Morphological Integration between the Face and Dentition throughout Ontogeny

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Abstract of the Dissertation

Morphological integration between the face and dentition throughout ontogeny

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Modern humans have flatter faces, wider palates and smaller teeth compared to chimpanzees and our early human ancestors. Many hypotheses concerning the evolution of the human face assume a relationship between the face and the teeth. It is likely that the face and teeth develop in a coordinated manner throughout the growth and development of an organism due to similar developmental origins, and functions, and the teeth residing in the maxillae. What is not fully understood is whether the face and teeth are two separate units (modules) that can evolve independently or if they are tightly correlated (integrated) during evolution. This dissertation analyzed the pattern and magnitude of morphological integration between the face and the teeth in humans and chimpanzees to test whether specific changes in the size and shape of the lower face during growth are associated with particular dental developmental events, such as the formation or eruption of the permanent molars. Computed tomography scans were used to generate 3D surfaces of the crania and dentition of chimpanzees and humans. The size and shape of the specimens were quantified with 3D landmarks, multivariate geometric morphometric analyses and traditional linear measurements. Specimens were divided into four dental stages based on permanent molar eruption to assess size and shape changes throughout ontogeny. The lower face and permanent dentition are integrated in humans and chimpanzees in adults and throughout ontogeny. A relatively more prognathic lower face, and a taller, narrower and longer palate are associated with more protruding and larger anterior teeth. Individuals with relatively broader midfaces, shorter palates, and less prognathic lower faces have more retracted, smaller and shorter anterior teeth. The magnitudes of integration are similar at equivalent dental stages of humans and chimpanzees, but the degree of integration declined during dental stages with mixed deciduous and permanent dentition. The face and teeth comprise one module, but shape covariation was primarily demonstrated between the face and the incisors and canines, and not the molars. This suggests some modularity between the incisors and molars that would allow the independent evolution of a flatter face and smaller anterior dentition even as molars increase in size.

Dedication Page

For my parents.

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List of Abbreviations

2B-PLS	Two-block partial least squares analysis
2D	Two-dimensional
3D	Three-dimensional
AMNH	American Museum of Natural History
BOSMA	Bosma Collection
CR	Covariance ratio
CT	Computed tomography
DART	Raymond A. Dart Collection of Human Skeletons
DMM	Digital Morphology Museum, Kyoto University
HYMS	Hull York Medical School
MCZ	Museum of Comparative Zoology
NMB	National Museum in Bloemfontein
PCA	Principal component analysis
PLS	Partial least squares
PMAE	Peabody Museum of Archeology and Ethnology
r	Pearson's correlation coefficient
RMCA	Royal Museum of Central Africa
r-pls	Two-block partial least squares analysis correlation coefficient
RV	Multivariate squared correlation coefficient between two vectors
SV	Singular value
SAM	South African Museum
SBU	Stony Brook University
UCL	University College of London
UCT	University of Cape Town
UL	University of Liverpool
USNM	Smithsonian Institution National Museum of Natural History

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Chapter 1 Introduction

Introduction

Jaws and teeth are commonly used to reconstruct phylogenetic relationships (Dembo, Matzke, Mooers, & Collard, 2015; Strait & Grine, 2004; Strait, Grine, & Moniz, 1997), describe new species (Berger et al., 2010; Leakey et al., 2001), and to estimate diet (Kay, 1975; Rosenberger & Kinzey, 1976), body size (Gingerich, 1977) and sexual dimorphism (Leutenegger & Kelly, 1977; Plavcan & van Schaik, 1992) in primate, including human, evolutionary studies. These analyses are frequently performed through separate investigations of the cranium, mandible or dentition which ignore the inter-relationships among these regions. Independence of characters is required to assess phylogenetic relationships, since utilizing correlated traits can bias analyses and produce unresolved evolutionary relationships among fossil taxa (Lieberman, 1999; Strait, 2001). Despite this tacit assumption of independence among craniodental regions, hypotheses of hominin evolution often imply coordinated evolution of the lower face and teeth.

The teeth and skulls of modern humans are morphologically different from our fossil ancestors. Compared to their extinct relatives, modern humans have evolved more orthognathic faces with high vertical foreheads, more parabolic palates, distinct canine fossae and reduced postcanine dental size (Lieberman, McBratney, & Krovitz, 2002; Weidenreich, 1947). This suite of craniofacial changes in modern humans has led to one of the central questions of human craniofacial evolution: why do humans have flatter faces and relatively smaller dentition than our fossil ancestors? It may be the case that only one of these traits was the target of selection if facial and dental features evolved in tandem due to underlying integrative processes. Therefore, understanding the relationship between the form of the face and the dentition in extant and fossil hominins could bring us one step closer to unraveling this particular evolutionary riddle (Simpson, Lovejoy, & Meindl, 1990).

In phylogenetic studies, it is assumed that facial and dental characters are independent (Collard & Wood, 2000), yet the face and dentition are functionally, developmentally and spatially linked (Boughner & Dean, 2008; Hlusko, 2004). The functional matrix hypothesis proposes that functional and environmental demands alter the size and shape of the cranium specifically, the neurocranium and face are mechanically changed by demands from the muscles and teeth or impacted through growth of the organs (Moss, 1968; Moss & Young, 1960). According to the functional matrix hypothesis, the lower face and dentition share similar masticatory functions and there would likely be an association between the two (Lieberman, Wood, & Pilbeam, 1996; Ward, Plavcan, & Manthi, 2010). In addition, the deciduous and permanent teeth mineralize and erupt within the alveolar processes of the maxilla and mandible. Furthermore, the structures of the dentition and face both arise from three embryological swellings, the frontonasal, maxillary and mandibular prominences (Helms, Cordero, & Tapadia, 2005; Tapadia, Cordero, & Helms, 2005), and neural crest cells both develop into bony jaws via intramembranous ossification (Kuratani, 2005; Kuratani, Matsuo, & Aizawa, 1997) and contribute to dental development, specifically the dentin and dental pulp (Pispa & Thesleff, 2003; Tucker & Sharpe, 2004). Due to these functional, spatial, and developmental associations, it is likely that there is covariation or integration between the growing facial skeleton and the teeth at particular developmental stages (Dean & Beynon, 1991) and a relationship between craniofacial form and dentition over evolutionary time (McCollum & Sharpe, 2001b).

Hypotheses about cranio-dental morphology in paleoanthropology frequently assume correlated change among the face, palate, mandible and dentition (Kimbel, Johanson, & Rak, 1997; Kimbel, Rak, Johanson, Holloway, & Yuan, 2004; McCollum, 1999; Suwa et al., 2009; Tobias, 1991; Ward et al., 2010). For example, although the craniofacial morphologies of humans and *Paranthropus* are distinct, they share subnasal orthognathism. McCollum (1999) proposed that features of the *Paranthropus* face such as a tall mandibular ramus, elongated infraorbital region, and anterior placed zygomatic root are also related to its relatively small anterior dentition and large posterior dentition. Suwa et al. (2009, p. 68e5) noted that *Ardipithecus ramidus* had a primitive "ape-like projecting midfacial muzzle," but lacked the marked anterior displacement of the lower face and dentition seen in *Pan troglodytes*. Suwa et al. (2009) hypothesized that this anterior displacement was related to the enlarged canine of *P. troglodytes*, but also perhaps to a wider gape. This implies that the more derived and less prognathic face of *Ar. ramidus* may be related to its smaller canine. Moreover, weaker subnasal prognathism of *Ardipithecus* was explicitly attributed to its smaller incisors (Suwa et al., 2009). Kimbel et al. (2004) described the shape of the early *Australopithecus afarensis* Garusi I maxilla as influenced by the canine root. Kimbel et al. (2004, p. 219) wrote, "the canine root in Garusi I directly shapes the morphology of the face lateral to the nasal aperture, as it does in many chimpanzees," while Ward et al. (2010) suggest that the maxillary breadth of Garusi I and *A. anamensis* was influenced by canine root basal area, but not canine root length. In addition, Tobias (1991) stated that the enlargement of tooth roots led to a deeper alveolar process of the maxilla and increase in height of the maxilla between the orbit and alveolar region in *Homo habilis*. The convex shape of the nasoalveolar clivus of the A.L. 666-1 Hadar maxilla, attributed to *Homo habilis,* is related to the incisor root curvature (Kimbel et al., 1997). Although the maxilla of *Kenyanthropus platyops* has no incisor or canine crowns, a relatively flat, orthognathic subnasal region is associated with small, equally sized incisor roots and small molars (Leakey et al., 2001; Spoor, Leakey, & Leakey, 2010). These hypotheses of facial evolution implicitly assume that the morphological traits of the teeth, face and mandible are correlated, and not independent.

The study of phenotypic trait correlation is called morphological integration (Olson & Miller, 1958). Traits that are functionally and developmentally related are often inherited together and evolve as integrated units (Cheverud, 1982, 1984; Lande, 1979). The cranium is composed of multiple units or modules, such as the face and neurocranium that are organized in a hierarchical nature and inherently integrated to grow and function together. The lower face or subnasal region and dentition are contained within the face module and the integration, or lack or independence, between the lower face and teeth can produce correlated changes between the two that may explain the maxillary morphology present in modern humans, chimpanzees and fossil hominins. The morphological integration of the face and dentition will be analyzed in this dissertation to assess the covariation between these two regions. This dissertation has three objectives that will describe the particular shape changes between the face and dentition and how strongly these traits covary throughout growth and development in humans and chimpanzees. The first objective is to evaluate the hypothesis that the dentition and face are morphologically integrated throughout ontogeny in humans and chimpanzees by determining if there is a strong association between facial shape and the form and spatial arrangement of the permanent dentition. If there is strong covariation (integration) between the facial skeleton and the teeth, this would suggest that the face and dentition are part of the same morphological unit and that selection would produce correlated trait changes throughout the face and dentition. For instance, enlargement or reduction of the dentition may cause associated changes in the size and shape of the face. Conversely, if there is weak association between the face and the dentition, this suggests that the face and teeth are separate modules that have the potential to evolve independently and can be analyzed together in phylogenetic analyses. The second objective of the project is to determine if the strength of the covariance between the face and dentition increases or decreases throughout ontogeny. Different ontogenetic stages may have different selective pressures and the response to selection may be influenced by the strength and pattern of integration (Goswami, Smaers, Soligo, & Polly, 2014). The third and final objective is to assess whether the pattern and/or magnitude of integration differ between chimpanzees and humans. If the pattern and/or magnitude of integration are similar between humans and chimpanzees, this would suggest a conservation of integration throughout the evolution of the hominin face. The reduced prognathism in modern humans, early *Homo*, and *Paranthropus* may be explained by similar patterns of integration.

Background

Morphological integration and modularity

Morphological integration is the coordinated expression of morphological elements that compose a phenotypic whole such that a change in one trait produces a change in another trait (Klingenberg, 2013; Olson & Miller, 1958; Smith, 1996). Groups of morphological traits that are integrated and strongly covary comprise a module (Raff, 1996). The composition of morphological modules are hypothesized a priori on the basis of spatial proximity, functional relationships (Klingenberg, 2009), or developmental morphogenesis (Boughner & Dean, 2008). Modules may also be identified a posteriori through covariation analysis between groups of traits. The pattern of covariation describes the combination of morphological traits and relative coordinated changes of these traits (Goswami & Polly, 2010) and the degree (or strength) of integration is quantified by measures of statistical association (Cheverud, 1982). When two or more modules of an organism have strong within-module covariance, but little or no among-module covariance, this particular pattern is characterized as modularity (Klingenberg, 2008; Klingenberg, Mebus, & Auffray, 2003; Wagner, 1996; Wagner & Altenberg, 1996). Integration strength and modularity are not absolute, but exist relative to one another along a gradation (Klingenberg et al., 2003; Schlosser & Wagner, 2004). Among morphological traits, modularity can be defined as the independence between two modules or a complete lack of statistical significance between to modules, while integration is characterized as strong or weak due to a significant statistical association between modules.

Modularity allows for the decoupling of trait associations and independent evolution of modules that have low integration (Ackermann & Cheverud, 2004b; Wagner, 1996), while spatially, functionally and developmentally related traits may be inherited together as a result of strong integration (Cheverud, 1982, 1984; Lande, 1979). These integrated traits or modules can lead to coordinated evolutionary change and adaptations where change in one module will produce a correlated change in another module (Merilä, Björklund, Pigliucci, & Preston, 2004). Alternatively, integration may constrain evolutionary change under stabilizing selection due to the lack of variation within the modules (Merilä et al., 2004; Mitteroecker, Gunz, Neubauer, & Müller, 2012). This would limit the evolution of new phenotypes and stasis could occur among these modules for a long period of time. Recent studies simulating the evolvability of modularity indicate that it is likely that modules are formed under directional selection (Goswami, Smaers, Soligo, & Polly, 2014; Melo & Marroig, 2015) while stabilizing selection maintains integration within a module. Not all integration or modularity is due to development or genetic effects.

Studies of integration and modularity of the primate cranium and dentition have primarily analyzed the adult cranium and dentition separately. These studies report strong integration between modules of the cranium and face in human and nonhuman primates (Ackermann, 2005; Ackermann & Cheverud, 2004b; Bastir & Rosas, 2005; Cheverud, 1995; González-José, Van Der Molen, González-Pérez, & Hernández, 2004; Lieberman, Ross, & Ravosa, 2000; Mitteroecker & Bookstein, 2008; Singh, Harvati, Hublin, & Klingenberg, 2012). Regarding the face, integration was relatively higher in the oral submodules of the face, composed of the palate and dentition, compared to the other submodules such as the zygomatic or the basicranium modules indicating a strong association between functionally and developmentally related traits (Ackermann, 2005; Cheverud, 1995). In contrast to analyses of the cranium, analyses of modularity and integration within the dentition of rodents, Old World monkeys and humans indicate modularity between the incisors and molars, with a greater degree of integration between the molars and premolars (Delezene, 2015; Gomez-Robles & Polly, 2012; Grieco, Rizk, & Hlusko, 2013; Hlusko, Sage, & Mahaney, 2011; Laffont, Renvoise, Navarro, Alibert, & Montuire, 2009; Ribeiro, de Andrade, de Souza, & Line, 2013).

