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SEXUAL DIMORPHISM IN SYMPHYSEAL RIGIDITY: A LONGITUDINAL STUDY

by

Laura L. Bonner

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Orthodontics
in the Graduate College of
The University of Iowa

May 2013

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Laura L. Bonner

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
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INTRODUCTION

Patterns of human mandibular growth are generally well understood and can be summarized as downward and forward movement relative to the anterior cranial base due to growth at the condyles and posterior regions of the mandible. Little, if any growth contributing to this forward movement actually occurs at the anterior portion of the mandible (Bjork 1963). In addition, translation and rotation of the mandible contribute to its final position. During ontogeny, significant remodeling occurs in specific resorptive and appositional patterns throughout the mandible, which contribute to its morphology (Enlow and Harris 1964). Differences in these patterns account for the variability in mandibular morphology amongst humans.

While mandibular remodeling patterns can be described, the developmental mechanisms that underlie variations in mandibular growth are less well understood. Understanding these mechanisms is important because aberrant patterns of mandibular growth have significant influences on occlusion and larger patterns of craniofacial growth. In orthodontics, effectively treating patients with skeletal discrepancies requires insight on what affects mandibular morphology.

Various factors likely influence mandibular morphology. A few proposed models include evolution, speech, spatial dynamics, and biomechanics (Weidenreich 1936; Robinson 1914; Marshall et al. 2011; Scott et al. 2010; Bouvier and Hylander 1984; Daegling 1993). In particular, mandibular growth has been linked to variation in masticatory function (Kaifu 1997; von Cramon-Taubadel 2011; Anton et al. 2010). The direct influence of masticatory loading on mandibular morphology is evident in various mammalian diet consistency studies. During ontogeny, an increase in masticatory loading has been shown to produce changes in the condyles (Bouvier and Hylander 1984), mandibular form, cortical bone thickness, and amount of bone remodeling (Bouvier and Hylander 1981). Furthermore, changes in cortical bone microstructure is

evident as higher mandibular loading results in secondary osteonal remodeling (Bouvier and Hylander 1996) and alterations in bone mineralization levels (Ravosa 2007).

The array of functional stresses and strains on the mandible have been mapped out on primates with in vivo strain gage analysis (Hylander 1984; 1985; Hylander et al. 1987). Specifically, the mandibular symphysis has been shown to exhibit three main types of stress and strain: lateral bending ("wishboning") in the transverse plane, vertical bending in the coronal plane, and dorsoventral sheer in the sagittal plane (Hylander 1984; 1985). It has been suggested that variations in masticatory loading results in different quantities of stress and strain on the symphysis (Hylander 1984; 1985; Daegling 1993; Anton et al. 2010; Fukase and Suwa. 2008; Dobson and Trinkaus. 2002). Also, the size of the mandible (i.e. length and bigonial breadth) plays an integral role in these stress and strain patterns (Weijs 1989; Daegling 1993). Perhaps variations in masticatory loading and mandibular size can account for differences in symphyseal morphology.

The goal of the present study is to examine the relationship between masticatory function and mandibular symphyseal bone properties using a longitudinal sample of humans. Our understanding of the functional influences on symphyseal morphology is enhanced by a study of the ontogeny of bending resistance in the symphysis. It has been established that adult males have significantly greater bite force production than females (Helkimo et al. 1977; Raadsheer et al. 1999; Kovero et al. 2002). Early in development, ages 3-6, there are no statistically significant differences in bite force production (Mountain et al. 2011; Rentes et al. 2002). These sex differences have been shown to appear during adolescence (Ingerval and Minder 1997). With the established differences in sex bite force production, do males and females show significantly different symphyseal biomechanical properties for a given mandibular size? If so, are these differences established early in development, or later in ontogeny? We will test the null hypothesis that for a given mandibular size, there are no differences in symphyseal rigidity between males and females during ontogeny.

LITERATURE REVIEW

Evolution and ontogeny of the symphysis

The mandibular symphysis is the union between the right and left halves of the mandible. Its form varies remarkably across mammals. Anthropoid primates (e.g. monkeys, apes, and humans) exhibit a fused symphysis, whereas prosimians (earliest primates e.g. lemurs and tarsiers) have unfused or partially fused symphyses (Scott et al. 2012).

Amongst the anthropoid primates, the cross-sectional form of the symphysis has a variety of unique features. As seen in Figure 1, a distinct "simian shelf" is seen on the lingual side of symphysis in higher primates (e.g. monkeys and apes), but not modern humans, *Homo sapiens.* Unique to *Homo sapiens* is the anterior projection of the chin (Coquerelle et al. 2010; Enlow 1966; Johnson et al. 1976), which appeared in the fossil record between the Middle and Late Pleistocene (Dobson and Trinkaus 2002). Other hominids during the time, such as *H. Neaderthalensis*, do not exhibit the development of a chin (Schwartz and Tattersall 2000). This recent phenomenon in human ancestry has fueled the investigation of symphyseal evolution and ontogeny.

Ontogeny of the higher primate symphysis reveals unique patterns of remodeling. In his study of Rhesus monkey cadaver mandibles, Enlow (1966) described the entire labial surface of the monkey symphysis as depository. The lingual side is resorptive, except for the simian shelf, which is depository. (See Figure 2) Johnson et al. (1976) found these same remodeling qualities of the symphysis in chimpanzees.

In contrast to the remodeling patterns of higher primates during ontogeny, modern humans exhibit patterns that result in a chin projection at the symphysis. Mostly a postnatal phenomenon, prominence of the chin develops as the mandible grows. Enlow and Harris (1964) elucidated the patterns of development in the symphysis by using human cadaver mandibles of persons aged 4-12 years. With microscopic examination of

stained layers of bone, they determined surfaces of periosteal and endosteal deposition and resorption. Specifically, the anterior periosteal surface of the symphysis at the level of the alveolar process was resorptive. The equivalent endosteal surface was appositional. The lingual cortical bone appeared to have abundant periosteal deposition and endosteal resorption. Thus, the development of chin projection at the symphysis was a result of the lingual recession of the alveolus, not apposition at prominence of the chin, pogonion (See Figure 2).

Bjork confirmed this pattern in his series of clinical studies to assess mandibular growth (Bjork 1955; 1963; 1968) He used metallic implants inserted into growing patients to radiographically assess patterns of growth. His 1963 article specified that the thickening of the symphysis occurred by apposition on the lingual side. Likewise, lengthening of the symphysis occurred by apposition on the inferior border. He states that the majority of mandibular growth occurs at the condyle, however the bone at pogonion was fairly stable (Bjork 1969).

Variation in the amount of chin projection amongst modern humans ranges from almost non-existent to very pronounced. Microscopically, Enlow and Harris (1964) indicated that the amounts of resorption and deposition in the anterior symphysis varied widely between their specimens. Kurihara et al. (1980) confirms this with their study of human mandibles from ages birth to 14.

Although general patterns of symphyseal remodeling have been defined in research, the underlying developmental mechanisms that create symphyseal variation are somewhat unclear. Proposed models include speech, sexual dimorphism, spatial dynamics, and biomechanics. The literature on this subject is extensive and somewhat inconclusive. In general, the hypotheses that have been formulated can be categorized into functional and non-functional explanations.

The role of function in symphyseal ontogeny and evolution

Functional studies of the human symphysis operate under the premise that bone is responsive to stress (Wolff 1892; Carter et al. 1991). In environments of increased loads, bone will respond by changing its mass and shape to disperse these loads. Likewise, in absence of stress, bone will be resorbed.

Most functional studies of the symphysis investigate the origins and evolution of the human chin. One of the earliest adaptive models of chin development dates back to the early 20th century. Robinson (1914) proposed a linguistic model. The evolution of articulate speech coincides with the development of the human chin. He focused on the increased size and action of the genio-glossus muscle, which is utilized in making speech sounds. Speaking at a rate of 150 words per minute, Robinson estimated that 500 different movements or adjustment of the genio-glossus must happen. The development of the genial tubercles, he states was key in allowing the genio-glossus to perform in such a way. This change in the muscle attachment parallels the evolution of the chin, which led Robinson to the conclusion that the chin developed as an adaptation to articulate speech. Similarly, Wallis (1917) claimed the chin was a function of facial expressions and the related muscular attachment near the symphysis.

The idea that bone will be resorbed in the absence of stress led Riesenfeld (1969) to make the assumption that the evolutionary reduction in size of the mandible indicates a reduction in strength. The diminution of the dentition in conjunction with a softer diet led to decreased biomechanical demands on the mandible. “Hypofunction” was claimed as the causal agent for the evolution of the chin. Riesenfeld experimented on rats to simulate evolution by extracting their incisors and severing the muscles of mastication. These rats developed a shortened mandible and an anterior protrusion at the symphysis. This suggests that hypofunction over time influenced development of the chin. However, Daegling (1993) refutes Riesenfeld’s experiment as a poor simulation of human evolution.

Global patterns of recent human mandibular variation appear to be influenced by loading history (von Cramon-Taubadel 2011; Kaifu 1997; Holmes and Ruff 2011). Von Cramon-Taubadel (2011) summarizes that "Variation in the masticatory behavior of hunter-gatherer and agricultural populations is hypothesized to be one of the major forces affecting the form of the human mandible. Hunter-gatherers have consistently longer and narrower mandibles than agriculturalists. These results support notions that a decrease in masticatory stress among agriculturalists causes the mandible to grow and develop differently." (p 19546). The presumably tougher diet of the hunter-gatherer populations is associated with a more robust mandible as seen in the comparison between prehistoric Jomon and modern Japanese (Kaifu, 1997). Holmes and Ruff (2011) found similar results in their comparison of prehistoric Tigara ("demanding masticatory regime") and proto-historic Arikara ("less demanding masticatory regime"). Furthermore, Fukase and Suwa (2008) demonstrated that the mandibular symphysis of the Jomon has greater bone mass and thicker cortical bone than modern Japanese. This suggests that loading history may have an effect on mandibular variation.

