

## Thin-Plate Spline Analysis of Mandibular Morphological Long-Term Changes Induced by Functional Jaw Orthopedics: The Role of Treatment Timing

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### Abstract

**Background:** Functional appliances are able to induce an elongation of the mandible with the best results obtained at pubertal or immediately postpubertal periods of skeletal development. However, no data are available in the literature relating the treatment timing and the long-term mandibular shape changes produced by functional appliances with TPS morphometric analysis. The aim of the present study was to evaluate the role of treatment timing on long-term mandibular morphological changes induced by functional treatment of Class II malocclusion followed by full-fixed appliance therapy.

**Methods:** The treated group consisted of 46 subjects (23 females and 23 males) with Class II malocclusion treated with either Bionator or Activator. The treated sample was evaluated at T1, start of treatment (mean age 9.9 years); and T2, long term observation (mean age 18.3 years). The treated group was divided into pre-pubertal (ETG) and pubertal groups (LTG) according to skeletal maturity observed at T1. Mandibular shape changes were analyzed on the lateral cephalograms with Thin-Plate Spline (TPS) analysis. Procrustes average mandibular configurations were subjected to TPS analysis by means of both cross-sectional between-group comparisons at T1 and at T2 and longitudinal within-group comparisons.

**Results:** The longitudinal T1-T2 comparison in the ETG revealed statistically significant mandibular shape changes, described as a vertical extension in the region of the mandibular condyle with a downward and forward dislocation of points Go, TgGo1, TgGo2 and a horizontal compression in the anterior region. The LTG showed statistically significant mandibular shape differences similar to those of the longitudinal comparison in the ETG. In the long term, the LTG exhibited a significant upward and backward direction of condylar growth with respect to the ETG.

**Conclusions:** Treatment with removable functional appliances performed at puberty is able to produce a significant posterior mandibular morphogenetic rotation that can contribute to the sagittal skeletal correction of Class II disharmony.

**Keywords:** Class II Malocclusion; Functional Jaw Orthopedics; Thin- Plate Spline Analysis; Treatment Timing

## List of Abbreviations

Arp	:	Articulare
Ara	:	Articulare Anterior
B	:	Point B
Co	:	Condylion
CVM	:	Cervical Vertebral Maturation
ETG	:	Early Treatment Group
Gn	:	Gnathion
Go	:	Gonion
LTG	:	Late Treatment Group
Me	:	Menton
Pg	:	Pogonion
TPS	:	Thin-Plate Spline
TgGo1	:	Tangent Gonion 1
TgGo2	:	Tangent Gonion 2

## Background

Class II malocclusion is described as an improper relationship between the maxillary and mandibular arches for skeletal problems, dental problems, or both of them [1]. Occlusal and craniofacial features of growing patients with Class II malocclusion have been analysed in the sagittal and vertical plane. The most important finding in Class II patients is mandibular skeletal retrusion, which is observed in about 80% of the cases. This characteristic appearance leads many clinicians and researchers to analyze the effects of functional treatment stimulating mandibular growth in growing patients [2-4]. Several studies revealed that functional appliances are able to induce an elongation of the mandible with the best results obtained at pubertal or immediately postpubertal periods of skeletal development [3].

Lateral cephalograms is one of the major diagnostic tools in the evaluation of skeletal modifications induced by functional therapy [5]. However, conventional cephalometric evaluation proved to be inaccurate in determining the location and mode in which changes in shape and size happen in the craniofacial complex [5-7].

A different morphometric approach to the comparison of

configurations of landmarks in two or more specimens is famous as Thin-Plate Spline (TPS) analysis, designed by Bookstein [6,8]. TPS analysis is a descriptive method evaluating shape changes regardless of size. His method has been developed and implemented as an improvement of conventional cephalometrics. It also allows the realization of transformation grids that capture differences in form making possible the visual interpretation and mathematical representation of the treatment effects [8-10].

Few studies [9,2] used TPS analysis to evaluate the long-term mandibular morphological changes induced by functional treatment of Class II malocclusion. TPS analysis showed that functional appliances induced significant posterior morphogenetic rotation of the mandible over the short term and this shape difference was not maintained over the long term [2].