In primates, there have been fewer studies of ontogenetic cranial integration, but integration has been identified among smaller functional regions of the face, such as the oral, nasal and zygomatic regions (Ackermann, 2005), between the face and mandible (Wellens, Kuijpers-Jagtman, & Halazonetis, 2013), and the orbit and neurocranium (Barbeito-Andrés, Anzelmo, Ventrice, Pucciarelli, & Sardi, 2016). Ackermann (2005) found similar patterns of facial ontogenetic integration among humans and great apes, but different strengths of integration. In addition, adult humans had a higher magnitude of integration particularly within the oral regions compared to other age categories.

Relationship between the skull and teeth

The teeth and facial bones may be functionally, spatially and embryonically related, but various studies of the skull and dentition offer conflicting views on how the dentition and facial skeleton relate to one another. The relationship between the skull and the size and shape of tooth roots and crowns have previously been investigated in rodents, dogs, humans and nonhuman primates (Anderson, Thompson, & Popovich, 1977; Cobb & Baverstock, 2009; Garn, Smith, & Cole, 1980; Plavcan & Daegling, 2006; Siegel, 1972; Smith, Wax, & Adler, 1989; Wood & Zuckerman, 1981). For instance, shorter tooth roots were correlated with less projecting faces, shorter palates and shorter faces in baboons, humans, rats and dogs (Riesenfeld & Siegel, 1970; Siegel, 1972). In addition, Plavcan and Daegling (2006) reported an association between mandibular canines and first molar crown size with mandibular size in anthropoid primates. In contrast, Cobb and Baverstock (2009) found no covariation using 2D geometric morphometric landmarks between postcanine root length and facial length, but reported postcanine tooth size was associated with a relative increase in facial height, midfacial projection, flexed cranial base and shorter subnasal region. These studies suggest, there is some association between crown or tooth size and facial height and subnasal length.

A number of genes and transcription factors interact during craniofacial morphogenesis and odontogenesis to control cranial bone formation, tooth patterning and tooth shape (Cobourne & Sharpe, 2003; McCollum & Sharpe, 2001a). Experimental studies in mice indicate that the inactivation of some of these genes produce deviations in the development of the face, palate and teeth and new phenotypes are expressed. For instance, mice that lack Dlx-1 and Dlx-2, which are expressed in the first and second pharyngeal arches, lack maxillary molars and have palatal and maxillary abnormalities, cleft palates and novel bone growth (Qiu et al., 1997). Without Dlx5/6+, which is expressed in the developing brain, cranium and limbs, mutant mice have very small upper incisors and misshapen maxillae (Depew, Lufkin, & Rubenstein, 2002; Robledo, Rajan, Li, & Lufkin, 2002). In addition, Msx1 deficient mice display a cleft palate, lack of incisor development, molar retardation at the tooth bud stage, absence of maxillary and mandibular alveolar processes, overlapping parietal bones, enlarged anterior fontanelles, and rectangular nasal bones (Satokata & Maas, 1994). Msx1 homeobox genes are expressed during morphogenesis of epithelial-mesenchymal interactions during tooth development (Chen, Bei, Woo, Satokata, & Maas, 1996; Satokata & Maas, 1994). Disruptions of these genes cause changes to the development of the teeth and the development of the cranium indicating the same genes are required for multiple ectodermal organs (Bei, 2009).

In contrast to the genes and transcription factors that interact to form the crania and teeth, some studies suggest that there may be genetic independence between tooth and jaw development. There are knockout genes that affect mandibular development but not dental development and genes that are required for dental development but have little effect on the mandible. For instance, mice without the *Ptx1* gene have shortened mandibles, but do not display abnormal tooth development (Lanctot, Lamolet, & Drouin, 1997; Lanctot, Moreau, Chamberland, Tremblay, & Drouin, 1999), while mice that are LEF-1 deficient display teeth arrested at the bud stage, with only localized defects to the alveolar ridge and coronoid process of the mandible (van Genderen et al., 1994). In addition, experimental analyses of mice indicate that the mandible develops normally in the absence of teeth (Paradis, Raj, & Boughner, 2013).

Yet, many individuals present with both craniofacial disorders and dental abnormalities, and many descriptions of craniofacial growth describe the teeth pushing the jaw forward as the tooth buds develop (Dixon, Hoyte, & Rönning, 1997). Moreover, patients with congenitally missing teeth have shorter upper and lower anterior facial heights (Lisson & Scholtes, 2005) and Scholtes, 2005), retrognathic or retrusive maxillae, and large inter-incisal angles (Créton, Cune, Putter, Ruijter, & Kuijpers-Jagtman, 2010) compared to individuals with normal dentition.

Few studies have analyzed the relationship between the dentition and jaw during ontogeny. Cranial and dental growth have been studied using descriptive and 2D radiographic analyses (Björk & Skieller, 1974; Brodie, 1942; Donald & Seong, 1965), but most studies are medical or orthodontic and focus on disease, craniofacial disorders, or malocclusion (e.g.

Alarcon, Bastir, Garcia-Espona, Menendez-Nunez, & Rosas, 2014; Bishara, 2000; Delaire, 1997). Several recent quantitative and qualitative studies of the mandible have described a positive relationship and covariation between the developing dentition and the shape of the mandibular symphysis in modern humans (Coquerelle et al., 2010; Fukase & Suwa, 2008; Fukase & Suwa, 2010; Krarup, Darvann, Larsen, Marsh, & Kreiborg, 2005). In analyses of the association between first molar crown shape and cephalometric craniofacial landmarks, Polychronis and Halazonetis (2014) detected a weak but significant covariation between the mandibular first molar crown shape and mandibular protrusion, maxillary retrusion and rotation of the cranial base in prepubertal and adult humans. No covariation was reported between the maxillary first molar and height or length of the face. The magnitude of integration between the molars and cranium and mandible declined from adolescence to adulthood in this sample (Polychronis & Halazonetis, 2014). A decline in integration with increase in age or development may occur between the mandible and teeth in humans and non human primates (Boughner & Hallgrimsson, 2008; Coquerelle et al., 2010; Plavcan & Daegling, 2006). In a study of integration between the mandible and developing dentition, Coquerelle et al. (2010) found strong covariation between the mandible and teeth through the emergence of the deciduous dentition followed by a decrease in magnitude of integration with age. These studies suggest that the degree of integration may change throughout ontogeny. The genetic, morphological and clinical literature present a complex picture of the relationship between the face and dentition. This dissertation offers an independent avenue by which to evaluate this conflict.

Chapter Organization

The primary objective of this dissertation is to investigate the pattern and magnitude of integration within the facial module, which includes the maxilla, premaxilla, palatines and dentition to determine if the lower face and dentition are two separate modules that can evolve independently or if the dentition and the lower face are integrated and could evolve in coordination.

The dissertation is organized in three analytical chapters with a concluding synthesis chapter. Most cranial remains of fossil hominins are adults, thus the objective in Chapter 2 is to assess the integration between the lower face and all permanent teeth in a larger sample of adult human and chimpanzees. The human and chimpanzee crania must be integrated as a whole as the various parts and bones must articulate to enclose the viscera, and the upper and lower dental arcades must occlude. A cranium that is completely modular in structure with no covariation among modules would not function. To determine if the magnitude of integration between the lower face and teeth is elevated relative to integration among other cranial regions, several other paired cranial and dental modules, including the upper face, occipital, lower face and upper teeth, were analyzed to establish a “baseline” of integration within the cranium. In Chapter 3, the objective is to assess the covariation between the teeth and face of humans and chimpanzees throughout ontogeny. Specifically, the goals are to determine the pattern of covariation found in association with certain dental development events, such as the eruption of the molars, and quantify the strength of integration between the dentition and maxilla at these different stages in humans and chimpanzees. Similar patterns of integration between humans and chimpanzees would suggest that similar patterns of integration may exist in fossil hominins. On the other hand, different patterns and magnitudes of integration throughout ontogeny or between humans and chimpanzees may indicate a change in covariance structure. Chapter 4, presents an assessment of the relationship between the subnasal region and the anterior teeth root angles and root lengths in chimpanzees and humans. The goal is to test the association between the subnasal morphology of fossil hominins and the incisors and canines and compare 2D measurements and angles of the subnasal region and dentition with the 3D analyses of chapter 2 and 3.

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Chapter 2 Relative covariation among the adult lower face and dentition of *Homo sapiens* and *Pan troglodytes*

Introduction

The dentition and crania are studied extensively in physical anthropology because of their durability and abundance in the fossil record. When compared to great apes and more archaic hominins, modern humans have more orthognathic faces, more parabolic palates and reduced dental size (Lieberman et al., 2002; Weidenreich, 1947). Cranial and dental morphological traits like these are frequently used to describe and classify taxa (Strait & Grine, 2004; Strait et al., 1997; Weidenreich, 1947). Their use in phylogenetic analyses assumes that facial and dental characters are independent (Collard & Wood, 2000). Yet, a number of hypotheses about cranio-dental morphology are predicated on the fact that these anatomical regions are tightly associated or integrated such that changes in the dentition will produce correlated changes in the face. For instance, Suwa et al. (2009) hypothesized that the subnasal prognathism of the chimpanzee face is related to the enlargement of the canine while the subnasal orthognathism of *Ardipithecus* is related to its relatively smaller incisors. Additionally, McCollum (1999) proposed that features of the *Paranthropus* face, such as a tall mandible and infraorbital region, are related to its relatively small anterior dentition and large posterior dentition. While the cranial morphologies and evolutionary histories of humans and *Paranthropus* are distinct, the hypotheses of facial evolution implicitly assume that the morphological traits of the teeth, face and mandible are integrated, and not independent. The relationship between the face and the teeth will be empirically evaluated in this study.

Morphological integration is the coordinated expression of morphological elements that compose a phenotypic whole such that a change in one trait produces a change in another (C. P. Klingenberg, 2013; Olson & Miller, 1958; Smith, 1996). Related to the concept of morphological integration is modularity. Modularity refers to the relative independence of some groups of traits, which comprise a single module, from other such modules (Klingenberg, 2008; Klingenberg et al., 2003; Wagner, 1996; Wagner & Altenberg, 1996). Modularity allows for mosaic evolution of skeletal parts that have low integration (Ackermann & Cheverud, 2004b; Wagner, 1996). The units of modularity and morphological integration studies are discrete morphological parts or modules (Raff, 1996). Morphological modules are identified *a priori* by spatial proximity (Klingenberg, 2009), functional relationships, developmental morphogenesis (Boughner & Dean, 2008) or are identified a posteriori through covariation analysis. In covariation analyses, the statistical significance of a correlation or covariance is used to assess the relationship between two parts. Biological organisms have many correlated parts that produce complex phenotypes. Through integration, evolutionary change may occur where functionally and developmentally related traits are inherited together while unrelated traits evolve separately (Cheverud, 1982, 1984; Lande, 1979). Integration can be viewed as an adaptation and a constraint (Merilä et al., 2004). If two traits are integrated, then change in one trait will produce a change in another to maintain a functioning unit in an organism. Alternatively, if there is strong degree of integration, then evolutionary changes will be constrained under stabilizing selection due to the lack of variation within the modules (Mitteroecker et al., 2012). Several recent studies have modeled the evolvability of integration or modularity (Goswami et al., 2014; Melo & Marroig, 2015). Melo and Marroig (2015) developed a model to evaluate the evolution of modularity under several evolutionary scenarios, such as genetic drift and selection. In their model, traits under directional selection were more correlated and formed modules, while stabilizing selection maintained correlation levels between traits within a module. Modularity was produced through divergent directional selection or corridor selection where one trait changed while another trait remained constant (Melo & Marroig, 2015).

One approach to studying cranial integration is through the framework of the functional matrix hypothesis (Moss & Young, 1960), which can be used to grossly delineate modules of the cranium into the neurocranium and the face which includes the dentition (Lieberman et al., 2000; Mitteroecker & Bookstein, 2008; Singh et al., 2012). Moss and Young (1960) proposed the functional matrix hypothesis to study the connections among different anatomical structures. They suggested that functional and environmental demands cause postnatal changes to the form (size and shape) of the cranium, specifically proposing that the neurocranial and facial osteological units are altered mechanically by demands from the muscles and teeth or spatially through the growth of viscera, such as the brain (Moss, 1968). The neurocranium has been further subdivided into the cranial vault, orbital region, and cranial base while the face contains oral, nasal, and zygomatic sub-modules (Ackermann & Cheverud, 2004b). Division of the face and neurocranium into submodules enables analyses of covariation within and between modules of the cranium.

Numerous studies have been performed to assess the presence of integration or modularity of the mammalian skull (Goswami & Polly, 2010; Haber, 2011; Porto, de Oliveira, Shirai, De Conto, & Marroig, 2008). Analyses of the primate cranium indicated a high degree of cranial integration (Ackermann, 2005; Ackermann & Cheverud, 2004b; Bastir & Rosas, 2005; Cheverud, 1995; González-José et al., 2004; Lieberman et al., 2000; Makedonska, 2014; Marroig, De Vivo, & Cheverud, 2004; Mitteroecker & Bookstein, 2008; Neaux, 2017; Singh et al., 2012) particularly in comparison to the dentition. Studies of the dentition of rodents, nonhuman primates and humans indicated a modular pattern in which the incisors and molars are independent modules, with a pattern of stronger integration within tooth classes or between adjacent teeth (Delezene, 2015; Gomez-Robles & Polly, 2012; Grieco et al., 2013; Hlusko et al., 2011; Laffont et al., 2009; Polychronis, Christou, Mavragani, & Halazonetis, 2013; Ribeiro et al., 2013).