The direct influence of masticatory loading on variation in mandibular form is shown in a variety of mammalian studies of experimental dietary consistency. A general reduction in mandibular size is associated with reduced masticatory function (Ravosa, 2007). During ontogeny, an increase in masticatory loading has been shown to produce changes in the condyles (Bouvier and Hylander 1984), mandibular form, cortical bone thickness, and amount of bone remodeling (Bouvier and Hylander 1981). Furthermore, changes in cortical bone microstructure is evident as higher mandibular loading results in secondary osteonal remodeling (Bouvier and Hylander 1996) and alterations in bone mineralization levels (Ravosa 2007).

When considering the specific effects of mechanical loading on symphyseal morphology, it is crucial to understand the stresses and strains placed on the symphysis. Anthropoid mandibles can be viewed from a biomechanical perspective as a curved beam

due to the fused symphysis (van Eijden 2000; Fukase 2007). Based on *in vivo* strain gauge experiments on macaques, Hylander (1984, 1985) identified three main types of stresses and strains present in the symphysis during mastication: lateral bending in the transverse plane, or "wishboning;" vertical bending in the coronal plane; and dorsoventral shear in the sagittal plane (Figure 3). Lateral bending produces tension on the lingual side of the symphysis and compression on the facial side. Vertical bending produces tension on the inferior side of the symphysis and compression on the superior side. Dorsoventral shear puts parallel shear stress on the symphysis.

Resistance to these stresses depends on the material properties of the bone (i.e. cortical bone versus trabecular bone) and the cross-sectional geometric shape of the bone. Cortical bone is stronger than trabecular bone, and therefore can resist more stress during mastication (van Eijden 2000). For example, it has been shown that cortical bone is concentrated on the lingual inferior borders of the symphysis (Fukase 2007; Holton et al. ND), which would suggest that these regions experience increased stress during mastication. Korioth et al. (1992) confirmed in their finite element analysis that "maximum principle stresses and strains were highest on the lower lingual" region (p. 69). Geometrically, a thicker symphysis facial-lingually will better resist lateral bending, and a taller symphysis will better resist vertical bending. Symphyseal cross-sectional shape is unimportant in resisting dorsoventral shear (Hylander 1984). Finite element analysis has supported the idea that resistance to bending is correlated with symphyseal dimensions, regardless of cortical bone distribution (Groning et al. 2011).

Many recent studies have suggested the evolution of the human chin is an adaptation to particular mechanical loads during mastication. Daegling (1993) argues that the chin is structural response to resist vertical bending. In comparison to apes, humans' shorter mandibles reduce lateral bending strains, but do not reduce vertical bending strains (Figure 4). Because of this reduction in lateral bending stresses, resistance to vertical bending became more important during human evolution. Dobson

and Trinkaus (2002) tested the predictions of Daegling (1993) by examining specimens of Middle and Late Pleistocene *Homo* and modern humans. Their findings also suggest a trend toward less resistance to lateral bending, while maintaining resistance to vertical bending. Groning et al. (2011) also confirmed this trend in a finite element analysis of Neaderthal and human mandibles. The symphysis maintained levels of vertical bending resistance with shorter mandibles and a concomitant decrease in lateral bending resistance. This suggests that symphyseal adaptation to mechanical loads during mastication may have played an important role in symphyseal evolution.

If functional loading has an influence on cortical bone distribution and symphyseal geometry (Hylander 1984; Daegling 1993; Fukase 2007; Holton et al. ND), then adult symphyseal morphology may be a reflection of the loading history of the mandible during ontogeny. Holmes and Ruff (2011) examined ontogenetic changes in mandibular corpus breadth, rigidity, and strength in two population samples with contrasting diets. The adult mandibles in the population with a tougher diet showed more robust characteristics in the mandible. However, the differences in robusticity were not seen in comparisons of the juvenile samples. This supports the notion that mechanical loading during ontogeny may play a role in determining adult symphyseal morphology.

Non-functional roles in symphyseal ontogeny and evolution

There is evidence to suggest that other factors have significant influence on symphyseal development.

Dobson and Trinkaus believe that the evolution of the chin was “at least partly independent of biomechanical demands.” (Dobson and Trinkaus 2002). Since the chin emerged in human evolution between the Middle and Late Pleistocene, Dobson and Trinkaus (2002) examined forty-two mandibles of our human ancestors during this time, some with chins and some without. If those with a chin exhibited different resistances to bending at the symphysis than those without, perhaps the chin developed because of

biomechanical demands. Their findings did not support a purely biomechanical model to chin development. The Neandertals (without chins) and modern humans (with chins) exhibited similar resistance to lateral bending, despite the longer mandible of the Neandertals. This suggests that the presence or absence of a chin is not important with regards to lateral bending forces.

Heritable phenotypes of mandibular morphology likely contribute to symphyseal ontogeny. Kaifu's study (1997) of ancient Jomon hunter-gatherers and modern Japanese humans suggests that symphyseal height seems to be genetic as is it remained minimally changed as functional demands of the mandible changed with a more modern soft diet. Furthermore, Fukase and Suwa (2008) found that the Jomon had more robust mandibles compared to modern Japanese, however these robust characteristics are manifested early in ontogeny. This suggests that a certain component of mandibular morphology is genetic.

In a recent study of masticatory loading and cortical bone properties in the symphysis, Holton et al. (ND) showed that as bite force magnitude increased in the sample, the ability to resist vertical bending predictably decreased. This is counter to the expectation that an increase in masticatory force production should equate to symphyseal dimensions that are suited to resist greater stress and strain.

Further challenging any functional explanations are Ichim et al. (2006), who modeled strain distributions of mandibles with and without chin projections. A CT scan of a human mandible was used to create the model with mentum osseum. They created the "chinless" model by removing the mentum osseum but keeping the same cortical bone thickness. When these two mandibles were put under simulated forces of incisor and molar mastication, they found similar strain distributions between them. Ichim et. al (2006) concluded that the development of the chin was unrelated to the biomechanical stresses placed on the mandible during mastication.

Larger patterns of facial development may influence symphyseal growth independent of function. Marshall et al. (2011) suggest that the differential jaw growth between the maxilla and mandible and compensatory dentoalveolar movements are responsible for the ontogeny of the chin. During normal adolescent growth the mandible outgrows the maxilla by approximately 4 mm (You et al. 2001). Occlusal interlocking is theorized to be the compensatory mechanism for this growth differential (Solow 1980; Ostyn et al. 1996; Low 2008). In other words, as the mandible outgrows the maxilla in the anterior-posterior direction, occlusal interlocking moves the mandibular teeth posteriorly in relation to pogonion and increases the bony chin projection. This mechanism is therefore responsible for the resorption of alveolus as B-point that was documented by Enlow and Harris (1964).

Further evidence of the link between the symphyseal morphology and larger patterns of facial development is provided by Durand and Hunt (2008). In their study of Euro-American and African-Americans, they found and inverse relationship between facial prognathism and chin size. Similar to Marshall et al. (2011), this suggests that overall facial patterns in an anterior-posterior dimension play an integral role in symphyseal form. Furthermore, Scott et al. (2010) revealed the importance of the vertical growth component of the maxilla- mandibular complex. Lower anterior face height was the primary variable influencing chin expression. Longer vertical facial height corresponded to reduced chin projection and increased symphyseal height (Mangla et al. 2011). Bastir and Rosas (2004) show that these ontogenetic vertical facial patterns are determined early in postnatal development, which suggests that symphyseal morphology is, in part, pre-determined by larger patterns of facial development.

The complex interaction of functional and non-functional determinants of symphyseal morphology is still not clear. Our understanding of the functional influences is enhanced by a study of the ontogeny of bending resistance in the symphysis. We know that adult males have significantly greater bite force production than females that is

manifested during adolescence. (Helkimo et al. 1977; Raadsheer et al. 1999; Kovero et al. 2002; Mountain et al. 2011; Rentes et al. 2002; Ingerval and Minder 1997). Therefore, if masticatory function has an influence on symphyseal morphology, we would predict that males and females show different ontogenetic scaling relationships with regard to bending resistances such that during growth, males should exhibit greater positive allometry with respect to biomechanically relevant aspects of symphyseal morphology.

