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PATTERNS OF MORPHOLOGICAL INTEGRATION IN THE DENTAL ARCHES OF INDIVIDUALS WITH MALOCCLUSION

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Abstract

Objectives—In humans, there is a large range of variation in the form of the maxillary and mandibular dental arches. This variation can manifest as either prognathism or retrognathism in either or both arches, which can cause malocclusion and lead to abnormal masticatory function. This study aims to identify aspects of variation and morphological integration existing in the dental arches of individuals with different types of malocclusion.

Methods—Coordinate landmark data were collected along the gingival margins of 397 scanned dental casts and then analyzed using geometric morphometric techniques to explore arch form variation and patterns of morphological integration within each malocclusion type.

Results—Significant differences were identified between Class II forms (increased projection of upper arch relative to the lower arch) and Class III forms (lower arch projection beyond the upper arch) in symmetrical shape variation, including anteroposterior arch discrepancies and abnormal anterior arch divergence or convergence. Partial least squares analysis demonstrated that Class III dental arches have higher levels of covariance between upper and lower arches ($RV=0.91$) compared to the dental arches of Class II ($RV=0.78$) and Class I ($RV=0.73$). These high levels of covariance, however, are on the lower end of the overall range of possible masticatory blocks, indicating weaker than expected levels of integration.

Conclusions—This study provides evidence for patterns of variation in dental arch shape found in individuals with Class II and Class III malocclusions. Moreover, differences in integration found between malocclusion types have ramifications for how such pathologies should be studied and treated.

Keywords

Dental arch form; masticatory complex; malocclusion; morphological integration; geometric morphometrics

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INTRODUCTION

The maxillary and mandibular dental arches are key components of the masticatory complex. Therefore, adequate spatial alignment of the dental arches is vital for proper function in mastication, verbalization, and respiration (Howell, 1986; Toro et al., 2006; Gotfredsen and Walls, 2007; Pirilä-Parkkinen et al., 2009; Souki et al., 2009; Sierpinska et al., 2014). Given the importance of the masticatory complex throughout the life span of an individual, discrepancies in maxillary/mandibular dental arch relationships, collectively referred to as malocclusion, are of great interest both biologically and clinically (Kanno and Carlsson, 2006; Schaefer et al., 2006; Ackerman et al., 2007; AlHarbi et al., 2008). A large body of literature on malocclusion, dating back to Angle's 1899 original description of Class I, II, and III malocclusion, has served as a baseline for studying and understanding the wide range of variation seen within the dental arches (Angle, 1899; 1907; Smith 1938; Ruf and Panherz, 1999; Basdra et al., 2000; Baccetti et al., 2005; Xue et al., 2010; Primožic et al., 2013; Buschang, 2014).

Malocclusions are caused by genetic and/or environmental factors that trigger abnormal relationships between the hard and soft tissue components of the facial complex (Singh 1999). The most commonly used clinical method to describe the relationships between the upper and lower teeth as they come together during occlusion is the Angle method (Angle 1900), which describes four relationships in the anterior-posterior (AP) plane, with one normal type and three malocclusion types. Class I normal occlusion (Figure 1) is present in about 30% of the population in the U.S. (Proffit et al., 1998), and is defined by a correct AP relation between the maxilla and mandible, with the teeth aligned in a catenary curve (along the line of occlusion) with the maxillary incisors overlapping the mandibular incisors by 2 mm in the vertical and horizontal planes. Class I malocclusion is present in approximately 50–55% of the U.S. population and shares the same maxillary/mandibular relationship of normal occlusion. However, in Class I malocclusion, individual teeth are abnormally positioned along the line of occlusion. Class II malocclusion (Figure 1) is present in 15% of the U.S. population and is characterized by an increased antero-posterior overlap (greater than 2mm) of the upper anterior incisors and a convex facial profile. Finally, Class III malocclusion (Figure 1) affects 1% of the U.S. population, and is characterized by a composite of skeletal patterns leading to the forward positioning of the lower teeth in relation to the upper teeth and a concave facial profile. Within each malocclusion type, intra-arch tooth position irregularities (i.e., dental crowding) and inter-arch deviations in the vertical and/or transverse dimension often co-exist, impairing masticatory function and increasing treatment difficulty (Proffit et al., 1998). While these metrics are useful for diagnosing clinical malocclusion and formulating treatment plans, they only provide a restricted set of phenotypes that limit comprehensive studies of abnormal dento-facial development, malocclusion etiology, and masticatory biomechanics.