Most studies of integration and modularity considered the cranium and dentition separately. Yet, integration of the face and dentition could be due to functional, developmental and/or spatial connections between the two (Boughner & Hallgrimsson, 2008; Hlusko, 2004). Therefore, we might expect integration of the maxilla and dentition due to their similar masticatory functions, spatial relationships and direct mechanical interaction during dental loading. The functional matrix hypotheses can be used to grossly delineate modules of the cranium into the neurocranium and the face which includes the dentition (Lieberman et al., 2000; Mitteroecker & Bookstein, 2008; Singh et al., 2012). Furthermore, the structures of the dentition and face both arise from the frontonasal prominence and from the first pharyngeal arches' maxillary and mandibular prominences (Helms et al., 2005; Tapadia et al., 2005). Thirdly, the dentition mineralizes and erupts from the alveolar bone of the maxilla. The dentition is spatially constrained to grow within the maxilla before eruption, and the maxilla increases in size to accommodate the erupting dentition. Due to these functional, developmental, and spatial associations, it is likely that there is covariation between the facial skeleton and the dentition. This study will analyze the dentition and face of *Pan troglodytes* and *Homo sapiens* simultaneously to determine if the two are strongly or weakly integrated (i.e., more modular).

The results will have implications for hominin systematics and craniodental evolution. If the teeth and face are tightly integrated, this may impact future cladistic analyses in that features of the teeth and face cannot be treated as independent characters. Additionally, in studies of hominin cranial evolution, some of the key differences in the lower facial morphologies of humans, great apes and fossil hominins have been hypothesized to be related to the relative sizes of the anterior or posterior dentition (McCollum, 1999; Suwa et al., 2009). If strong integration is found within *Homo* and *Pan*, this may suggest possible scenarios for the coordinated evolution of morphological traits that produce the modern human form or past fossil hominin morphology.

Previous investigations of the relationship between the skull and teeth were primarily correlation analyses or clinical studies. Traditional morphometric as well as geometric morphometric studies found correlations between tooth shape and size and aspects of mandibular anatomy (Anderson et al., 1977; Cobb & Baverstock, 2009; Garn et al., 1980; Plavcan & Daegling, 2006; Siegel, 1972; Wood & Zuckerman, 1981). Analyses of humans and nonhuman primates indicated a positive correlation between various measures of the teeth and the skull (Anderson et al., 1977; Garn et al., 1980; Plavcan & Daegling, 2006; Siegel, 1972; Smith et al., 1989; Wood & Zuckerman, 1981). For instance, in experimental and morphometric studies of baboons, humans, rats and dogs, animals with shorter tooth roots exhibited less protruding faces as well as decreased palatal and facial length (Riesenfeld & Siegel, 1970; Siegel, 1972). Similarly, crown dimensions of the mandibular canine and first molar were correlated with mandibular size but not with mandibular robusticity across a broad taxonomic sample of nonhuman anthropoid species (Plavcan & Daegling, 2006). Contrary to these previous studies, Cobb and Baverstock (2009) analyzed postcanine tooth roots and cranial shape using 2D landmarks in adult chimpanzees and found no covariation between postcanine tooth root length and facial length. However, total crown to root apex length of the postcanine dentition was associated with a relative increase in facial height, midfacial projection, flexion of the cranial base angle and reduced nasoalveolar clivus length (Cobb & Baverstock, 2009). Polychronis and Halazonetis (2014) detected a weak but significant covariation between the crown shape of the lower first molar of dental casts and cephalometric craniofacial landmarks, but no covariation with the upper first molars. While these studies indicated that the size of tooth crowns and roots are correlated with the size/shape of the face and mandible, the analyses were generally restricted to the size of the posterior permanent dentition, only utilized 2D or traditional morphometrics and did not consider shape variation of the tooth row.

Analyses of the primate skull indicate similar patterns of integration among different primate species, but it is often difficult to compare the degree of integration across studies due to the various methodologies utilized (Klingenberg, 2013). In addition, there is no framework for what values indicate “high” or “low” integration for given structures or taxa. Modularity and integration exist along a continuum in which patterns and magnitudes are relative to other paired modules. For instance, if a magnitude of integration is reported between two modules in a cranial analysis, the relative magnitude of covariance is unknown. In this study, the pattern and magnitude of covariation (or integration) between the lower face and permanent dentition in adult humans and chimpanzees will be analyzed. In addition, the magnitude of covariation among other predetermined regions of the cranium will be analyzed to determine the relative covariation present in these samples of adult humans and chimpanzees. These analyses will assess the degree to which the teeth and lower face are distinct modules or highly integrated. It is predicted that there will be strong covariation/higher integration between regions of the face that are spatially, developmentally and functionally related, such as the upper face and lower face compared to regions of the cranium that do not share such clear associations, such as the occipital bone and dentition.

Materials and Methods

Sample

To analyze and visualize the dentition and the cranium in three dimensions (3D), computed tomography (CT) scans of adult humans (n=49) and chimpanzees (n = 46) of mixed sex were utilized (Table 2.1). These taxa were chosen to create an extant phylogenetic bracket for hominins to assess shared patterns of development, interpret patterns of morphological integration in extinct hominins and to compare the results of this study to existing hominin evolution and integration research. Only non-pathological adult specimens with at least one unworn representative of each tooth were analyzed. The complete eruption of the third molar with root closures and fusion of the spheno-ooccipital synchondrosis categorized the specimens as adults. Human CT scans were acquired from specimens housed at the South African Museum (SAM), University of Cape Town (UCT), the National Museum in Bloemfontein (NMB), and from the Raymond A. Dart Collection of Human Skeletons (DART) at the University of the Witwatersrand. The specimens from SAM, UCT, NMB are Khoesan in origin (Morris, 1987) and primarily archaeological, while the crania from the Dart Collection are mainly derived from modern anatomical cadavers with known sexes, population groups, ages and death dates (Dayal, Kegley, Strkalj, Bidmos, & Kuykendall, 2009). Sex of the Khoesan crania from SAM, UCT and NMB was assessed utilizing the os coxae when available, otherwise sex was classified as unknown from data provided by Frederick Grine.

Chimpanzee specimens were used from the American Museum of Natural History (AMNH), Smithsonian Institution (NMNH), University College of London (UCL), and University of Liverpool (UL), Museum of Comparative Zoology, Harvard University (MCZ), Peabody Museum of Archeology and Ethnology, Harvard University (PMAE), and the Digital Morphology Museum (DMM). Due to the limited availability of complete crania with mostly complete dentition, different subspecies of *Pan troglodytes (P. t.)* were combined in analyses. Specimens were classified as *P. t. troglodytes, P. t. verus,* and *P. t. schweinfurthii.*

Table 2.1 Sample size and sex distribution

Species	Female	Male	Unknown	Total
Humans	12	26	11	49
Chimpanzees	27	19	0	46

Scanning methods and 3D Reconstructions

I scanned specimens from the AMNH at the Stony Brook Hospital on a GE VCT Lightspeed CT scanner in the Department of Radiology and specimens from the MCZ and PMAE on an X-Trek HMST 225 microCT at Harvard University’s Center for Nanoscale Systems. Specimens scanned at Stony Brook were scanned at 140 kV and 200 mA and have an isometric voxel size ranging from 0.187-0.33. The parameters of the CT scans obtained from other museums and researchers varied, but slice intervals were no more than 1 millimeter. Several recent studies (Ford & Decker, 2016; Whyms et al., 2013) recommend a slice interval of 1.25 mm or less for cranial CT scans to ensure accurate reconstruction and measurement of the dentition and crania. Avizo 8.1 visualization software was used to segment the teeth and crania from all specimens using a combination of manual and semi-automated approaches. 3D surfaces of the crania and teeth were generated using the constrained smoothing algorithmic software function.

Landmarks

Three-dimensional landmarks were placed on the 3D reconstructions of the crania and dentition using Avizo 8.1 (Figure 2.1). Landmarks were chosen to quantify the shape of the face, dentition and cranium. The landmarks were divided into general regions based on their location including the lower face, upper face, dentition, and the occipital (Tables 2.2, 2.3). Landmark configurations of all specimens were superimposed by generalized Procrustes analysis (GPA) to remove the effects of translation, rotation and scale, and to create shape variables (Rohlf & Slice, 1990). During GPA, centroids of each specimen are translated to the origin; each specimen's landmark configuration is then scaled to unit centroid size and rotated to minimize the squared distances among corresponding landmarks (Rohlf & Slice, 1990). The resulting data are called Procrustes (shape) coordinates and were utilized in the 3D analyses. Separate GPAs were performed for each cranial analysis. Missing landmarks were estimated from the Procrustes coordinates using thin plate splines in the "geomorph" package version 3.0.2 (Adams & Otarola-Castillo, 2013) in R 3.3.1 (R Core Team, 2016). To estimate the missing landmark locations on an incomplete specimen, a reference specimen containing the mean shape of the complete landmark set from the dataset was used. Next, the landmarks that the incomplete specimens and the reference specimen share were used to align the two specimens. Then, the thin plate spline was used to estimate the missing landmark coordinates in the incomplete specimen (P. Gunz, Mitteroecker, Neubauer, Weber, & Bookstein, 2009).

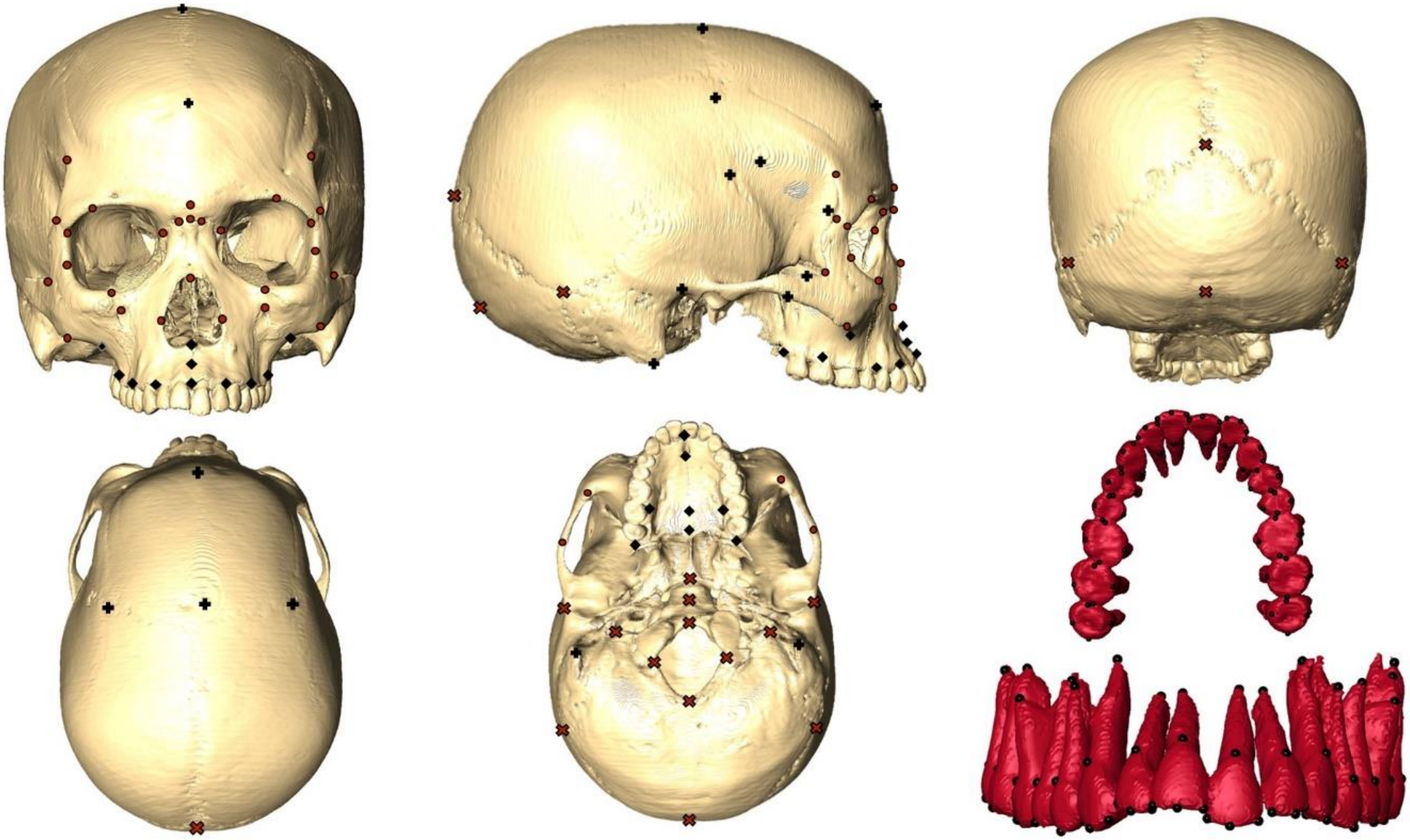

Figure 2.1 Cranial and dental landmarks. Red circle- upper face landmarks, black diamonds-lower face landmarks, black cross-vault landmarks, red “X”- occipital landmarks, black circles- tooth landmarks.