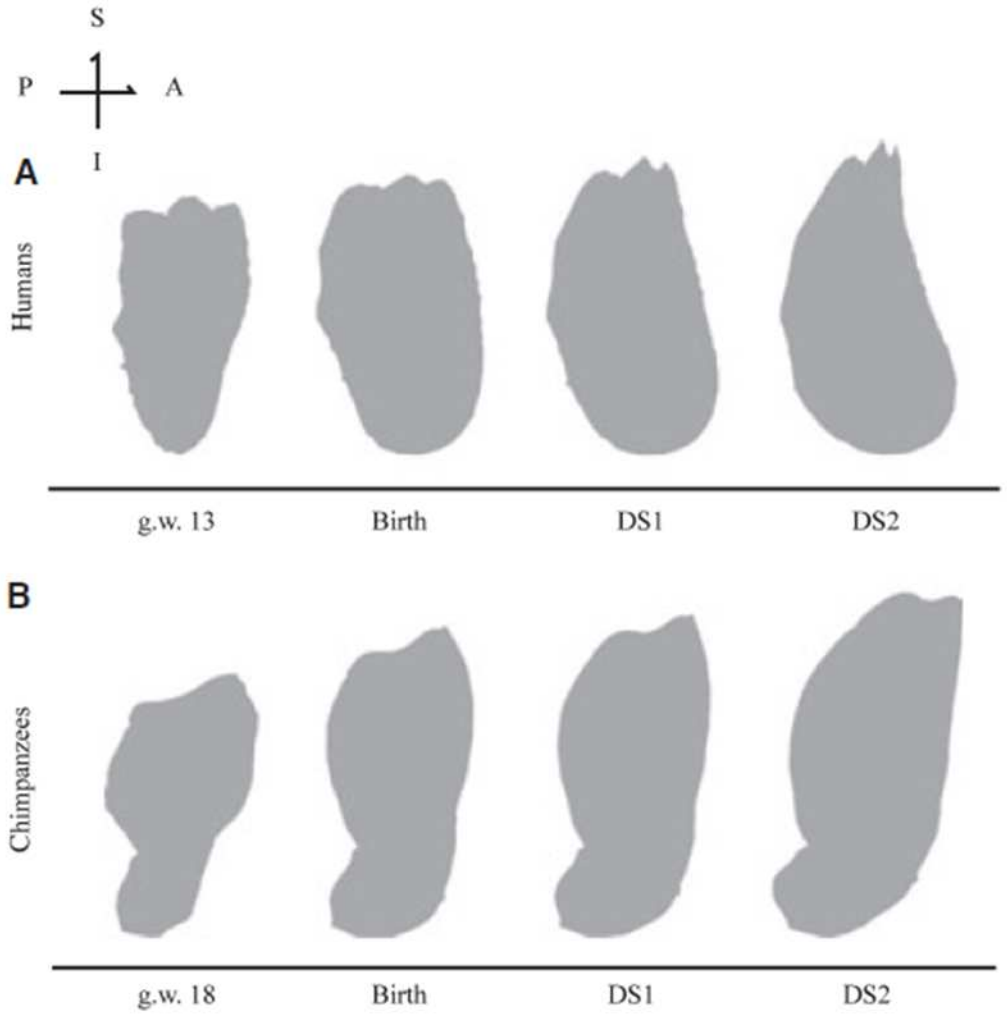

Figure 1. Mid-sagittal plane sections of the human and chimpanzee symphysis during growth. The symphysis of the human develops a distinct chin button in the anterior, whereas the chimpanzee develops a protrusion on the lingual of the symphysis, termed the "simian shelf."

Source: Coquerelle, M., F. Bookstein, J. Braga, D. Halazonetis, and G. Weber. 2010. "Fetal and infant growth patterns of the mandibular symphysis in modern humans and chimpanzees." *J Anat* 217:507-520.

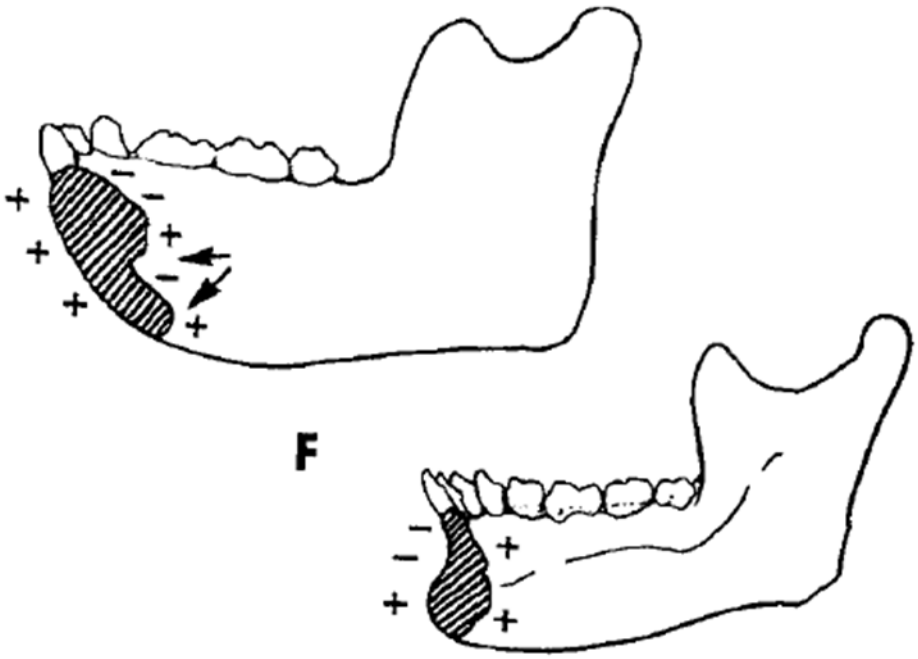

Figure 2. Depositional (+) and resorptive (-) surfaces on a Rhesus monkey (above) and modern human (below).

Source: Enlow, D. 1966. "A comparative study of facial growth in Homo and Macaca." *Am J Phys Anthrop* 24:293-308.

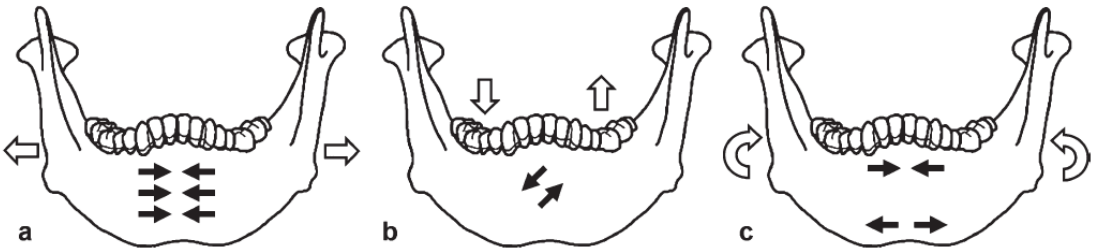

Figure 3. Potential loads at the human mandibular symphysis during masticatory function (modified from Fukase, 2007).

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* White arrows indicate effects of muscle forces. Black arrows indicate the stress and strain placed on the labial of the symphysis. A) Lateral transverse bending (wishboning) in the transverse plane places compressive forces on the labial surface, and tensile forces on the lingual. B) Dorsoventral shear in the sagittal plane places parallel shear stresses on the symphysis. C) Vertical bending in the coronal plane places compressive forces on the superior symphysis (alveolar region) and tensile forces on the inferior symphysis.

Source: Groning, F., J. Liu, M. Fagan, and P. O'Higgins. 2011. "Why do humans have chins? Testing the mechanical significance of modern human symphyseal morphology with finite element analysis." *Am J Phys Anthropol* 144:593-606.

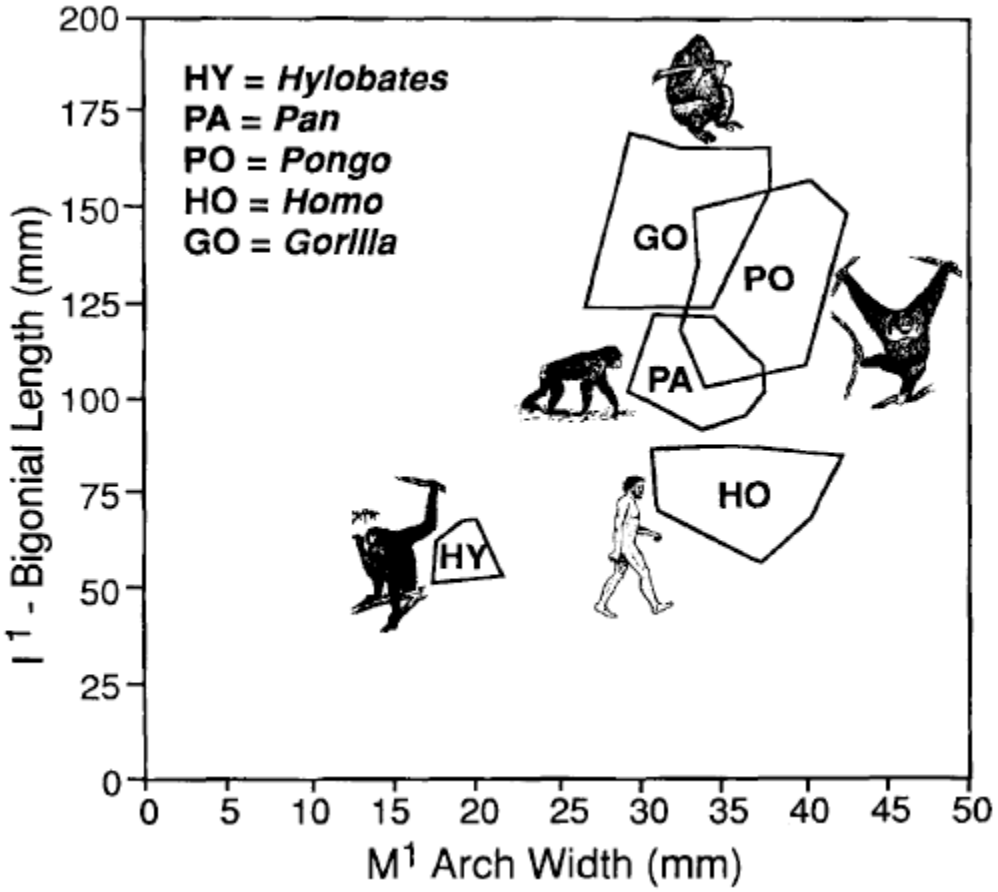

Figure 4. The relationship of mandibular length to arch width in modern hominids. A polygon encloses the range of values for each taxon with mean values indicated by location of taxon labels. Humans (HO) exhibit shorter mandibles than higher primates, while maintaining arch width. The mandibular dimensions of humans reduce the effects of lateral transverse bending on the symphysis compared to higher primates.