However, no data are available in the literature relating the treatment timing and the long-term mandibular shape changes produced by functional appliances with TPS morphometric analysis. The aim of present study was to evaluate, by means of TPS analysis, the role of treatment timing on the long-term mandibular morphological changes induced by functional treatment of Class II malocclusion (Bionator or Activator) followed by fixed appliances.

## Methods

The study project was approved by the Ethical Committee at the University of XXXXXXXX (201/16), and informed consent was acquired from the 88 patients' parents. Forty-six subjects with Class II division 1 malocclusion (23 males, 23 females) were retrospectively selected. All subjects were treated either with the Bionator (26 subjects) or the Activator (20 subjects) and composed the treatment group. All subjects presented the following dentoskeletal feature at T1 when the pre-treatment lateral cephalogram was obtained:

overjet > 5 mm, full Class II or end-to-end molar relationships, ANB angle > 4°, and an improvement in facial profile when the lower jaw was postured in a forward position [11]. In addition, patients had to present with lateral cephalograms available at T1, at the start of treatment (mean age: 9.9 ± 1.3 years) and at T2, in the long-term, after puberty (CS5 or CS6 depending on the cervical vertebral maturation method) (mean age: 18.3 ± 2.1 years).

The treated sample was divided into two groups depending on skeletal maturity evaluated at T1 by means the Cervical Vertebral Maturation (CVM) method [12]. CVM staging was performed by an observer (L.F.) calibrated in this method. The demographic data of the Early Treatment Group (ETG) and Late Treatment Group (LTG) are reported in Table 1.

	Age at T1 (ys)		CVM stages at T1	Age at T2 (ys)		CVM stages at T2	T1-T2 interval (ys)	
	Mean	SD		Mean	SD		Mean	SD
Early Treated Group (n=23, 13f 10m)	9.5	1.2	19 CS1 4 CS2	17.9	2.3	10 CS5 13 CS6	8.4	2.5
Late Treated Group (n=23, 10f 13m)	10.2	1.3	6 CS2 17 CS3	18.5	2.1	8 CS5 15 CS6	8.3	2

**Table 1:** Demographics for the early treated and late treated groups.

### Treatment protocol

The treatment protocol consisted of a therapy composed of either a Bionator realized without coverage of the mandibular incisors [11,13] or of an acrylic monobloc attached to the upper arch by Adams clasps and with capping of the upper and lower incisors [14].

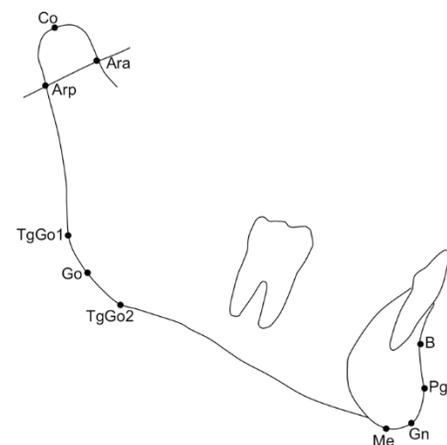
The end of the functional therapy ceased with the achievement of Class I molar relationships; consequently, the fixed therapy was performed in the permanent dentition. The T2 observations were collected and evaluated without considering the treatment results in relation to correction of Class II malocclusion in the individual patients. This strategy helped in further reducing potential selection bias of the investigation.

All patients in both the private practice and the University Clinic were treated by two expert clinicians (P.C. and K.F.) with a similar clinical experience in the management of the 2 functional devices. All the patients were instructed to wear their appliances 16 hours a day until the end of the treatment. As occurs in studies including any removable appliance, compliance varied among the patients

Both the functional appliances were realized with the same degree of mandibular protrusion and the construction bites were taken with the same modality in both groups. It was decided to combine the patients treated with both Bionator and Activator because of the effectiveness and the mechanism of action of these 2 appliances were similar [14].

