Morphometric Analysis of Mandibular Growth in Skeletal Class III Malocclusion

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Background: The craniofacial growth patterns of untreated individuals with skeletal Class III malocclusion have rarely been systemically investigated. This study used morphometric techniques to investigate the growth characteristics of the mandible in individuals with skeletal Class III malocclusion.

Methods: Lateral cephalometric head films of 294 individuals with untreated skeletal Class III malocclusion (134 males, 160 females) were selected and divided into five triennial age groups (T1–T5) and by gender to identify the morphologic characteristics and sexual dimorphism in changes of mandibular growth. Procrustes, thin-plate spline, and finite element analyses were performed for localization of differences in shape and size changes. Maximum and minimum principal axes were drawn to express the directions of shape changes.

Results: From T1 (age 6–8 years) to T4 (age 15–17 years), the distribution of localized size and shape changes of the mandible was very similar between the two genders. From T1 to T2 (age 9–11 years), significant lengthening of the condylar region was noted (23.4–39.7%). From T2 to T3 (age 12–14 years), the greatest size and shape change occurred at the condylar head (27.4–34.9%). From T3 to T4, the greatest size and shape changes occurred in the symphysial region (23.6–42.1%). From T4 to T5 (age ≥18 years), significant sexual dimorphism was found in the distribution and amount of localized size and shape changes. Females displayed little growth increments during T4. Despite differences in the remodeling process, the whole mandibular configurations of both genders exhibited similarly significant upward and forward deformation from T4 to T5.

Conclusion: We conclude that thin-plate spline analysis and the finite element morphometric method are efficient for the localization and quantification of size and shape changes that occur during mandibular growth. Plots of maximum and minimum principal directions can provide useful information about the trends of growth changes. [J Formos Med Assoc 2006;105(4):318–328]

Key Words: Class III malocclusion, finite element analysis, growth

Skeletal Class III malocclusion is one of the most difficult facial deformities to manage because of the great diversity in the anatomic craniofacial structures and the unpredictable growth in patients with this skeletal pattern.¹⁻⁸ Early orthopedic treatment during growth has been proposed for patients with skeletal Class III malocclusions, but the treatment responses vary greatly.⁷⁻¹¹ In order to achieve accurate diagnosis and obtain appropriate early orthopedic treatment plans for patients with skeletal Class III malocclusion, knowledge of the craniofacial growth pattern of these patients is important.

Few studies on the normal growth and development of untreated individuals with skeletal Class III malocclusion have been reported. The main reasons for this lack of information are the relatively low prevalence of Class III malocclu-
sion and the performance of early intervention in many patients with anterior crossbite. Previous studies that were conducted using longitudinal data featured few patients and short observation periods, and some of these subjects underwent minor orthodontic therapy to correct anterior crossbite. Few cross-sectional studies have been reported with adequate numbers of subjects to clearly identify patterns of change. Consequently, little definitive information is available on the craniofacial growth of untreated individuals with skeletal Class III abnormalities.

Most previous studies of skeletal Class III growth were performed using the roentgenographic cephalometric method. This approach depends upon reference planes and points. If the registration points or planes vary greatly, use of this technique may lead to misdiagnosis or misinterpretation. As the linear and angular measurements made by traditional methods are insufficient for the analysis of size and shape changes of complex craniofacial forms, newer geometric morphometric methods for shape comparisons have been developed to measure the biological size and shape changes induced by growth and treatment. These approaches include thin-plate spline analysis, Euclidean distance matrix analysis, finite element scaling analysis, tensor analysis, Fourier analysis, and shape-coordinate analysis. These methods are all preferable to conventional cephalometry in that they provide explanatory visualization of shape changes and highlight regions of localized dissimilarity.

The purpose of the present study was to investigate the growth characteristics of the mandible in untreated Class III malocclusion. Due to the paucity of longitudinal data and ethical concerns, a cross-sectional study design was used to identify mandibular morphologic differences between different age groups from childhood to adulthood.