Source: Daegling, D.J. 1993. "Functional morphology of the human chin." *Evol Anthropol* 1:170-177.

MATERIALS AND METHODS

Subject selection

All subjects selected for this study were participants in the Iowa Facial Growth Study, which started in 1946. The growth study accepted volunteers based on their "likelihood of continuing residence in the community and willingness to participate" (Meredith 1959). The sample of 125 children was predominantly northwest European ancestry and resided in the area surrounding Iowa City, IA. Each subject was examined annually from the age of 3-5 until age 17, and then once after age 21. Radiographs, dental casts and anthropometric were taken. Lateral cephalometric radiographs were made at 3 month intervals until age 6. Biannual radiographs were made from 6-12 years old and annual radiographs were made from 12-17 years old. One adult radiograph was made after age 21.

From this data set, 19 female and 20 males were chosen. Selection was based primarily on completeness of longitudinal data and clarity of radiographs. There was no prior knowledge of the subjects' growth patterns. All data from the subjects were categorized in to nine distinct age ranges for analysis: 3-4.9, 5-6.9, 7-8.9, 9-10.9, 11-12.9, 13-14.9, 15-16.9, 17-18.9 and over 20 years of age.

Radiographic data collection

All original lateral cephalometric radiographs were digitized using an Epson Expression 10000XL v3.04A scanner. All images were uploaded into Dolphin Imaging Version 11.0.03.41 Premium software, which was used for the collection of two-dimensional coordinate landmark data needed for tracing the symphysis and scaling each radiograph. The external cortical border of the symphysis was traced, along with the points: articulare – pogonion (for mandibular length) and sella-nasion (for radiographic scale). All landmark identification was completed by one person.

Quantification of symphyseal properties

All cephalometric tracings were uploaded into ImageJ 1.45 and scaled to pixels/mm based on the known absolute distance from Sella to Nasion. The area of mid-sagittal symphysis, including alveolus, was filled in to become a solid object (example in Figure 5). This image was rotated so the mandibular plane, Me-Go, was horizontal. MomentMacro in ImageJ was used to calculate the properties of the solid cross-sectional symphysis. The biomechanical properties of the mandibular symphysis were assessed using second moments of area (Van Eijden 2000; Fukase and Suwa 2008; Dobson and Trinkaus 2002), which measure the resistance to bending about a given axis (See Figure 6). All symphyseal parameters assessed in this analysis, and their biomechanical and biological significance are found in Table 1.

Due to the limitations of lateral cephalographs (e.g. age of study, quality of radiographs) it was difficult to clearly delineate the area of cortical bone; as such, the present study uses a solid cross-sectional area of the symphysis for biomechanical assessment. While it is desirable to calculate biomechanical properties from actual cortical bone cross-sections rather than external contours (e.g. Dobson and Trinkaus 2002), there is a strong correlation between second moments of area derived from both cortical bone and external bone contours. For example, Stock and Shaw (2007) found correlations in the range of 0.838 – 0.979 in various postcranial skeletal elements. Holton et al. (ND) found strong correlations between internal symphyseal properties (second moments of area) predicted from external contours of the symphysis (Table 2). However, given the low correlation between cortical bone area and total area (r^2=0.190), it is not possible to predict cortical bone area using external symphyseal parameters. As such, the use of total area in this sample is more a reflection of overall symphyseal size rather than a proxy measure for the amount of symphyseal cortical bone in the midsagittal plane. Thus, while the use of external symphyseal contours does not allow for the assessment of regional variation in cortical bone thickness (e.g. Fukase and Suwa 2008),

it allows for the study of longitudinal changes in other important biomechanical parameters.

Statistical analysis

To test the null hypothesis that, for a given mandibular size, there are no differences in symphyseal rigidity between males and females, a scaling analysis was performed using mandibular length as a measure of overall mandibular size. First, all variables were log transformed and growth allometries were assessed using reduced major axis regression. Clarke's test was used to test for significant differences in growth allometries (Clarke 1980). This is a modified t-test that is designed specifically to test for significant differences in reduced major axis regression lines. If the growth of the mandibular symphysis is influenced by masticatory force production, then males should be characterized by greater positive allometry when compared to females.

To further test the null hypothesis, ANCOVA was used assess the interaction between symphyseal properties and sex, mandibular length, and sex+mandibular length. If there is a tendency for males to exhibit a relative increase in symphyseal biomechanical parameters during development, then the results of the ANCOVA should indicate a significant interaction between sex+mandibular length. Finally, individual residuals from a pooled ordinary least squares analysis regressing symphyseal parameters on mandibular length was conducted. Significant differences in residuals between males and females were tested using ANOVA. If there is a tendency for males to exhibit increased symphyseal biomechanical parameters relative to females, then males should exhibit significantly greater residual values when compared to females.

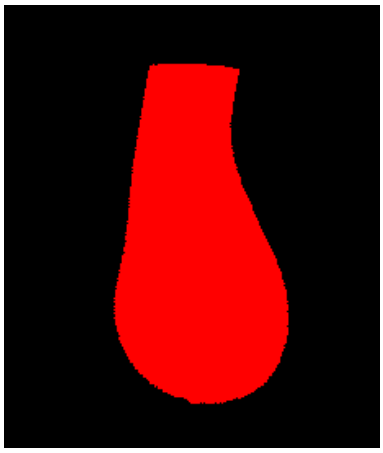

Figure 5. Example of solid cross-sectional symphysis used for analysis of biomechanical properties.

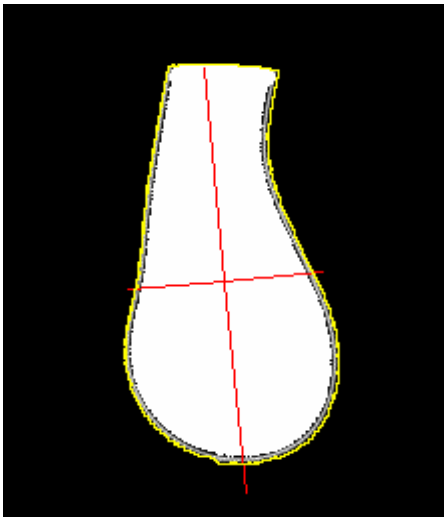

Figure 6. Example of axis used to calculate second moments of area. Second moments of area are calculated to assess biomechanical properties of the symphysis. Figure produced by Momentmacro for ImageJ.

Table 1

Definitions of variables calculated

Variable	Definition	Biomechanical significance
TA	Total area of cross-sectional symphysis	Measure of overall size of symphysis
I_{max}	Moment of inertia	Resistance to vertical bending
I_x	Moment of inertia	Resistance to vertical bending
I_{min}	Moment of inertia	Resistance to transverse bending
I_y	Moment of inertia	Resistance to transverse bending
MN length	Art-Po	Proxy moment arm of trans. bending Proxy for overall MN size

Table 2

Least-squares linear regression statistics for internal symphyseal properties predicted from external symphyseal contours

Variable	r^2	b_1	b_0	*P*	SSE
Cortical area	0.190	2.582	0.653	0.055	0.115
Ix	0.839	-0.908	1.154	<0.001	0.090
Imax	0.832	-0.919	1.155	<0.001	0.090
Iy	0.949	-0.223	1.065	<0.001	0.730
Imin	0.955	-0.310	1.073	<0.001	0.073

Source: Holton, N.E. 2013. "Mandibular cross-sectional properties." Unpublished raw data.

* In general, correlations between internal properties and external cortical contours are in the range of 0.832 – 0.979.

RESULTS

The results of our analysis indicate there are no differences in growth allometries between males and females for any of the variables measured (symphyseal area, I_x, I_y, I_{max}, I_{min}). Table 3 and Figures 7 through 11 show that in regards to total cross sectional areas of the symphysis, the least major axis slope for males is 0.91 and 0.90 for females ($p > 0.05$). With respect to vertical bending resistance (I_x and I_{max}) the regression slopes for males are 0.88 and 0.90 ($p > 0.05$) respectively, and for females, 0.91 and 0.95 ($p > 0.05$) respectively. Similarly, the regression slopes for lateral bending resistance (I_y and I_{min}) for males are 1.10 and 1.00 and for females are 1.07 and 0.97

The ANCOVA analysis tests for significant differences in the interaction between symphyseal cortical properties, sex, and mandibular length. Shown in Table 4, there is a significant relationship between mandibular length and symphyseal properties during growth ($p<0.001$). However, there is no relationship between symphyseal properties and sex. Additionally, there is no tendency for males and females to differentiate as mandibular length increases.

Residuals derived from the ordinary least squares regression of mandibular length and symphyseal cortical properties were tested using ANOVA, shown in Table 5 and Figures 12 through 16. The results indicate that measurements of all male and female symphyseal properties are distributed evenly above and below the regression line.