Recently, researchers have identified this knowledge gap and have begun employing other, more comprehensive, methodologies for understanding arch variation (Perez et al., 2006; Kieser et al., 2007; Banabilh et al., 2009; Gómez-Robles and Polly, 2012; Polly, 2012; Alarcón et al., 2014). One such analytical tool that has had increasing popularity in the study of arch form is geometric morphometrics (Kieser et al., 2007; Banabilh et al., 2009). While geometric morphometric (GM) techniques have been employed in other scientific fields for at least the last two decades, this approach to phenotypic analysis is relatively new to the dental sciences (Singh et al., 2004; Singh and Abramson, 2008; von Cramon-Taubadel, 2011).

Geometric morphometric methods allow for complex analyses of size and shape based on coordinate landmark data in two- or three-dimensional space (Bookstein, 1991; Richtsmeier et al., 2002). This technique enables researchers to explore morphological variation beyond what is feasible with traditional linear metric analyses. At its core, GM-based methods effectively isolate morphological variation into separate size- and shape-related properties (Rohlf and Marcus, 1993; Adams et al., 2004; Zelditch et al., 2004). This facilitates the examination of morphology in terms of shape variation without the confounding influence of size. In biology, shape variation is often used as a morphological proxy for genetic variation, and the interplay between genes and morphology has served as the basis for numerous studies of genotype vs. phenotype interactions in many different biological systems (Debat and David, 2001; Klingenberg et al., 2001; Workman et al., 2002; Klingenberg et al., 2004; Miller et al., 2014; da Fontoura et al., 2015). Typically, studies of morphological variation in bilaterally symmetric structures (such as the dental arches) address both aspects of symmetric and asymmetric shape variation. Symmetric shape variation is defined as the average of the actual landmark configuration and its mirrored landmark configuration, while asymmetric shape is simply the actual landmark configuration minus the symmetric landmark configuration (see Klingenberg et al., 2002). The utility of such a method in dental malocclusion studies is also clear. By collecting and analyzing coordinate landmark data from dental casts, the present study captures more complex patterns of dento-alveolar morphological variation than is possible with standard clinical datasets alone, adding to the classic definitions of the malocclusion phenotypes, and giving further insight into the phenotypic complexity underlying this condition.

The study of relationships between the shape of maxillary and mandibular arches, in cases of moderate or severe malocclusion, also serves as an important venue for research on morphological integration. Definitions of morphological integration are varied across the literature, but all revolve around a central theme: morphological integration is a measure of interaction between two or more components within a system (Olson and Miller, 1951; 1958; von Dassow and Munro, 1999; Winther, 2001; Lieberman et al., 2000; Bookstein et al., 2003; Hansen, 2003). While there are several ways to measure this interaction (Magwene, 2001; Polanski and Franciscus, 2006; Mitteroecker and Bookstein, 2007; Polanski, 2011), the most common involves an analysis of covariation between structures. Depending on the strength of this covariation, the structures in question are said to be either integrated or modularized. Integration implies a strong relationship between the form of two structures, where a change in form (and possibly function) of one structure results in a similar level of change in another structure (Olson and Miller, 1958; Lieberman et al., 2000;

Bookstein et al., 2003; Ehrich et al., 2003). Modularity, on the other hand, implies a weak relationship between structures, where modification to one structure results in either little or no change in another structure (von Dassow and Munro, 1999; Winther, 2001; Hansen, 2003).

It is important to understand that morphological integration exists along a continuum and determinations of “integration” and “modularity” are relative to the systems that they describe. For example, aspects of the craniofacial complex, such as the face, cranial vault, and cranial base, may be more modularized (Polanski and Franciscus, 2006; Bastir, 2008; Mitteroecker and Bookstein, 2008) in humans, while components specifically within the face may be more integrated (Bookstein et al., 2003; Wellens et al., 2013). Additionally, there is a large degree of variation in the expression of morphological integration in the maxillae and mandibles of different primate groups, indicating different evolutionary trajectories in the formation of the masticatory complex (Hallgrímsson et al., 2004a; Bastir et al., 2004). Ultimately, all components within a biological system, by definition, must be integrated (Klingenberg, 2008). Given this reality, studies of morphological integration must focus on relative levels of integration when comparing different groups or structures within a given group.

