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Early recognition of mandibular growth pattern using geometric morphometrics

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THESIS

EARLY RECOGNITION OF MANDIBULAR GROWTH PATTERN USING GEOMETRIC MORPHOMETRICS

by

MEGHAN GRAHAM

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B.A. Tufts University, 2009

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Reader Approval Page

Approved by

First Reader ______________________________

Dr. Leslie A. Will, DMD, MSD
Program Director and Department Chair
Department of Orthodontics and Dentofacial Orthopedics

Second Reader ______________________________

Dr. Melih Motro, DDS, PhD
Clinical Assistant Professor and Research Director
Department of Orthodontics and Dentofacial Orthopedics

Third Reader ______________________________

Dr. Joseph Bouserhal, DDS, MS, PhD, DURCO, DUOLG, DUIT
Adjunct Clinical Professor
Department of Orthodontics and Dentofacial Orthopedics

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MEGHAN GRAHAM

Boston University, Henry M. Goldman School of Dental Medicine, 2017

Leslie A. Will, DMD, MSD, Department Chair, Department of Orthodontics and Dentofacial Orthopedics

ABSTRACT

Objective: The objective of this study is to determine the earliest time point in growth when a difference in mandibular shape of dolichocephalic and brachycephalic subjects is distinguishable.

Materials & Methods: 11 dolichocephalic and 14 brachycephalic subjects were selected using lateral cephalograms from the Forsyth/Moorrees Twin Study using a method described by Rocky Mountain Orthodontics. 23 landmarks outlining the mandible were identified on the lateral cephalograms of each subject from their earliest age (5-8 years) to their latest (16-18 years) using TPSdig software. The 2 dimensional coordinates for each landmark were then exported to TPSUtil. From TPSUtil, the TPS data was then converted to a .csv file in Microsoft Excel and imported into MorphoJ for analysis. Primary morphometric analysis consisted of generalized Procrustes analysis, principal component analysis, and discriminant function analysis.

Results: The first 5 principal components for both facial types accounted for the majority of the variance. Discriminant function analyses were not significant for any phenotype or age group pairing, suggesting that the overall shape difference was too small to be detected between groups and over time starting at age 7. A plot of the Procrustes coordinates for the brachycephalic group versus the dolichocephalic group revealed that there were differences in shape between the two phenotypes, but this difference was statistically insignificant.

Conclusions:

The mandible increases in size with age, with minimal change in shape. Mandibular shape is established by the age of 7. The difference in mandibular shapes of the two phenotypes was not statistically significant.

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Growth and development of the Maxilla and Mandible

Facial type, or growth pattern, has long been of interest to researchers, teachers, and most importantly orthodontic clinicians. The growth pattern of an orthodontic patient is essential to successful diagnosis and treatment planning. Malocclusions, such as open bite or deep bite, result from several different etiological factors during the growth period, one of the main factors being the growth pattern of the mandible[1]. Being aware of this growth pattern early can allow the orthodontist to plan their treatment mechanics better to prevent worsening of an open bite or deep bite, for example. Before discussing different growth patterns, it is important to have a basic understanding how the facial structures develop. The main craniofacial structures that an orthodontist is typically concerned with are the cranial base, the maxilla, and the mandible. This discussion will focus on the maxilla and mandible because cranial base growth ceases early at about age 7[2] and because orthodontic treatment focuses much more on the maxilla and mandible than on the cranial base.

The most rapid and intense period of growth occurs during infancy and early childhood[3]. In fact, the cranial structures most closely approximate their adult size earlier than any other part of the body. This is due to the cephalocaudal growth gradient of the body, which means the cranial vault growth is completed before maxillary growth, and maxillary growth is completed before mandibular growth. The mandible is one of the last facial hard tissue components to stop growing[4]. There are also different speeds at which the different dimensions of the face develop. A study by Goldstein[5] demonstrated that the face grows fastest in length, followed by depth, and lastly width.

In 1965, Enlow[6] and Bang[7] described growth and remodeling of the maxilla in great detail. A general statement is often made that the maxilla grows down and forward, and although this is true, it is an over-simplification according to Enlow[6] and Bang[7]. There are many complex interactions and remodeling processes that occur to cause the maxilla to move down and forward. Bone is deposited on the posterior of the maxillary tuberosity. This allows the arch to lengthen for the eruption of the second molars thereby increasing the entire anterior-posterior length of the maxilla. This movement is coordinated with the simultaneous posterior movement of the zygomatic arch. The zygomatic arch grows posteriorly by bone deposition on its posterior surface and resorption on the anterior surface. Bone is also deposited on the lateral portion of the zygomatic arch and resorbed on its medial surface, which contributes to the widening of the face. The nasal process of the maxilla grows by surface deposition laterally, anteriorly, and superiorly. The palatine process grows downward due to surface deposition on the oral side combined with resorption on the nasal side as well as from the labial surface of the anterior maxillary arch. The premaxilla also grows in a downward direction via bony deposit on the lingual side and resorption on the labial side. These coordinated processes of resorption and deposition on various borders of the maxilla, as described by Enlow[6], is what causes it to move downward and forward during growth. It is clear that this is in fact a complex process and not a single event. The mandible too, grows and moves down and forward due to similar processes of resorption and deposition.

Bjork's[8] implant study of facial growth gave great insight into the growth of the mandible. He found that there was minimal growth at the chin and that most of the growth in the length of the mandible occurred at the condyle. There was some thickening at the posterior surface of the symphysis and apposition on the lower border, which contributed only minimally to the increase in length of the mandible during growth. His study also showed that there was significant variation between the shape of each individual's basal arch and mandibular angle. This shape also depended on growth of the condyle.

It is important to note, however, that although condylar growth can increase mandibular length, its cartilage is not a primary site of mandibular growth. According to Moss[9], condylar cartilage are sites at which secondary, compensatory growth occurs. A more in depth explanation of Moss's Functional Matrix theory helps to provide a better understanding of mandibular growth, as well as overall facial growth. According to Moss[9], each of the many functions that occur in the head region are carried out by a functional cranial component. Each component consists of a functional matrix and a skeletal unit. The functional matrix, such as muscle, carries out the function and the skeletal unit protects and/or supports the functional matrix. Each change in size, shape, or position of these skeletal units is always secondary to the growth of its relative functional matrix.

There are two types of functional matrices, periosteal and capsular, which have differing but complementary roles in skeletal growth. The periosteal functional matrix affects the microskeletal unit, while the capsular functional matrix affects the macroskeletal unit. For example, growth change in size and shape at the coronoid process are a direct result of temporalis function. If the temporalis muscle is cut there is a resulting decrease in size and shape of the coronoid process. Regarding the capsular functional matrix, the orofacial capsule surrounds and protects the oronasopharyngeal cavity and its functions of mastication, swallowing, and speech. Primary expansion of these spaces causes the bones surrounding it to be carried outward. Therefore, mandibular growth can be seen as a combination of the morphological effects of capsular and periosteal matrices[9]. Simply put, capsular growth causes expansion of the surrounding skeletal units. The mandible itself is a macroskeletal unit and is secondarily translated into a new space and position due to capsular growth of surrounding musculature and soft tissue. These interactions lead to a combination of bone deposition and resorption, just as in the maxilla. There is bone deposition at the external surface of the mandible and resorption on the internal surface, which leads to an increase in its transverse dimension. At the ramus, there is deposition on the posterior border and resorption on the anterior, which leads to an adjustment in the thickness of the ramus. At the coronoid process, there is deposition at the anterior border and resorption of the posterior leading to anterior displacement of the coronoid process.

As is evident, the growth process of the mandible and maxilla is a complicated process and one that orthodontic practitioners continue to seek to understand. However, within these general processes there is a great deal of individual variation. Not everyone will grow the same and understanding this is essential to successful orthodontic treatment.

Facial Types

Due to inherent variations in growth, not everyone will look the same. All patients can be categorized into a specific facial type, with several different methods of categorization.

According to Ricketts there are three facial types based on growth vector. These patterns are dolichofacial, brachyfacial, or mesofacial types[10]. Mesofacial type patients have a favorable orthodontic prognosis due to a harmonious maxilla-mandibular relationship, with a normal soft tissue profile and musculature. Dolichofacial patients exhibit a vertical growth pattern with long and narrow dental arches, often with crowding and a Class II division 1 malocclusion. The mandibular gonial angle is often obtuse with an anterior open bite, which can cause strained soft tissue. These facial patterns can be challenging to treat orthodontically due to the excessive anterior vertical height as well as the strained soft tissue. Brachyfacial patients exhibit a short and wide face. The mandible is broad and square and they are often associated with Class II, division 2 malocclusions. In comparison to the dolichofacial pattern, these patients have horizontal growth patterns with deep bites and closing mandibular rotation.

