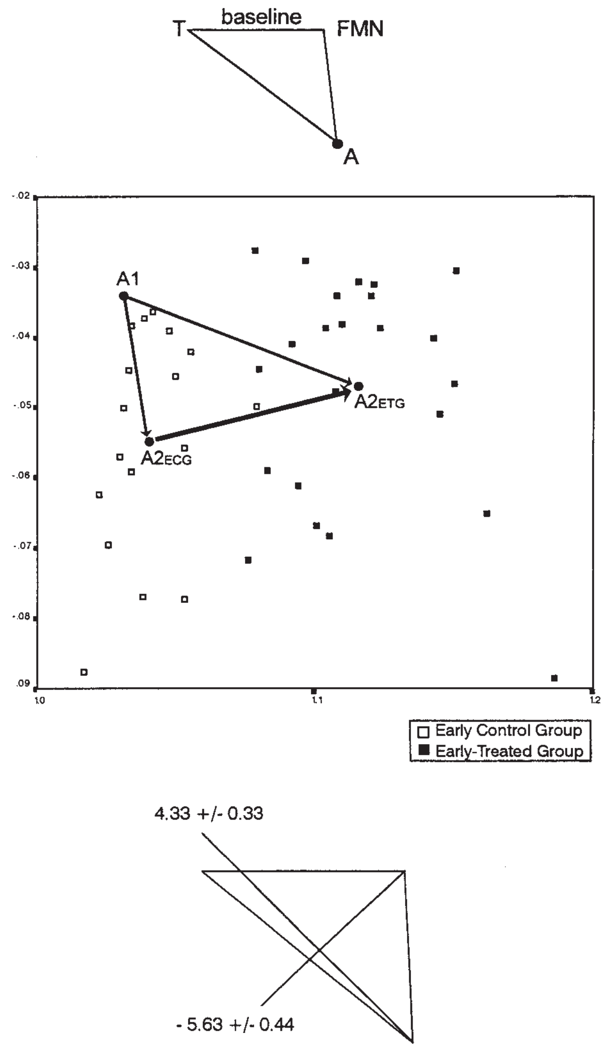


**Fig 2.** Graphic display of shape changes in ETG and ECG (maxillary triangle). Scatterplot represents annualized individual displacements of point A at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies vector difference of mean shape changes in the two groups.) Tensor analysis shows the treatment effect in the maxillary triangle (numbers indicate annualized percentage variations along the principal axes).

### Comparison Between LTG and LCG

In the maxillary triangle, the late treatment effect is described as a mean vector difference pointing upward and forward in relation to the T-FMN baseline (Fig 4). The groups did not differ significantly ($P = .134$) in this change of shape-coordinates, as shown by Hotelling's $T^2$ test. Tensor analysis of the late treatment

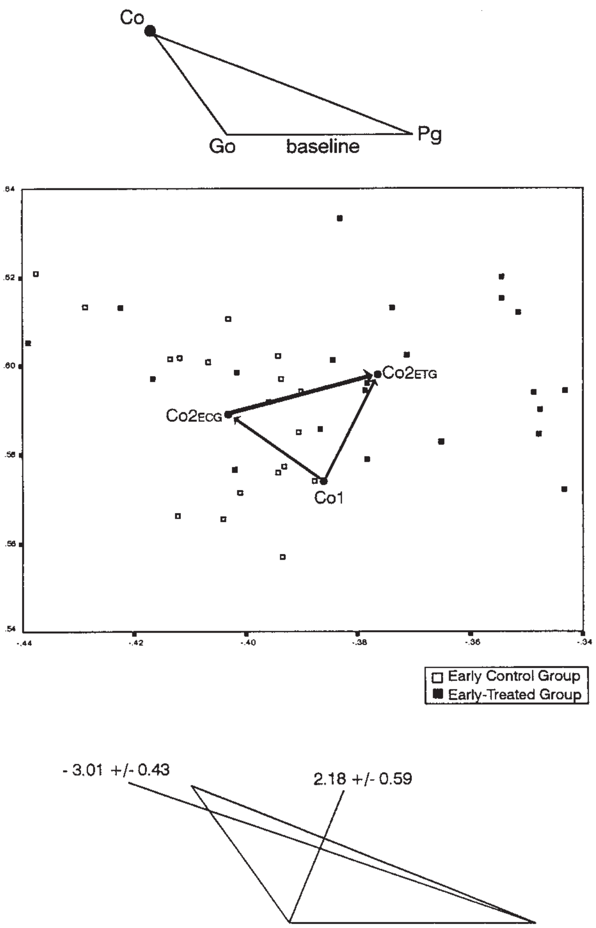


**Fig 3.** Graphic display of shape changes in ETG and ECG (mandibular triangle). Scatterplot represents annualized individual displacements of Condylion at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies vector difference of mean shape changes in the two groups.) Tensor analysis shows the treatment effect in the mandibular triangle (numbers indicate annualized percentage variations along the principal axes).