While the study of morphological integration has roots in the 1950s (Olson and Miller, 1958), advances in geometric morphometric methods have provided new means for exploring this concept in biological systems (Bastir and Rosas, 2005; Mitteroecker et al., 2012; Klingenberg, 2008; 2014). In the present study, the question under examination is whether or not Class I, Class II, and Class III arch relationships display different levels and patterns of morphological integration. Given that the dental arches function together during mastication, one would expect levels of integration between the maxilla and mandible to be relatively high in cases with good occlusion (Corruccini and Beecher, 1984; Bastir and Rosas, 2005; Schaefer et al., 2006). However, dental arch discrepancies present in malocclusions could demonstrate variation in the degree and patterning of integration within the masticatory complex. As such, the aim of this study is to examine differences, if any, in morphological integration in Class I, Class II, and Class III arch phenotypes, in both relative strength and patterning, and to determine if certain patterns of mandibular/maxillary arch integration are indicative of certain types of malocclusion.

MATERIALS AND METHODS

The study protocol was reviewed and approved by the Institutional Review Board (IRB) at the University of Iowa. A waiver of consent was requested and approved by the IRB, given that this sample is based on existing records. Pre-treatment orthodontic records including lateral cephalograms, photographs, and dental casts of Class II, and Class III adults seeking orthodontic treatment at the University of Iowa Orthodontic Graduate and Faculty Practice Clinic, University of Iowa Hospital Dentistry Clinic, or surrounding area Private Practice Clinics from 1971–2012 were reviewed to find eligible subjects for this study. Additionally, dental cast data from the Iowa Fluoride Study (Warren et al., 2000; 2001) were employed to obtain a sample of untreated Class I (normal arch relationship) controls from eastern Iowa. A total of 397 individuals met our eligibility criteria (Table 1) (Moreno et al., 2013; 2014).

This clinical sample (n=276) was comprised of post-pubertal subjects (100 males >18, 176 females > 16) of self-reported Caucasian (90.6%), Asian (3.6%), African-American (4.0%), or other ancestry (1.8%). Of these, 147 displayed moderate or severe Class II malocclusion, while 129 demonstrated moderate or severe Class III malocclusion. The Class I (n=121) comparative sample from the Iowa Fluoride Study consisted of n=64 males and n=57 females of largely Caucasian decent.

Identification of Angle Class I, II, and Class III malocclusion was conducted using established cephalometric and dental norms as shown in (Table 1) and described previously (Moreno et al., 2013; 2014). Dental casts of the upper and lower dental arches were trimmed according to the American Board of Orthodontics guidelines (<http://www.americanboardortho.com>) to match the patient's natural occlusion, and were digitized with a NextEngine Laser scanner (NextEngine, Inc.). Upper and lower arch dental casts were scanned together in natural occlusion confirmed by cast trim and intraoral photos taken with the subject in natural occlusion. The resulting three-dimensional scans were landmarked using Landmark editor (Wiley et al., 2005). A total of 58 landmarks were placed along the gingival margins to quantify dento-alveolar shape (following Schaefer et al., 2006 and Staley and Reske, 2006), and then analyzed using MorphoJ (Klingenberg, 2011) to compare patterns of phenotypic variation and integration between Class I, II, and Class III malocclusion (see Table 2, Figure 2).

All landmark data were registered into a single coordinate plane using the Procrustes fit procedure in MorphoJ (Klingenberg, 2011). Since object symmetry (Klingenberg et al., 2002) exists in the dataset, separate components for symmetrical and asymmetrical shape variation were computed and analyzed in order to avoid issues of multicollinearity in the data (Mardia et al., 2000; Klingenberg et al., 2002). In addition to shape-based analyses, shape variation was also examined, in light of overall variation in size (allometry). Allometry can potentially complicate results given that the sample is comprised of both males and females, and previous studies have shown evidence of sexual dimorphism in the size of the dental arches (Al-Shahrani et al., 2014; Ungar, 2014). Symmetric and asymmetric shape components were regressed against centroid size in order to examine this relationship and determine if further size-related adjustments were needed in analyses of dental arch shape.

Two-block partial least squares analysis (2B-PLS) was employed to examine the interrelationships of maxillary and mandibular dental arches in the sample. To accomplish this, the 58 landmark dataset was split into two hypothesized blocks of 29 landmarks each. Block 1 included all 29 landmarks along the maxillary gingival margin (denoting the maxillary arch), while block 2 included all 29 landmarks along the mandibular gingival margin (denoting the mandibular arch). PLS is a method of measuring covariation and, as a result, RV coefficients (analogous to a multivariate r^2 coefficient, Rohlf and Corti, 2000; Bookstein et al., 2003; Klingenberg, 2009) were used to determine the overall level of integration between the dental arches blocks in all three groups (Class I, II, III). Subsequently, we randomly generated 10,000 different pairs of blocks to create a distribution of hypothetical landmark relationships which ranged from extremely integrated to modularized. This procedure was used to determine where the proposed maxillary arch/