Sassouni[11,12] also used lateral cephalograms to examine and classify patient facial types, but it was done in a different way. Patients that vary from the norm are classified into four different categories based on vertical and skeletal disproportions. The vertical category included patients with deep bites and open bites, while the skeletal category included patients with Cl II or Cl III skeletal relationships. The open bite and deep bite categories are determined by examining the divergence of the four planes of the face in relation to each other. These four planes (supraorbital, palatal, occlusal, and mandibular), when examined on a lateral cephalogram, will be close to parallel to one another and will only converge at a point distant from the face in a deep bite patient. The opposite is true for the open bite cases. These skeletal planes converge towards each other at a point close to the face. Other dimensional deviations are also used to further classify these patients. In the deep bite cases, the total posterior face height is almost equal to that of the anterior facial height, and the lower face height is usually smaller than the upper face height. This is due to usually a long ramus, which is often almost the same length as the corpus. The exact opposite dimensional deviations are seen in open bite cases. The total posterior facial height is much shorter than the anterior, and the lower anterior facial height is greater than the upper anterior facial height. The ramus is shorter, typically with an antegonial notch. Sassouni describes the skeletal disproportion types based on several criteria including anterior cranial base length and cranial base angle. In skeletal Cl II patients there is a long anterior cranial base with a large cranial base angle. The skeletal Cl III patients have a short anterior cranial base and a small cranial base angle. Patients can have varying combinations of vertical and skeletal disproportions. This type of classification of patients is much different from Ricketts' because it not only addresses growth vectors but also the physical shape of skeletal structures and their relation to one another.

Schudy[13]used a similar way of thinking to Sassouni in classifying patients into a certain facial type. He, like Sassouni[11,12], used vertical growth and anterior posterior growth when making his classifications. Sassouni believed growth of the face is best described as a constant battle between vertical and anterior posterior growth. It was through the studying of the interaction between these two different directions of growth that the terms "hypodivergent" and "hyperdivergent" were introduced. Schudy[13] described a hyperdivergent patient as one where the anterior posterior growth won the battle over the vertical growth. In these cases the anterior posterior growth is greater. The opposite is true in hyperdivergent cases, where the vertical growth exceeds the anterior-posterior growth. Ricketts, Sassouni and Schudy each used original and unique methods in describing facial patterns. This shows that there is no one correct way to classify patients, but it also shows that different results might be achieved depending on what method is used.

Radiographic imaging allowed those like Schudy, Sassouni and Ricketts to make great advancements in the understanding of the growth process and its differences between individuals. It also provided a way to attempt to predict a patient's velocity and direction of growth in different ways.

Growth Prediction and Orthodontics

For orthodontists, being able to have an idea about the direction of future growth of their patients is extremely important since growth can either work in the orthodontists favor or against it[14]. Having a good understanding of the growth of the patient allows for better treatment planning and therefore a more stable result[14]. Different growth directions, or facial types, as previously described all require special attention in the treatment planning process and different types of treatment mechanics. For example, in a patient that has a very steep mandibular plane, open bite, and a Cl II malocclusion, the future growth direction is obvious and the treatment plan should involve skeletal anchorage for intrusion of the upper posterior molars. However, it is not these types of cases that can trip an orthodontist up mid-treatment. The type of growth of these patients is obvious to an orthodontist. The cases that are worrisome to treatment plan are the milder cases that show only a tendency towards skeletal growth discrepancies prior to their growth spurt. These are worrisome especially because, according to Bishara and Jakobsen[15] facial pattern becomes more expressed with age. For example, at age 7 a slightly hyperdivergent patient may end up with a much steeper mandibular plane several years later. In these types of cases, Bishara[14] recommends that the clinician assumes the "worst case scenario" and that the more mildly divergent patient will grow in a unfavorable direction. For example, in a borderline hyperdivergent patient, the orthodontist should avoid extrusive forces so if the patient does grow unfavorably the appropriate mechanics are already being used. Therefore, understanding the growth pattern of a growing patient allows the orthodontist to use preventative mechanics in order to avoid worsening any underlying growth pattern that has not yet fully expressed itself.

Lateral Cephalometrics

Today, most orthodontists use lateral cephalograms to evaluate craniofacial growth patterns, as well as dental malocclusions, deformities, and post-treatment results. However, prior to the development of radiographs, clinicians were only able to diagnose and treatment plan based on the dentition and intra- and inter-arch relationships.

In 1895, Roentgen[16] changed the world of medicine and dentistry with the remarkable discovery of x-rays. In 1928, an article describing the first lateral cephalogram to be taken was published by Dewey and Riesner.[17] Dewey and Riesner stabilized the patient's head and aligned the head using the eye-ear plane at a right angle to the floor. The cassette was placed against the patient's face and the radiograph was taken. This is part of the beginning of what we now know today as cephalometry.

In 1931, Hofrath[18] and Broadent[19] took cephalometrics a step further and simultaneously published methods in obtaining standard radiographs. Because of these two men, orthodontists now had a clinical tool to study the relationship between the teeth, jaws, and overall craniofacial complex in both the horizontal and vertical dimensions. This led to the development of a number of analyses to compare a patient to population standards.

The main purpose of cephalometric analyses is to assess the relationship of the cranium and cranial base, the maxilla, the mandible, and the dentition. The analysis itself is carried out on a tracing or a digital model. Landmarks are selected based on specific skeletal structures. These landmarks have x,y coordinates which may be used in a computerized analysis to produce various linear and angular measurements. The clinician can then compare these patient numbers to normal data and use this information in the treatment planning process[18].

The first published cephalometric analysis was developed by Downs[20] in 1948. His analysis was based on a reference group of 25 untreated, white adolescents whom he determined to have ideal dental occlusions. In 1953, Steiner[21] followed with his own analysis also based on a rigidly selected sample, similar to Downs. Despite the suggestion that his sample was based on a single Hollywood star, components of his analysis are still used today. In fact, he was the first to develop an analysis that provided guidelines for using the measurements for treatment planning, while also emphasizing the interrelationship between measurements.[18]

In1954, Tweed[22] published an analysis based on three planes: Frankfort horizontal plane, mandibular plane, and lower incisor plane. Tweed also chose patients with good occlusion based on his assumption that good occlusion contributes to a harmonious facial balance.

Sassouni's[23] analysis in 1955 was the first to emphasize vertical and horizontal relationships and proportions. He established that the mandibular plane, occlusal plane, palatal plane, Frankfort plane, and inclination of the anterior cranial base all converge to a single point in well-proportioned faces. In fact, Sassouni is the one who coined the term, *skeletal open bite* because as he pointed out, if the intersection of the planes are close to the face and then rapidly diverge as they move anteriorly, the patient is predisposed to an open bite. The opposite is true for skeletal deep bite patients. The planes converge far posterior to the face and diverge only slightly as they move anteriorly. Many other analyses followed including Ricketts[24], Enlow[25], McNamara,[26] Harvold[27], and Jacobson[28].

Geometric Morphometrics

Traditionally, conventional lateral cephalometric analyses, such as those previously described, have been used to assess growth direction, diagnose, and treatment plan orthodontic patients as well as track their growth progress through treatment. These analyses are looking at facial shape and growth base on linear and angular measurements only. For example, in one study Nanda[29] examines the skeletal-facial changes in growth of 20 males and 20 females by looking at various linear and angular measurements such as the length between sella and supramentale, or the angle nasion-sella-supramentale. Bjork[30] also assesses growth in his implant study, where implants are placed in various craniofacial structures and monitored over a period of time. Bjork looks at several angular and linear measurements in this study to assess growth of the mandible. He assesses growth rotation of the mandible in relation to the cranial base by comparing the angle between the nasion-sella lines for different time points from each patient.

These traditional cephalometric measurements and analyses have several limitations in terms of diagnosis and treatment planning. Lateral cephalograms are two-dimensional images of a three-dimensional structure. Reading the films can be difficult due to distortion caused by superimposition of different structures. The superimposition makes it difficult to determine the difference between the right and left sides[31]. This distortion, along with landmark identification error, is what leads to inaccuracy in computing linear and angular measurements[32]. Linear measurements may also be inaccurate due the divergence of the x-ray beams from the source to the film, which causes varying enlargement of the cranial structures[33].

Another way to treatment plan and assess patient growth is to go beyond these standard linear and angular measurements and use geometric morphometrics. The term morphometrics comes from the Greek “morph”, meaning “shape”, and “metron” meaning "measurement”. Morphometrics is the quantitative study of biological shape variation.[34] It examines the geometrical form of organisms, combining biology, geometry, and statistics, and is therefore a more accurate way of comparing shapes[35].