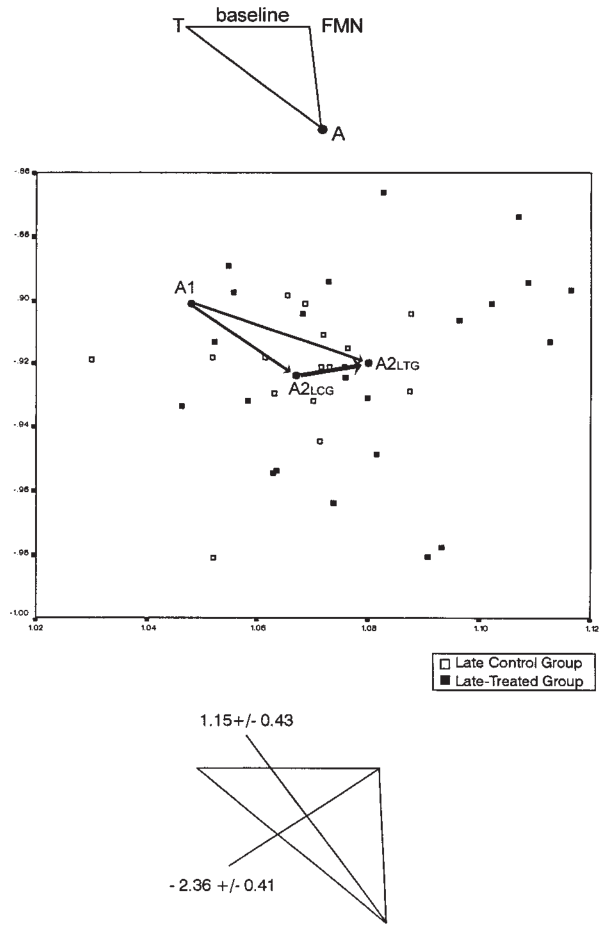


**Fig 4.** Graphic display of shape changes in LTG and LCG (maxillary triangle). Scatterplot represents annualized individual displacements of point A at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies vector difference of mean shape changes in the two groups.) Tensor analysis shows treatment effect in maxillary triangle (numbers indicate annualized percentage variations along principal axes).

effect in the maxilla identified a direction of greatest rate of change (–2.36%/12 months) nearly bisecting the angle T-FMN-A, and a direction of least rate of change (1.15%/12 months) nearly bisecting the angle FMN-A-T (Fig 4). Therefore, late treatment resulted in an opening of the angle T-FMN-A, leading to a forward and upward displacement of point A, though to a lesser extent than in the early-treated group.

As for the mandibular triangle, the mean vector difference (late treatment effect) represents a movement of Condylion in a downward and forward direction, a finding that was not statistically significant ($P$ = .064; Fig 5). Tensor analysis of the late treatment effect on the mandible showed a direction of greatest rate of change (–2.81%/12 months) oriented 30° clockwise of line Co-Go and a direction of least rate of change (–1.74%/12 months) approximately along the line Go-Pg (Fig 5). As for the biological interpretation, the bisector of the principal axes aligns with the bisector of the angle Co-Go-Pg. This means that the edge Co-Pg is rotating in a counterclockwise direction in relation to the gonial angle, with point Co moving towards point Go along Co-Go and point Pg moving away from Gonion along Go-Pg.

Change in centroid size from $T_1$ to $T_2$ did not differ significantly between late treated and control groups for the maxillary triangle (2.36 ± 1.59 for LTG and 2.23 ± 1.22 for LCG; $P$ = .79), whereas centroid