Methods

Subjects

Lateral cephalometric head films of 294 children and young adults (134 males, 160 females) were selected from the files of the Orthodontics Department of National Taiwan University Hospital. These films were obtained during the patients’ initial visit to our department. The inclusion criteria for the study were as follows: Chinese ethnicity; lateral cephalograms of adequate quality; diagnosis of skeletal Class III malocclusion; no cleft lip or cleft palate or any other craniofacial deformities; no history of active orthodontic treatment; normal morphology and number of teeth; mandibular plane (MP) angle (sella nasion [SN]–MP angle) between 28° and 38°; and absence of marked midline deviation. Subjects were grouped according to age into five triennial ranges and also by gender. The sample distribution in the resulting 10 groups of patients with skeletal Class III malocclusion is shown in Table 1.

Digitization of mandibular landmarks

The lateral cephalograms were traced with a 0.3-mm lead pencil on frosted acetate tracing films in random order and checked by one investigator. Twelve homologous mandibular landmarks were identified and digitized (Figure 1, Table 2). These

| Table 1. Sample distribution in 10 age and gender groups of individuals with skeletal Class III malocclusion |
|--------------------------------------------------|------------------|------------------|------------------|------------------|------------------|
| Stage                                            | T1       | T2       | T3       | T4       | T5 |
| Age range, yr                                    | 6–8      | 9–11     | 12–14    | 15–17    | ≥ 18 |
| Gender                                           | M        | F        | M        | F        | M   |
| Group                                            | M1       | F1       | M2       | F2       | M3  |
| Subjects, n                                      | 17       | 22       | 36       | 39       | 12  |
| Total number of subjects                         | 39       | 75       | 30       | 37       | 113 |
landmarks were selected with preference given to those that encompassed developmental sites, were easily distinguishable, and were located in the midsagittal plane where possible. All cephalograms were retracted after a 1-week interval, and the landmarks were redigitized by the same person. None of the landmarks showed a discrepancy of greater than 1% for each x,y coordinate on duplicate digitization. Thus, errors of identification were neglected.

**Procrustes superimposition and statistical estimation**

The scaled mean mandibular configurations of each age group for both sexes (Groups M1, M2, M3, M4, M5, F1, F2, F3, F4, F5) were generated by Procrustes analysis. This analytical method, using the least squares principle, was also used to translate, rotate, and iteratively scale the coordinates of every subject in each group until all subjects’ configurations in this group could no longer be improved by the least-squares fit. The mean configurations at each stage for both sexes were tested for significance using Goodall’s F test.

**Interpolation using the thin-plate spline function**

Prior to the application of finite element methodology, the thin-plate spline function was used to interpolate points within the mandibular mean geometry. The interpolation function mapped points of the mean configuration of one group onto corresponding points of the mean configuration of the other group.

**Finite element scaling analysis**

Finite element scaling analysis using the strain tensor principles was incorporated with the spline interpolation function to create a triangular mesh within the mean mandibular configurations. A total of 8100 linear triangular elements were obtained for each configuration. Nodal coordinates of each triangular element in the mean mandibular configuration for each stage (age group) were compared with the corresponding coordinates of the next stage. The differences in these coordinates were used to calculate the growth strains of the triangular elements and were further computed and transferred into descriptions of maximum and minimum principal axes of growth tensors. Size changes were computed as the product of the principal axes, and shape changes as the ratio of the greater principal axis divided by the lesser principal axis. The measures of these size and shape changes were color-mapped into each initial geometric form and provided graphical displays of the change in configurations. The maximum and minimum axes were also graphically displayed to express the directions and magnitudes of the localization of the extension and contraction vectors within the mandibular form.
Results

Goodall’s F test
Residuals from the Procrustes analysis were tabulated and compared by means of an F distribution (Table 3). The level of a significant difference between the mean mandibular configurations was set at \( p < 0.05 \) or \( p < 0.01 \) for all comparisons. Further graphical analyses were performed when significant differences between all stages were identified.

Mandibular growth changes from T1 to T2
The localized size changes in the mandibular configuration of males and females from T1 (age 6–8 years) to T2 (age 9–11 years) are shown in Figures 2A and 2E, respectively. The localized shape changes of males and females are shown in Figures 2B and 2F, respectively. The plots of maximum and minimum principal directions of tensor vectors in the mandibular configuration of males are shown in Figures 2C and 2D, and those of females are shown in Figures 2G and 2H.