In order to compare shapes, specific landmarks along their outlines must be selected. Each landmark is chosen based on significant reasoning, which may be functional, developmental, structural, or evolutionary. The criteria for choosing landmarks are: “1) homologous anatomical loci that 2) do not alter their topological positions relative to other landmarks, 3) provide adequate coverage of the morphology, 4) can be found repeatedly and reliably, and 5) lie within the same plane.”[36] The landmarks are plotted as an x,y or x,y,z Cartesian coordinates. Plotting of the coordinate landmarks creates a geometric shape. For example, the morphometric form of the mandible may be computed via marking many significant landmarks including B point, gonion, gnathion, condylion, etc. on a lateral cephalogram. These landmarks and shapes can easily be digitized to allow for computer program analysis. There are several different methods for computer-program analysis of the coordinates. The analysis that is of interest to this study and one of the most widely used methods is the Generalized Procrustes Analysis. In the Generalized Procrustes Analysis, the shape formed by the landmarks are superimposed using a common landmark reference system via rotation and translation. Scaling is also done in order to eliminate size variation[37]

As humans grow, size of structures may increase and shapes change. Angular and linear measurements can be used to compare size, such as with standard lateral cephalometric analysis. However, shape may also change during development, but cannot be analyzed accurately without morphometrics. As explained previously, morphometrics eliminates variation in size. For example, one study by Hutchinson[38] used morphometrics to examine the relationship between the tongue and mandibular shape from ages 20 weeks of gestation to 3 years after birth. By using morphometrics this study was able to highlight the relationship between the growth of the tongue and mandible. It showed that during the time period examined, only tongue size increased, with shape remaining the same, whereas with the mandible, size and shape both changed. This data obtained via morphometrics allowed the authors to hypothesize a functional and developmental relationship between the tongue and the mandible that would have been difficult to examine otherwise.

In a study by Nicholson et al[39], morphometrics and the Procrustes method of analysis were used quantitatively to evaluate both geographic and functional patterning of the mandible in order to determine the effects of biological scaling on mandibular form.

The mandible of humans was examined via 28 landmarks in 3-dimensional form. Morphometric analyses allowed the authors to conclude that the mandibular shape exhibits both climatic and functional patterning. Both the Hutchinson[38] and Nicholson[39] studies use morphometric analyses as a means to examine mandibular form in relation to function. Although morphometrics has proven to be useful as shown in these types of studies, it is of interest of this study to also examine its usefulness in analyzing the establishment of mandibular shape in the growing patient.

Procrustes Superimposition

After landmarks are strategically selected using the appropriate criteria as previously described, the shapes must be superimposed using a Generalized Procrustes Analysis in order to be compared.

The term “Procrustes” comes from a character from Greek mythology, who was the son of Poseidon and a rogue smith that lived between Athens and Eleusis. This was a sacred route for many travelers, and one on which Procrustes would offer the hospitality of a bed to sleep in to these weary travelers. He could claim that the bed would fit them perfectly. What the travelers did not know was that Procrustes intended to make the travelers fit the bed perfectly rather than visa versa. In order to do so, he would cut the limbs off of any one who was too tall to fit the bed, and would stretch out any one who was too short to fit the bed. In other words, he eliminated any size variation of his travelers and made them fit perfectly to his bed[40,41].

Therefore, it makes sense why the Generalized Procrustes Analysis is called such, because it is a multivariate technique that eliminates size variation through the translation, rotation, and scaling of individual data matrices to allow for comparison of shape only. The average of these matrices is called the consensus matrix.

When making a comparison between objects, the difference between their shapes is called the Procrustes distance. The Procrustes distance is the summed squared distances between corresponding landmarks[36]. Scaling is performed during this superimposition so the concept of size is completely removed. For example, if a Procrustes Superimposition were performed on two spheres with different diameters their Procrustes difference would be zero. They are the exact same shape. However, if a superimposition were performed on a sphere and a cube, the Procrustes difference would be large since the two objects will never fully superimpose no matter how they are rotated, translated, or scaled. Any remaining differences that cannot be explained by translation, rotation, or scaling are called Procrustes residuals. The residuals can also be plotted to demonstrate shape variance of a configuration matrix.

Principal Component Analysis (PCA)

Once the Generalized Procrustes Analysis is completed, the shapes can be compared statistically using several analyses. One way to do this comparison is by performing a Principal Component Analysis (PCA). A PCA is a mathematical method of analyzing the individual and consensus matrices generated by the Generalized Procrustes Analysis. It reduces the complexity of a data set, with minimal information loss, in order to identify patterns in the data and express it to highlight their similarities and differences[42,43]. It takes a data set with a large number of interrelated variables and converts it into a new data set of uncorrelated variables, also known as principal components. PCA does so by redistributing the total variances among a set of data points onto orthogonal axes (i.e. x and y axes), which are the principal components. PC1, the first axis, accounts for the most variance in the data that cannot be explained by any scaling, rotation, and translation that is done by the Generalized Procrustes Analysis. Each subsequent PC is orthogonal to the previous PC. For example PC2 is defined in the direction that is orthogonal to PC1 and accounts for the second most amount of variance in the data (Figure 1). This continues on with each PC being defined in an orthogonal direction to the one preceding it with decreasing contribution to the variance of the data. This continues on to PC3, PC4, etc[44]. Since the majority of the variance is captured in the first few PCs, only the first few PCs are considered when analyzing the results of a PCA. The rest of the PCs only account for a very small percentage of the variance and are therefore considered insignificant[45].

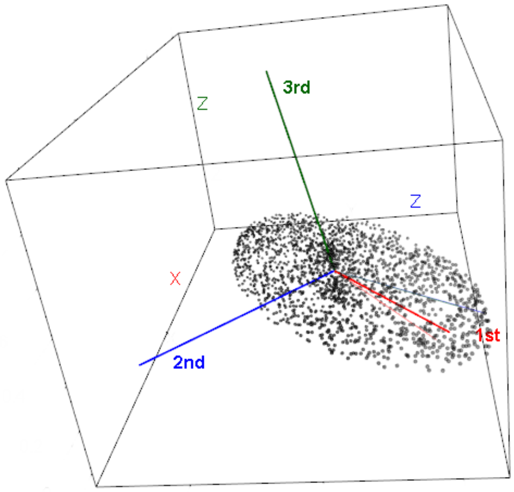

Figure 1: Illustration of a Principal Components Analysis. This figure shows a PCA applied to a data cloud. The first, second, and third principal components are shown here[66].

PCA can be applied to a plot of the Procrustes residuals (what is left over after superimposition of landmarks by scaling, rotation, and translation) in order to demonstrate the variance of the configuration matrix. This application of PCA to the Procrustes residuals is simply an arrangement and analysis of the data of the covariant matrix. Therefore, it is not a representation of any particular biological reality. Rather it is a way of depicting the variance of any one individual to the mean along the PC axis

Discriminant Function Analysis

Discriminant Function Analysis (DFA) is another analysis that can be performed to analyze the data once the Procrustes Superimposition is performed. It examines the separation between two groups and helps to answer questions such as: Can we discriminate two groups based on their morphometric traits? Are the groups significantly different in shape? [44]

DFA is a multivariate statistical technique that is used to investigate the relationship between several numerical independent variables and a single nominal independent variable[46]. In other words it determines whether groups can be distinguished reliably.

Furthermore, it describes the difference between the means of two groups across the mean of an entire sample, which is what was done in this study. It calculates the mean difference of an entire sample and compares it to the mean of the two groups. The greater the difference between the means, the more different the groups are, and the less difference between the means the more alike the two groups are.

Plotting the DFA is a graphical way of understanding the statistical analysis. If the means of the two groups are different, then the distribution plots of the individual groups will be separate. And if the groups are more similar, the distribution plots will be overlapping. Another way DFA describes the comparison between two groups is through a generated p-value. A p-value of 0.05 or less would indicate that the mean of the two groups are very far apart from each other, or in other words, the two groups are statistically significantly different. A p-value of 0.05 or greater indicates that two groups are close to the mean of the entire sample are therefore similar, or in other words, the two groups lack a statistical significant difference.

Geometric Morphometrics in Orthodontic Literature

In this study, we intend to use geometric morphometrics to assess shape change of the mandible over time. One of the main reasons for this is because a review of the current literature does not reveal any previous studies that have looked specifically at facial growth using geometric morphometrics. Most of the studies that have used geometric morphometrics used it to assess facial shape changes due to different types of treatment or to asses facial shape differences in different malocclusions, but very little can be found that simply assesses shape change of facial structures. Doucet et al[47] used Procrustes superimposition to examine the effects that maxillary distraction osteogenesis had on the mandible in cleft lip and palate patients. Franchi et al[48] used Procrustes superimposition and thin plate spline analysis, another form of morphometric analysis, to examine the effects of early class III treatment on the mandibular shape. Freudenthale[49] used Procrustes superimposition, thin plate spline analysis and other geometric morphometric analyses to examine the role that craniofacial shape has on malocclusions. Alarashi et al[50] used PA cephalograms and thing plate spline analysis to examine the dentoskeletal features of patients with Cl II malocclusions. Through this analysis they were able to determine that Cl II malocclusions were different from Cl I malocclusions in terms of skeletal shape in the frontal plane. Clearly there is not a shortage of literature utilizing geometric morphometrics, but there is little that discusses growth changes. Therefore, this study aims to add to the literature and provide better scientific knowledge on shape change due to growth, including the use of geometric morphometrics.