### TPS analysis

The following mandibular landmarks were digitized on the lateral cephalograms of all treated patients at T1 and at T2: Articulare (Arp), Articulare anterior (Ara), Tangent gonion 1 (TgGo1, point of tangency on the line passing through Arp to the gonial region), Gonion (Go), Tangent gonion 2 (TgGo2, point of tangency on the line passing through Me to the gonial region Gnathion) (Gn), Menton (Me), point B (B), Condylion (Co), and Pogonion (Pg), (Figure 1).



**Figure 1:** Cephalometric mandibular anatomical landmarks.

Based on lateral films, cephalograms of all the subjects were hand traced on a 0.03-inch thick 125 frosted acetate paper by a single observer (C.P.) and checked by another (L.F.) Landmarks for the description of the mandibular region were digitized by using a specific software (Viewbox 3.1, dHAL Software, Kifissia, Greece) and a digitizing table (Numonics, Lansdale, Pennsylvania, USA). In this investigation a TPS software (tpsRegr, version 1.38, Ecology & Evolution, SUNY, Stonybrook, New York, USA) computed the orthogonal least squares Procrustes average configuration of mandibular landmarks in both Early and Late treated groups by means the generalized orthogonal least squares procedure [15]. Procrustes average configurations were subjected to TPS analysis by means of cross sectional comparisons of the ETG versus the LTG at T1 and at T2 and by means of longitudinal T1-T2 comparisons within the early and late treated groups.

Shape differences were subjected to statistical analysis performed by calculating residuals from Procrustes analysis and by comparing these residuals using a generalized Goodall F test (tpsRegr, version 1.38, Ecology & Evolution, SUNY, Stonybrook, New York, USA).

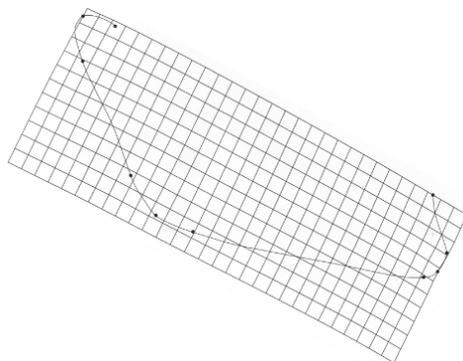
Centroid size was used as the measure of the geometric size of mandibular region and it was calculated as the square root of the sum of the squared distances from each landmark to centroid of each specimen's configuration of landmarks [8]. To analyze the method error, 20 cephalograms were randomly selected. All films were retraced and digitized a second time after 15 days by the same observer (L.F). Method of moments' estimator [16] was used to calculate the method error as a combination of location of landmarks, tracing, and digitization for the X and Y co-ordinates of every cephalometric landmark. A test for allometry (Hotelling's T-square test) checking for shape depending on size (tpsRegr, version 1.38, Ecology & Evolution, SUNY, Stonybrook, NY) was performed for those comparisons revealing significant shape differences.

**Results**

The method error ranged from a minimum of 0.20 mm (Y co-ordinate of point Co) to a maximum 0.54 mm (Y co-ordinate of point Go). As for the cross-sectional comparisons, no statistically significant mandibular shape changes (P= 0.832) were found when comparing the ETG and LTG at T1 (Table 2, Figure 2).

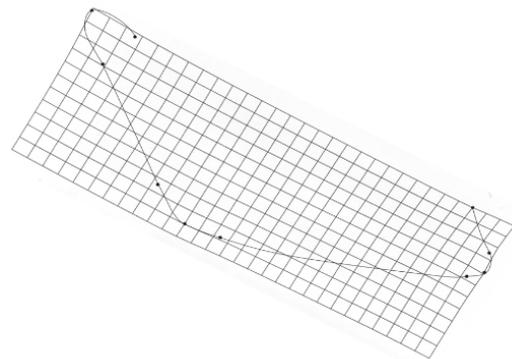
Group	Sum of residuals	F-value	P-value
ETG vs LTG at T1	0.094	0.662	0.832
ETG vs LTG at T2	0.113	1.83	0.024
ETG at T1 vs ETG at T2	0.106	3.601	0
LTG at T1 vs LTG at T2	0.101	5.41	0

**Table 2:** Sum of residuals, Generalized Goodall F values and probability of statistical equivalence between mean mandibular configurations for the Early Treatment Group (ETG) and Late Treatment Group (LTG) as determined by Procrustes analysis.