Increase in size was revealed in the whole mandibular configuration in both genders except at the lower posterior border of the ramus between points Pb (posterior border of ramus) and Go (gonion), where a negative allometry (0.1–6.7% decrease in local size) was seen only in males, while females had a small positive allometry in this region (5.5–9.1%). The greatest increase in size occurred at the upper posterior portion of the ramus and the condylar region (26.4–39.7% in males; 23.4–30.6% in females). The mandibular corpus and the dentoalveolar region showed moderate increase in local size (13.2–19.8% in males; 16.2–19.8% in females). Males exhibited a 26.4–39.7% increase in local size at the anterior border of the chin, while females showed only a 5.5–9.1% increase in this region.

The mandibular corpus was highly isotropic with little or no change in shape (0.0–3.6% in males; 0.1–2.2% in females). The area above the gonial angle exhibited anisotropy of 21.5–25.1% in males and 8.8% in females. The area below the condylar neck showed 17.9–21.5%

| Table 3. Residuals, F values and probability of statistics equivalence between mean mandibular configurations for different age groups as determined by Procrustes analysis |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Males           | Females         |                 |                 |                 |
|                 | F value         | Probability     | F value         | Probability     |                 |
| T1 vs. T2       | 3.0721          | < 0.001         | 2.6317          | < 0.001         |                 |
| T2 vs. T3       | 2.6582          | < 0.001         | 1.9436          | < 0.005         |                 |
| T3 vs. T4       | 1.7746          | < 0.025         | 1.5582          | < 0.05          |                 |
| T4 vs. T5       | 1.5336          | < 0.05          | 1.5473          | < 0.05          |                 |

Figure 2. From T1 (age 6–8 years) to T2 (age 9–11 years): localized (A) size changes (scale unit = 100%) and (B) shape changes in the mandibular configuration of male subjects; plot of the (C) maximum principal directions and (D) minimum principal directions in the mandibular configuration of male subjects (extension vectors plotted in blue and compression vectors in red); localized (E) size changes and (F) shape changes in the mandibular configuration of female subjects; plot of the (G) maximum principal directions and (H) minimum principal directions in the mandibular configuration of female subjects.
change in shape in males and 8.8–13.1% in females. Regions of the mandibular symphysis and anterior dentoalveolus showed minimal shape change of 3.6–10.8% in males and greater shape change of 13.1–15.3% in females. The area between points Pm (suprapogonion) and Pog (pogonion) had moderate anisotropy of 14.4–17.9% in males and 8.8% in females.

The extension vectors are plotted in blue and the compression vectors in red in the plots of maximum and minimum principal directions of tensor vectors (Figures 2C, 2D, 2G and 2H). The upper portion of the ramus and the condylar region had greater extension vectors parallel to the Ar (articulare)–Pb line, with a lesser extent perpendicular to the Ar–Pb line. The lower border of the mandibular corpus had greater vectors extending horizontally along the Go–Me (menton) axis and smaller vectors extending perpendicular to the Go–Me axis. The extension vectors for the gonial angle region were directed forward anteriorly along the Go–Ab (anterior border of ramus) axis, while the compression vectors were directed vertically along the Pb–Go line. Downward and forward vectors were seen at the mandibular symphyseal area. Smaller horizontal extension vectors and larger vertical extension vectors were found at the anterior alveolar area in males. However, females had horizontal compression vectors instead of extension vectors at the anterior dentoalveolar region.

Mandibular growth changes from T2 to T3

The localized size changes in the mandibular configuration of male and female subjects from T2 to T3 (age 12–14 years) are shown in Figures 3A and 3E, respectively. The localized shape changes of males and females are shown in Figures 3B and 3F, respectively. The plots of maximum and minimum principal directions of tensor vectors in the mandibular configuration of males are shown in Figures 3C and 3D, and those of female subjects are shown in Figures 3G and 3H.

Both males and females showed an increase in size in the whole mandibular configuration except at the anterior alveolar region in males, which showed a 0.0–5.4% decrease in local size. The greatest increase in size occurred at the condylar region (27.4–32.8% in males; 30.3–34.9% in females). The region at the anterior border of the chin had a positive allometry of 11.0% for males and 25.7% for females. The rest of the mandibular area showed an increase of 16.4–21.9% in local size in males and 2.9–7.4% in females.