This study uses geometric morphometrics to overcome the inherent limitations of conventional lateral cephalometric methods of examining skeletal growth changes[51,52,53,54,55]. Analyzing growth of a biological structure warrants examination and description of its shape and form[56]. This can be done by geometric morphometrics, but not by lateral cephalometric analysis, which only generates linear and angular measurements. Geometric morphometrics allows for more advanced statistical analysis in examination of shape variation through Generalized Procrustes Analysis and Principal Component Analysis.

In this study geometric morphometrics is used to analyze the shape change of the mandible overtime from early childhood (5-6 years old) to late adolescence (16-18 years old). The shape of dolichocephalic subjects was compared to brachycephalic subjects overtime in order to determine the earliest time point in growth when a difference in mandibular shape between these two facial types is distinguishable. Therefore, the hypothesis is that there is a difference in mandibular shape between brachycephalic and dolichocephalic subjects at an early time point.

Materials and Methods

This study is a retrospective, cross-sectional analysis of consecutive lateral cephalograms of brachycephalic and dolichocephalic subjects. Subjects were selected from the Forsyth/Moorrees Twin Study (#H-31945), which contains orthodontic records from 501 families with twins or triplets taken at the Forsyth Infirmary for Children in Boston, Massachusetts from 1959-1975.Subjects were Caucasian and of Western European descent. The approval of the Institutional Review Board (IRB) of the Boston University Medical Campus was obtained (#H-33674).

Sample selection

Subjects were required to have consecutive cephalograms that spanned 8-10 years in order to be able to compare growth before and after the growth spurt. The earliest cephalograms had to be at age 8 years or earlier and the latest at least 16 years of age in order to be able to examine the subjects at pre- and post-pubertal time points. The subjects' handwrist radiographs were examined for SMI staging. An SMI of 10 or above was used to indicate that the majority of growth had been completed[57].

Syndromic patients and those with prior orthodontic treatment were excluded from the study. Subjects with more than two unreadable lateral cephalograms, and subjects with more than two missing lateral cephalograms between the ages of 6-19 were excluded from the study. Table I shows how many subjects were available at each time point. Subjects with obvious tipping and rotation of the head were also excluded. If the subjects were part of a pair of monozygotic twins only one was included to avoid potential duplication and skewing of the data.

Table I: Distribution of subjects at each age

Age	# of Subjects	Age	# of Subjects
5	10	**12**	24
6	18	**13**	25
7	20	**14**	24
8	25	**15**	25
9	24	**16**	22
10	25	**17**	19
11	25	**18**	11

Table II: Cephalometric measurements used to determine facial pattern

Cephalometric Measurement	Description	Figure 2	Norms	SD
Facial Depth	The angle formed by the planes Nasion - Pogonion and Frankfort Horizontal.	1	87°, @ 9 years old, ↑ 0.3°/year	± 3
Facial Axis	The angle formed by the plane CC to Gnathion and the Basion - Nasion Plane. (CC = Center of Cranium, landmark formed by the intersection of the two lines Basion-Nasion and PT-Gnathion).	2	90°	±3.5
Mandibular Plane	The angle formed between the mandible plane (Gonion-Gnathion) and the Frankfort Horizontal Plane (Porion to Orbitale)	3	26° ↓0.3°/year	±4.5
Lower Facial Height	The intersection of Anterior Nasal Spine-Xi and Xi-Protuberance Menti. (Xi is a point located at the geographic center of the ramus)	4	45°	±4
Mandibular Arc	The angle formed by the Corpus and Condyle Axes.	5	26 °@8.5 years old, ↑0.5°/year	±4

Facial type was determined using a method described by Rocky Mountain Orthodontics[10]. Five cephalometric measurements (Table II, Figure 2) were done at the latest age of each subject, which ranged from 15 to 18 years old, depending on what lateral cephalograms were available for each subject.

Each measurement chosen is significant in determining the facial pattern. The facial depth determines the role of the mandible in sagittal discrepancy by looking at its horizontal position relative to the cranium. The facial axis indicates the direction of growth of the mandible. The mandibular plane angle determines the vertical divergence of the mandible. The lower facial height determines the divergence of the maxilla and mandible relative to each other. Lastly, the mandibular arc indicates the relationship between the mandibular ramus and corpus.

The Z-scores were calculated for each of these measurements. The mean of the Z scores was then calculated to yield a determining score for the facial pattern (Table 3). A negative mean score was considered dolichocephalic and a positive, brachycephalic. Subjects with a mean score of 1 or greater in absolute value were included in this study as dolichocephalic and brachycephalic subjects. Therefore a score of -1 or less was considered dolichocephalic and a score of +1 or greater was considered brachycephalic.

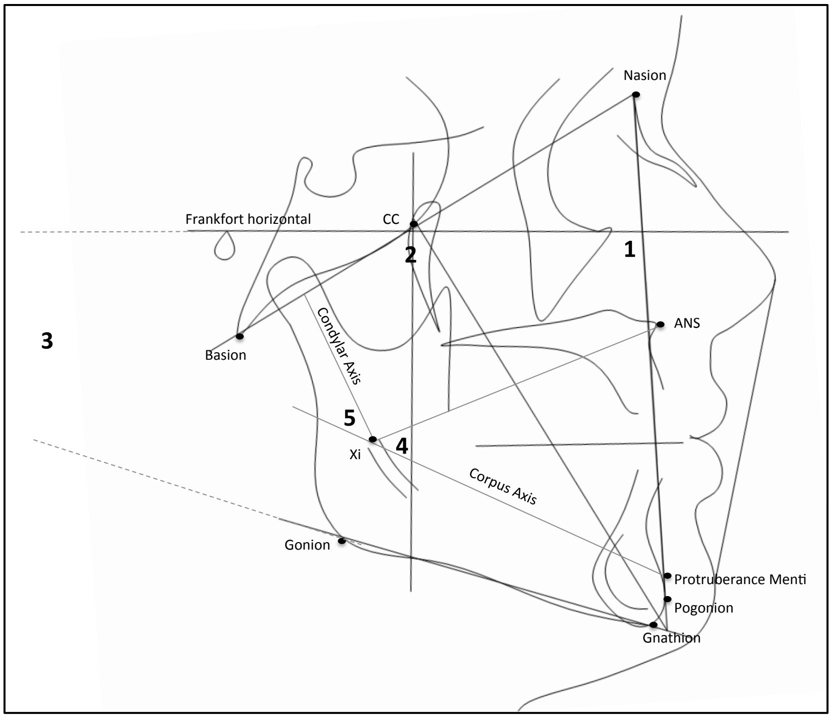

Figure 2: Rickett's Lateral Cephalometric tracing with depiction of the measurements that were used in this study. See Table 1.

Table III: Z-scores calculated on the latest time point for each subject

Brachycephalic Subject	**Z-score**	**Dolichocephalic Subject**	**Z-score**
1	1.14	1	-1.74
2	1.84	2	-1.86
3	1.02	3	-1.03
4	1.36	4	-1.04
5	1.23	5	-1.04
6	1.25	6	-1.92
7	1.54	7	-1.42
8	1.58	8	-1.06
9	1.04	9	-1.38
10	2.41	10	-1.01
11	1.25	11	-1.66
12	1.99		
13	2.40		
14	1.25		

Landmark Selection, Identification and Analysis

After screening, 11 dolichocephalic and 14 brachycephalic subjects were selected for the study. A total of 316 lateral cephalograms were examined. Each of these cephalometric radiographs were converted to JPEG files and imported into the computer software program TPSDig (F.J. Rohlf, http://life.bio.sunysb.edu/morph/, version 1.40). A single investigator identified 23 landmarks that outlined the mandible, using both anatomical landmarks and semilandmarks (Figure 3, Table IV) and traced them using the TPSDig software. The 2 dimensional coordinates for each landmark were then exported to TPSUtil (F.J. Rohlf, http://life.bio.sunysb.edu/morph/, version 1.74). From TPSUtil, the TPS data was then converted to a .csv file in Microsoft Excel (Microsoft Corporation, version 14.7.1). The .csv data file was then imported into MorphoJ (Klingenberg Lab, University of Manchester, version 1.06d[58]) for analysis.

Primary morphometric analysis consisted of Generalized Procrustes superimposition and principal component analysis. Matrix correlations were performed for each age group (5-17 years old). The data were further divided based on phenotype, and principal components analysis (PCA) of each facial type was also performed. Several other tests were done: Matrix correlation of the covariance matrices of the brachycephalic and dolichocephalic groups; and discriminate function analysis (DFA) for each group comparing consecutive ages was done (i.e., compared age 5 to 6, 6 to 7, 7 to 8, etc). Intraclass correlation was calculated by tracing 30 random cephalometric radiographs from the subject pool at least 4 weeks after the initial tracings were completed.