Table 2.2 Cranial landmark descriptions, abbreviations and region (module) assignment

Landmark	Abbrev	Definition	Region
Glabella	**g**	Most anterior midline point on the frontal bone	**upper face (uf)**
Nasion	**n**	Point at which the internasal and frontonasal sutures meet in the midline	**uf**
Rhinion	**rhi**	Most inferior point of the internasal suture	**uf**
Frontotemporale L, R	**ft**	Point where the temporal line reaches its anteromedial position on the frontal	**uf**
Orbitale superior L, R	**osup**	The most superior midpoint of the orbital margin	**uf**
Frontomalare temporale L, R	**fmt**	Point where the frontozygomatic suture crosses the outer orbital rim or temporal line	**uf**
Frontomalare orbitale L, R	**fmo**	Point where the frontozygomatic suture crosses the inner orbital rim	**uf**
Infranasion L, R	**in**	Intersection of nasofrontal, nasomaxillary, maxillofrontal sutures.	**uf**
Dacryon L, R	**d**	Apex of lacrimal fossa, as it impinges on frontal bone. Also usually meeting of frontal, maxillary and lacrimal bones; intersection of lacrimomaxillary suture and frontal bone.	**uf**
Ectochonchion L, R	**ec**	Intersection of most anterior surface of lateral border of orbit and a line bisecting the orbit along its long axis	**uf**
Jugale L, R	**ju**	Point in the depth of the notch between the temporal and frontal processes of the zygomatic	**uf**
Zygoorbitale L, R	**zo**	Point at which the zygomaticomaxillary suture meets the orbital rim	**uf**
Zygomaxillare L, R	**zm**	Most inferior point of the zygomaticomaxillary suture	**uf**
Alare L, R	**al**	Most lateral point on the nasal aperture	**uf**
Infraorbital foramen L, R	**if**	Most superior point of the infraorbital foramen	**uf**
Nasospinale L, R	**ns**	Point on the anterior nasal spine which crosses a line drawn from the lowest points of the nasal aperture	**lower face (lf)**
Midsubnasal clivus L, R	**mcli**	Midline midpoint between nasospinale and prosthion	**lf**
Prosthion	**pr**	Most anterior midline point on the maxillary alveolar process b/w the central incisors	**lf**
I2-C contact L, R	**I2C**	Most inferior point on the maxilla between I2 and C	**lf**
P3-P4 contact L, R	**P3P4**	Point of contact projected onto buccal alveolar surface of P3-P4	**lf**

Ectomolare L, R	**ecm**	Most lateral point on the buccal surface of the alveolus of the second molar	**lf**
Malar root origin L, R	**mro**	The point where malar root arises from the maxilla (often a point of concavity between molar juga and malar root)	**lf**
Maxillary tuberosity L, R	**mt**	Most posterior point on the occlusal surface of the alveolus	**lf**
Orale	**ol**	Midline point of intersection on the hard palate with a line tangent to the posterior margins of the central incisor alveoli	**lf**
Incisivion	**inc**	Most posterior point on the incisive foramen	**lf**
Palatomaxillary	**pm**	The point of intersection of the palatine and the maxillary bones at the junction of the transverse and median palatine sutures	**lf**
Staphylion	**sta**	The point where the interpalatal suture intersects a line joining the deepest indentation of the posterior palate	**lf**
Endomolare L, R	**enmL**	Most lingual point on the lingual border of the alveolus of the second molar	**lf**
Sphenobasion	**spba**	Point where the midsagittal plane intersects the basilar suture; Midline point of sphenooccipital suture	**occipital (o)**
Basion	**ba**	Point on the anterior border of the foramen magnum in the midline	**o**
Opisthion	**op**	Midsagittal point on the posterior border of the foramen magnum	**o**
Foramen magnum lateral L, R	**fml**	The most lateral point on the margin of the foramen magnum and posterior to occipital condyle	**o**
Jugular foramen lateral L, R	**jfl**	Most posterior-lateral point on the foramen taken on the suture, but on the occipital end – if gap present, take lateral most point on occipital bone, where the suture would have been.	**o**
Lambda	**l**	Intersection of the sagittal and lambdoid sutures	**o**
Inion	**i**	Ectocranial midline point at the base of the external occipital protuberance. Point at which superior nuchal lines merge in midline;	**o**
Asterion L, R	**as**	Point where lambdoid, parietomastoid and occipitomastoid sutures meet.	**o**

Table 2.3 Bilateral dental landmarks

Landmark description	Abbrev	Landmark description	Abbrev
M3 crown most inferior buccal point	M3inf	P3 crown most inferior buccal point	P3inf
M3 crown most superior midline point at cervix	M3sup	P3 crown most superior midline point at cervix	P3sup
M3 mesial root apex	M3root	P3 mesial root apex	P3root
M3 crown distal most point	M3d	P3 crown distal most point	P3d
M3 crown mesial most point	M3m	P3 crown mesial most point	P3m
M3 crown lingual most point	M3l	P3 crown lingual most point	P3l
M2 crown most inferior buccal point	M2inf	C crown most inferior labial point	Cinf
M2 crown most superior midline point at cervix	M2sup	C crown most superior midline point at cervix	Csup
M2 mesial root apex	M2root	C mesial root apex	Croot
M2 crown distal most point	M2d	C crown distal most point	Cd
M2 crown mesial most point	M2m	C crown mesial most point	Cm
M2 crown lingual most point	M2l	C crown lingual most point	Cl
M1 crown most inferior buccal point	M1inf	I2 crown most inferior labial point	I2inf
M1 crown most superior midline point at cervix	M1sup	I2 crown most superior midline point at cervix	I2sup
M1 mesial root apex	M1root	I2 mesial root apex	I2root
M1 crown distal most point	M1d	I2 crown distal most point	I2d
M1 crown mesial most point	M1m	I2 crown mesial most point	I2m
M1 crown lingual most point	M1l	I2 crown lingual most point	I2l
P4 crown most inferior buccal point	P4inf	I1 crown most inferior labial point	I1inf
P4 crown most superior midline point at cervix	P4sup	I1 crown most superior midline point at cervix	I1sup
P4 mesial root apex	P4root	I1 root apex	I1root
P4 crown distal most point	P4d	I1 crown distal most point	I1d
P4 crown mesial most point	P4m	I1 crown mesial most point	I1m
P4 crown lingual most point	P4l	I1 crown lingual most point	I1l

Statistical analyses

The goals of the project were to analyze the pattern and magnitude of covariation between the form of the adult face and dentition. The pattern of integration describes the association or covariation between traits that will evolve in coordination (Goswami & Polly, 2010), while the degree (or strength) of integration corresponds to the strength of the phenotypic statistical association (Cheverud, 1982). In order to contextualize the degree of integration between the face and teeth, it was necessary to determine a baseline of integration within the cranium. This baseline was created by calculating the pairwise magnitudes of covariation among other cranial regions, specifically the upper face, lower face, occipital bone and dentition. The integration within the dentition was assessed as an additional marker and the teeth were subdivided into left and right halves. The right and left halves of the dentition must function as a singular unit during mastication, are mostly symmetric and are expected to have a strong degree of integration. Thus, the paired cranial modules analyzed between module covariation while the two halves of the dentition established a baseline for within module covariation. As discussed previously, developmental, functional and direct spatial associations lead me to hypothesize that there will be stronger covariation/higher integration between the upper and lower regions of the face and between the lower face and dentition. In contrast, the occipital bone primarily develops from endochondral ossification, is part of the neurocranium that houses the brain and is spatially separated from the lower face and dentition. Due to different development, functions and spatial relationships, the magnitude of integration between the regions of the face and the occipital bone is expected to be less than that between two closely related parts of the face. For the same reasons it is predicted that the teeth and the occipital will also have lower integration.

To analyze how the shape of one cranial region covaries with that of another region, two-block partial least squares (2B-PLS) analysis was used. In this study, the modules are the dentition, lower face, upper face, and occipital bone (Table 2.2). Using the cross-covariance matrix, the 2B-PLS analysis finds pairs of linear combinations of variables that maximize the covariance between two predetermined blocks of variables with no assumption that one block of landmarks is independent or dependent (Bookstein et al., 2003; Rohlf & Corti, 2000). The covariance between the paired axes (one from each block of landmarks / module) is called the singular value (SV) which is similar to the eigenvalue of a PCA but reflects the magnitude of covariance rather than variance as in a PCA. Also similar to PCA, orthogonal pairs of axes, called singular axes or singular warps, are extracted such that the first pair of PLS axes explain the greatest proportion of total covariance with successive pairs of axes accounting for the greatest proportion of, as yet, unexplained covariance (Mitteroecker & Bookstein, 2008; Rohlf & Corti, 2000). Scores for each specimen on the singular axes are calculated for each block and corresponding singular axes from each bock are visualized as bivariate plots (Mitteroecker et al., 2012).

Separate 2B-PLS analyses were performed on the human and chimpanzee samples and then a combined human and chimpanzee analyses were performed. To retain information about the size, position and scale of the dental and facial blocks relative to one another, a single GPA was performed on all of the landmarks in each species (Baab, 2013; Klingenberg, 2009). Pooled within-sex group mean centered 2B-PLS analyses were used for the chimpanzee analyses to account for the sexual dimorphism present in the dentition (particularly the canine), and a pooled within-species group mean centered 2B-PLS was used for the combined human-chimp analyses. In the pooled analyses, the centroid of each population is determined and the differences from the mean are calculated and used in the 2B-PLS analyses, eliminating shape differences due to sex or species. 2B-PLS analyses were performed in MorphoJ (Klingenberg, 2011). To visualize the pattern of covariation in the 2B-PLS analyses, 3D visualizations were created in Landmark Editor V3.6 (Wiley et al., 2005) to reflect the direction of shape change along the PLS axes.

Additionally, to compare the patterns of morphological integration between chimpanzees and humans the angles between PLS1 singular axes (shape changes) from the lower face and teeth 2B-PLS were calculated in degrees and permutations tests performed to test for significant differences between the angles (McNulty, Frost, & Strait, 2006; Vioarsdóttir & Cobb, 2004; Zelditch, Swiderski, Sheets, & Fink, 2012). The human and chimpanzee lower face and dental landmarks were subjected to a joint procrustes superimposition, 2B-PLS analyes were performed, and the PLS1 vector angles compared between humans and chimpanzees. The angle between the human shape vector and the chimpanzee shape vector were compared to angles obtained from a random distribution of vectors of similar size. An angle of 0 indicates identical trajectories. An angle of 90 degrees indicates that the vectors are independent of each other and the shape variation is uncorrelated. Therefore, the smaller the angle, the more comparable the shape changes. A significant difference between angles indicates a difference in covariance patterns. Angle calculation and permutation tests were performed in MorphoJ v1.06 (Klingenberg, 2011).

To quantify the magnitude of integration, three statistical measures were utilized including the correlation coefficient for each pair of singular axes from the 2B-PLS analyses, the RV coefficient and the covariance ratio. The correlation coefficient (r-pls) between the scores for each pair of singular 2B-PLS axes can be seen as a measure of integration for the sample along each corresponding pair of axes. A higher correlation indicates increased integration between any two modules such as the teeth and face, for a particular pair of PLS axes (Rohlf & Corti, 2000). The RV coefficient determines the overall strength of association between the blocks of variables (Klingenberg, 2009). The RV coefficient is analogous to a multivariate squared correlation coefficient (R) and indicates the association between two vectors (v) (Escoufier, 1973). It is the sum of the squared covariance between the two sets of variables divided by the total amount of variation. It ranges from zero to one. A score of zero indicates complete independence between blocks, and one indicates perfect covariance between the blocks (Klingenberg, 2009). Therefore, larger RV coefficients indicate integration between two modules, whereas lower numbers indicate more modularity. The RV coefficient, and the correlation between the PLS scores for each specimen along each pair of singular axes, were assessed for statistical significance using permutation tests (n= 10,000) with a null hypothesis of independence between the two blocks.

Several studies have found that the RV coefficient is unreliable and sensitive to changes in sample size and landmark numbers (Adams, 2016; Fruciano, Franchini, & Meyer, 2013; Smilde, Kiers, Bijlsma, Rubingh, & van Erk, 2009). For instance, large sample sizes lower the RV coefficient and a higher number of variables increases the RV coefficient (Adams, 2016). However, the RV coefficient was included in this study because it is a measure of overall integration and it has been utilized extensively in integration studies (e.g. Gomez-Robles & Polly, 2012; Jojic, Blagojevic, & Vujosevic, 2012; Labonne, Navarro, Laffont, Chateau-Smith, & Montuire, 2014; Miller et al., 2016). In this study, the analyses were first run with the full number of landmarks and all available specimens, but were then re-run to address the known issues with the RV coefficient. Specifically, each module was limited to eight landmarks in each module, therefore only 16 landmarks were analyzed at a time. The number of landmarks in each block was kept small to not exceed the degrees of freedom and the same number of landmarks (8) was utilized in each block or module to avoid one block overweighting the analysis (Mitteroecker et al., 2012). In order to ascertain the impact of choosing different subsets of 8 landmarks from a given block, a number of nonrandom subsets of landmarks was generated that were distributed evenly across a given module (e.g., the lower face) (Table 2.4). The landmarks utilized in the limited landmark subsets were chosen to describe biologically relevant shape changes such as the maxilla, landmarks around the eye, crown height or palate shape. The results of the limited landmark analyses are reported as the average RV values for those analyses, the range of RV coefficients and the range of correlations of PLS1. Utilizing the same number of landmarks and a similar sample size in humans and chimps facilitates the comparison of integration values across species.

Multiple subsets of landmarks were chosen to capture the morphology of the regions of the face, teeth and occipital to compare relative magnitudes of covariation, but a random selection of lower face and teeth landmarks may produce similar magnitudes of integration to the morphologically relevant subsets of landmarks. To further test the RV coefficient and if the chosen nonrandom selection of landmarks produces a greater magnitude of integration than randomly selected landmarks, ten RV analyses of randomly selected landmarks were also computed for chimpanzees and for humans separately. Each landmark was assigned a number and then eight lower face and eight dental landmarks were randomly drawn ten times without replacement in R (R Core Team, 2016). Ten different random landmark combinations were generated for chimpanzees and humans. It was expected that the analyses that included subsets of landmarks that captured the overall morphology of the lower face and teeth would have higher RV coefficients than the randomly selected landmarks. Just as the previously mentioned 2B-PLS analyses, analyses were performed on humans and on chimpanzees separately utilizing the pooled within-sex analyses.