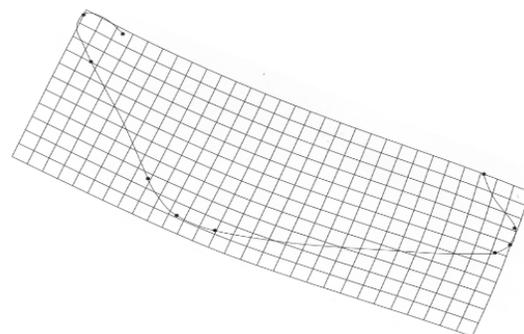
**Figure 2:** Thin-Plate Spline (TPS) graphical display of cross-sectional mandibular shape changes between the early and late treated groups at T1 (magnification factor x3).

When comparing the ETG and LTG at T2, statistically significant (P=0.024) mandibular shape changes were found with the greatest deformation located in the condylar region (Table 2, Figure 3). These deformations could be described as a horizontal extension associated mainly with an upward and backward dislocation of point Co in the LTG versus the ETG. In the gonial region the vertical extension was due mainly to a downward dislocation of point Go. In the anterior region the late treated group showed a horizontal extension due to a forward and downward dislocation of point Pg.



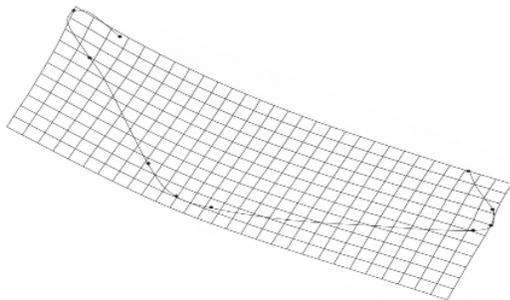
**Figure 3:** Thin-Plate Spline (TPS) graphical display of cross-sectional mandibular shape changes between the early and late treated groups at T2 (magnification factor x3).

The longitudinal T1-T2 comparison in the early treated group revealed statistically significant (P=0.000) mandibular shape changes (Table 2, Figure 4). This deformation could be described as a vertical extension in the region of the mandibular condyle associated mainly with an upward and backward dislocation of point Co, Ar, and Ara. The changes in the gonial region was due to a downward dislocation of points Go, TgGo1, and TgGo2. In the anterior region the early treated group at T2 showed a horizontal compression due mainly-to a backward dislocation of point B.



**Figure 4:** Thin-Plate Spline (TPS) graphical display of longitudinal T1-T2 mandibular shape changes in the early treated group (magnification factor x3).

The LTG showed statistically significant ( $P=0.000$ ) mandibular shape differences that were similar to those of the longitudinal comparison in the ETG (Table 2, Figure 5). In the condylar region shape changes were characterized by a marked horizontal extension associated mainly with an upward and backward dislocation of point Co. The vertical extension in the gonial region was due mostly to a downward dislocation of point Go, TgGo,1 and Tg-Go2. In the anterior region there was a horizontal extension of the symphyseal region with a forward dislocation of point Pg.



**Figure 5:** Thin-Plate Spline (TPS) graphical display of longitudinal T1-T2 mandibular shape changes in the late treated group (magnification factor x3).

The test for allometry revealed that the significant mandibular shape modifications were not significantly dependent on size differences either in the cross-sectional comparison between the samples at T2 (Hotelling's T-square test: 0.370;  $P=0.455$ ) or in the longitudinal T1-T2 comparison in the early treated group (Hotelling's T-square test: 0.268;  $P=0.706$ ) or in the longitudinal T1-T2 comparison in the late treated group (Hotelling's T-square test: 0.995;  $P=0.474$ ).

## Discussion

No paper in literature evaluated the role of treatment timing and the long-term mandibular shape modifications produced by functional appliances via geometric morphometric analysis. The current investigation, therefore, was aimed at elucidating the role of treatment timing on the long-term mandibular morphological changes induced by functional treatment in growing patients with Class II malocclusion followed by fixed appliances by means of TPS analysis.