Table 3

Analysis of sex differences in growth allometries for symphyseal cortical properties relative to log-transformed mandibular length

Dependent Variable		Male	Female	Clarke's T score	P
ln $Area^{1/2}$	Slope	0.91	0.90	0.235	P>0.05
	SE	0.04	0.04		
	R	0.67	0.63		
	95% CI	0.83-0.99	0.82-0.99		
ln $I_x^{1/4}$	Slope	0.88	0.91	0.705	P>0.05
	SE	0.04	0.04		
	R	0.73	0.70		
	95% CI	0.80-0.95	0.83-0.99		
ln $I_y^{1/4}$	Slope	1.10	1.07	0.335	P>0.05
	SE	0.05	0.05		
	R	0.69	0.67		
	95% CI	0.99-1.20	0.97-1.17		
ln $I_{max}^{1/4}$	Slope	0.90	0.95	0.846	P>0.05
	SE	0.04	0.04		
	R	0.75	0.72		
	95% CI	0.83-0.98	0.87-1.03		
ln $I_{min}^{1/4}$	Slope	1.00	0.97	0.381	P>0.05
	SE	0.05	0.06		
	R	0.57	0.48		
	95% CI	0.89-1.11	0.86-1.09		

* All analyses were conducted using reduced major axis regression and significant differences in slopes were tested using Clarke's test (Clarke 1980). There were no significant allometric differences between males and females for any of the variables.

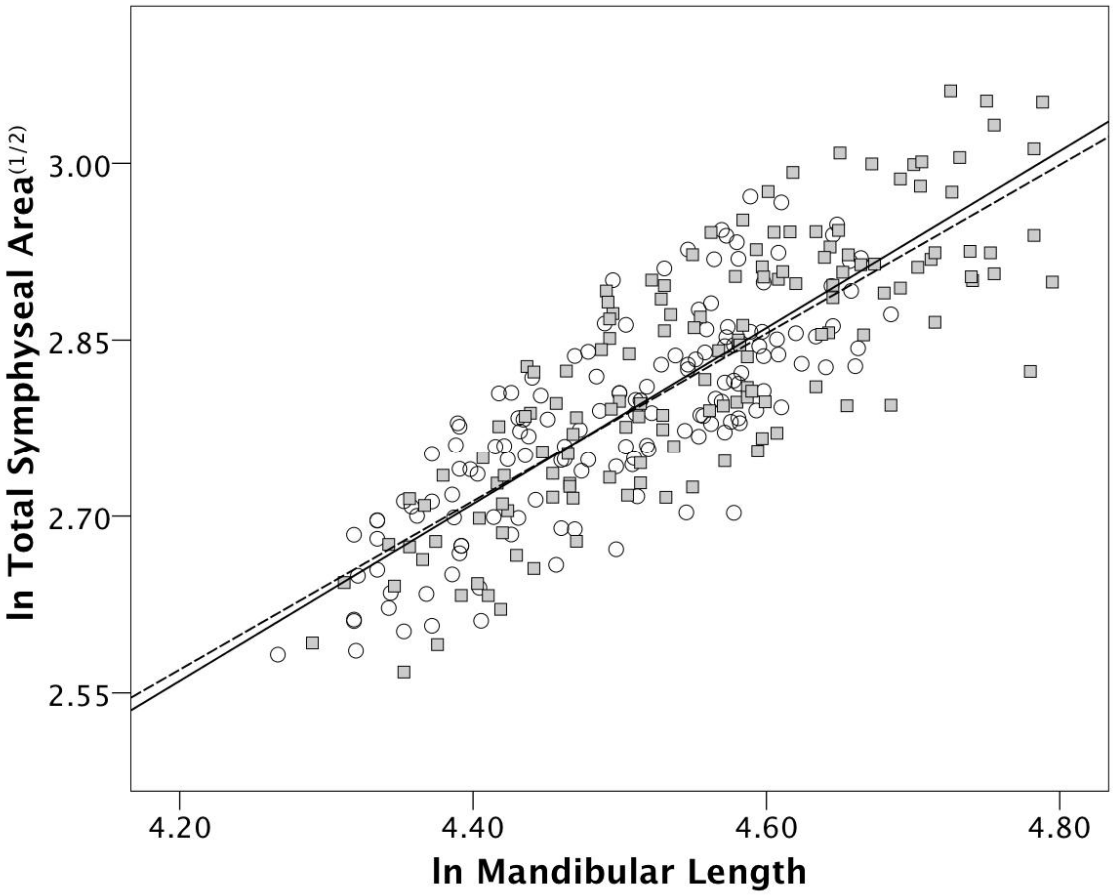

Figure 7. Reduced major axis regression. Sex differences in growth allometries for total symphyseal area relative to log-transformed mandibular length.

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* Solid square denotes male. Circle denotes female. Solid line denotes male regression. Dashed line denotes female regression.

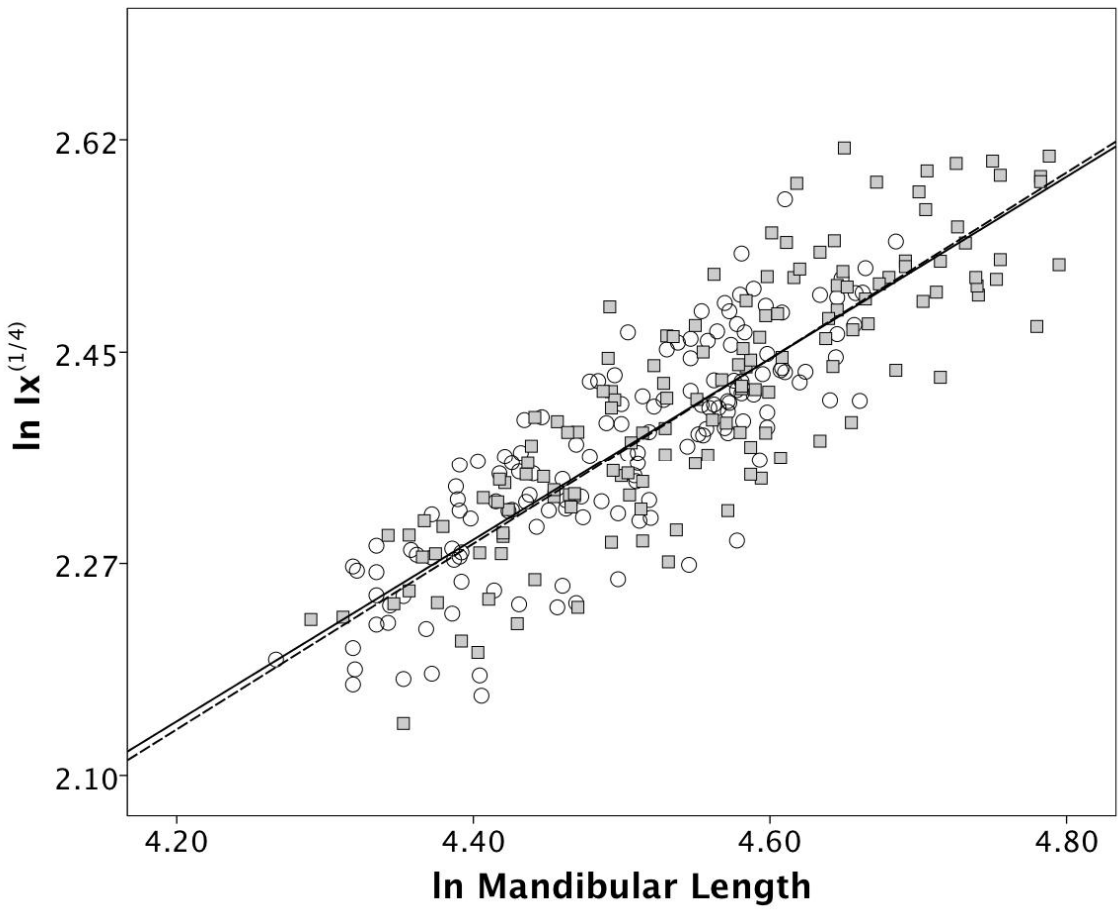

Figure 8. Reduced major axis regression. Sex differences in growth allometries for vertical bending resistance (I_x) relative to log-transformed mandibular length.

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* Solid square denotes male. Circle denotes female. Solid line denotes male regression. Dashed line denotes female regression.

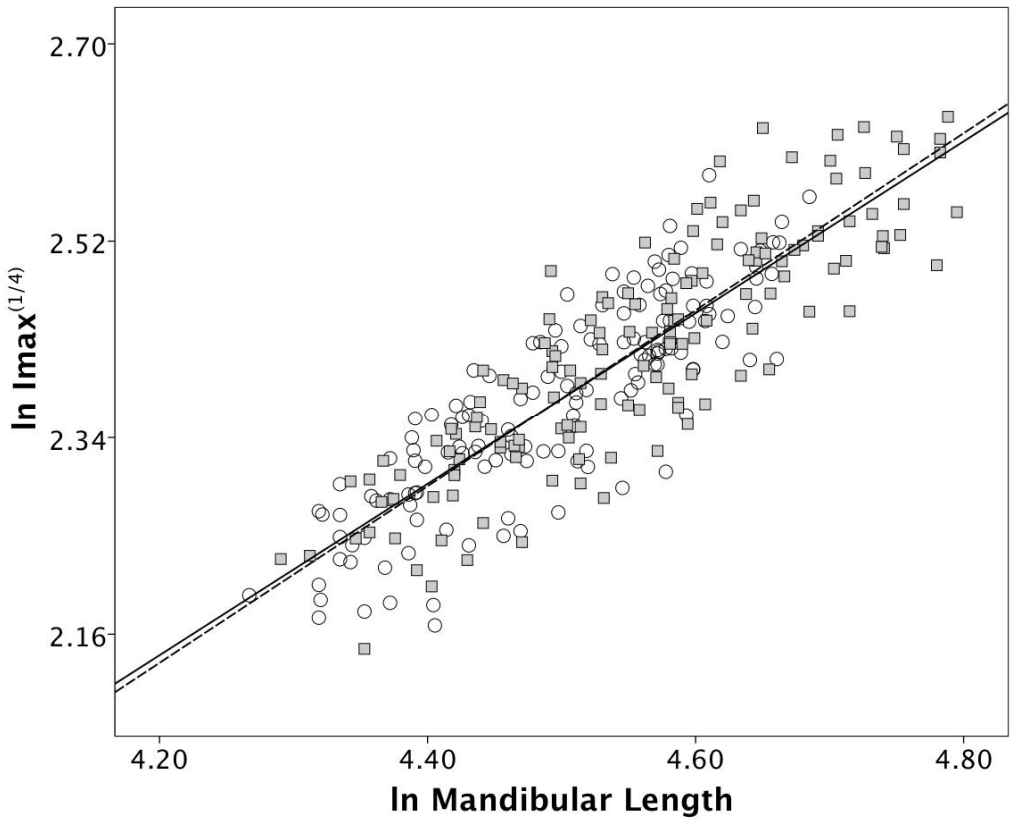

Figure 9. Reduced major axis regression. Sex differences in growth allometries for vertical bending resistance (I_{max}) relative to log-transformed mandibular length.