The overall mandibular configuration was highly isotropic with little or no change in shape (0.0–2.8% in males; 0.1–2.5% in females) except...
in the condylar region, the incisive alveolar region, and the area between points B (position of deepest concavity on anterior profile of the mandibular symphysis) and Pm. The condylar region exhibited greatest anisotropy of 16.5–19.2% in males and 14.5–16.9% in females. The area between points B and Pm showed moderate anisotropy (about 13.8% in males and 7.3–9.3% in females). The incisive alveolus had shape change of only 8.3% in males and 7.3–9.3% in females.

The condylar region had greater extension vectors parallel to the Cd (condylion)–Ar axis, and smaller extension vectors perpendicular to the Cd–Ar axis. The area between points B and Pm had greater extension vectors parallel to the B–Pm line, and minimal extension vectors perpendicular to the B–Pm line. The mandibular incisive alveolar region exhibited horizontal compression vectors and very small extension vectors.

**Mandibular growth changes from T3 to T4 in males**

The localized size changes in the mandibular configuration of males from T3 to T4 (age 15–17 years) are shown in Figure 4A, and the localized shape changes are shown in Figure 4B. The plots of maximum and minimum principal directions of tensor vectors are shown in Figures 4C and 4D, respectively.

The greatest positive allometry occurred at the anterior border of the chin (30.2–42.1%). The upper portion of the mandibular ramus showed a 24.2% increase in size. The mandibular corpus increased by about 18.3%. The condylar area, gonial angle region, anterior dentoalveolar portion, and the anterior inferior border of the chin had the least positive allometry (0.4–6.3%).

Shape changes only occurred at the upper posterior border of the mandibular ramus and at the mandibular symphysis. The region between points Ar and Pb showed evidence of anisotropy of about 17.1–22.8%. The mandibular symphysis exhibited 17.1–39.8% anisotropy, whereas the area between Pm and Pog showed the greatest change in shape (34.1–39.8%). The rest of the mandibular body was highly isotropic with little or no change in shape (ranging from 0.0% to 5.8%).

The extension vectors for the upper portion of the ramus paralleled the Ar–Pb line. The mandibular symphysis had compression vectors paralleling the Me–Gn (gnathion) axis and extension vectors directed downward and forward perpendicular to the Me–Gn axis.

**Figure 4.** From T3 (age 12–14 years) to T4 (age 15–17 years): localized (A) size changes (scale unit = 100%) and (B) shape changes in the mandibular configuration of male subjects; plot of the (C) maximum principal directions and (D) minimum principal directions in the mandibular configuration of male subjects (extension vectors plotted in blue and compression vectors in red); localized (E) size changes and (F) shape changes in the mandibular configuration of female subjects; plot of the (G) maximum principal directions and (H) minimum principal directions in the mandibular configuration of female subjects.
Mandibular growth changes from T3 to T4 in females
The localized size changes in the mandibular configuration of females from T3 to T4 are shown in Figure 4E, and the localized shape changes are shown in Figure 4F. The plots of maximum and minimum principal directions of tensor vectors are shown in Figures 4G and 4H, respectively.

The greatest positive allometry occurred at the anterior border of the chin (17.1–30.1%). The upper posterior border of the mandibular ramus showed a 10.7–17.1% increase in size. The mandibular corpus increased by about 4.2%. However, the gonial angle region, the anterior dentoalveolar portion, the condylar region and the anterior inferior border of the chin showed signs of negative allometry.

The mandibular symphyseal region showed evidence of anisotropy of about 13.5–31.5%, whereas an area of marked anisotropy (27.0–31.5%) was found localized between points Pm and Pog. Change in shape of 13.5–18.5% occurred at the upper posterior border of the mandibular ramus. The condylar head and the incisive alveolar region exhibited anisotropy of about 13.5%. The mandibular corpus showed about 9.1% change in shape.