mandibular arch blocks fell in the actual total distribution of possible block configurations. This analysis is required to give context to RV coefficient scores and is often employed in the literature (Hallgrímsson et al., 2004b; 2006; Klingenberg, 2009). For example, given that the dental arches are a key component of the masticatory complex, we expect that overall levels of integration (denoted by relatively high RV coefficients) between the maxillary and mandibular landmarks will be high. However, our hypothesized blocks consisting of the maxillary arch (block 1) and the mandibular arch (block 2) may not demonstrate the highest RV scores when compared to other blocks consisting of random landmarks across both of the arches. This test, therefore, allows us to see the relative level of integration between the hypothesized maxillary and mandibular dental arches, and produce a better overall picture of morphological integration in the sample.

RESULTS

Allometry

Allometric relationships in the pooled Class I, II, and III sample were examined for size-related symmetric and asymmetric shape variation. A significant relationship was found between symmetric variation in the dental arches and centroid size ($p < 0.001$), yet this variation only accounted for 2.4% of the overall variation in shape seen in the sample. This indicates that, while there is a significant allometric component to shape variation in the sample, its overall effect on shape is very minor (Figure 3). Interestingly, shape variation in the dental arches with respect to overall dental arch size appears to follow Class II and Class III phenotypic relationships, where larger individuals tend to be Class III, while smaller individuals tend to be Class II ($p = 0.02$). With respect to the asymmetric component of variation, it was found that size did not have a significant relationship with shape ($p = 0.55$, see Figure 4). Given the low impact of overall size on total shape, results based on the raw coordinate data were the primary focus for this study. Allometric residuals, however, were also analyzed with respect to symmetric shape variation only.

PLS

Two-block partial least squares (2B-PLS) analyses for the symmetrical and asymmetrical shape components of the sample were performed to highlight patterns of morphological variation and integration in the dental arches in Class I, II, and III individuals. 2B-PLS analyses were run with both the maxillary and mandibular arches being registered simultaneously using a within configuration Procrustes fit, given that the focus here is to examine the relationship of the arches as part of a functional unit, as opposed to the dental arches in isolation. The latter would necessitate Procrustes fits for the mandibular and maxillary arches separately (Rohlf and Corti, 2000; Klingenberg, 2009).

A 2B-PLS analysis of the symmetric component yielded an RV coefficient of 0.92 ($p < 0.0001$) for the relationship between the maxillary and mandibular dental arches in the total sample. The major component of shape variation for this PLS analysis (PLS1 accounting for 87.9% of the variation) highlights an antero-posterior relationship difference between the dental arches, with the maxillary arch being more protrusive in Class II individuals and the mandibular arch being more protrusive in Class III individuals (Figure

5). Similar results were noted for the allometric-scaled symmetric shape component, with an RV coefficient of 0.92 ($p < 0.0001$) and a slightly lower percent variance explained for PLS1 (87.6%). In both cases, the hypothesized blocks (the upper and lower dental arches) demonstrated slightly lower than average levels of integration compared to the overall distribution of possible blocks, indicating that the maxillary and mandibular blocks for the entire malocclusion sample are relatively weakly integrated.

A similar 2B-PLS conducted on the asymmetric component also shows a strong relationship between the upper and lower arches, with an $RV = 0.88$ ($p < 0.0001$). This test cannot distinguish between Class II and Class III individuals based on the patterning of asymmetric variation between the upper and lower arches. Class I individuals, however, displayed lower levels of asymmetric shape variation compared to Class III individuals ($p = 0.04$), but not compared to Class II individuals ($p = 0.44$). The main component of shape variation in this PLS (PLS1, 94.9% variation explained) indicates variation in the transverse relationships between the upper and lower arches, with a slight cant to the orientation of the gingival margins (Figure 6). As with the symmetric component above, these two dental arch blocks display slightly lower than average levels of integration when compared to the entire distribution of possible blocks.

While the above tests examine the degree of covariation between the upper and lower arches in the total sample, a separate 2B-PLS was run for our Class II and III samples as well as our Class I sample to independently determine if levels of covariation differed between the upper and lower arches within each classification, i.e., to test if one type of malocclusion was more highly integrated than the other. This was done using only the symmetric component of shape variation as the asymmetric component did not vary significantly between malocclusion types, with exception of one test between Class I and III.