2.4 Nonrandom subsets of eight landmarks by cranial region for the limited landmark analyses

Lower face	Teeth	Upper face	Occipital
ns, pr, ecmLR, ol, mtLR, pm	LR M1 and M2 inf, sup	Eye LR: osup, d, ec, zo,	spba, ba, op, jfLR, l, asLR
ns, pr, ecmLR, ol, mtLR, sta	LR M1, M2 inf, root	nose: n, rhi, inLR, alLR ifLR	spba, ba, op, fmlLR, l, asLR
ns, pr, P3P4LR, mtLR, ol, sta	LM2, LM1 inf, d, m, l	g, n, fmtLR, zoLR, zmLR	ba, op, jflLR, l, in, asLR
	RM2, RM1 inf, d, m, l	n, rhi osup, dL, ecL, zoL, zmL, alL	
	LM2, LM1 inf, d, m, l	LR fmt, zo, zm, ju	
	LR M1, M2 inf, sup		
	LR M1, C inf, sup		
	LR M1, C inf, sup		
	LR M1, C inf, root		
	L M1 C inf, d, m, l		
	LR I1, I2 inf, sup		
	LR I1, I2 inf, sup		
	LR I1, I2 inf, root		
	LR I1, I2 inf, root		
	LI1, LI2 inf, d, m, l		
	RI1, RI2 inf, d, m, l		
	LI1, LI2 inf, d, m, l		
	LR M2, P4 inf, sup		
	LR M2, P4 inf, sup		
	LR M2, P4 inf, root		
	LM2, LP4 inf, d, m, l		
	LR I1, C inf, sup		
	LR I1, C inf, root		
	LI1, LC inf, d, m, l		
	LR M2, I1 inf, sup		
	LM2, LI1 inf, d, m, l		

See Tables 2.2 and 2.3 for landmark abbreviations

Finally, the covariance ratio (CR), a measure of pairwise covariances between variables, was utilized to quantify the magnitude of integration or modularity (Adams, 2016). The CR coefficient is a ratio of the overall covariation between predetermined modules compared to the overall covariation present within the modules. The null hypothesis of the method assumes that the landmarks are randomly associated. A CR value between 0 and 1 characterizes a more modular structure where the degree of covariation between modules is less than the covariation within the modules. A CR value greater than one reflects more covariation between modules than within the two modules, or more integration. Permutation tests assessed the significance of the CR coefficient where the CR coefficient of the two predetermined modules was compared to a CR distribution that contained randomly assigned landmarks by module. If the observed CR is less than the distribution, than there is more modularity in the dataset than predicted by chance. Confidence intervals were generated from 1000 iterations of the distribution. Calculation of the covariance ratio was performed with the human and chimpanzee samples individually and the female and male chimpanzee samples separately to detect any sex differences. Analyses were performed in the "geomorph" package version 3.0.2 (Adams & Otarola-Castillo, 2013) in R 3.3.1 (R Core Team, 2016).

Results

Patterns of integration between the lower face and teeth

Adult chimpanzees and humans have a similar pattern of covariation between the lower face and teeth. PLS analyses of chimpanzees, humans, and a combined analysis of humans and chimpanzees utilizing all lower face and teeth landmarks illustrate that the pattern of covariation is conserved in both species (Figures 2.2-2.4). For all of the PLS analyses, the first pair of PLS axes (PLS 1) explains most of the covariation and will be reported and described. Along the PLS1 in all three analyses, individuals with relatively broader midfaces, shorter palatal lengths and flatter (less prognathic) faces had more retracted, smaller and, shorter anterior teeth (Figures 2.2-2.4). Specimens with relatively more prognathic lower faces and taller, narrower and longer palates with more protruding teeth.

To statistically assess if the pattern of integration was similar between the separate human and chimpanzee analyses, the angle between the PLS1 shape vectors was calculated as 44.22º ($p < 0.0001$). While the overall pattern of covariation between the lower face and dentition in chimpanzees and humans is similar, the larger angle indicates that humans exhibit greater changes in relative palate breadth on PLS1. This differences in palatal shape produces the difference between the two shape vectors.

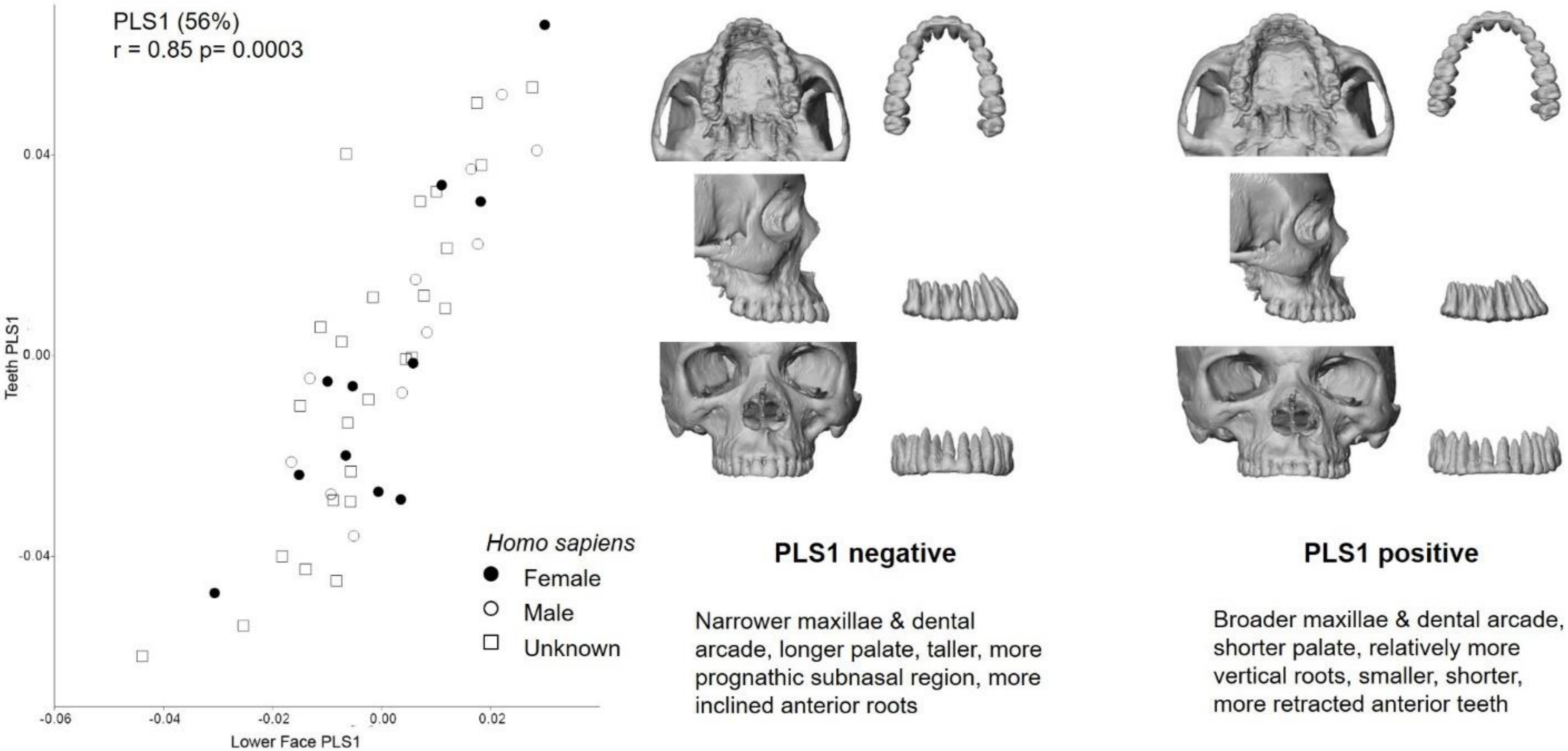

Figure 2.2 Bivariate scatter plot of human 2B-PLS scores and 3D visualizations of the lower face and dental shape changes along PLS1

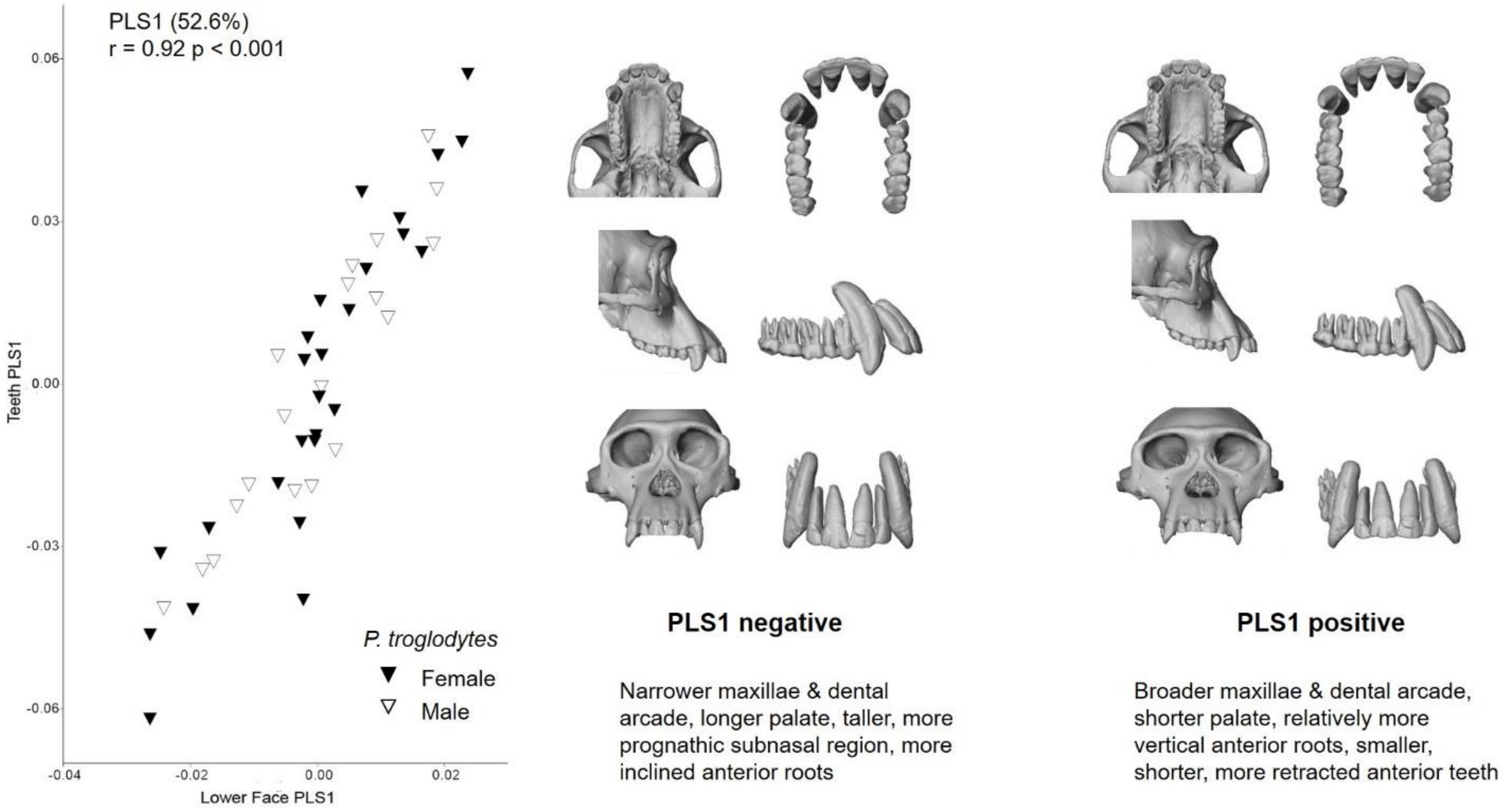

Figure 2.3 Bivariate scatter plot of chimpanzee 2B-PLS pooled within sex analysis and the 3D visualizations of lower face and dental shape changes along PLS1

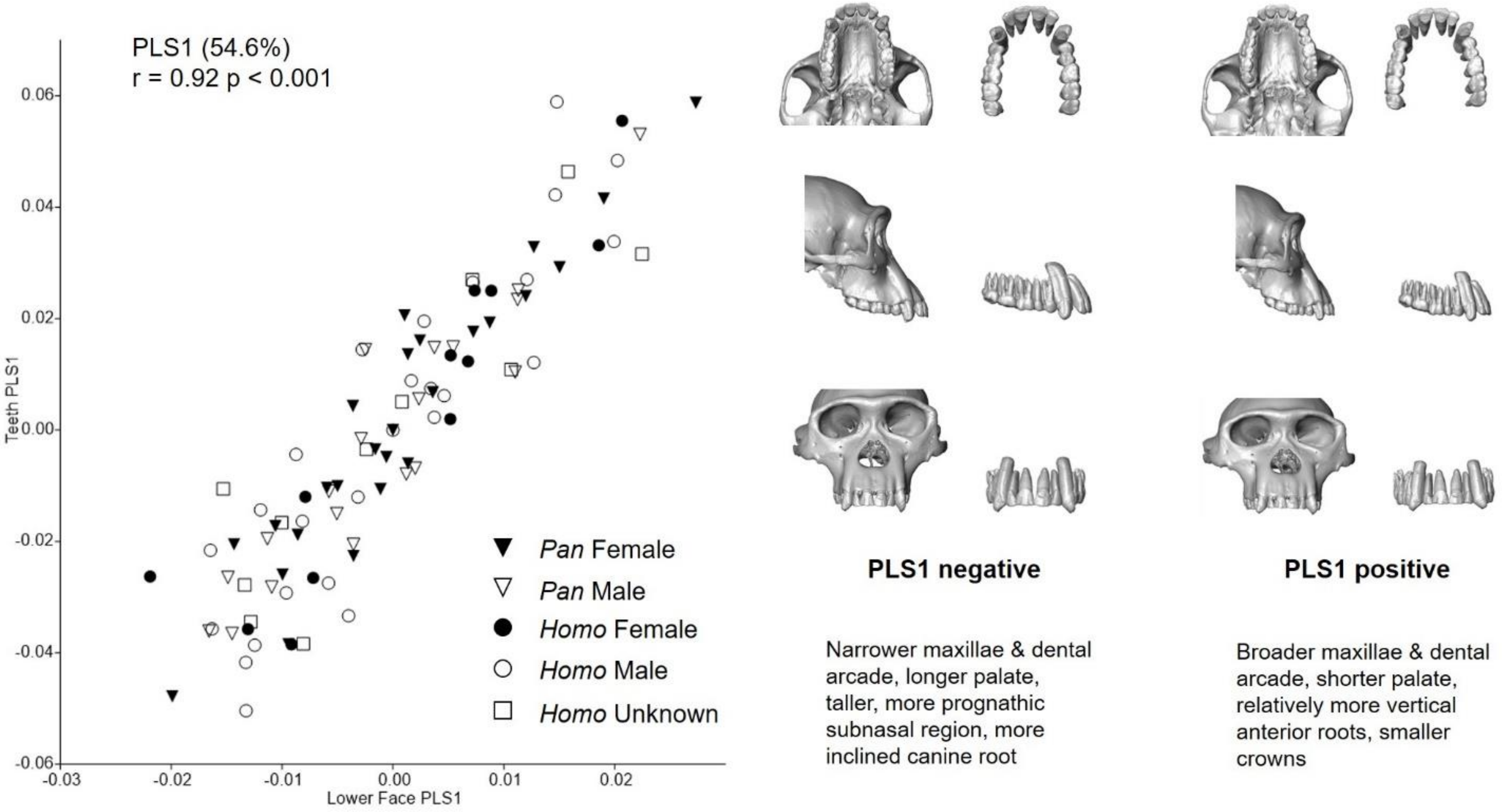

Figure 2.4 Bivariate scatter plot of human and chimpanzee 2B-PLS pooled within species scores and 3D visualizations of shape changes along PLS1