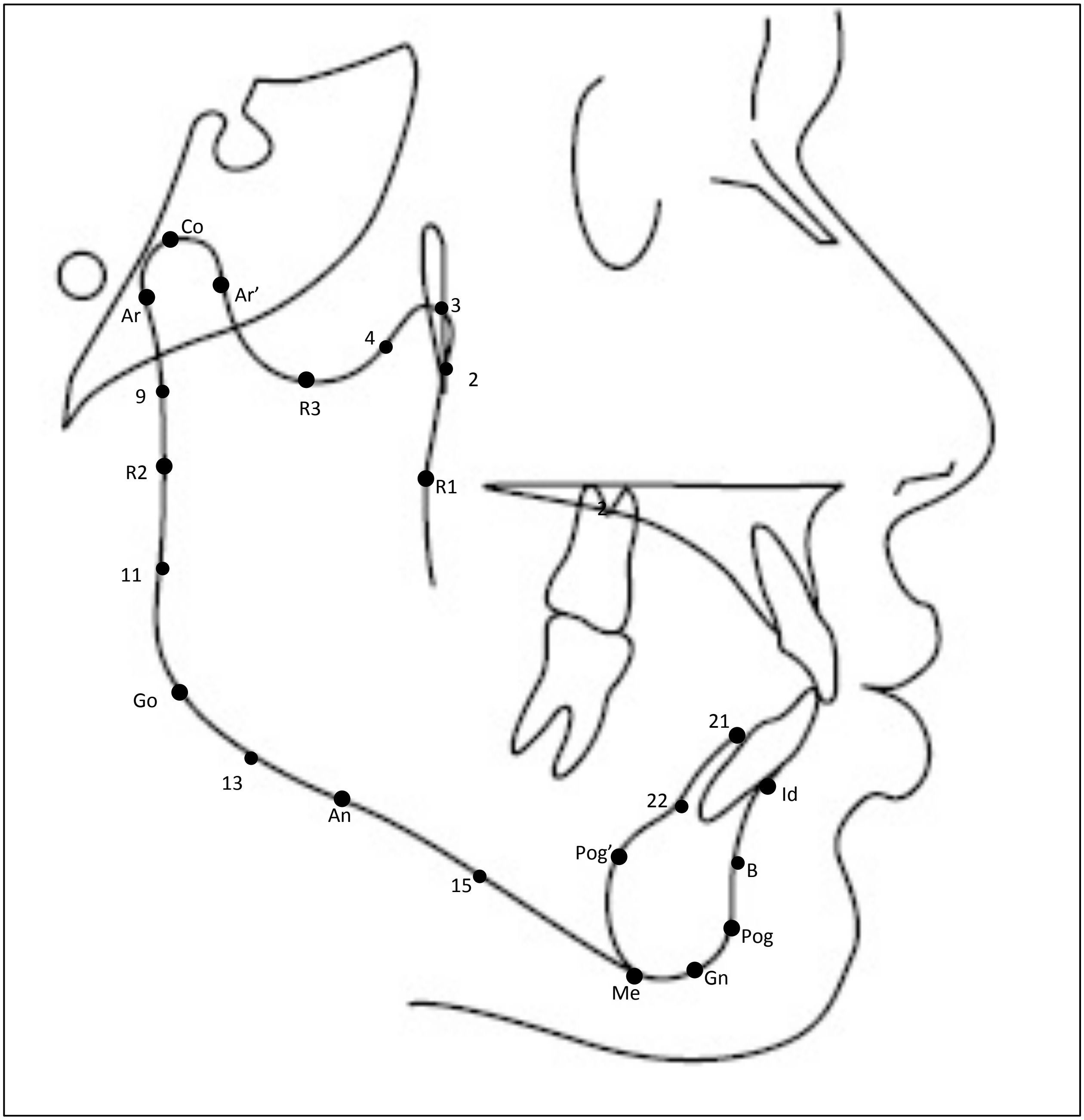

Figure 3: Diagram of landmarks and semi landmarks

Table IV: Lateral Cephalogram landmarks and semi landmarks

Landmark		**Definition**
1	R1	The deepest point on the curve on the anterior border of the ramus
2	Md2	Semi-landmark on the coronoid process opposite to R4
3	Md3	The most superior point on the coronoid process
4	Md4	Semi-landmark between 2 and R3
5	R3	The midpoint of the coronoid notch
6	Articulare’ (Ar’)	Point on the condylar process opposite articulare
7	Condylion (Co)	Most posterior/superior point on the condyle of mandible
8	Articulare (Ar)	Junction between inferior surface of the cranial base and the posterior border of the ascending ramus of the mandible
9	Md9	Semi-landmark on the posterior border of the ramus between Articulare and R2
10	R2	A point located on the posterior border of the ramus opposite of R2
11	Md11	Semi-landmark on the border of the posterior ramus between R2 and Go.
12	Gonion (Go)	The most lateral external point at the junction of the horizontal and ascending rami of the mandible
13	Md13	Semi-landmark equidistant between R2 and Go
14	Antegonion (An)	The highest point in the antegonial notch
15	Md15	Semi-landmark between An and Me
16	Menton (Me)	Lowest point on mandibular symphysis
17	Gnathion (Gn)	The most anterior and inferior point on the bony outline of the chin, situated equidistant from pogonion to menton.
18	Pogonion (Pog)	The most anterior point of the bony chin
19	Supramentale (B point)	The deepest point in the bony outline of the mandible between infradentale and the pogonion
20	Infradentale (Id)	The most anterior point of the alveolar crest, situated between the lower central incisors
21	Md21	Point opposite to Infradentale
22	Supramentale’ (B point’)	Point on the mandibular symphysis opposite to supramentale
23	Pogonion’ (Pog’)	Point on the mandibular symphysis opposite pogonion

Results

The principal component analysis shows that the first 5 principal components account for 70.8% of the variability of the brachycephalic sample and 65.1% of the variability of the dolichocephalic sample (Table IV).

A plot of the Procrustes coordinates for the brachycephalic group versus the dolichocephalic group (Fig. 4) revealed that there were differences in shape between the two groups. The condyle in the dolichocephalic group is more posterior than the brachycephalic group, and the brachycephalic group has a flatter mandibular plane and shorter symphysis. However, these shape differences were not statistically significant. Additionally, comparing pre- and post- pubertal age pairs revealed no statistically significant difference in shape between brachycephalic and dolichocephalic types.

Table V
Principal Components for Brachycephalic and Dolichocephalic Subjects

Principal Component	**% Variance Brachycephalic**	**% Variance Dolichocephalic**
1	25.391	21.880
2	16.457	18.500
3	14.747	9.555
4	8.598	9.204
5	5.891	5.595
Cumulative	70.812	65.099

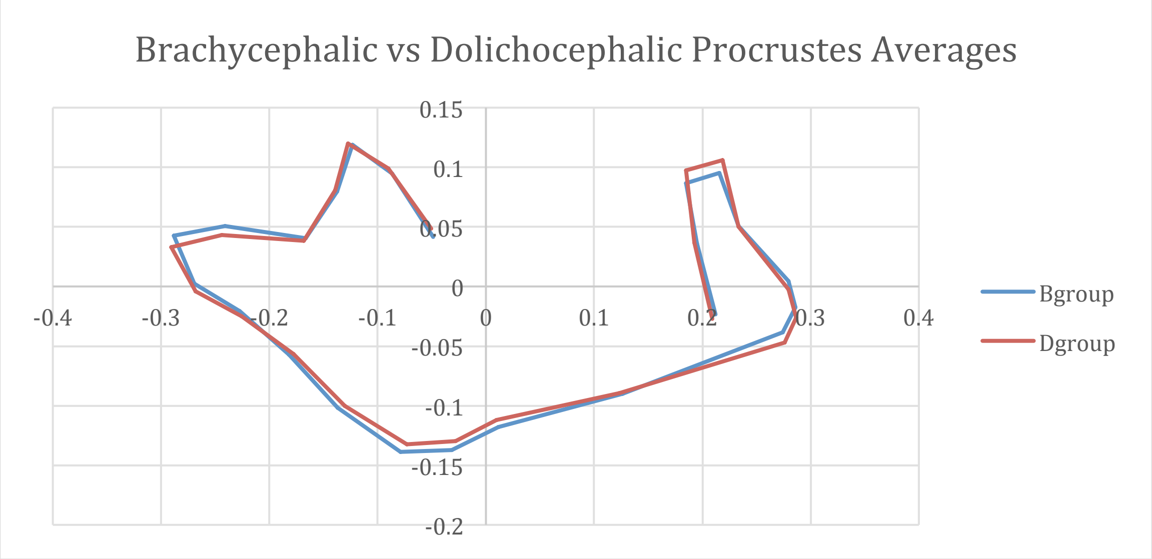

Figure 4: Average Procrustes Plot of Brachycephalic (B-group, blue) versus Dolichocephalic Subjects (D-group, red) generated in Excel.