Results showed that Class I ($RV = 0.73$, $p < 0.0001$) and Class II ($RV = 0.78$, $p < 0.0001$) individuals display considerably lower levels of covariation in upper and lower arch forms when compared to Class III individuals ($RV = 0.91$, $p < 0.0001$). Patterns of shape variation in the dental arches within each occlusion type mimic those observed in the whole sample. The primary axis of shape variation depicts gingival margin AP, and vertical discrepancies and relative transverse dimension discrepancies characterized by a retrognathic lower arch in the Class II vs. a prognathic lower arch in the Class III malocclusion types (Figures 7 and 8). Class I individuals displayed variation largely in the vertical relationship of the arches, with only minor levels of AP displacement noted. In the case of the Class II sample, levels of covariance between the upper and lower arches are at the very low end of the range of potential blocks, and therefore are considered to be more weakly integrated in their relationship (Figure 7). The Class III sample arches, however, demonstrate a pattern similar to that of the entire malocclusion sample in that their distribution is closer to the mean and therefore more strongly integrated (relatively speaking, see Figure 8). For comparison, the Class I sample hypothesized maxillary and mandibular blocks were more similar to the Class II sample in that their values were relatively low compared to the overall distribution of random blocks for the whole sample (Figure 9). This, like the Class II sample, also indicates that the Class I sample is relatively weakly integrated in upper vs. lower arch form.

Overall results indicate that Class I and Class II maxillary and mandibular dental arches tend to be more weakly integrated when compared to Class III dental arches.

DISCUSSION

Given that the mandibular and maxillary arches grow and function as a unit, malocclusion discrepancies caused by environmental, habitual, or genetic factors may lead to disconnection in the integrated morphology of the dental arches (Gómez-Robles and Polly, 2012). With this in mind, morphological integration analyses provide important insights into the explanation for how such integration is affected in cases with moderate and severe malocclusion. Results showed relatively high levels of covariation between the maxillary and mandibular arches overall, even in the presence of moderate or severe malocclusion. Recent work on another orthodontic sample also found that the maxillo-mandibular complex was itself an integrated unit, separate from other aspects of the craniofacial complex (Wellens et al., 2013). This result is not surprising given the requirement of the masticatory complex in numerous essential biological functions (mastication, respiration, and communication). It should be noted that, while RV coefficients between the upper and lower dental arches for the three subsamples are high, these coefficients fall on the lower end of the overall range of possible blocks. This indicates that the arches, as defined by our landmark sets, are actually more weakly integrated than expected in these samples. When examining both RV coefficients and maxillary/mandibular block placement across the range of possible block configurations, Class III cases had higher levels of morphological integration compared to Class I and Class II cases. Given that the Class III phenotype is often the result of increased growth of the mandible, this result suggests that the mandible is potentially more deterministic in the overall development of both dental arches. The weaker correlation between the maxillary and mandibular arch in both Class I and Class II individuals indicates that the shapes of the maxillary and mandibular arches in these groups are less related and, therefore, changes in shape (via growth, trauma, behavior, or other factors) in one arch is less likely to have a direct effect on the other arch.

In Class II malocclusion, non-nutritive sucking habits, such as finger and thumb sucking, can create discordance in the relationship between the maxillary and mandibular dental arches (Góis et al., 2008). This behavior can have a drastic effect on the shape of the maxillary dental arch, often times creating a situation of increased maxillary protrusion, as well as other occlusal issues. Also, differences between tongue and lip pressures may be associated with specific shape variation in the dental arches. In some cases, such pressures can exacerbate a Class II malocclusion (Lambrechts et al., 2010). Given that there are myriad behavioral factors that can play into the development of maxillary arch prognathism, this could also account for lower levels of integration with our Class II subjects.

The results found in the present study have interesting ramifications for both the growth of the maxillary complex and for treatment of malocclusion. In cases where there is excessive growth of the mandibular arch, the maxillary arch must further alter its shape to ‘keep up’ with these changes in mandibular arch form. Alternatively, when the maxillary arch experiences more growth, the mandibular arch does not need to alter its form as much. Given the results of this study, it is possible to hypothesize that actions taken to correct the

mandibular arch in a Class III discrepancy will ultimately have a greater impact on maxillary arch form (albeit a more complex one, see below), while a similar corrective measure employed on a Class II maxillary arch would have less impact on the overall shape of the mandibular arch.