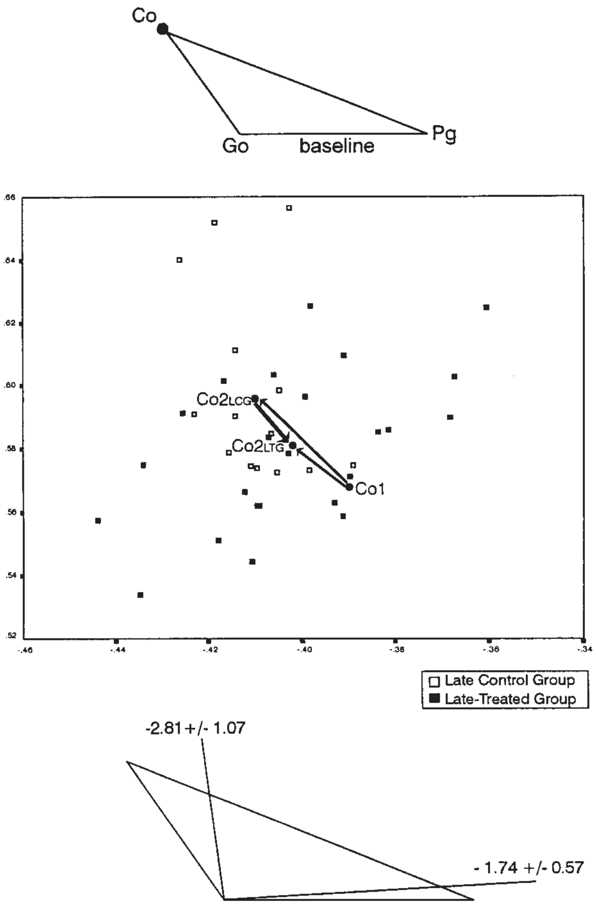


**Fig 5.** Graphic display of shape changes in LTG and LCG (mandibular triangle). Scatterplot represents annualized individual displacements of Condylion at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies vector difference of mean shape changes in the two groups.) Tensor analysis shows treatment effect in mandibular triangle (numbers indicate annualized percentage variations along principal axes).

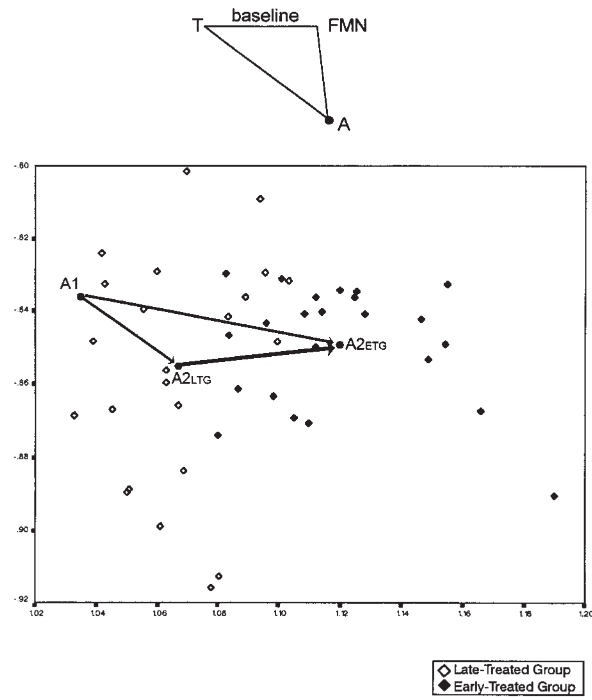


**Fig 6.** Graphic display of shape changes in ETG and LTG (maxillary triangle). Scatterplot represents annualized individual displacements of point A at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies vector difference of mean shape changes in the two groups.)

size change was significant for the mandibular triangle (2.49 ± 2.33 for LTG and 5.31 ± 2.85 for LCG; $P < .01$).

### Comparison Between ETG and LTG (Limited to Shape-coordinate Analysis Due To the Influence of Intergroup Size Differences on Both Tensor and Centroid Analyses)

In the maxillary triangle, shape comparison ("treatment timing" effect) can be described as a mean vector difference pointing forward nearly parallel to the T-FMN baseline (Fig 6). Hotelling's $T^2$ test assessed significant differences between the two treated groups ($P < .001$). In the mandibular triangle, the mean vector difference is expressed as a movement of Condylion in an upward and forward direction, a result that was statistically significant ($P < .05$; Fig 7).

### Comparison Between ECG and LCG (Limited to Shape-coordinate Analysis Due to the Influence of Intergroup Size Differences on Both Tensor and Centroid Analyses)

In the maxillary triangle, shape comparison ("growth" effect) can be described as a slight forward and downward displacement of point A in relation to the cranial base (Fig 8). Hotelling's $T^2$ test did not show significant differences between the two untreated groups ($P = .155$). In the mandibular triangle, the mean vector difference is expressed as a movement of Condylion in a slight upward and forward direction relative to the line Go-Pg, but this difference was not statistically significant (Fig 9).

