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Thin-plate spline analysis of treatment effects of rapid maxillary expansion and face mask therapy in early Class III malocclusions

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SUMMARY An effective morphometric method (thin-plate spline analysis) was applied to evaluate shape changes in the craniofacial configuration of a sample of 23 children with Class III malocclusions in the early mixed dentition treated with rapid maxillary expansion and face mask therapy, and compared with a sample of 17 children with untreated Class III malocclusions. Significant treatment-induced changes involved both the maxilla and the mandible. Major deformations consisted of forward displacement of the maxillary complex from the pterygoid region and of anterior morphogenetic rotation of the mandible, due to a significant upward and forward direction of growth of the mandibular condyle. Significant differences in size changes due to reduced increments in mandibular dimensions were associated with significant shape changes in the treated group.

Introduction

One of the most compelling tasks of dentofacial orthopaedics is the achievement and diffusion of adequate morphometric tools in cephalometric diagnosis and in the appraisal of treatment results. Conventional cephalometrics, based on linear and angular measurements, has shown an increasing number of limitations along with the proposal and implementation of new biometric analyses of landmark data (e.g. elliptic Fourier analysis, finite element analysis, tensor and shape co-ordinate analysis; Blum, 1973; Bookstein, 1982; Lestrel, 1982; Cheverud *et al*., 1983; Lavelle, 1985; Moss *et al*., 1985; Lestrel and Roche, 1986). The major advantages of these still evolving methods include separate evaluation of shape (or of shape change) and size, no need for reference structures or lines, and visualization of morphological changes.

A recent morphometric approach to the comparison of configurations of landmarks in two or more specimens is known as 'Thin-Plate Spline analysis', developed by Bookstein (1989). Thin-Plate Spline (TPS) transformation produces a rigorous quantitative analysis of the spatial organization of shape change that can be decomposed into a series of components ranging in scale from features that span the entire form ('principal warps') to those that are highly localized ('partial warps'; Swiderski, 1993). In TPS analysis, the differences in two configurations of landmarks are expressed as a continuous deformation using regression functions in which homologous points are matched between forms to minimize the bending energy (Richtsmeier *et al.*, 1992). 'Bending energy' can be defined as the energy that would be required to bend an infinitely-thin metal plate over one set of landmarks, so that the height over each landmark is equal to the co-ordinates of the homologous point in the other form (Bookstein, 1989). TPS analysis facilitates the construction and display of transformation grids that capture the shape change between forms as an evolution of the method originally proposed by Thompson in 1917. For a more detailed review of theoretical bases and calculation procedures of TPS morphometrics, see Bookstein (1989, 1991), Rohlf and Marcus (1993), Rohlf *et al.* (1996), and Singh *et al.* (1997).

TPS analysis has been applied recently by Singh *et al.* (1997) to the description of cranial base configuration in subjects with Class III malocclusions compared with Class I controls. The same method had been used previously to identify congenital mid-facial deformities in Apert's syndrome (Bookstein, 1991). However, TPS analysis of craniofacial changes induced by orthodontic/orthopaedic treatment in longitudinal studies including untreated controls has not yet been performed.

The aim of the present study was therefore to illustrate, by means of TPS analysis, the shape changes in the craniofacial configuration of children with Class III malocclusions treated with rapid maxillary expansion (RME) and face mask therapy in the early mixed dentition when compared with a matched sample of children with untreated Class III malocclusions.

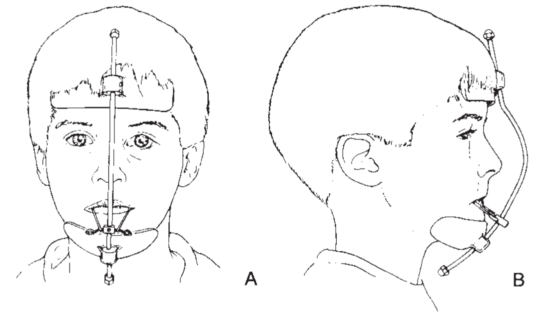

Figure 1 Face mask according to design of Petit (1983). (A) Frontal view. (B) Lateral view. The face mask comprises a single midline rod connected to a chin pad and a forehead pad. Elastics are connected bilaterally to an adjustable midline crossbow. (Modified from McNamara and Brudon, 1993.)