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* Solid square denotes male. Circle denotes female. Solid line denotes male regression. Dashed line denotes female regression.

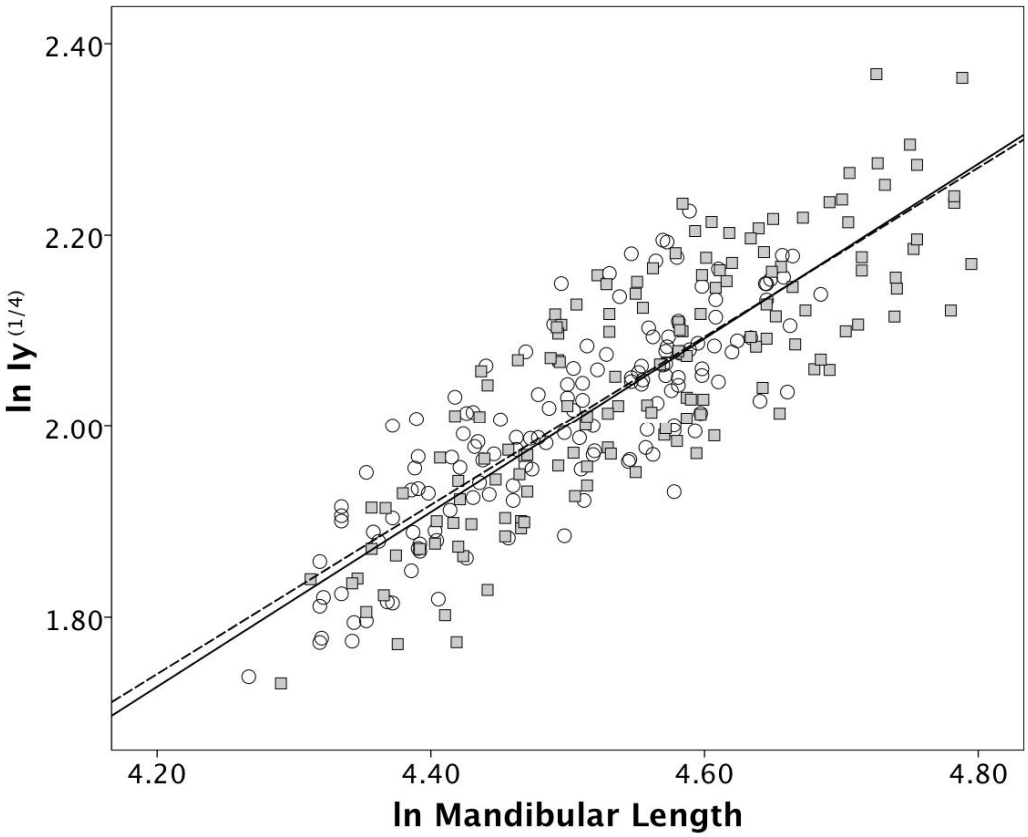

Figure 10. Reduced major axis regression. Sex differences in growth allometries for transverse bending resistance (I_y) relative to log-transformed mandibular length.

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* Solid square denotes male. Circle denotes female. Solid line denotes male regression. Dashed line denotes female regression.

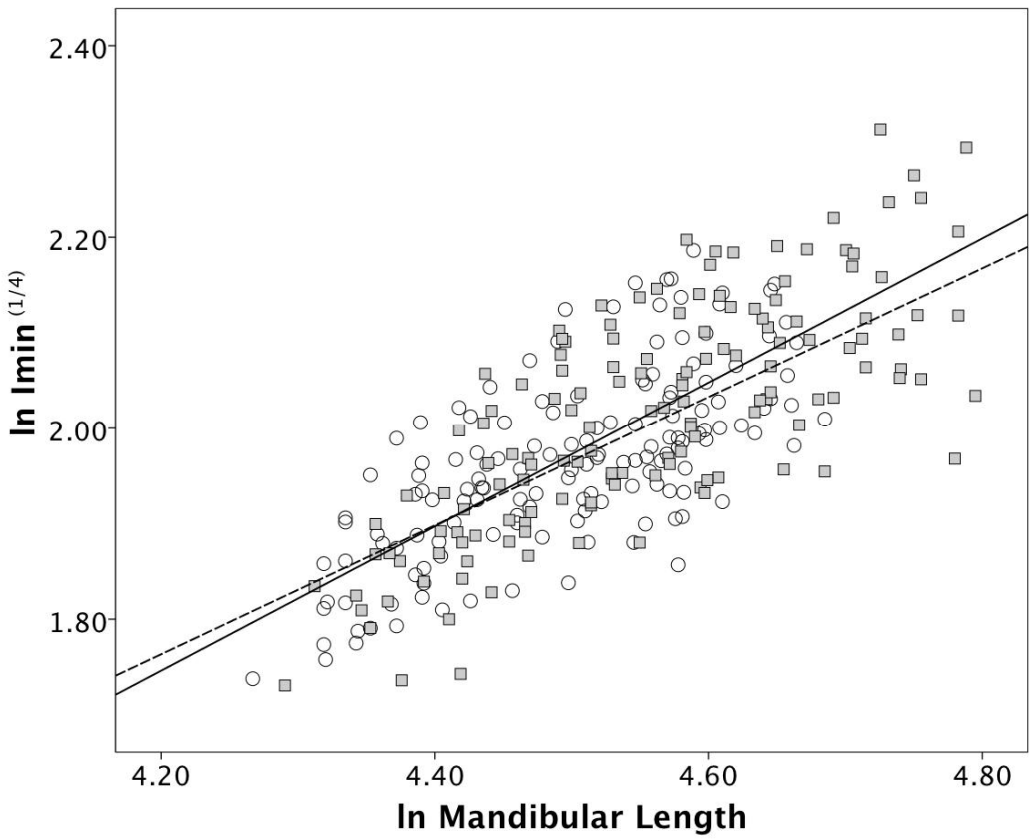

Figure 11. Reduced major axis regression. Sex differences in growth allometries for transverse bending resistance (I_{min}) relative to log transformed mandibular length.

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* Solid square denotes male. Circle denotes female. Solid line denotes male regression. Dashed line denotes female regression.

Table 4

Results of ANCOVA testing for significant differences in the interaction between symphyseal cortical properties, sex and mandibular length

Variable	Sex		Mandibular Length		Sex*Mandibular Length	
	F	P	F	P	F	P
Area	0.305	0.581	526.740	<0.001	0.312	0.577
I_x	0.090	0.764	711.875	<0.001	0.087	0.768
I_y	0.163	0.687	596.266	<0.001	0.154	0.698
I_{max}	0.178	0.673	794.636	<0.001	0.181	0.671
I_{min}	0.939	0.333	308.904	<0.001	0.986	0.322

Table 5

ANOVA results for sex comparison of residual values derived from OLS regression of log-transformed symphyseal cortical properties on log-transformed mandibular length

Variable	F	P
Area	0.067	0.796
Ix	0.037	0.848
Iy	0.230	0.632
Imax	0.014	0.907
Imin	0.888	0.347