Magnitude of integration of all landmarks

When all landmarks in each module were analyzed in humans and chimpanzees, the RV coefficients and PLS1 correlation coefficients (r-pls) reflect similar magnitudes of covariation, such that the lower face and teeth analyses and analyses comparing the right and left halves of the dentition have relatively higher magnitudes of integration than the other pairwise module comparisons (e.g., between upper face or lower face and occipital bone) (Table 2.5). Human and chimpanzee adults displayed similar RV coefficients and r-pls magnitudes in each of the paired modules. For instance, between the lower face and occipital similarly low magnitudes of integration were observed while the two halves of the dentition indicated relatively and absolutely large magnitudes of integration in humans and chimpanzees. However, as discussed above, comparing the RV coefficient across analyses utilizing different sample sizes and landmarks numbers is problematic. Although the human and chimpanzee samples sizes were equivalent, analyses with a greater number of landmarks produced larger RV values than analyses with less landmarks. The occipital-teeth analyses were predicted to have a lower magnitude of integration, but humans had a relatively high RV (0.57) and r-pls (0.93), which was equivalent to the human upper face-teeth analyses.

Magnitude of integration of landmark subsets

Unlike the analyses with all landmarks in each module, the limited landmark analyses do allow comparisons within and across species because the analyses utilized a similar number of individuals and sixteen landmarks, eight per module, that were evenly distributed across the morphological regions. In the limited landmark analyses, the lower face and teeth have the highest relative average RV values (chimpanzees, 0.5, humans 0.49,) compared to the other paired analyses (Tables 2.6, A1, A2). In absolute terms, the RV coefficients are highest in the a priori lower face-teeth analyses and the random lower face-teeth analyses as predicted. The average RV coefficients and the r-pls ranges decrease in magnitude from the lower face-teeth, to the upper face-lower face, upper face-teeth, lower face-occipital, upper face-occipital, and occipital-teeth. Humans and chimpanzees have similar average RV values (Table 2.6) and similar RV and r-pls coefficients for paired analyses among the various subsets (Tables A1-A14). Humans have higher average RV coefficients among the upper face-teeth and occipital-teeth analyses, but for many of these analyses, the RV coefficients or r-pls coefficients were not significant ($p > 0.05$) (Tables A8 and A14). The lower face-occipital, upper face-occipital and occipital-teeth subset analyses had the lowest average magnitudes of integration among the paired analyses as predicted (Table 2.6). In addition, the r-pls for many of these analyses were not significant (Table A9- A14). The various landmark analyses within modules had similar RV and r-pls coefficients, with the largest ranges occurring in analyses that included the teeth. In the lower face and teeth subsets, lower face and crown landmarks or crown height generally had higher magnitudes of integration than landmarks analyzing lower face and tooth height (Tables A1 and A2).

Covariance ratio

The left and right halves of the dentition and the lower face and teeth have absolutely higher CR values and are relatively more integrated than the other paired cranial modules (Table 2.7). The other cranial modules such as the lower face-occipital and occipital-teeth have lower CR values, and relatively more modularity than the lower face and teeth. Chimpanzees also have relatively higher CR values for the lower face and teeth, upper face and lower face, and within the two halves of the dentition than humans. Chimpanzee analyses were divided into smaller groups by sex to test if sexual dimorphism altered the CR. Most of the combined *Pan* analyses, except for the dentition, displayed slightly lower CR values than the sex specific analyses. For the *Pan* and *Pan* M lower face-teeth and *Pan*, *Pan* F and *Pan* M Teeth L-Teeth R analyses, the null hypothesis that the landmarks were randomly associated was not rejected ($p>0.05$) indicating more integration than modularity in those paired analyses, and no complete integration.

Table 2.5 Two-block partial least squares analyses (2B-PLS) results and RV coefficients for paired analyses utilizing all landmarks in each module.

Module 1	Module 2	Total number of landmarks	Species	RV	RV p-value	Singular value (SV)	SV p-value	Covariance explained (%)	r-PLS1	r-PLS1 p-value
Lower Face	Teeth	115	*Pan*	0.60	**<0.0001**	0.000357	**<0.001**	52.65	0.92	**<0.001**
			Homo	0.53	**<0.0001**	0.000419	**<0.001**	56.02	0.85	**0.0003**
Upper Face	Lower Face	46	*Pan*	0.49	**<0.0001**	0.000385	**<0.001**	50.07	0.86	**<0.001**
			Homo	0.55	**<0.0001**	0.000334	**<0.001**	51.12	0.92	**<0.001**
Upper Face	Teeth	123	*Pan*	0.56	**<0.0001**	0.000302	**<0.001**	38.53	0.93	**<0.001**
			Homo	0.46	**0.0004**	0.000313	**0.0004**	45.59	0.84	**0.0281**
Lower Face	Occipital		*Pan*	0.36	**0.0001**	0.000189	**0.0001**	56.85	0.75	**0.0011**
		30	*Homo*	0.36	**0.0024**	0.000164	**0.0109**	33.70	0.75	0.083
Upper Face	Occipital	38	*Pan*	0.40	**<0.001**	0.000271	**<0.001**	61.18	0.86	**0.029**
			Homo	0.35	**0.002**	0.000143	**0.015**	30.46	0.75	0.1308
Occipital	Teeth	107	*Pan*	0.57	**<0.001**	0.000263	**<0.001**	57.66	0.93	**<0.001**
			Homo	0.44	**<0.0001**	0.000277	**<0.001**	52.47	0.88	**0.0006**
Teeth Left	Teeth Right	96	*Pan*	0.88	**<0.001**	0.000516	**<0.001**	57.18	0.97	**<0.001**
			Homo	0.87	**<0.001**	0.000649	**<0.001**	74.53	0.97	**<0.001**

Values in bold are statistically significant at $p \leq 0.05$.

Table 2.6 Summary of PLS analyses of landmark subsets

Module 1	Module 2	Species	RV range	RV average	PLS1 r range	Covariance explained (%)
Lower Face Random	Teeth Random	*Pan*	0.47 - 0.64	0.54	0.82 - 0.90	38.2 - 65.9
		Homo	0.37 - 0.57	0.5	0.75 - 0.91	34.9 - 67.12
Lower Face	Teeth	*Pan*	0.36 - 0.7	0.5	0.74 - 0.93	37.4 - 78.5
		Homo	0.33 - 0.63	0.49	0.79 - 0.93	29.4 - 59.4
Upper Face	Lower Face	*Pan*	0.31 – 0.54	0.41	0.76 - 0.87	36.8 - 50.0
		Homo	0.33 - 0.47	0.41	0.71 - 0.92	33.1 - 57.8
Upper Face	Teeth	*Pan*	0.22 - 0.62	0.36	0.59 - 0.97	38.4 - 83.2
		Homo	0.34 - 0.70	0.51	0.60 - 0.98	47.6 - 84.7
Lower Face	Occipital	*Pan*	0.30 - 0.37	0.32	0.71 - .77	56.5 - 61.2
		Homo	0.35 - 0.44	0.4	0.76 - 0.84	32.3 - 39.1
Upper Face	Occipital	*Pan*	0.27 - 0.42	0.35	0.68 - 0.79	47.0 - 54.0
		Homo	0.30 - 0.34	0.32	0.60 - 0.77	29.6 - 40.1
Occipital	Teeth	*Pan*	0.17 - 0.47	0.3	0.54 - 0.88	35.8 - 72.8
		Homo	0.32 - 0.63	0.46	0.75 - 0.97	39.9 - 56.5

Values in bold are statistically significant at $p \leq 0.05$.

Table 2.7 Covariance ratio of cranial modules

Module 1	Module 2	Species	CR	CR Interval	p-value
Lower Face	**Teeth**	*Homo*	0.90	0.877 - 0.969	**0.001**
		Pan	0.96	0.938 - 0.990	0.048
		Pan F	0.95	0.930 - 0.995	**0.017**
		Pan M	0.99	0.958 - 1.019	0.113
Upper Face	**Lower Face**	*Homo*	0.73	0.708 - 0.869	**0.001**
		Pan	0.83	0.814 - 0.921	**0.002**
		Pan F	0.85	0.824 - 0.954	**0.001**
		Pan M	0.92	0.894 - 1.000	**0.010**
Upper Face	**Teeth**	*Homo*	0.73	0.706 - 0.853	**0.001**
		Pan	0.74	0.736 - 0.863	**0.001**
		Pan F	0.81	0.792 - 0.919	**0.001**
		Pan M	0.81	0.810 - 0.952	**0.001**
Lower Face	**Occipital**	*Homo*	0.73	0.729 - 0.890	**0.001**
		Pan	0.66	0.658 - 0.826	**0.001**
		Pan F	0.72	0.698 - 0.915	**0.001**
		Pan M	0.78	0.766 - 0.953	**0.003**
Upper Face	**Occipital**	*Homo*	0.77	0.740 - 0.893	**0.001**
		Pan	0.70	0.694 - 0.831	**0.001**
		Pan F	0.76	0.743 - 0.919	**0.001**
		Pan M	0.77	0.779 - 0.931	**0.001**
Occipital	**Teeth**	*Homo*	0.75	0.729 - 0.875	**0.001**
		Pan	0.60	0.598 - 0.771	**0.001**
		Pan F	0.64	0.629 - 0.846	**0.001**
		Pan M	0.73	0.717 - 0.924	**0.001**
Teeth L	**Teeth R**	*Homo*	0.91	0.900 - 0.953	**0.001**
		Pan	1.00	0.980 - 1.014	0.223
		Pan F	0.99	0.974 - 1.010	0.049
		Pan M	0.99	0.966 - 1.023	0.226

Values in bold are statistically significant at $p \leq 0.05$.

Discussion

The principal goals of this study were to 1) assess congruence in the pattern of covariation between the lower face and dentition of humans and chimpanzees and 2) test the hypothesis that the face, particularly the lower face, and dentition are highly integrated as hypothesized due to shared function, development and spatial association. In order to achieve the first goal, similarity between the first pair of axes calculated from a 2B-PLS was quantified and visually assessed. To achieve the latter, the magnitude of integration between the face and dentition was compared to a range of values found among different regions of the cranium. This study indicated significant covariation between the lower face and the dentition. Specifically, there was an association between broader, more orthognathic midfaces, with wider palates and smaller, shorter and more retracted anterior teeth. Chimpanzees and humans displayed similar patterns of lower face and dental covariation. As quantified by the RV coefficient, the PLS1 correlation coefficients, and the CR values, the lower face and teeth are relatively more integrated than the other paired modules. Yet, the CR values also indicate modular structure present within the cranium because no value was over one. This implies that in many of the analyzed modules of the cranium, covariation is slightly higher within the modules than between the two modules.

The pattern of covariation between the lower face and teeth is similar in humans and chimpanzees representing the conservation of patterns of cranial integration throughout human evolution (Ackermann & Cheverud, 2000, 2004b; Cheverud, 1996; Marroig & Cheverud, 2001; Marroig et al., 2004; Neaux, 2017; Singh et al., 2012; Villmoare et al., 2014). Individuals with taller, narrower and more prognathic faces have more protruding and longer rooted anterior teeth. This appears to confirm earlier research indicating that variation in tooth root length is related to relative facial protrusion (Riesenfeld, 1977; Riesenfeld & Siegel, 1970), and facial height (Cobb & Baverstock, 2009). The pattern of integration between humans and chimpanzees is similar, but not identical along the first pair of PLS axes. The angle (44.22º) between the human and chimpanzee PLS1 shape vectors reflects the shape differences along PLS1 where humans have relatively wider palates and chimpanzees have a more sloped subnasal clivus. This angle represents a moderate association between the two shape vectors and is similar to other comparisons of integration among humans or between humans and chimpanzees (Gomez-Robles & Polly, 2012; Neaux, Guy, Gilissen, Coudyzer, & Ducrocq, 2013).