Subjects and methods

Subjects

Twenty-three subjects of European ancestry with occlusal and skeletal Class III malocclusions in the early mixed dentition (11 females and 12 males) were selected for the treatment group. Cephalograms were taken at the following time periods: pre- (T_1) and post-treatment (T_2). The mean age of the treated group was 6 years 9 months ± 7 months at T_1 and 7 years 9 months ± 7 months at T_2, with a mean treatment period of 1 year ± 5 months. Seventeen subjects (nine females and eight males) with untreated Class III malocclusions were selected from the files of the Department of Orthodontics of the University of Florence to comprise the control group. This sample was used as a comparison group as it matched the treated group as to race, stage of dental development, and Class III occlusal and skeletal signs. The mean age of the control group 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.

Treatment protocol

The components of the orthopaedic face mask therapy in the treated group comprised a face mask (according to the design of Petit, 1983; Figure 1), a bonded maxillary acrylic splint expander with vestibular hooks (Figure 2), and heavy elastics (McNamara and Brudon, 1993). In patients with maxillary transverse deficiency, the midline expansion screw of the bonded maxillary expander 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 was still activated, usually once a day for 1 week to 10 days, to disrupt the maxillary sutural system.

At the time of delivery of the face mask, bilateral 3/8-inch, 8 oz. elastics typically were used for the first 1–2 weeks of treatment to ease the adjustment of the patient to the appliance. The force generated then was increased by using $\frac{1}{2}$-inch, 14 oz. elastics and finally $\frac{5}{16}$-inch, 14 oz. elastics. The direction of elastic traction was

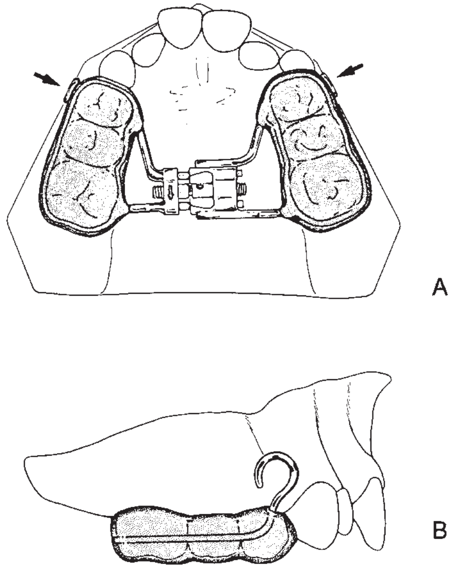

Figure 2 Bonded maxillary expander. (A) Occlusal view (the arrows indicate the position of the hooks for elastic protraction). (B) Lateral view. This acrylic splint expander comprises a metal framework and expansion screw to which a 3-mm thick splint has been adapted. (Modified from McNamara and Brudon, 1993.)

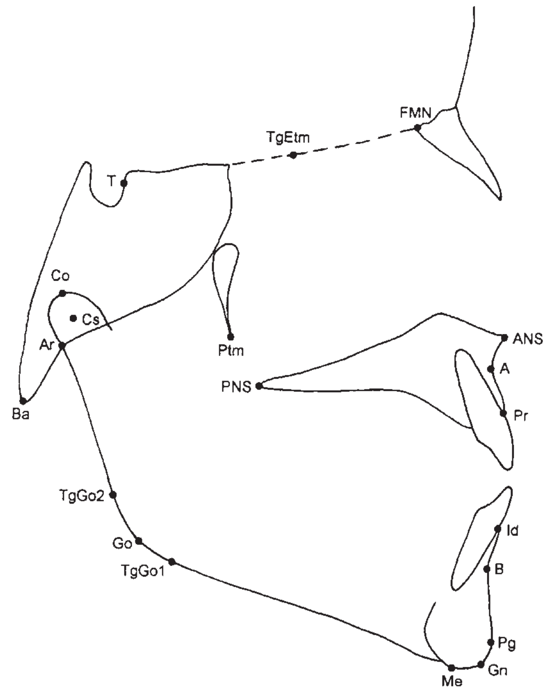

Figure 3 Landmarks of craniofacial configuration.

forward and downward from the hooks on the bonded maxillary expander to the adjustable crossbar of the face mask, so that the elastics did not interfere with the function of the lips (Figure 1). The patients were instructed to wear the face mask on a full-time basis except during meals.