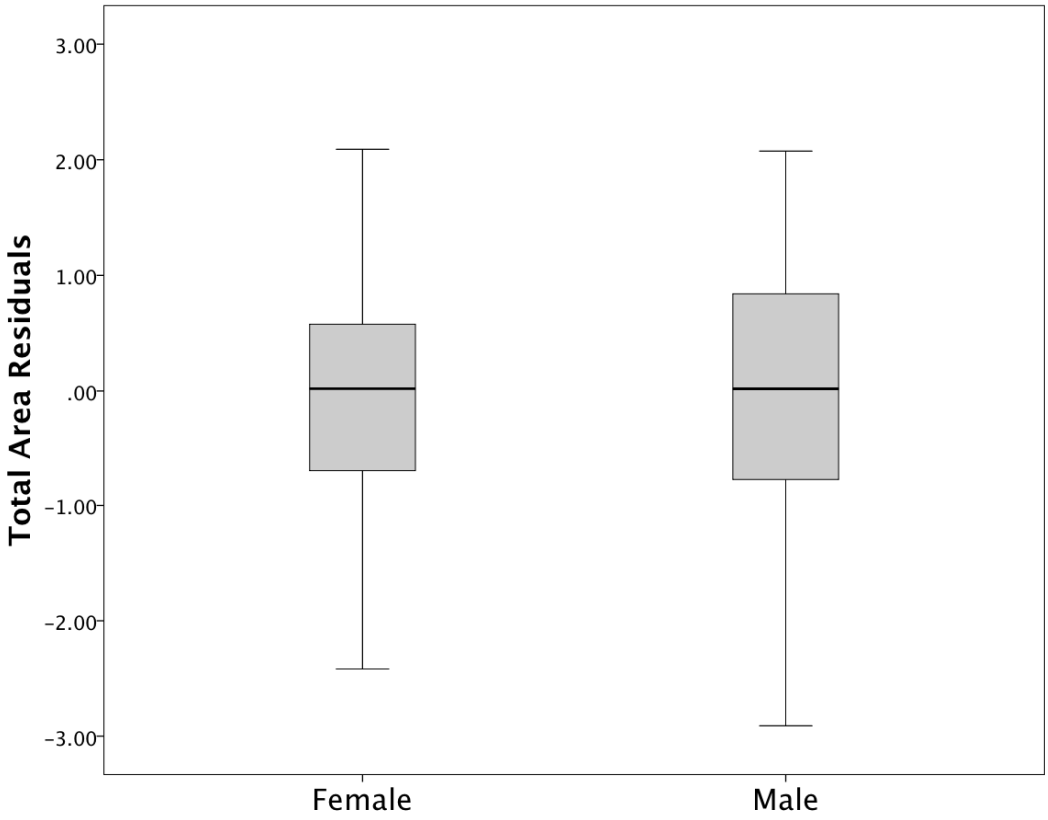

Figure 12. Box plot of residual values derived from OLS regression of log-transformed total symphyseal area on log-transformed mandibular length.

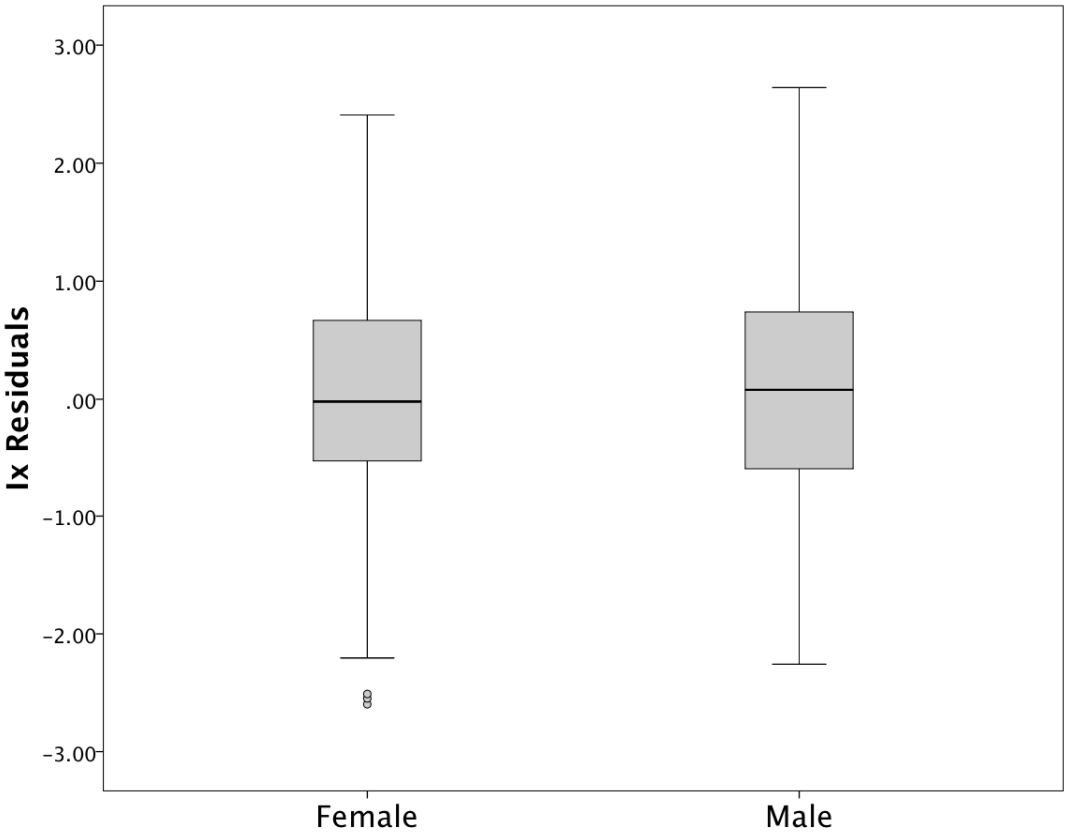

Figure 13. Box plot of residual values derived from OLS regression of log-transformed resistance to vertical bending (I_x) on log-transformed mandibular length.

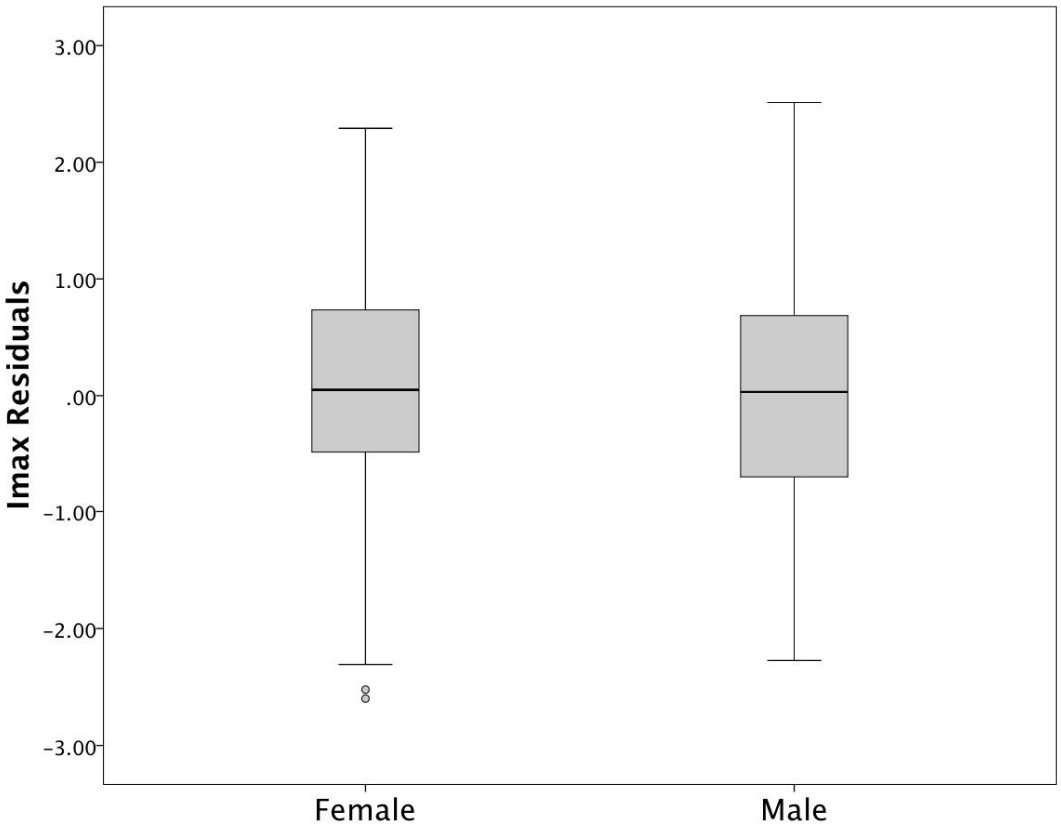

Figure 14. Box plot of residual values derived from OLS regression of log-transformed resistance to vertical bending (I_{max}) on log-transformed mandibular length.

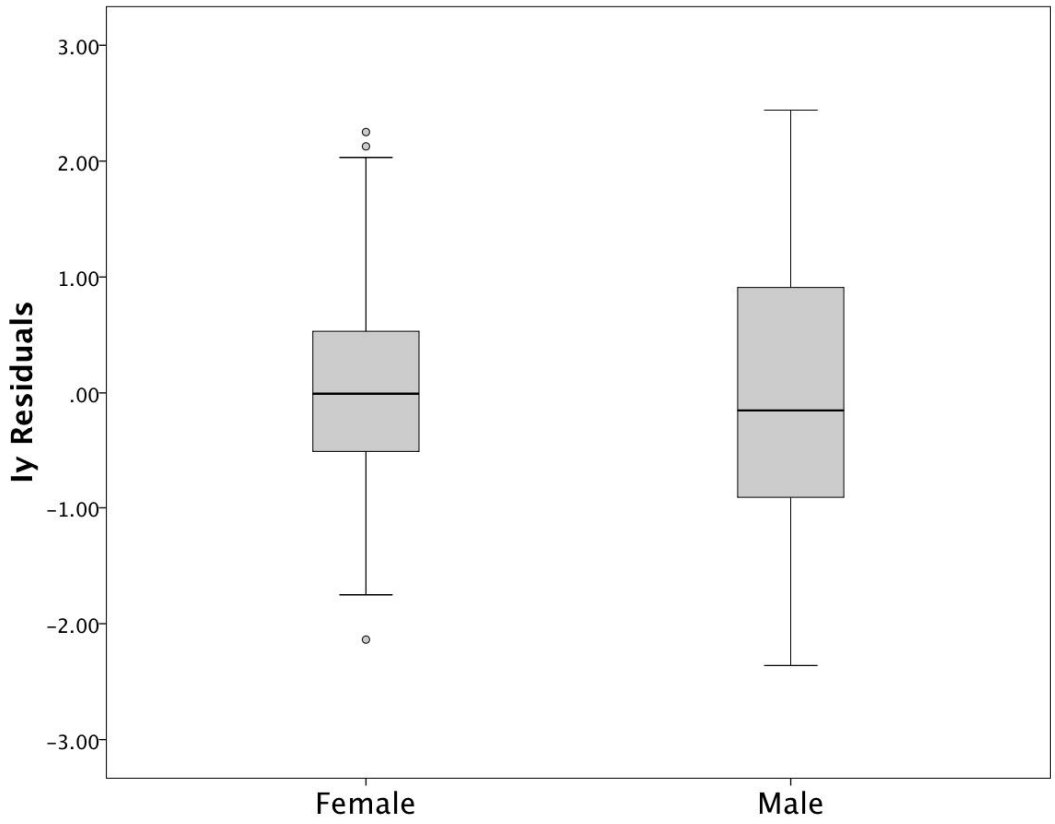

Figure 15. Box plot of residual values derived from OLS regression of log-transformed resistance to transverse bending (I_y) on log-transformed mandibular length.