Discriminant function analysis of brachycephalic versus dolichocephalic groups, however, was not statistically significant for any phenotype or age group pairing, suggesting that although there is a shape difference, according to the Procrustes plot, the overall shape difference was too small to be considered statistically significant (Tables VI, VII, VIII). The matrix correlation of the covariance matrices of the brachycephalic and dolichocephalic groups also supports this with a high correlation of 0.825 (Table IX). The results can be considered to be accurate since the intraclass correlation reliability test yielded an intraclass correlation of 0.970 (Table X).

Table VI: Discriminant Function Analysis: Brachycephalic versus Dolichocephalic Subjects	
Age	**P-value**
5	0.9429
6	0.9808
7	0.9733
8	0.9603
9	0.9889
10	0.9893
11	0.8699
12	0.9600
13	0.9293
14	0.8634
15	0.9799
16	0.9515
17	0.9846
18	0.9978

Table VII: Discriminant Function Analysis of age group pairing		
Age Range	**DFA Brachycephalic (P-Value)**	**DFA Dolichocephalic (P-value)**
5 to 6	0.9870	0.9997
6 to 7	0.9999	0.9978
7 to 8	0.9985	1.000
8 to 9	0.9597	0.9999
9 to 10	0.9887	1.000
10 to 11	0.9987	0.9999
11 to 12	0.9991	1.000
12 to 13	0.9997	0.9994
13 to 14	0.9996	1.000
14 to 15	0.9999	0.9997
15 to 16	0.9999	0.9998
16 to 17	1.000	0.9999
17 to 18	0.9999	0.9971

Table VIII: Discriminant Function Analysis: Comparing Pre- and Post-Pubertal by phenotype

Age Range	DFA Brachycephalic (P-Value)	DFA Dolichocephalic (P-value)
7 to 16	0.9218	0.9428

Table IX: Matrix Correlation Analysis: Brachycephalic versus Dolichocephalic

Matrix Correlation	0.82514419

Table X: Intraclass Correlation Coefficient

	Intraclass Correlation	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Average Measures	0.970	0.956	0.981	32.96	51	561	0.000

Discussion

Understanding the growth pattern of patients has long been an interest of orthodontists[59, 60, 13]. Typically growth has been predicted using conventional lateral cephalometrics, which has its limitations. This study attempted to examine the growth of the mandible in a different manner by comparing dolichocephalic and brachycephalic patients using geometric morphometrics and various statistical analyses. Rather than examining growth over time using traditional angular and linear cephalometric measurements, geometric morphemetrics was used to allow for examination of the pure shape change of the mandible with growth by eliminating any translation, rotation, or size variation.

The most significant finding of this study was revealed by discriminant function analysis in the examination of consecutive age groups. This analysis showed no significant change with age starting at 7 years old. As Table I shows, the majority of the sample had radiographs starting at age 7, but even the subjects that had radiographs starting at ages 5 and 6 exhibited the same pattern of no shape change. This leads to the assumption that from a very young age the shape of the mandible does not change, but rather only increases in size. A clinical implication for this is that the orthodontist can assume that the shape of the mandible of a young child will remain the same, and only size will change (increase) as the patient grows. It is difficult to presume any further clinical implications since effect of treatment on function of the two facial types was not examined in this study.

These results are similar to those found by Bishara and Jakobsen[15] in a study examining the longitudinal change in patients that are described as having long, average, and short faces. They reported that 77% of the people they examined had the same facial type at ages 5 and 25. The other 23% did not maintain their facial type, but they were on the borderline between facial types at age 5. This partially supports the DFA results that show no change in mandibular shape starting between ages 5 to 7.

It cannot be assumed, however, mandibular shape is the same from birth. At some point prior to age 7, the mandibular shape is changing. In a study examining dry mandibles from 31-40 gestational weeks to 36 months postnatal, Hutchinson et al[61] showed that the mandibular size and shape does in fact change. Using morphometrics they found that any size and shape change from 31 gestational weeks to 11 months was statistically insignificant. However, over the entire span from 31 gestational weeks to 36 months postnatal, there were statistically significant changes reported. Morphometrically, the anterior part of the mandibular arch and the mental region changed from a smooth and round shape to a more sharp and narrow adult-like appearance. A study by Trenouth[62] showed similar results and determined that there is some change in shape in skeletal structures, including the mandible, very early on its development. This study also looked at dry skulls of fetuses using geometric morphometrics. It concluded that there is a change in shape in the fetal mandible as it develops mostly due to development of these coronoid and condylar processes as well as the ramus. Therefore, these studies show that the mandibular shape is changing prior to and after the patient is born. Our study shows that eventually the early shape change ceases sometime around the ages of 5 to 7 years.

As discussed, the DFA, matrix correlation, and Generalized Procrustes Analysis each show a similarity between the facial types and not only between ages within the groups themselves. A study by Lavelle[63] showed similar results. This study examined the outline form of the mandible using the medial axis transformation technique. The results showed a marked overall similarity between mandibular outline of subjects grouped by Cl I, Cl II, or Cl III occlusion. The subjects only showed subtle contrasts between the degree of separation between the coronoid and condylar processes as well as the orientation of the ramus to the corpus.

Another morphometrics study by Ferrario et al[64] shows contrasting results to our study. In this study, pre-treatment radiographs of girls ages 11-15 were divided according to their divergence using mandibular plane and sella nasion (MP-SN). The mandibular outlines were digitized and the differences in shapes were examined using an elliptical Fourier analysis. This analysis showed that there was in fact a significant difference between the hypodivergent, normodivergent, and hyperdivergent groups. These contrasting results are an indication that perhaps our current study required subjects with a greater deviation from the norm in order to be able to detect the difference in shape between the groups. It may also point to the fact that our methods were not sensitive enough to detect the differences in shape. Future methods could investigate geometric morphometric methods of analysis as well as subjects with a greater mean score from the norm in terms of facial type.

Lastly, the plot of the Procrustes coordinates (Fig. 4) showed an overall shape difference between the dolichocephalic and brachycephalic groups. The condyle is position more posteriorly in the dolichocephalic group, the mandibular plane is flatter in the brachycephalic group, and the symphysis is shorter in the brachycephalic group. These results from the Generalized Procrustes Analysis, from which the Procrustes plot was generated, however, were not statistically significant, indicating that the two groups are not statistically significantly different. This similarity, or lack of statistically significant difference, is confirmed by the discriminate function analysis between the two facial types (Table VI). It is also confirmed via the high matrix correlation coefficient of 0.825 (Table IX).

The changes shown here are supported by those shown in studies by Bjork[65] and Bjork and Skieller[59]. Both of these studies showed that there are changes in the mandible and its rotation over time and that there are different types of rotation. They described growth of the mandible and rotation based on superimposition of follow up radiographs of patients that had had implants placed for this purpose. Orienting the implant line drawn through two implants in the mandible assessed growth of the mandible. The growth was described as several different types of rotation along with accompanying changes to the skeletal structures. Two examples are forward rotation with the center of rotation near the lower incisors, and backward rotation where the center of rotation is near the molars. In the forward rotation example, an increase in posterior facial height is described partially due to increase in ramus height. In the backward rotation type, the symphysis swings back due to sagittal growth at the condyle. These are two different types of patients with two different types of growth happening in their mandible. Therefore, the changes seen in this Procrustes Superimposition can be considered parallel with the findings of Bjork and Skieller. In the dolichocephalic subjects, which have longer faces and mandible that tends to be rotated clockwise, the condylar region seems to be more posteriorly positioned just as in the backward rotation type described by Bjork and Skieller. The increased ramus height shown in the brachycephalic, or short face, subject in the Procrustes Superimposition is in congruence with the forward rotation example described by Bjork and Skieller[59],[65]. However, these results from our study were not statistically significant. There are several possible reasons for this.

First, it must be pointed out that subject sample size is not a reason for the lack of difference shown between the facial types and age groups. A post-hoc power analysis was performed and showed that this study has a power of 0.99. However, there are several other possible reasons for this similarity seen between the two different phenotypes. The first is that the mandibular shape is inherently similar between the two facial types. The two facial types look different clinically, but if they share a similar mandibular shape, than perhaps the clinical difference may be due to variation in other craniofacial skeletal structures that were not captured with the landmarks used in this study. Bishara and Jakobsen's[15] study showed that vertical relationships did in fact change with age. Vertical relationships became more pronounced in adulthood. In other words, if a person was categorized as having a long face at age five, it continued to grow longer, and if there was an open bite it continued to get worse. Therefore, if the mandibular shape is not changing with growth, there may be a change in shape occurring elsewhere in the craniofacial complex to cause the worsening of vertical relationships in long (dolichocephalic) subjects or short (brachycephalic) subjects.