The extension vectors for the upper posterior portion of the ramus were in a direction parallel to the Ar–Pb line, and the compression vectors were perpendicular to the Ar–Pb line. The mandibular symphysis had compression vectors parallel to the Me–Gn axis and extension vectors directed downward and forward perpendicular to the Me–Gn axis. The mandibular corpus had extension vectors parallel to the Ab–Me axis and compression vectors perpendicular to the Ab–Me axis.

Mandibular growth changes from T4 to T5 in males
The localized size changes in the mandibular configuration of males from T4 to T5 (age ≥ 18 years) are shown in Figure 5A, and the localized shape changes are shown in Figure 5B. The plots of maximum and minimum principal directions of tensor vectors are shown in Figures 5C and 5D, respectively.

The greatest increase in size occurred at the mandibular symphysis region (10.4–16.3%). The region at the posterior border of the upper ramus had about 7.5–10.4% increase in size. The rest of the mandibular regions showed slight positive allometry of about 1.7–4.6%.

The anterior border of the mandible showed the greatest anisotropy of 10.3–13.8%. The posterior border of the upper portion of the ramus showed 6.9–10.3% change in shape. The condylar head and the posterior half of the mandibular corpus showed 6.9% change in shape. The rest of the mandibular regions showed minimal changes of 1.7–5.2%.

The extension vectors at the anterior border of the mandible were parallel to the Gn–Me axis, while the compression vectors were perpendicular to the Gn–Me axis. The most anterior and inferior border of the chin had greater extension vectors parallel to the Gn–Me axis and smaller extension vectors perpendicular to the Gn–Me axis. Extension vectors at the posterior border of the upper ramus were parallel to the Ar–Pb line. The posterior part of the mandibular corpus had small vertical extension vectors and horizontal compression vectors.

Mandibular growth changes from T4 to T5 in females
The localized size changes in the mandibular configuration of females from T4 to T5 are shown in Figure 5E, and the localized shape changes are shown in Figure 5F. The plots of maximum and minimum principal directions of tensor vectors are shown in Figures 5G and 5H, respectively.

Very little increase in size was detected at the condylar region, the upper portion of the mandibular ramus, the mandibular corpus, and the symphyseal area (0.0–4.0%). In contrast, the gonial angle region exhibited localized negative allometry (about 2–10% decrease in size).

The area above the gonial angle exhibited greatest anisotropy (10.0–11.4%). The posterior dentoalveolar region and the most anteroinferior
border of the chin showed 8.5% change in shape. The condylar head, the upper posterior portion of the ramus, and the anterior region of the mandible showed the least amount of anisotropy (1.4–2.8%).

The gonial angle region had significant compression vectors parallel to the Pb–Go axis. The extension vectors at the most anteroinferior border of the mandible were parallel to the Gn–Me axis, while the compression vectors were perpendicular to the Gn–Me axis. The posterior alveolar region had compression vectors parallel to the Ab–Me axis and extension vectors perpendicular to the Ab–Me axis.

Discussion

Geometric morphometric analysis is superior to conventional cephalometry in that: no conventional reference lines are required; an explanatory visualization of morphologic differences is provided; and it can localize the actual sites where the size and shape changes occur. Several morphometric approaches have been proposed in the last two decades. Each technique has relative merits and is able to provide certain types of information. Fourier analysis uses mathematical techniques to quantify shape changes, but it does not provide graphical outputs. Thin-plate spline analysis displays the differences between two configurations by means of transformation grids, but the presentations of findings as eigenvalues, partial warps, and bending energies might not be appropriate for use by clinicians. The finite element analysis generates color-coded configurations that allow visualization of the distribution of size and shape changes within the configurations. However, the poverty of accepted landmarks used in this method leads to the generation of too few triangular elements, and the large element size employed fails to reflect detailed local differences. Recently, finite element morphometry has been proposed by Singh et al to integrate the finite element modeling and the thin-plate spline interpolating function. The drawbacks caused by interpreting changes from limited numbers of triangular elements could be overcome through the mapping function of thin-plate spline analysis. However, color-coded displays of size and shape differences cannot express the directions of change. Therefore, in addition to graphical displays of size and shape changes (following the method introduced...
by Singh et al), we used maximum and minimum principal directions in this study to describe the magnitudes and directions of morphologic changes within the mandibular configuration. The directions and amount of principal strain tensors can express the trend in growth change within the mandibular configuration.