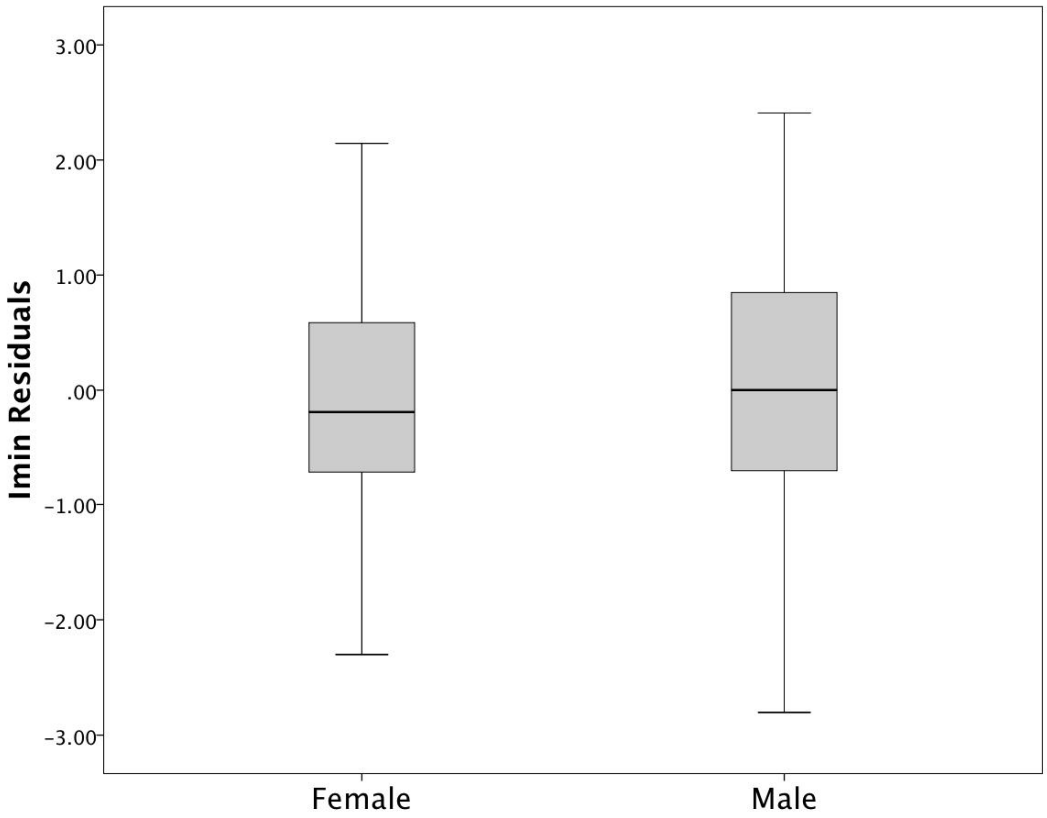

Figure 16. Box plot of residual values derived from OLS regression of log-transformed resistance to transverse bending (I_{min}) on log-transformed mandibular length.

DISCUSSION

From both anthropologic and orthodontic standpoints, understanding the relationship between form and function is important. In the realm of anthropology, the ability to interpret behavior from skeletal morphology is closely tied to the amount of correspondence between form and function. Orthodontically, understanding functional relationships can help predict growth and development of the human skull. In turn, this could lead to avenues of changing or modifying a person's growth. While the present study is limited in total sample size and lack of *in vivo* bite force data, it nevertheless provides a longitudinal perspective of masticatory function and symphyseal form during ontogeny, which samples of individual skulls cannot provide.

If symphyseal bone distribution responds to masticatory forces, then we would expect that as the mandible grows, the symphysis would correspondingly remodel to accommodate increased symphyseal stresses (Daegling 1993; Fukase 2007). Biomechanically speaking, increasing the mandibular length increases the moment arm that puts bending forces on the symphysis. Therefore, a longer mandible should correlate with a symphysis that is able to resist more vertical and transverse bending. Our results indicate this is true. For both males and females, as the mandibular length increased during ontogeny, so did the symphysis' robustness and ability to resist bending forces.

Is this relationship due to general facial growth or specifically a cause and effect of increasing bite forces? As discussed earlier, biting force of adult males and females is significantly different, with males exhibiting greater forces. However, this difference in bite force production does not manifest until adolescence. Therefore, if the form of the symphysis does correlate highly with function, then we would expect males, in comparison with females, to exhibit a disproportional increase in symphyseal rigidity relative to length of the mandible. The analysis does not show this relationship. Instead, both male and female growth allometries followed strikingly similar and overlapping

patterns. There were no significant male-female differences in allometric slopes for any of the variables examined.

In the complex array of influential factors that determine mandibular morphology, perhaps symphyseal form, at least in narrow morphological comparisons, may vary independently of masticatory function. For example, symphyseal form may vary as general facial patterns vary. It has been shown that people with long vertical facial patterns exhibit a symphysis that has a large height and small anterior-posterior depth (Mangla et al. 2011). Anterior vertical facial proportions with associated mandibular patterns are established early in ontogeny (Bishara and Jakobsen 1985; Bastir and Rosas 2004). Fukase and Suwa (2008) demonstrated that infant and juvenile symphysis of the ancient Jomon mandible exhibited most of the robust characteristics that the adult symphysis did. In other words, aspects of an individual's symphyseal morphology are determined early in development as their general facial pattern is. Another example of how symphyseal morphology could be independent of function is found in the hypothesis that chin development occurs from differential jaw growth of the maxilla and mandible (Marshall et al. 2011). As the mandible outgrows the maxilla during adolescence, the occlusal interlocking of the dentition creates compensatory posterior movement of the mandibular alveolus and teeth. In turn, alveolar recession in the anterior symphysis occurs giving the symphysis its final form.

Bjork (1969) established that variation of vertical facial height is linked to the rotation of the mandible during growth. In addition, as vertical facial proportions including symphyseal height vary, so does the orientation of the muscles of mastication (Pepicelli et al. 2005; Chan et al. 2008). As such, variation in symphyseal morphology may be part of a larger suite of features that influences variation in masticatory force production rather than the reciprocal. Different orientation of the masticatory muscles creates different mechanical advantages of the muscles, which could explain why those with longer vertical facial patterns (and therefore a taller, narrower symphysis) exhibit

smaller bite forces (Throckmorton et al. 1980). This suggests that the general facial pattern and corresponding symphyseal form influenced bite force, not the other way around. To further test this relationship, Ingervall and Bitsanis (1987) increased bite force production through masticatory muscle training in children to see if mandibular rotation and vertical facial dimensions changed. Even with effective increases in bite forces, mandibular rotations and vertical facial dimensions seem unchanged, which suggests that vertical facial form is more of a determinant of function, than the reciprocal.

If a functional relationship exists, the external cortical outline of the symphysis may not be the best measure of masticatory effects. When determining the robustness of a long bone, Stock and Shaw (2007) show a high correlation between using the external periosteal dimensions and cross-sectional geometry, i.e. cortical bone endosteal and periosteal outlines. In regards to the mandibular symphysis, Holton et al. (ND) showed high correlations between internal symphyseal properties predicted from external symphyseal contours. However, perhaps the subtleties of the effects of mastication on symphyseal form exist in the distribution of cortical bone, which the current study could not address. Three-dimensional computed tomography (CT) scans have been used to determine the relationship of function and cortical bone distribution in anthropologic samples (Ruff 2008; Fukase 2007) and living human subjects (Holton ND). These studies all have the limitation of using cross-sectional and static adult data to determine functional relationships. As radiation exposure levels of CT scans is reduced, perhaps a longitudinal study of cortical bone distribution will be viable. Until then, there exist many limitations in longitudinal studies of symphyseal ontogeny.

CONCLUSIONS

The purpose of this study was to assess the relationship between masticatory function and symphyseal form. Specifically, does the bending resistance of the symphysis during ontogeny reflect loading history? With the known difference in bite force production between males and females that manifests during adolescence, we examined biomechanical parameters of the mandibular symphysis in a longitudinal sample.

Male and female symphyseal growth allometries were the same, indicating that the differences in bite force established during adolescence did not affect the symphyses' resistance to vertical and transverse bending. Due to limitations in lateral cephalograms, only the external cortical outline of the symphysis was used to assess the biomechanical parameters. Perhaps the external contours of the symphysis are guided by non-functional factors (e.g. general facial growth patterns and differential jaw growth) and the subtle effects of function on morphology are found cortical bone distribution. To test this, computed tomography (CT) scans could be employed to delineate cortical bone parameters in the symphysis. Ideally, a longitudinal sample with in vivo bite force data would be used. However, due to high radiation exposures in CT scans, a longitudinal study may not be feasible at this time.

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