Several statistical measures were utilized to estimate the magnitude of integration in this study including the correlation coefficient (r-pls) for each pair of singular axes from the 2B-PLS analyses (Rohlf & Corti, 2000)), the RV coefficient (Klingenberg, 2009), and the covariance ratio (Adams, 2016). The subset analyses allowed for comparison of magnitudes of integration across species and modules, while patterns of covariation were performed utilizing all landmarks in each module. There were similarities and differences between the all-landmark and subset analyses. In the all-landmark and subset analyses, the lower face-teeth and upper face-lower face analyses were relatively more integrated than the other cranial modules and humans and chimpanzees had similar magnitudes of integration. In addition, the RV coefficient and the r-pls coefficients computed with all of the landmarks were within the range of the limited landmark subset analyses, but the average RV and r-pls coefficients were lower in magnitude in the subset analyses. In analyses where decreased integration was expected, such as the lower face and occipital, the RV and r-pls declined in the landmark subset analyses sample compared to the all-landmark analyses. Lower r-pls coefficients indicate a more moderate level of integration between the lower face and occipital than the higher correlation coefficients (> 0.9 r-pls) in the all landmark analyses. When all landmarks were utilized in the various paired cranial analyses, RV and r-pls correlation coefficients were larger in analyses with more landmarks (Table 2.5) and could lead to the overestimation of the strength of integration between two modules.

Interestingly, the analyses of the random lower face and dental landmarks produced a slightly higher average RV coefficient than the selected limited landmarks, but the RV average was within the range of the limited landmark sets. This higher average RV may be due to chance or indicate a conservation of the lower face and dental modules and suggest that landmarks can be substituted for others resulting in the same general patterns and magnitudes of integration. Alternatively, this may highlight the effect of spatial proximity and correlation between landmarks that is difficult to avoid in morphometric analyses (Adams, 2016; Goswami, 2006a; Mitteroecker et al., 2012). A single GPA was utilized in this study to preserve the relative size, position, scale and covariance between the face and dentition and to examine to covariation of the face and teeth in the context of the face as a whole. The influence of spatial proximity could be mediated in the future by utilizing separate GPA's of the individual modules, which does not preserve the size, position or scale of the two modules relative to each other, or by clustering landmarks based on interlandmark distances (Adams, Rohlf, & Slice, 2013).

The CR coefficients for the lower face and teeth in both humans and chimpanzees were larger than the other paired cranial modules and closer to one, indicating relatively more integration. The two halves of the dentition were analyzed as a baseline for within module covariation, and the results of the lower face and teeth are similar to the value for the left and right dentition, suggesting that the lower face-teeth are relatively as integrated as the two halves of the dentition and may represent a single module. Yet, the CR coefficients for all of the cranial modules in human and chimpanzees were less than one implying that some modularity is present among the cranial modules. This indicates while there is integration between two parts, there is still a modular structure and more covariation within modules than between modules. This also illustrates that integration and modularity exists along a continuum and the distinction between the two is not discrete. Adams (2016) suggests utilizing the CR coefficient and the correlation coefficient from the 2B-PLS to assess integration and modularity within a dataset. Following his guidelines, the CR coefficient, the limited RV coefficients and the r-pls of the lower face and teeth indicate a high magnitude of integration between the two modules.

Only a few two dimensional (2D) and three dimensional (3D) studies have been performed assessing the integration among the developing dentition and the human mandible (Coquerelle et al., 2010; Coquerelle et al., 2013), among regions of the human crania and molars (Polychronis & Halazonetis, 2014; Terhune, Cooke, & Otarola-Castillo, 2015) or the chimpanzee crania and tooth roots (Cobb & Baverstock, 2009). In adult platyrrhines, there is a significant relationship between the upper and lower molars and the cranium and glenoid fossa (Terhune et al., 2015), while Polychronis and Halazonetis (2014) found a small covariation between cranial and mandibular cephalometric landmarks and 3D lower first molar shape, but no covariation with the upper first molar in humans. Polychronis and Halazonetis (2014) analyzed the cranium and mandible of modern humans as part of a craniofacial complex, which most likely reduced the covariation between the dentition and face. In the limited subset analyses in the current study, the upper molar crowns had similar magnitudes of covariation with the lower face as the incisor crowns and the lower face and the dentition had the highest magnitudes of integration among the paired subset analyses (Tables A1 and A2). In the analyses of the lower face and all dental landmarks, much of the pattern of shape change is visually identifiable in the 3D cranial morphs between the lower face and anterior dentition.

As a result of integration between the lower face and dentition, directional selection of the dentition may produce coordinated palatal shape changes. Both *Homo* and *Paranthropus* have orthognathic faces and smaller anterior teeth than other hominins, but humans and *Paranthropus* differ in postcanine tooth size. McCollum (1999) proposed a relationship between the anterior and postcanine dentition and features of the *Paranthropus* midface. Villmoare et al. (2014) reported the presence of a premaxillary module within the palate of great apes and fossil hominins and increased variation within the premaxilla of hominins such as *A. africanus, P. boisei, P. robustus,* and *P. aethiopicus.* This increased variation in the premaxilla, which houses the incisors, would allow for selection and evolutionary changes due to dietary adaptations (Villmoare et al., 2014). Although the authors did not analyze the dentition, they proposed that the orthognathism of *Paranthropus* was related to selection for smaller dentition, a reduced palate and a smaller premaxilla and was not related to large postcanine dentition. Orthognathic faces in *Homo* and *Paranthropus* could be explained by modularity within the palate (Villmoare et al., 2014). In this study, I did not investigate the premaxilla as a module within the palate, but broader, flatter faces with shorter, wider palates covaried with smaller and more retracted anterior teeth. The relative molar size and shape compared to that of the incisors did not change with maxillary or palatal shape, which may suggest some modularity within the dentition. Modularity within the mammalian and primate dentition has been documented (Delezene, 2015; Gomez-Robles & Polly, 2012; Grieco et al., 2013; Hlusko et al., 2011; Laffont et al., 2009; Polychronis et al., 2013; Ribeiro et al., 2013) and the presence of a premaxilla submodule within the lower face, would be a similar unit illustrating the gradient of covariance among modules. Selection on the premaxilla or regions of the dentition such as the incisors or molars may produce flatter or more prognathis craniofacial forms, but the premaxilla and dentition are smaller modules integrated within the larger module of the lower face in humans and chimpanzees.

Conclusion

In morphological integration studies, the pattern and magnitude of integration of two modules is usually assessed in isolation and there is no relative determination of integration throughout a structure. This study analyzed the covariation between the lower face and dentition and the covariation between the upper face, lower face, dentition and occipital to assess a range of integration present within the study sample. In addition, the dentition was used to assess covariation within a module. The lower face and teeth are relatively more integrated than the other paired cranial modules and *Pan* and *Homo* display similar patterns and magnitudes of integration in the lower face and teeth. Future analyses of the developmental relationship between the face and dentition may enhance the understanding of lower face and teeth covariation.

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Chapter 3 Integration between the lower face and dentition throughout ontogeny

Introduction

The study of ontogeny is fundamental to understanding patterns of adult variation and morphological evolution. Ontogeny can be divided into growth and development, with growth defined as changes in size and development defined as changes in shape (Gould, 1977). The ontogeny of humans and chimpanzees, our closest living relatives, serve as a foundation for comparisons and reconstructions of fossil hominin ontogenies. Many of the trends seen in the evolution of the hominin skull, such as the enlargement of the neurocranium and retraction of the face, are similar over both ontogenetic and phylogenetic time (Bookstein et al., 2003). For instance, modern and fossil *Homo* have similar patterns of covariation between the median plane of the cranial vault, face and basicranium in analyses of ontogenetic and evolutionary integration (Bookstein et al., 2003). However**,** humans and great apes have different ontogenetic patterns and life histories where modern humans exhibit increased brain growth and delayed dental, skeletal and sexual maturation compared to great apes (Bogin, 1999; Leigh, 1996, 2001; Robson & Wood, 2008).

There have been numerous studies of the cranial growth and ontogeny of humans, great apes and fossil hominins that describe the trajectory of postnatal cranial shape change (Arnold, Zoellner, & Sebastian, 2004; Bastir, O'Higgins, & Rosas, 2007; Bastir & Rosas, 2004a, 2004b; Cobb & O'Higgins, 2007; Humphrey, 1998; Lieberman, 1999; O'Higgins, Bastir, & Kupczik, 2006; Penin, Berge, & Baylac, 2002; Sardi & Rozzi, 2007). The cranial bones grow and develop at a rate consistent with the growth and maturation of the tissues, muscles and brain they surround (Moss & Young, 1960). Therefore, ontogenetic changes in the brain and dentition are reflected in the cranial vault and face, respectively. Humans and chimpanzees have different cranial ontogenetic trajectories. The growth rate of the chimpanzee brain and thus its neurocranium slows after birth, whereas the human cranial vault is characterized by rapid growth from birth to the eruption of the first molar (Bogin, 1999; Penin et al., 2002). In humans, the cranial vault and basicranium mature faster than the face and post-cranial skeleton (Bastir, Rosas, & O'Higgins, 2006; Humphrey, 1998). Skull measurements of the human frontal bone, occipital bone, and mandible reach approximately 90% of adult size by the eruption of the second molar followed by the growth of the face (Humphrey, 1998). Following the differences in cranial growth, analyses of craniofacial ontogenetic trajectories also suggest that population and species specific shape differences are apparent prenatally or early postnatally that lead to additional differences later in ontogeny (McNulty et al., 2006; Mitteroecker, Gunz, Bernhard, Schaefer, & Bookstein, 2004; Vioarsdóttir & Cobb, 2004; Zumpano & Richtsmeier, 2003).

Differences in dental maturation also exist between human and chimpanzees. Humans and great apes have different patterns, timing, and rates of dental mineralization and eruption (Conroy & Mahoney, 1991; Kuykendall, 1996). Modern human dental eruption is delayed compared to chimpanzees, and humans have a distinctive dental eruption sequence compared to other great apes. In humans, the permanent first molar and first incisor erupt at approximately the same time, followed by the second incisors, canines, premolars, second molar, and third molars (Conroy & Vannier, 1987; Mann, Lampl, & Monge, 1990). In chimpanzees, *generally* the first permanent molars erupt, followed by the incisors, premolars, second molars, canines and third molars with variation in the premolar eruption sequence (Smith, Crummett, & Brandt, 1994).

Although the human and chimpanzee crania and dentition have different ontogenetic growth rates and patterns of dental development, the teeth and lower face are spatially related, share similar masticatory functions and have embryonic origins (Boughner & Hallgrimsson, 2008; Hlusko, 2004). It is likely that the face and teeth are associated during growth and throughout evolution. Morphological integration is the coordinated expression of morphological elements that comprise a phenotypic whole such that a change in one trait produces a change in another (Klingenberg, 2013; Olson & Miller, 1958; Smith, 1996). When two or more traits are integrated, they have a coordinated pattern of morphological change (Goswami & Polly, 2010) and a measureable degree of covariation (Cheverud, 1982).

Studies regarding the genetic basis of craniodental anatomy, craniofacial disorders, and morphological integration of the teeth and facial bones offer conflicting views on how the dentition and facial skeleton relate to one another over ontogeny. The teeth and jaws may be developmentally independent because the timing and morphogenesis of each is controlled by many complex factors (Boughner & Hallgrimsson, 2008) and evolutionarily, the dentition and jaw of vertebrates may have evolved independently (McCollum & Sharpe, 2001b). Experimental analyses of mice indicate that the mandible develops normally in the absence of teeth (Paradis et al., 2013). In addition, there are knockout genes that affect mandibular development but not dental development and genes that are required for dental development but have little effect on the mandible. For example, mice without the Ptx1 gene have shortened mandibles but do not display abnormal tooth development (Lanctot et al., 1997; Lanctot et al., 1999) while mice that are LEF-1 deficient display teeth arrested at the bud stage, with only defects to the alveolar ridge and coronoid process of the mandible (van Genderen et al., 1994). Together, these studies suggest there may be genetic independence between tooth and jaw development. Yet, many individuals present with both craniofacial disorders and dental abnormalities, and many descriptions of craniofacial growth describe the teeth pushing the jaw forward as the tooth buds develop (Dixon et al., 1997). Moreover, patients with congenitally missing teeth have shorter upper and lower anterior facial heights (Lisson & Scholtes, 2005), retrognathic or retrusive maxillae, and large inter-incisal angles (Créton et al., 2010) compared to individuals with normal dentition.

The cranium and dentition have been primarily analyzed separately in morphological integration or modularity studies. Covariation analyses of the primate dentition suggest modularity between the anterior and postcanine dentition in adult specimens (Delezene, 2015; Grieco et al., 2013; Hlusko et al., 2011; Ribeiro et al., 2013). In contrast, many craniofacial studies have identified ontogenetic integration in the oral, orbital, nasal and zygomatic regions of the face (Ackermann, 2005), between the face and mandible (Wellens et al., 2013), and the orbit and neurocranium (Barbeito-Andrés et al., 2016). Few studies have analyzed the relationship between the dentition and jaw during ontogeny. Clinical orthodontic and dental studies have investigated cranial growth through descriptive and 2D radiographic analyses (Björk & Skieller, 1974; Brodie, 1941; Donald & Seong, 1965), but usually focus on malocclusion, disease and craniofacial disorders (e.g. Alarcon et al., 2014; Bishara, 2000; Delaire, 1997). Recent qualitative and quantitative studies indicate there is a positive relationship between the developing dentition and mandibular symphyseal shape and inclination in humans (Coquerelle et al., 2013; Fukase & Suwa, 2008; Fukase & Suwa, 2010; Krarup et al., 2005). Polychronis and Halazonetis (2014) describe a weak covariaton between the mandibular first molar distal crown cusps with mandibular protrusion, maxillary retrusion and roation of the cranial base in prepupertal and adult humans. Additionally, some researchers have found that there is a lower degree of integration between the dentition and mandible in adult humans, nonhuman primates and mice compared to juvenile samples (Boughner & Hallgrimsson, 2008; Coquerelle et al., 2010; Plavcan & Daegling, 2006) suggesting the teeth and lower jaws may be more strongly integrated during early ontogeny with the degree of integration declining postnatally.