There is considerable variation in maxillo-mandibular relationships across human populations. Eastern Asian populations have documented higher cases of Class III malocclusion and mandibular prognathism (Singh, 1999). Conversely, European populations demonstrate very low levels of mandibular prognathism, but increased instances of maxillary projection and Class II malocclusion (Gábris et al., 2006). The implications of the integration patterns noted here might imply that Eastern Asian populations, where instances of Class III malocclusion are greatest (estimates as high as 40% of all cases), also have higher levels of integration in the masticatory and facial complex. European populations, on the other hand, may show significantly lower levels of masticatory and facial integration by comparison.

A recent study by Alarcón and colleagues (2014) was unable to detect differences in integration patterns between skeletal Class II and III individuals showing variation in A-P dimensions, but was able to identify differences in morphological integration between individuals with different vertical dimensions to the face (i.e., dolicho- and brachyfacial individuals). While skeletal classification did not directly correlate with patterns of morphological integration, relatively high levels of covariation between the cranium and mandible (roughly 60%) were noted for both Class II and III (Alarcón et al., 2014). Given that these forms of malocclusion generally demonstrate abnormally high levels of antero-posterior variation between the upper and lower dental arches, Alarcón et al. (2014) interpret this to mean that cranial configuration may have an influence on A-P malocclusion patterns. Interestingly, they find that Class III individuals, who demonstrate increased mandibular prognathism, had a higher level of morphological integration ($r=0.75$) compared to Class IIs with a retrognathic mandible ($r=0.71$).

Another relatively recent study (Auconi et al., 2011) has also looked at this issue of integration in dental malocclusion, albeit with a different methodology. Using network analysis, which shares some similarity to 2B-PLS, Auconi and colleagues showed that the network structure of Class III malocclusion patients are, in fact, more integrated than Class II patients. They also interpret this result as an indication that any morphological changes experienced in a Class III malocclusion will have a greater systemic impact (given the higher degree of connectedness in their network analysis) compared to someone with Class II malocclusion.

The present study also finds that levels of morphological integration within the dental arches for Class III individuals tend to be higher than in both Class I and Class II individuals. This result is in line with the published studies mentioned above. An important distinction here is that this study focuses specifically on three-dimensional dental arch form rather than two-dimensional cephalometric data. While the masticatory complex involves many hard- and soft-tissue craniofacial components, the occlusal components of the complex play a vital role in the ability to properly process food. As such, it is of primary importance to not only

test for patterns of integration or modularity within the cranium at large, but also to focus on these patterns within the dental arches specifically. The results provided here point to the possibility that overall cranio-dental form may be more integrated in individuals who have prognathic mandibles, while this effect is less pronounced in cases with retrognathic mandibles.

CONCLUSIONS

The aim of the present study was to expand the characterization of dental arch phenotypes and address issues of symmetric and asymmetric variation (via morphological integration) within the maxillary and mandibular arches in moderate or severe cases of malocclusion. The data suggest that, while antero-posterior discrepancies form the bulk of dental arch morphological variation in Class II and Class III malocclusion, there is also a component of vertical variation in dento-alveolar height that corresponds to preferentially horizontal and vertical growth patterns. Class III individuals have higher overall levels of integration when compared to both Class I and Class II individuals, indicating that any change (either in natural growth, behavior, trauma, or clinical intervention) in the mandibular arch would have a stronger impact on the maxilla than a similar change in a Class II maxillary arch would have on the mandibular arch.

Future work in this area should include closer consideration of both environmental and genetic factors, as well as their interplay with the masticatory system, particularly in the form and function of the dental arches. Also, additional data should be collected on the dentition, in addition to arch form, to provide a closer look at how tooth size, tooth shape, and orientation impact the overall form of the masticatory complex. This research also demonstrates that future work examining masticatory complex and overall facial integration patterns, as well as patterns of growth and development, across human populations is warranted. Such data, combined with the methods employed in this study, could yield very promising insight into the etiology of the masticatory complex and potential issues that lead to misalignment of the dental arches.

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Figure 1.

An illustration of Angle Class I, II, and III maxillo-mandibular arch relationships: A) Class I, B) Class II, and C) Class III.

Figure 2.
A dental cast scan demonstrating the position of all 58 landmarks used in the study.

Figure 3.

Regression of the symmetric shape component on centroid size indicating a significant ($p < 0.001$) but minor (2.4% of the total variation) effect of allometry. Red dots represent Class I individuals, green dots represent Class II individuals, and blue dots represent Class III individuals.

Figure 4. Regression of the asymmetric shape component on centroid size, highlighting a non-significant ($p=0.55$) effect of allometry in asymmetric shape variation. Red dots represent Class I individuals, green dots represent Class II individuals, and blue dots represent Class III individuals.