However, as mentioned earlier, the more likely possibility for similarity between the phenotypes is that that the subjects were only between 1 to 2 standard deviations from the norm (Table 2). Perhaps if subjects with a more extreme deviation from the norm were selected the results would show a statistically significant difference in mandibular shape. It is also possible that our sample distribution of brachycephalic and dolichocephalic subjects may have been different had a different method of selecting subjects were used. Sassouni[11] and Schudy[13] both used methods of classifying facial types that differed from Ricketts and were possibly more comprehensive. They looked at more landmarks that encompassed both anterior-posterior and vertical dimensions. Sassouni[11] looked at positional as well as dimensional deviations, including accounting for muscular attachment on the mandible. The Ricketts measurements did not account for muscular attachment, which typically can have an effect on the shape of the mandible and is responsible for the antegonial notching in patients with increased vertical dimensions[11]. Schudy[13] looked at posterior and anterior facial height as well as lower facial height and total facial height to classify subjects, but he also considered the gonial angle as well. He described the gonial angle as being obtuse in skeletal open bite patients and more acute in skeletal deep bite patients. The gonial angle was also not addressed by the Ricketts measurements that were used in this study. Therefore had other measurements and methods of classifying facial type been used, including examining the gonial angle or antegonial notching, there may have been a different sample size and variation in distribution of subjects used for the study, and possibly different overall results.

The principal component analysis showed that the first 5 principal components account for a majority of the variance in the two facial types: 70.812% for brachycephalic sample and 65.099% for the dolichocephalic sample. Since a PCA is a mathematical depiction of a statistical analysis, these results simply point to the fact the five principal components are responsible for a majority of the variation in the matrices of the Generalized Procrustes Analysis. It does not point towards any biological variation.

Ultimately this study was unable to determine at what age the two different phenotypes become distinguishable. At age 5, the subjects were already similar with each other and with consecutive ages within in their own phenotype. Despite the lack of statistical significant difference, this finding is extremely important because it points to the fact that the pattern is established earlier than the earliest age examined by our study. Therefore, the mandibular pattern is most likely established before the age of 7

The null hypothesis, stating that the two phenotypes are similar in mandibular shape over time, can therefore be accepted. The results show that there is in fact a similarity between the groups.

Strengths

Through the use of geometric morphometrics, this study was able to determine that the shape of the mandible does not change after 7 years of age. This is significant because it can allow the orthodontic clinician to safely assume that whatever growth pattern and shape of the mandible they see in their patients at a young age will remain the same and only change in size as the patient gets older. They can then treatment plan accordingly. Future studies should examine the effects of treatment on mandibular shape to enhance this treatment planning. Orthodontists may be able to further enhance their treatment planning if they have the knowledge of knowing that certain treatments can alter an unfavorable mandibular shape.

This study also provides a template for future studies on shape and growth of facial structures. It does so by adding to the scarce literature on this topic and provides an example of how to use geometric morphometrics to examine the mandible.

Limitations

The Forsyth Twin Study, although very valuable in many aspects, but it has its limitations. After examining a majority of the subjects in the Forsyth database, many of the subjects barely met the criteria by 1 standard deviation from the norm. A population with a greater deviation from the norm would have been ideal because it may have highlighted the skeletal differences in shape between brachycephalic and dolichocephalic subjects.

Lack of statistically significant difference between the two facial phenotypes may also be due to the fact that other skeletal structures were not examined in this study. There may be variations in other structures, such as the maxilla, cranial base, or dentition that may reflect the clinical difference seen in brachycephalic and dolichocephalic patients. These structures were not encompassed in the landmarks used in this study. However, when typing the patients, several of the landmarks used to make the measurements included other skeletal structures other than just the mandible. Freudenthaler et al[49] examined the relationship between craniofacial shape and malocclusion. It showed that there was a significant relationship between mandibular shape and the type of malocclusion. The distocclusion subjects exhibited a more acute gonial angle and shorter vertical dimension. The mesiocclusion group showed the opposite pattern. This indicates that there is in fact some type of relationship between the occlusion and mandibular shape and therefore future studies should incorporate the dentition into the morphometric analysis.

Recommendations for future studies

As mentioned previously, this study only encompassed the mandible. Future studies should include additional landmarks of other facial structures, such as the cranial base, maxilla, and dentition. These structures may also change and vary in shape with age, so examining them overtime may reveal further variation between brachycephalic and dolichocephalic subjects.

Future studies may also examine treatment effects on mandibular shape change. This current study excluded any subjects with previous orthodontic treatment or those undergoing orthodontic treatment and demonstrated that the mandibular shape remains constant with little variation after age 7. It would be interesting for a future study to examine mandibular shape after functional appliances are used as treatment to see if this treatment can induce mandibular shape change.

Future studies should also address sexual dimorphism since this study did not. In order to be able to look at sexual dimorphism with enough power more subjects will be needed. This would allow for comparison of male versus female within each facial type.

Lastly, another possibility for a future study is to use geometric morphometrics to create a new and original indexing system for mandibular shape. The idea would be to digitize a large number of lateral cephalograms and use geometric morphometrics to analyze the shapes and divide them into different groups. Most likely this will yield a bell-shaped curve with the most common shape on the top of the curve and the extremes on either side. The shapes in the middle and on either side can be given original names and used to create an index system. This would allow an orthodontist to digitize the shape of a patient's mandible and then see where it lies on the index created by the bell curve. Understanding where the patient lies in the index system would be similar to labeling a patient as normodivergent, hypodivergent, and hyperdivergent. Depending on what it is labeled, the patient will require different treatment precautions and mechanics. Taking on this study would require in-depth knowledge of geometric morphometrics and expertise in using the software, as well as access to a database with a large number of cephalograms.

Summary and Conclusions

This study revealed that the mandibular shape is established by the age of 7 and does not change as the patient ages. It was unable to determine the earliest time point in growth when a difference in mandibular shape of dolichocephalic and brachycephalic subjects is distinguishable. The brachycephalic and dolichocephalic subjects did not show a statistically significant difference in mandibular shape between each other and over time in the study. Therefore, it was impossible to determine an age at which they are distinguishable. A patient population with greater deviation from the norm would have been more ideal for this study and may have in fact revealed a distinguishable difference.

REFERENCES

1. Nielsen IL. Vertical malocclusions: etiology, development, diagnosis and some aspects of treatment. *Angle Orthodontist* 1991;61(4):247–60.

2. Proffit WR. Concepts of Growth and Development. In: *Contemporary Orthodontics*; 2013:36–40.

3. Petrovic A, Stutzmann J, Oudet C. *Control processes in the postnatal growth of the condylar cartilage of the mandible. In: Determinants of Mandibular Growth and Form. Center for Human Growth and Development*. Ann Arbor, Michigan; 1975.

4. Ohtsuke F. A factor analysis of cranial base and vault dimensions in children. *American Journal of Physical Anthropology* 1982;58(3):271–9.

5. Goldstein M. Changes in dimensions and form of the face and head with age. *American Journal of Physical Anthropology* 1936;22:37–89.

6. Enlow D. Growth and remodeling of the human maxilla. *American Journal of Orthodontics* 1965;51(6):446–64.

7. Enlow, DH and Bang S. Growth and remodeling of the human maxilla. *American Journal of Orthodontics* 1965;51(6):446–64.

8. Bjork A. The use of metallic implants in the study of facial growth in children: Method and application. *American Journal of Physical Anthropology* 1968;29(2):243–54.

9. Moss MRR. The Role of the Functional Matrix in Mandibular Growth. *Angle Orthodontist* 1968;38(2):95–103.

10. RMO, Orthodontics RM. Cephalometric Analysis. :1–93. Available at: https://www.rmortho.com/wp-content/themes/rmo/rmods/rmods_syllabus.pdf. Accessed February 22, 2017.

11. Sassouni V. A classification of skeletal facial types. *American journal of orthodontics* 1969;55(2):109–23.

12. Sassouni V, Nanda S. Analysis of dentofacial vertical proportions. *American journal of orthodontics* 1964;50(11):801–23.

13. Schudy FF. The Rotation Of The Mandible Resulting From Growth: Its Implications In Orthodontic Treatment. *Angle Orthodontist* 1965;35(1):36–50.

14. Bishara SE. Facial and Dental Changes in Adolescents and Their Clinical

Implications. *Angle Orthodontist* 2000;70(6):471–83.

15. Bishara S, Jakobsen J. Longitudinal changes in three facial types. *American Journal of Orthodontics* 1985;88:466–502.