## DISCUSSION

The effects on the craniofacial skeleton induced by facial mask (FM) therapy seldom have been investigated with adequate samples in the past,[17-19] especially with respect to the determination of optimum timing

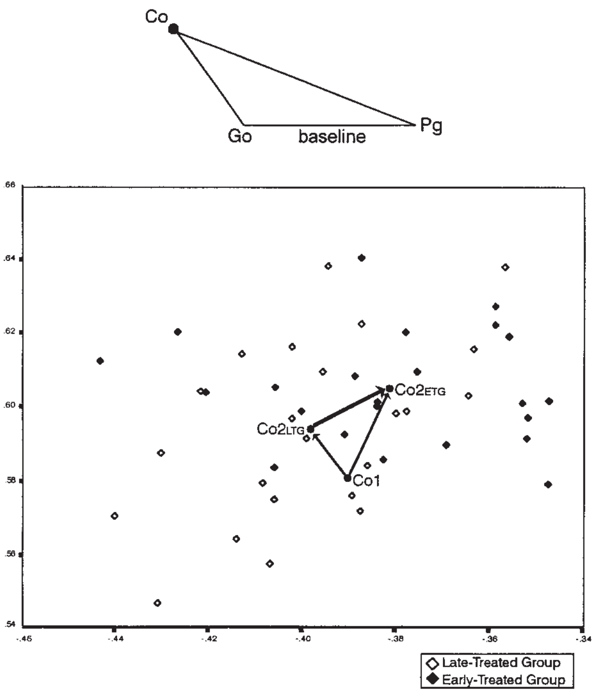


**Fig 7.** Graphic display of shape changes in ETG and LTG (mandibular triangle). Scatterplot represents annualized individual displacements of Condylion at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies vector difference of mean shape changes in the two groups.)

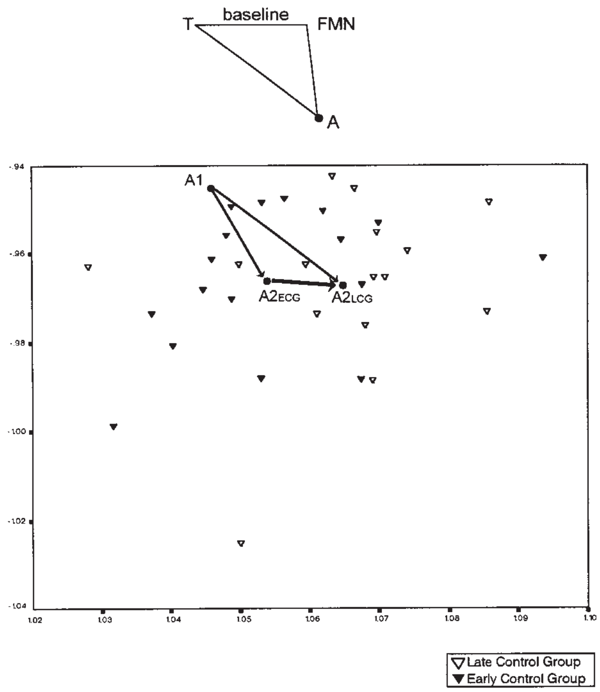


**Fig 8.** Graphic display of shape changes in ECG and LCG (maxillary triangle). Scatterplot represents the annualized individual displacements of point A at $T_2$ relative to a common starting point at $T_1$.

for this type of therapy. A previous study[20] by our group showed that treatment of Class III malocclusion of maxillary orthopedic protraction is most effective in the early mixed dentition. The present investigation used shape-coordinate and tensor analyses in order to compare the results of early intervention with RME and FM on Class III malocclusion in the mixed dentition to those of late intervention in the mixed dentition. Peculiar features of our study are: (1) the use of white subjects with untreated Class III malocclusion in the early and late mixed dentitions as control groups. These groups matched treated groups as to race, gender, age at the first observation, and craniofacial characteristics at first observation.[20] (2) A nonconventional cephalometric analysis that allowed for separate evaluation of size and shape changes. (3) All treated subjects underwent a concomitant treatment phase with RME with the use of a standardized protocol in order to disrupt the circumaxillary sutural system.

The findings of the present study confirm that treatment of Class III malocclusion with RME and FM in the early mixed dentition induces more favorable craniofacial changes when compared with treatment in the late mixed dentition. In particular, maxillary shape changes induced by treatment in the early group were represented by a significantly greater displacement of point A in a forward and upward direction when compared with controls and with the LTG. More to the point, Fig 2 shows the clear separation between the ETG and ECG as revealed by shape-coordinate analysis. Beyond statistical considerations, therefore, this finding entails an important clinical meaning, as nonconventional analysis was able to demonstrate that each and every early treated patient exhibited favorable maxillary shape changes when compared with early untreated controls.