Thin-plate spline analysis

The following homologous landmarks were digitized on the lateral films of all subjects at T_1 and T_2 (Figure 3): point T (the most superior point of the anterior wall of the sella turcica at the junction with tuberculum sellae), point TgEtm (point of tangency of the stable basicranial line to the lamina cribrosa of the ethmoid bone), FMN (fronto-maxillary-nasal suture), Point A (A), Point B (B), prosthion (Pr), infradentale (Id), gnathion (Gn), menton (Me), TgGo1 (point of tangency of the mandibular plane to the gonial region), gonion (Go), TgGo2 (point of tangency of the ramal plane to the gonial region), articulare (Ar), condylion (Co), centre of the condyle (Cs) (i.e. a point equidistant from the anterior, posterior, and superior borders of the condyle head), pterygomaxillary fissure (Ptm), basion (Ba), anterior nasal spine (ANS), posterior nasal spine (PNS). The definitions of these landmarks can be found in Björk (1947), Riolo *et al.* (1974), and Tollaro *et al.* (1996). Digitization of landmark co-ordinates from cephalograms was achieved using appropriate software (Viewbox, version 1.9, Halazonetis, 1994) and a digitizing tablet (Numonics 2210, Numonics, Lansdale, Pennsylvania, USA). All cephalograms were digitized by the same individual (T.B.). Method error in landmark identification has been reported elsewhere (Baccetti *et al.*, 1998).

Thin-plate spline software (Rohlf, 1997) computed the orthogonal least-squares Procrustes average configuration of landmarks in both treated and control groups at T_1 and at T_2, using the generalized orthogonal least-squares procedures described in Rohlf and Slice (1990). The average craniofacial configurations were subjected to TPS analysis by contrasting the average configuration at T_2 with that at T_1 in both groups. Each of the two total splines was decomposed into affine and non-affine components. The affine transformation provides information about size differences, rotation and uniform shape change. The non-affine component, due to pure non-uniform shape changes, is depicted as a principal warp and can be decomposed further into partial warps, the individual magnitude representing the importance of the partial warp to the total fit. The partial warps have anatomical interpretability and they are necessary for an understanding of the statistical significance of the overall shape changes.

Shape changes in the craniofacial configuration due to treatment or growth in Class III malocclusions were inspected visually for interpretation. Statistical multivariate analysis (Hotelling's T^2 test) was applied to shape changes from T_1 to T_2, calculated on partial warp scores (Rohlf *et al.*, 1996) in the treated group compared with the control group. Centroid size was used as the measure of the geometric size of each specimen and was calculated as the square root of the sum of the squared distances from each landmark to the centroid of each specimen's configuration of landmarks. Size changes from T_1 to T_2 in the treated group were compared with those assessed in control group (*t*-test).