Figure 5.

Shape variation along PLS1 of the raw symmetric shape component for the 2B-PLS analysis. A) Wireframes representing positive warp scores in posterior, lateral, and superior view (in dark blue). B) Wireframes representing negative warp scores in posterior, lateral, and superior view (in dark blue). Average shape is represented in gray.

Figure 6.

Shape variation along PLS1 of the raw asymmetric shape component for the 2B-PLS analysis. A) Wireframes representing positive warp scores in posterior and superior view (in dark blue). B) Wireframes representing negative warp scores in posterior and superior view (in dark blue). Average shape is represented in gray.

Figure 7.

Shape variation along PLS1 of the raw symmetric shape component for the 2B-PLS analysis of the Class II sample only. A) Wireframes representing positive warp scores in posterior, lateral, and superior view (in dark blue). B) Wireframes representing negative warp scores in posterior, lateral, and superior view (in dark blue). Average shape is represented in gray.

Figure 8. Shape variation along PLS1 of the raw symmetric shape component for the 2B-PLS analysis of the Class III sample only. A) Wireframes representing positive warp scores in posterior, lateral, and superior view (in dark blue). B) Wireframes representing negative warp scores in posterior, lateral, and superior view (in dark blue). Average shape is represented in gray.

Figure 9. Shape variation along PLS1 of the raw symmetric shape component for the 2B-PLS analysis of the Class I sample only. A) Wireframes representing positive warp scores in posterior, lateral, and superior view (in dark blue). B) Wireframes representing negative warp scores in posterior, lateral, and superior view (in dark blue). Average shape is represented in gray.

Table 1

Table listing criteria for inclusion/exclusion in the study sample.

Clinical Sample Inclusion Criteria Adults (female > 16 years, male > 18 years)		Clinical Sample Exclusion Criteria
At least 2 of the following:		Any of the following:
Class II	Class III	
Cephalometric angle ANB > 4	Cephalometric angle ANB < 0	History of severe facial trauma
Overjet > 4	Overjet < 0, at least edge-to-edge or anterior cross bite	Previous orthodontic treatment
Angle CII molar or canine relationship on at least one side	Angle CIII molar or canine relationship on at least one side	Presence of facial syndromes
	Wits (female < 0, male < -1)	Missing or poor quality records
Convex profile	Concave profile	Missing or impacted teeth other than 3 rd molars
Note: Both Class II division 1 and division 2 subjects were included.		Retained primary teeth

Table 2

A listing of all landmarks employed in the study.