The main advantages of TPS analysis of cephalometric landmark configurations compared to conventional cephalometrics include: optimal superimposition of landmarks to evaluate the shape modifications regardless of size changes in complex skeletal configurations without the use of any conventional reference line; explanatory visualization of craniofacial shape changes using transformation grids; the delineation of overall variations into more detailed, local changes [8].

TPS analysis showed that significant mandibular shape changes were found in the cross-sectional comparison between the

ETG and LTG at T2, and in the longitudinal T1-T2 comparisons within the ETG and the LTG (Figure 3-5). These significant deformations involved mainly the mandibular condyle that exhibited an upward-backward growth direction. In the longitudinal T1-T2 comparison within the treated samples a downward dislocation of point Go was also evident, most probably as a result of skeletal compensation of mandibular growth in Class II patients with an increase in mandibular ramus height. These findings are in line with previous controlled long-term cephalometric studies [3,13] that reported a significant long-term increase in the height of the mandibular ramus as a result of Bionator therapy.

The significant difference in mandibular shape at T2 can be described as a horizontally extended grid along the entire mandibular length (Co-Gn) in the LTG versus the ETG (Figure 3). This shape modification can be described as a mandibular "posterior morphogenetic rotation" [17] a biological mechanism that can concur to the sagittal skeletal correction of Class II disharmony, as it is associated with "stretching" along the entire mandible. The upward and backward direction of condylar growth was associated with a forward and downward dislocation of point Pg.

These favourable shape changes in the long-term evaluation were not similar to those reported by another morphometric investigation on the effects of functional appliances [2] who described an anterior growth rotation of the mandible involving mainly the mandibular condyle, which exhibited an upward-forward direction of growth, in the treated group when compared with the control group. These different results can be explained by the fact that in the Franchi, et al. [2] study the treated and control samples were analysed without taking into consideration the role of treatment timing. In the current study, the treated group was divided into a pre-pubertal group (ETG) and a pubertal group (LTG) performed in the current according to individual skeletal maturity. Therefore, one of the most relevant findings in this study was that the treatment timing plays an important role also on the long-term mandibular skeletal shape changes produced by functional appliances.

These changes were essentially similar in both groups with a more marked "posterior morphogenetic rotation" that occurred in the LTG. It is interesting to note that the current investigation confirmed the results of a recent long-term controlled study [18] on the role of treatment timing on the long-term effects produced by functional therapy. Treatment with a removable functional appliance that includes the peak in mandibular growth appears to be more effective than treatment performed before the peak, as it induces more favorable mandibular skeletal changes. Treatment with removable functional appliances at puberty induced a significant long-term enhancement of mandibular growth with an increase in mandibular ramus height and protrusion of the chin.

## Conclusions

The functional treatment with removable appliances implemented at puberty period is able to induce a significant mandibular

“posterior morphogenetic rotation” that can concur to the sagittal skeletal correction of Class II malocclusion, as it is associated with “stretching” along the entire mandible and especially in the condylar region.

## Declarations

### Ethics approval and consent to participate

Signed informed consent for releasing diagnostic records for scientific purposes was available from the parents of the patients. The protocol was reviewed and approved by the Ethics Committee of the University of Rome “Tor Vergata” (Rome, Italy) (protocol number 201/16), and procedures followed adhered to the World Medical Organization Declaration of Helsinki.

### Consent for publication

Not applicable

### Availability of Data and Materials

Not applicable

### Competing Interests

The authors declare that they have no competing interests.

### Funding

The authors declare that no funding was given for the realization of the present study.

## Author’s Contribution

CP Supervised the cephalometric landmark localization and revised the manuscript critically. ECL performed the tracing, and draft the manuscript. RL participated in the data acquisition and manuscript drafting. KF helped in the interpretation of the results. JAM screened the patient’s records, and performed the CVM staging. PC coordinated the research project and revised the manuscript critically. LF revised the manuscript and did the statistical analysis. All authors read and approved the final manuscript.

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Endnotes

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