Maxillary shape changes in the LTG were not significant when compared with corresponding controls. The upward component in the displacement of point A agrees with the results of previous biomechanical studies that found that posteroanterior traction applied to the maxilla results in a more upward inclination of the palatal plane[21-23] after treatment. In future clinical applications of facial mask therapy, it is recommended that the elastic traction should be directed even more downward in order to counteract the tendency toward counterclockwise rotation of the maxilla.

Centroid size analysis showed that size changes in

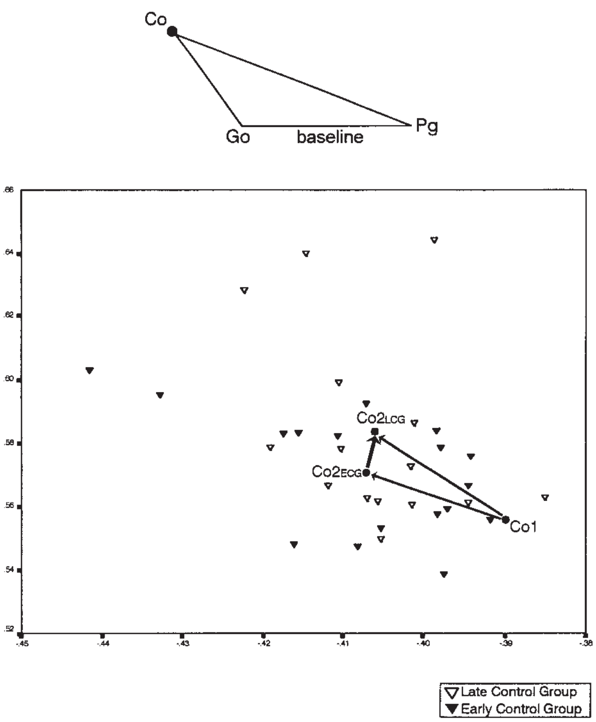


**Fig 9.** Graphic display of shape changes in ECG and LCG (mandibular triangle). Scatterplot represents annualized individual displacements of point Co at $T_2$ relative to a common starting point at $T_1$. (*Thicker arrow* identifies the vector difference of mean shape changes in the two groups.)

the maxilla were significantly greater only in the ETG. As for the effects in the mandible, early treatment induced a significantly more upward and forward direction of condylar growth when compared to controls and to the LTG. Tensor analysis demonstrated a significant closure of the gonial angle and a "shrinkage" of the mandible approximately along total mandibular length (Co-Pg). According to Lavergne and Gasson,[24] this mechanism, namely anterior morphogenetic rotation of the mandible, is a biologic process that is able to dissipate excesses of mandibular growth relative to the maxilla. In fact, centroid size analysis revealed that early treatment with the facial mask produced smaller increments in mandibular size. It is interesting to observe that similar morphogenetic changes in the mandible have been recorded in children with Class III malocclusion treated with a functional appliance as early as in the deciduous dentition.[16,25,26]

The present study also provides information about growth changes in untreated subjects with Class III malocclusion in the early and late mixed dentition. There have been very few previous studies that have considered a longitudinal sample of untreated Class III controls, and these samples typically have been of Asian ancestry.[27,28] Both shape-coordinate and tensor analysis show how, in untreated Class III malocclusion, maxillary growth has an important vertical component, whereas the growth of the mandibular condyle is in a backward and upward direction. This differential growth leads to growth increments along the direction of total mandibular length, increments that make the clinical problem worse. A comparison between untreated Class III and Class I samples obviously is needed to draw definite conclusions about physiologic growth changes in Class III malocclusion. A further interesting use of shape-coordinate analysis in the future will be to investigate over the long term possible skeletal morphologic changes both in the maxilla and in the mandible of treated subjects with Class III malocclusion, with emphasis on treatment timing.

## CONCLUSIONS

The findings of the present study showed that FM and RME therapy were able to induce a significant enhancement of the forward growth of the maxilla and a significantly more upward-forward direction of growth of the mandibular condyle (leading to smaller increments in mandibular total length) in the early-treated group when compared to the late-treated group and to untreated controls. Orthopedic treatment of Class III malocclusion is more effective in the early mixed dentition than in the late mixed dentition.

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