Our results revealed that significant modifications in mandibular morphology occurred at all maturation stages for both genders. During the growth interval from T1 to T2, the greatest positive allometry occurred at the condylar region and the upper posterior portion of the ramus in both males and females. Significant modifications in shape were also noticed in this area, which displayed significant lengthening along the Cd–Ar axis (an upward and slight forward direction of condylar growth). The gonial angle region exhibited significant reshaping in both groups, especially in males, where the gonial angle tended to become more acute. The incisive alveolus grew vertically to corroborate with the vertical condylar growth. The symphysis exhibited a downward and forward growth. The distribution of localized size changes of the mandibular configurations was similar between the sexes during this period. The closure of the gonial angle and the upward–forward growth of the condyle implied the existence of a tendency for anterior morphogenic rotation of the mandible.

During the growth interval from T2 to T3, the greatest increase in local size and change in shape occurred at the condylar head, which had an upward and forward growth. The rest of the mandibular configuration did not show much shape change, while the localized size continued to increase during this period. The amount and distribution of localized size and shape changes were comparable between the genders.

During the growth interval from T3 to T4, the greatest size and shape changes took place at the symphysial region between points B and Pog, which exhibited substantial growth directed anteroinferiorly. The upper posterior border of the ramus had a moderate amount of vertical growth. The mandibular corpus showed very little signs of anteroinferior growth. The distribution of localized size and shape changes were similar between the two genders. However, the overall growth increments decreased in female subjects (except at the area between points B and Pog), while male subjects maintained a considerable increase in size.

During the growth interval from T4 to T5, significant sexual dimorphism was noted in the distribution and amount of localized size and shape changes. Females showed very little growth increments in the whole mandibular configuration, while considerable localized shape modifications were noticed. The gonial angle in females became more acute. A forward and upward rotation of the mandibular corpus and posterior alveolus was evident. The most anteroinferior border of the symphysis (region of Pog–Gn–Me) also revealed a forward and upward deformation resulting in a stronger appearance of the mental protuberance. Meanwhile, growth increments continued in males. The upper posterior border of the ramus exhibited a vertical lengthening of up to 10.4%. The anteroinferior border of the symphysis (Pog–Gn–Me) demonstrated an additional 16.3% increment in size. The anterior border of the mandible revealed an upward and forward deformation. The region near the antegonial notch displayed a downward deformation. Thus, the whole mandibular configuration in males also exhibited an upward and forward rotation. This result is in accordance with the metallic implant studies of Björk, which showed that the mandible rotated during growth. This remodeling in shape was an attempt to dissipate excessive mandibular growth increments in relation to the maxilla and to maintain a proportional relationship in the craniofacial structures.

Due to the nature of the cross-sectional approach, we could not highlight individual variations. We failed to detect a definitive pubertal growth spurt in males or females as the subjects were grouped triennially according to their chronologic ages. Thus, individual skeletal maturation was not evaluated. However, we found that males showed considerable growth even beyond 17 years of age, while females displayed small
growth increments at the age of 15–17 years. It was interesting that, during the stages in which growth increments occurred, the distribution of localized size and shape changes was very similar between the two genders. Further investigations that group samples according to their individual skeletal maturity are needed. Either appraisal of the skeletal maturation stage from cervical vertebrae or hand radiographs should be performed prior to grouping of the subjects.

Although based on cross-sectional data, this study demonstrated general trends in localized size and shape changes in mandibular configuration from childhood to adulthood in subjects from Taiwan with skeletal Class III malocclusion. Those who exhibited opposite extremes of vertical growth pattern (with SN–MP angle < 28° or > 38°) were excluded from the study to minimize the confounding effects that different vertical facial patterns might cause. The morphometric analyses used in this study appeared to be efficient for the description and quantification of the size and shape changes that occurred during mandibular growth. The plots of maximum and minimum principal directions provided clearer visualization of the trends in growth changes within the mandibular configuration.

We conclude that thin-plate spline analysis and finite element morphometry are efficient methods for the localization and quantification of the size and shape changes that occur during mandibular growth. The plots of maximum and minimum principal directions allow better visualization of the trends in growth changes.

References