Name	No.	Description	Source
s0	1	Rt 2nd Molar embrasure point – Maxilla	Staley & Reske, 2006
s1	2	Most cervical point of tooth on edge of gingiva - Rt 2nd molar - Maxilla	Schaefer et al., 2006
s2	3	Rt 1st Molar embrasure point – Maxilla	Staley & Reske, 2006
s3	4	Most cervical point of tooth on edge of gingiva - Rt 1st molar - Maxilla	Schaefer et al., 2006
s4	5	Rt 2nd Premolar embrasure point – Maxilla	Staley & Reske, 2006
s5	6	Most cervical point of tooth on edge of gingiva - Rt 2nd premolar - Maxilla	Schaefer et al., 2006
s6	7	Rt 1st Premolar embrasure point - Maxilla	Staley & Reske, 2006
s7	8	Most cervical point of tooth on edge of gingiva - Rt 1st premolar - Maxilla	Schaefer et al., 2006
s8	9	Rt Canine embrasure point - Maxilla	Staley & Reske, 2006
s9	10	Most cervical point of tooth on edge of gingiva - Rt canine - Maxilla	Schaefer et al., 2006
s10	11	Rt Lateral Incisor embrasure point - Maxilla	Staley & Reske, 2006
s11	12	Most cervical point of tooth on edge of gingiva - Rt lateral incisor - Maxilla	Schaefer et al., 2006
s12	13	Rt Central Incisor embrasure point - Maxilla	Staley & Reske, 2006
s13	14	Most cervical point of tooth on edge of gingiva - Rt central incisor - Maxilla	Schaefer et al., 2006
s14	15	Central incisor embrasure point - Maxilla	Schaefer et al., 2006
s15	16	Most cervical point of tooth on edge of gingiva - Lt central incisor - Maxilla	Schaefer et al., 2006
s16	17	Lt Central Incisor embrasure point - Maxilla	Staley & Reske, 2006
s17	18	Most cervical point of tooth on edge of gingiva - Lt lateral incisor - Maxilla	Schaefer et al., 2006
s18	19	Lt Lateral Incisor embrasure point - Maxilla	Staley & Reske, 2006
s19	20	Most cervical point of tooth on edge of gingiva - Lt canine - Maxilla	Schaefer et al., 2006
s20	21	Lt Canine embrasure point - Maxilla	Staley & Reske, 2006
s21	22	Most cervical point of tooth on edge of gingiva - Lt 1st premolar - Maxilla	Schaefer et al., 2006
s22	23	Lt 1st Premolar embrasure point - Maxilla	Staley & Reske, 2006
s23	24	Most cervical point of tooth on edge of gingiva - Lt 2nd premolar - Maxilla	Schaefer et al., 2006
s24	25	Lt 2nd Premolar embrasure point - Maxilla	Staley & Reske, 2006
s25	26	Most cervical point of tooth on edge of gingiva - Lt 1st molar - Maxilla	Schaefer et al., 2006
s26	27	Lt 1st Molar embrasure point - Maxilla	Staley & Reske, 2006
s27	28	Most cervical point of tooth on edge of gingiva - Lt 2nd molar - Maxilla	Schaefer et al., 2006
s28	29	Lt 2nd Molar embrasure point - Maxilla	Staley & Reske, 2006
s29	30	Lt 2nd Molar embrasure point - Mandible	Staley & Reske, 2006
s30	31	Most cervical point of tooth on edge of gingiva - Lt 2nd molar - Mandible	Schaefer et al., 2006
s31	32	Lt 1st Molar embrasure point - Mandible	Staley & Reske, 2006
s32	33	Most cervical point of tooth on edge of gingiva - Lt 1st molar - Mandible	Schaefer et al., 2006
s33	34	Lt 2nd Premolar embrasure point - Mandible	Staley & Reske, 2006
s34	35	Most cervical point of tooth on edge of gingiva - Lt 2nd premolar - Mandible	Schaefer et al., 2006
s35	36	Lt 1st Premolar embrasure point - Mandible	Staley & Reske, 2006
s36	37	Most cervical point of tooth on edge of gingiva - Lt 1st premolar - Mandible	Schaefer et al., 2006
s37	38	Lt Canine embrasure point - Mandible	Staley & Reske, 2006
s38	39	Most cervical point of tooth on edge of gingiva - Lt canine - Mandible	Schaefer et al., 2006

Name	No.	Description	Source
s39	40	Lt Lateral Incisor embrassure point - Mandible	Staley & Reske, 2006
s40	41	Most cervical point of tooth on edge of gingiva - Lt lateral incisor - Mandible	Schaefer et al., 2006
s41	42	Lt Central Incisor embrassure point - Mandible	Staley & Reske, 2006
s42	43	Most cervical point of tooth on edge of gingiva - Lt central incisor - Mandible	Schaefer et al., 2006
s43	44	Central incisor embrassure point - Mandible	Schaefer et al., 2006
s44	45	Most cervical point of tooth on edge of gingiva - Rt central incisor - Mandible	Schaefer et al., 2006
s45	46	Rt Central Incisor embrassure point - Mandible	Staley & Reske, 2006
s46	47	Most cervical point of tooth on edge of gingiva - Rt lateral incisor - Mandible	Schaefer et al., 2006
s47	48	Rt Lateral Incisor embrassure point - Mandible	Staley & Reske, 2006
s48	49	Most cervical point of tooth on edge of gingiva - Rt canine - Mandible	Schaefer et al., 2006
s49	50	Rt Canine embrassure point - Mandible	Staley & Reske, 2006
s50	51	Most cervical point of tooth on edge of gingiva - Rt 1st premolar - Mandible	Schaefer et al., 2006
s51	52	Rt 1st Premolar embrassure point - Mandible	Staley & Reske, 2006
s52	53	Most cervical point of tooth on edge of gingiva - Rt 2nd premolar - Mandible	Schaefer et al., 2006
s53	54	Rt 2nd Premolar embrassure point - Mandible	Staley & Reske, 2006
s54	55	Most cervical point of tooth on edge of gingiva - Rt 1st molar - Mandible	Schaefer et al., 2006
s55	56	Rt 1st Molar embrassure point - Mandible	Staley & Reske, 2006
s56	57	Most cervical point of tooth on edge of gingiva - Rt 2nd molar - Mandible	Schaefer et al., 2006
s57	58	Rt 2nd Molar embrassure point - Mandible	Staley & Reske, 2006