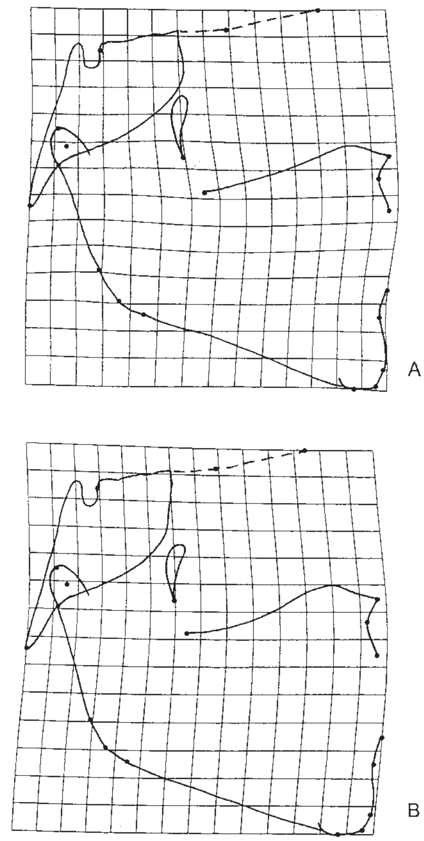

Figure 4 Treated group. Graphical display showing craniofacial shape changes (A) as total spline and (B) as partial warp with the largest magnitude (no. 16 in Table 1). The graphical display of non-affine transformation principal component (A) shows advancement of the maxilla and compression in the region of the anterior surface of the mandibular symphysis. The partial warp with the largest magnitude (B) focuses on the compression in the horizontal axis in the region of the mandibular condyle.

Results

Thin-plate spline analysis allowed for graphical display of shape changes from T_1 to T_2 in the craniofacial configuration in both the treated group (Figure 4) and the untreated group (Figure 5). Table 1 shows the contribution of each partial warp toward the total spline in the treated and untreated samples. Hotelling's T^2 test revealed statistically significant differences ($F = 30.99$; $P < 0.001$) for the shape changes in the treated group when compared with those in the control group. Centroid size increments were significantly smaller in the treated group ($t = 3.76$; $P < 0.01$).

Thin-plate spline analysis of shape changes in the treated group (Figure 4)

The graphical display of non-affine transformation principal component (Figure 4A) showed an extension in the horizontal axis in the maxillary region and a compression in the region of the anterior surface of the mandibular symphysis. In particular, the shape change comprised maxillary advancement at points ANS, A, and Pr. A forward and slightly downward deformation at point PNS (moving from point Ptm) also was evident.

Table 1 Contribution of each partial warp towards the total spline of averaged craniofacial configuration in treated and control groups. The partial warps with the largest magnitude in both groups are marked with an asterisk.

Treated group (n = 23)				Control group (n = 17)			
Partial warp	Eigenvalue	Bending energy ($\times 10^{-4}$)	Magnitude ($\times 10^{-6}$)	Partial warp	Eigenvalue	Bending energy ($\times 10^{-4}$)	Magnitude ($\times 10^{-6}$)
1	818.59	15.61	1.91	1	804.53	8.94	1.11
2	618.98	38.73	6.26	2	720.64	10.76	1.49
3	402.17	73.57	18.29	3	315.56	26.82	8.50
4	364.90	14.45	3.96	4	243.49	12.28	5.04
5	257.73	9.59	3.72	5	215.76	55.53	25.74
6	169.37	4.99	2.95	6	194.50	31.10	15.98
7	141.59	161.85	114.31	7	183.24	0.87	0.47
8	128.15	14.12	11.02	8*	132.38	107.48	81.19
9	81.49	23.91	29.35	9	71.93	20.10	27.93
10	66.92	71.41	106.71	10	52.39	29.51	56.12
11	41.00	7.90	19.28	11	42.37	18.73	44.21
12	28.55	1.81	6.36	12	30.61	10.60	34.62
13	18.13	42.53	234.55	13	19.08	0.90	4.72
14	12.72	2.27	17.85	14	13.06	0.47	3.60
15	6.20	8.21	132.46	15	6.28	0.59	9.37
16*	3.75	21.94	585.00	16	3.63	1.94	53.40
17	2.42	9.50	392.89	17	2.47	4.91	198.37
Total	3162.66	522.39		Total	3051.92	341.53	

The partial warp with the largest magnitude (Table 1 and Figure 4B) revealed a compression in the horizontal axis in the regions of the mandibular condyle and of the antero-inferior border of the symphysis. The component of maxillary advancement was still present.

Thin-plate spline analysis of shape changes in the control group (Figure 5)

The analysis of non-affine principal component of shape change in the untreated group (Figure 5A) revealed little overall deformation and consisted of slight compression in the horizontal axis in the anterior region of the maxilla associated with a slight extension in the region of the mandibular condyle and of the antero-inferior portion of the mandibular symphysis. The partial warp with the largest magnitude (Table 1 and Figure 5B) confirmed the compression in the anterior part of the maxilla and the extension in the chin area.