16. Roentgen WK. On a new kind of rays. 1896.

17. Dewey R. Radiographic Study of Facial Deformities. *International Journal of Orthodontia* 1928.

18. Proffit WR. Orthodontic Diagnosis: The Problem Oriented Approach. In: *Contemporary Orthodontics*; 2013:182–203.

19. Broadbent BH. A new X-ray technique and its application to orthodontics. *Angle Orthodontist* 1931;1:45–66.

20. Downs, WB. Variation in facial relationships: their significance in treatment and prognosis. *American Journal of Orthodontics* 1948;(34):812–40.

21. Steiner CC. The use of cephalometrics as an aid to planning and assessing treatment. Report of a case. *American Journal of Orthodontics* 1960;46(10):721–35.

22. Tweed CH. The Frankford-Mandibular Incisor Angle (FMIA) in Orthodontic Diagnosis, Treatment Planning and Prognosis. *The Angle Orthodontist* 24(3):121–69.

23. Sassouni VA. A classification of skeletal facial types. *American Journal of Orthodontics* 1969;55(2):109–23.

24. Ricketts, RM. Cephalometric Synthesis. *American Journal of Orthodontics* 1960;46(9):647–73.

25. Enlow, DH, Moyers, RE, Hunter, WS, McNamara Jr J. A procedure for the analysis of intrinsic facial form and growth. An equivalent-balance concept. *American Journal of Orthodontics* 1969;56(1):6–23.

26. McNamara J. A method of cephalometric evaluation. *American Journal of Orthodontics* 1984;86:449–69.

27. Harvold E. *The Activator in Interceptive Orthodontics*.; 1974.

28. Jacobson A. The “Wits” appraisal of jaw disharmony. *American Journal of Orthodontics* 1975;67(2):125–38.

29. Nanda RS. Profile and their significance in orthodontic diagnosis. *American Journal*

of Orthodontics 1971;59(5):501–13.

30. Skieller, Vibeke, Bjork, Arne, linde-hansen T. Prediction of mandibular growth rotation evaluated from a longitudinal implant sample. *Turk ortodonti dergisi : Ortodonti Derneg'nin resmi yayin organidir = Turkish journal of orthodontics* 1984;86(5):359–70.

31. Park S-H, Yu H-S, Kim K-D, Lee K-J, Baik H-S. A proposal for a new analysis of craniofacial morphology by 3-dimensional computed tomography. *American Journal of Orthodontics* 2006;129(5):23–34.

32. Baumrind S, Frantz R. The reliability of head film measurements 2. Conventional angular and linear measurements. *American Journal of Orthodontics* 1971;60(5):505–17.

33. Naragond A, Kenganal S, Sagarkar R, Kumar S. Diagnostic Limitations of Cephalometrics in Orthodontics: A Review. *IOSR Journal of Dental and Medical Sciences* 2012;3(1):30–5.

34. Bookstein F. Combining the tools of geometric morphometrics. In: *Advances in Geometric Morphometrics*; :131–51.

35. Bookstein FL. Size and Shape Spaces for Landmark Data in Two Dimensions. *Statistical Science* 1986;1:181–222.

36. Zelditch ML, Swidferski DL, Sheets HD. Chapter 4: Theory of Shape. In: *Geometric Morphometrics for Biologists* 2nd ed. San Diego, CA: Elsevier Inc; 2012:75–102.

37. Rohlf, James F; Slice D. Extensions of the Procrustes method for the optimal superimposition of landmarks. *Systematic Biology* 1990;39(1):40–59.

38. Hutchinson, Erin; Kieser, Jules A.; Krame B. Morphometric Growth Relationships of the Immature Human Mandible and Tongue. *European Journal of Oral Sciences* 2014;22(3):181–9.

39. Nicholson, Elisabeth and Harvati K. Morphometric Growth Relationships of the Immature Human Mandible and Tongue. *American Journal of Physical Anthropology* 206AD;131:368–83.

40. Baskerville JR. Observer and subject bias: Lessons from procrustes. *Academic Emergency Medicine* 2010;17(9):1032. Available at: http://onlinelibrary.wiley.com/store/10.1111/j.1553-2712.2010.00833.x/asset/j.1553-2712.2010.00833.x.pdf;jsessionid=C65C446F4C1621086FD7BD654CCB896E.f03t04?v=1&t=izmwyh8k&s=aec00da4741edd6f9adfe8e569c659d0e627a23a.

41. Anon. Procrustes. Available at:

https://en.wikipedia.org/wiki/Procrustes#In_Greek_mythology. Accessed February 26, 2017.

42. Smith LI. A tutorial on Principal Components Analysis Introduction. 2002:1–26. Available at: http://www.mendeley.com/research/computational-genome-analysis-an-introduction-statistics-for-biology-and-health/.

43. Davies AMC, Fearn T. Back to basics : applications of principal component analysis. *Spectroscopy Europe* 2005;17(2):30–1.

44. Strauss RE. *Morphometrics for Nonmorphometricians*. (Elewa AMT, ed.). Springer; 2010.

45. Hallgrimsson B, Percival CJ, Green R, Young NM, Mio W, Marcucio R. Morphometrics, 3D Imaging, and Craniofacial Development. *Current Topics in Developmental Biology* 2015;115(November):561–97. Available at: http://dx.doi.org/10.1016/bs.ctdb.2015.09.003.

46. Goodstein RE. An Introduction to Discriminant Analysis. *Journal of Research in Music Education* 1987;35(1):7–11.

47. Doucet JC, Herlin C, Bigorre M, Bäumler C, Subsol G, Captier G. Mandibular effects of maxillary distraction osteogenesis in cleft lip and palate. *International Journal of Oral and Maxillofacial Surgery* 2014;43(6):702–7.

48. Franchi L, Pavoni C, Cerroni S, Cozza P. Thin-plate spline analysis of mandibular morphological changes induced by early class III treatment: A long-term evaluation. *European Journal of Orthodontics* 2014;36(4):425–30.

49. Freudenthaler J, Celar A, Ritt C, Mitterocker P. Geometric morphometrics of different malocclusions in lateral skull radiographs. *Journal of orofacial orthopedics = Fortschritte der Kieferorthopadie : Organ/official journal Deutsche Gesellschaft fur Kieferorthopadie* 2016:11–20.

50. Alarashi M, Franchi L, Marinelli A, Defraia E. Morphometric analysis of the transverse dentoskeletal features of class II malocclusion in the mixed dentition. *Angle Orthodontist* 2003;73(1):21–5.

51. Carlyle T. Overbite: Craniofacial associations, treatment and posttreatment changes: A lateral cephalometric study. *American Journal of Orthodontics and Dentofacial Orthopedics* 1987;74(6):685–6.

52. Hägg U, Attström K. Mandibular growth estimated by four cephalometric measurements. *American Journal of Orthodontics and Dentofacial Orthopedics*

1992;102(2):146–52.

53. Dung D, Smith R. Cephalometric and clinical diagnoses of open bite tendency. *American journal of orthodontics and dentofacial orthopedics* 1988;94(6):484–90.

54. West K, McNamara Jr J. Changes in the craniofacial complex from adolescence to midadulthood: A cephalometric study. *American journal of orthodontics and dentofacial orthopedics* 1999;115(5):521–32.

55. Love R, Murray J, Mamandras A. Facial growth in males 16 to 20 years of age. *American journal of orthodontics and dentofacial orthopedics* 1990;97(3):200–6.

56. Neha. Sizing the Shape : Understanding Morphometrics. *Journal of Clinical Diagnostic Research* 2015;9(1):21–6.

57. Fishman LS. Radiographic evaluation of skeletal maturation A clinically oriented method based on hand-wrist films. *Angle Orthodontist* 1982;52(2):88–112.

58. Klingenberg C. MorphoJ: an integrated software package for geometric morphometrics. 2011:353–7.

59. Skieller BA. Facial development and tooth eruption. An implant study at the age of puberty. *American Journal of Orthodontics* 1972;62(4):339–83.

60. Sassouni V. A classifiation of skeletal facial types. *American Journal of Orthodontics* 1969;55(2):109–23.

61. Hutchinson EF, L'Abbé EN, Oettlé AC. An assessment of early mandibular growth. *Forensic Science International* 2012;217(1–3):233. Available at: http://dx.doi.org/10.1016/j.forsciint.2011.11.014.

62. Trenouth MJ. Shape changes during human fetal craniofacial growth. *J Anat* 1984;139(4):639–51.

63. Lavelle C. A Study of Mandibular Shape. *British Journal of Orthodontics* 1984;11(2):69–74.

64. Ferrario VF, Sforza C, De Franco DJ. Mandibular shape and skeletal divergency. *European Journal of Orthodontics* 1999;21(2):145–53.

65. Björk A. Predication of Mandibular Growth Rotation. *American Journal of Orthodontics and Dentofacial Orthopedics* 1969;55(6):585–99.

66. Vogler R. Illustration of principal component analysis (PCA). *Joy of Data* 2013.

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