Discussion

The method of the TPS analysis applied to cephalometric landmark configurations presents several advantages with respect to both conventional cephalometrics and to previous morphometric techniques: (1) an 'optimal' superimposition of landmarks for the analysis of shape change in complex skeletal configurations without the use of any conventional reference line; (2) an explanatory visualization of the deformations due to growth and/or treatment using 'transformation grids'; (3) the decomposition of generalized modifications into more specific, local changes.

TPS analysis has been used to describe shape differences in various craniofacial structures in children with malocclusions or dysmorphogenetic syndromes when compared with normal subjects (Bookstein, 1991; Singh *et al.*, 1997). A specific feature of the present study is the use of TPS analysis to investigate the craniofacial changes induced by orthopaedic treatment by means of a longitudinal morphometric study.

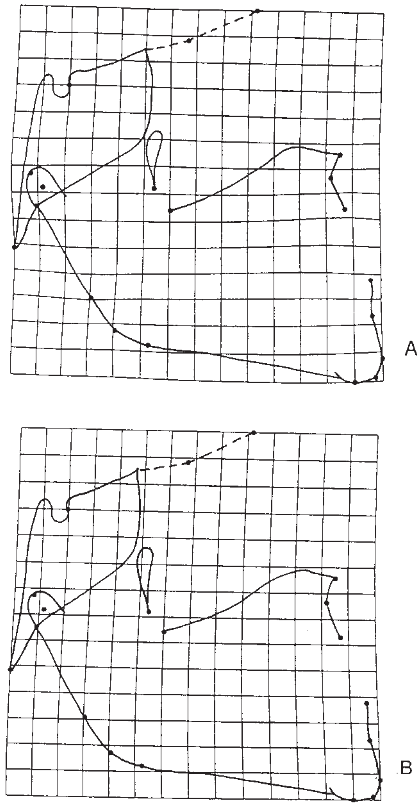

Figure 5 Control group. Graphical display showing craniofacial shape changes (A) as total spline and (B) as partial warp with the largest magnitude (no. 17 in Table 1). The analysis of non-affine principal component of shape change in the untreated group (A) reveals little deformation consisting of slight compression in the horizontal axis in the anterior region of the maxilla associated with a slight extension in the region of the mandibular condyle and of the antero-inferior portion of the mandibular symphysis. The partial warp with the largest magnitude (B) confirmed the slight antero-inferior extension in the chin area.

TPS analysis demonstrated significantly different shape changes in the craniofacial configuration of children with Class III malocclusions treated with RME and face mask in the early mixed dentition when compared with controls. The findings indicate that the treated group exhibited a forward displacement of the maxilla associated with a marked advancement of the posterior nasal spine (point PNS) in relation to the pterygo-maxillary suture (point Ptm). This skeletal change is corroborated as previous work by Melsen and Melsen (1982) demonstrated the possibility to disarticulate the palatal bone from the pterygoid process in the infantile and juvenile (early mixed dentition) periods. The slightly upward displacement in the region of point ANS and the downward displacement in the region of point PNS in the treated children suggest that early RME and face mask therapy induces a counter-clockwise rotation of the palatal plane concomitant with maxillary advancement. A careful control of the direction of the extra-oral elastic force vector therefore has to be carried out in order to counteract this effect, when not desired.

The generalized effect of the therapy on mandibular structures can be interpreted as a forward direction of condylar growth associated with a restriction in sagittal advancement of the symphysis. These skeletal modifications can be interpreted as a result of anterior morphogenetic rotation of the mandible. According to Lavergne and Gasson (1977), anterior morphogenetic rotation of the mandible is a biological mechanism which leads to a reduced increase in total mandibular length (Co–Pg) in order to dissipate excessive growth of the mandible relative to the maxilla. The same mechanism has been described as a major treatment effect in children with Class III malocclusions treated with a functional appliance (Tollaro *et al.*, 1995, 1996).

The effectiveness of early RME and face mask therapy of Class III malocclusions also included significant changes in size which can be ascribed mainly to a reduction in the mandibular dimensions.

Future studies should assess shape/size changes induced by RME and face mask treatment of Class III malocclusions at later ages and compare the effects of early and late treatment, in order to substantiate indications for optimum treatment timing for this type of orthopaedic therapy.

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