The present study examines the covariation between the face and dentition in chimpanzees and humans throughout ontogeny. This study has three hypotheses:

1) Ontogenetic changes in the form of the face are related to the relative size and shape of the developing and erupting deciduous and permanent dentition. Specifically, a taller subnasal region and more prognathic anterior maxilla will co-occur with increase in the angulation of the permanent anterior teeth and wider palate (McCollum, 1999). Here the shape will reflect the shape of the teeth and the 3D spatial arrangement of the teeth and the movement of the teeth throughout ontogeny relative to the face.
2) The strength of integration between the dentition and maxilla changes throughout ontogeny within each taxon. It is predicted that the magnitude of integration will decline with the complete eruption of the deciduous dentition based on previous empirical work (Boughner & Hallgrimsson, 2008; Coquerelle et al., 2010; Plavcan & Daegling, 2006; Zelditch & Carmichael, 1989)
3) Third, the pattern and magnitude of developmental integration between the face and dentition throughout ontogeny will be the same in humans and chimpanzees. This hypothesis is the null hypothesis of no difference based on adult and ontogenetic studies of cranial integration that report no differences between pattern of integration in humans and chimpanzees (Ackermann, 2005; Singh et al., 2012) and similar magnitudes of integration, possibly due to shared evolutionary history.

Materials and Methods

Sample

To analyze and visualize the dentition and the cranium in three dimensions (3D), computed tomography (CT) scans of 234 immature and adult humans and chimpanzees of mixed sex were utilized (Table 3.1). These taxa were chosen to create an extant phylogenetic bracket for hominins to assess shared patterns of development, compare the results of this study to existing hominin evolution and integration research and, ultimately, interpret patterns of morphological integration in extinct hominins. Human and chimpanzee specimens and CT scans were acquired from a variety of museums and repositories (Tale 3.2). Due to the limited availability of complete crania with mostly complete dentition, different subspecies of *Pan troglodytes* were combined in the analyses. Specimens in the sample included members of *P. t. troglodytes, P. t. verus,* and *P. t. schweinfurthii.* Sex was generally unknown for all of the immature specimens and is difficult to accurately estimate prior to puberty. Sex for some of the adult human and juvenile specimens was collected from museum or researcher records, otherwise sex was classified as unknown.

Table 3.1 Dental stage description and sample size.

Dental Stage	Dental stage description	Human	Chimpanzee
DS2	any deciduous teeth erupted	28	26
DS3	permanent first molar (M1) eruption	30	32
DS4	permanent second molar (M2) eruption	28	28
DS5	permanent third molar (M3) eruption	30	30

To determine what specific facial shape changes occur around particular dental developmental events, specimens were divided into dental stages (e.g., Laitman, Heimbuch, & Crelin, 1978). Dental stages (DS) were used because the exact ages of most museum specimens are unknown and the hypotheses are tied to events in molar development rather than chronological age. While humans and chimpanzees have a different timing and sequence of many of their teeth, the molars erupt in a similar sequence from M1 to M3 (Smith et al., 1994). The four DS are similar to previous studies and will encompass the most specimens for robust sample sizes (Table 3.1). The broad dental stages were chosen due to the preservation bias of most museum specimens and to maximize the number of individuals in each stage. Approximately 30 specimens were included in each dental stage for each species. A power analysis for the correlation analyses was performed as per Cohen (1992) based on a large effect size (or one that is visible to the naked eye; r=0.5), a conventional power value of 0.8 and p-value of 0.05. A minimum of ~30 individuals per dental stage is necessary to have a large effect size. A large effect size was specified to establish whether there is a strong integration signal that would have a discernible influence on evolution.

Scanning methods and 3D Reconstructions

I scanned specimens from the AMNH at the Stony Brook Hospital on a GE VCT Lightspeed CT scanner in the Department of Radiology and specimens from the MCZ and PMAE on an X-Trek HMST 225 microCT at Harvard University's Center for Nanoscale Systems. Specimens scanned at Stony Brook were scanned at 140 kV and 200 mA and have an isometric voxel size ranging from 0.187-0.33. The parameters of the CT scans obtained from other museums and researchers varied, but slice intervals were no more than 1 millimeter. Several recent studies (Ford & Decker, 2016; Whyms et al., 2013) recommend a slice interval of 1.25 mm or less for cranial CT scans to ensure accurate reconstruction and measurement of the dentition and crania. Avizo 8.1 visualization software was used to segment the teeth and crania from all specimens using a combination of manual and semi-automated approaches. 3D surfaces of the crania and teeth were generated using the constrained smoothing algorithmic software function.

Table 3.2 Skeletal collections, collection abbreviations and repository source of Homo and Pan CT scans

Collection	Abbrev	Species	Source
American Museum of Natural History	AMNH	*Homo, Pan*	Scanned for this study, Lynn Copes
Hull York Medical School	HYMS	*Homo, Pan*	Paul O'Higgins
Raymond A. Dart Collection of Human Skeletons, University of Witwatersrand	DART	*Homo*	Frederick E. Grine & Ian J. Wallace
Museum of Comparative Zoology, Harvard University	MCZ	*Pan*	Scanned for this study, Copes (Copes, Lucas, Thostenson, Hoekstra, & Boyer, 2016), Daniel Lieberman
National Museum of Bloemfontein	NMB	*Homo*	Frederick E. Grine
National Museum of Natural History	USNM	*Homo*	Kristofer Helgen, Matthew Tocheri, 3D Primate Collection
Peabody Museum of Archaeology and Ethnology, Harvard University	PMAE	*Pan*	Scanned for this study, Copes (Copes et al., 2016), Daniel Lieberman
Pennsylvania State University	PSU	*Homo, Pan*	Scanned for this study, collection of Joan Richstmeier
Pennsylvania State University, National Museum of Natural History	Bosma	*Homo*	Scanned for this study, in care of Joan Richstmeier and on loan to USNM (Shapiro & Richtsmeier, 1997)
Primate Research Center Digital Morphology Museum	DMM	*Pan*	http://dmm.pri.kyoto-u.ac.jp
Royal Museum of Central Africa	RMCA	*Pan*	Emmanuel Gilissen
South African Museum	SAM	*Homo*	Frederick E. Grine
Stony Brook University	SBU	*Pan*	Scanned for this study from the collection of Randall Susman
University of Cape Town	UCT	*Homo*	Frederick E. Grine
University College of London	UCL	*Homo, Pan*	Paul O'Higgins
University of Liverpool	UL	*Homo, Pan*	Paul O'Higgins

Landmarks

Three-dimensional landmarks were placed on the 3D reconstructions of the crania and dentition using Avizo 8.1 (Figure 3.1). Landmarks were chosen to quantify the shape of the lower face and dentition. Dental landmarks were located on the upper first incisors, canines and first molars, representing teeth that are common in all of the dental stages analyzed (Table 3.3), thus allowing across-stage analyses. Landmark configurations of all specimens were superimposed by generalized Procrustes analysis (GPA) to remove the effects of translation, rotation and scale (Rohlf & Slice, 1990). During GPA, centroids of each specimen are translated to the origin; each specimen's landmark configuration is then scaled to unit centroid size and rotated to minimize the squared distances among corresponding landmarks (Rohlf & Slice, 1990). The resulting data are called (Procrustes) shape variables and were analyzed using standard multivariate statistical techniques. To assess the shape changes in the same tangent space, one GPA was performed for the lower face landmarks and the permanent dental landmarks (first molars, canines and first incisors). Missing landmarks were estimated from the Procrustes coordinates using thin plate splines in the "geomorph" package version 3.0.3 (Adams & Otarola-Castillo, 2013) in R 3.3.1 (R Core Team, 2016). To estimate the missing landmark locations on an incomplete specimen, a reference specimen containing the mean shape of the complete landmark set was used from the dataset. Next, the landmarks that the incomplete specimens and the reference specimen share were used to align the two specimens. Then, the thin plate spline was used to estimate the missing landmark coordinates in the incomplete specimen (P. Gunz et al., 2009).

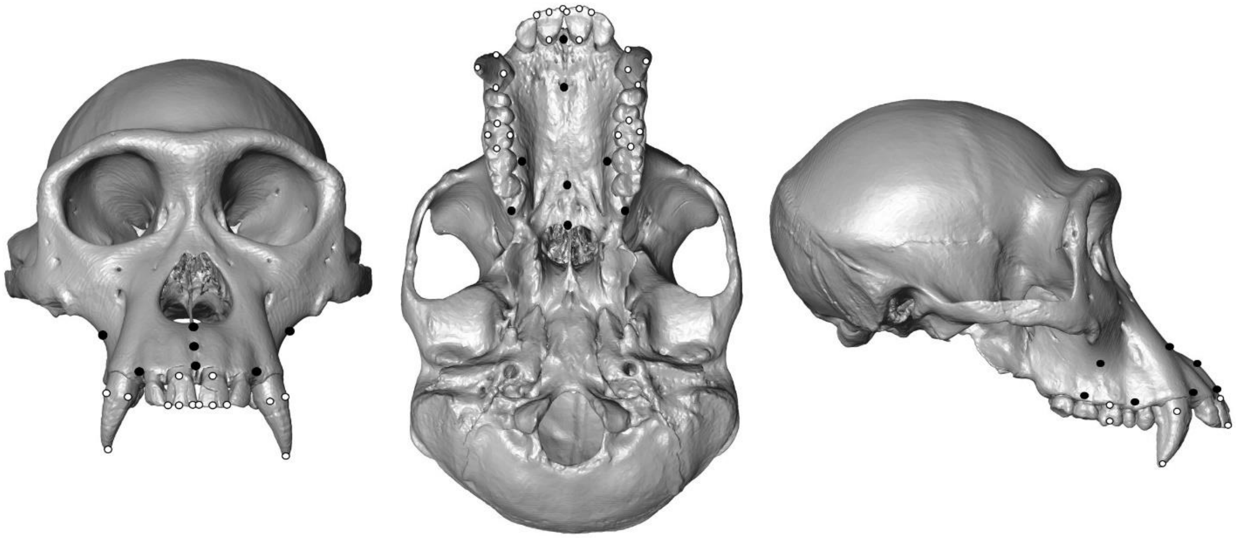

Figure 3.1. Cranial and dental landmarks. Lower face landmarks (black circle) and bilateral dental crown landmarks (white circle) of the first incisor (I1), canine (C), first molar (M1).

Table 3.3 Lower face and dental landmark definitions and abbreviations

Landmark	Abbrev	Definition
Lower face		
Nasospinale L, R	ns	Point on the anterior nasal spine which crosses a line drawn from the lowest points of the nasal aperture
Midsubnasal clivus L, R	mcli	Midline midpoint between nasospinale and prosthion
Prosthion	pr	Most anterior midline point on the maxillary alveolar process b/w the central incisors
I2-C contact L, R	I2C	Most inferior point on the maxilla between I2 and C
P3-P4 contact L, R	P3P4	Point of contact projected onto buccal alveolar surface of P3-P4
Ectomolare L, R	ecm	Most lateral point on the buccal surface of the alveolus of the second molar
Malar root origin L, R	mro	The point where malar root arises from the maxilla (often a point of concavity between molar juga and malar root)
Maxillary tuberosity L, R	mt	Most posterior point on the occlusal surface of the alveolus
Orale	ol	Midline point of intersection on the hard palate with a line tangent to the posterior margins of the central incisor alveoli
Incisivion	inc	Most posterior point on the incisive foramen
Palatomaxillary	pm	The point of intersection of the palatine and the maxillary bones at the junction of the transverse and median palatine sutures
Staphylion	sta	The point where the interpalatal suture intersects a line joining the deepest indentation of the posterior palate
Dental (bilateral)		
Incisor 1 inferior	I1inf	I1 crown most inferior labial point
Incisor 1 superior	I1sup	I1 crown most superior midline point at cervix
Incisor 1 distal	I1d	I1 crown distal most point
Incisor 1 mesial	I1m	I1 crown mesial most point
Incisor 1 lingual	I1l	I1 crown lingual most point
Canine inferior	Cinf	C crown most inferior labial point
Canine superior	Csup	C crown most superior midline point at cervix
Canine distal	Cd	C crown distal most point
Canine mesial	Cm	C crown mesial most point
Canine lingual	Cl	C crown lingual most point
Molar 1 inferior	M1inf	M1 crown most inferior buccal point
Molar 1 superior	M1sup	M1 crown most superior midline point at cervix
Molar 1 distal	M1d	M1 crown distal most point
Molar 1 mesial	M1m	M1 crown mesial most point
Molar 1 lingual	M1l	M1 crown lingual most point

Statistical Analyses

This project had three objectives: to determine if ontogenetic changes in the size and shape of the face are related to the developing and erupting permanent dentition; assess if the strength of integration between the dentition and maxilla changes throughout ontogeny within each taxon; and test if the pattern or association between traits, and magnitude of developmental integration is different between chimpanzees and humans.

To analyze how facial shape covaries with dental development at certain dental stages and across stages, two-block partial least squares (2B-PLS) analysis was used. The 2B-PLS method explores the pattern of covariation between two blocks or modules of traits and computes the strength of integration between two predetermined modules (Bastir & Rosas, 2005; Bookstein et al., 2003; Coquerelle et al., 2013; Klingenberg & Zaklan, 2000; Mitteroecker & Bookstein, 2008; Mitteroecker et al., 2012; Rohlf & Corti, 2000; Singh et al., 2012). In this study the predetermined modules are the dentition and lower face (Figure 3.1, Table 3.3). Using the cross-covariance matrix, the 2B-PLS analysis finds pairs of linear combinations of variables that maximize the covariance between two predetermined blocks of variables with no assumption that one block of landmarks is independent or dependent (Bookstein et al., 2003; Rohlf & Corti, 2000). Similar to PCA, orthogonal pairs of axes, called singular axes or singular warps, are extracted where the first pair of PLS axes explain the most total covariance and the last extracted pair of axes explain the least total covariance (Mitteroecker et al., 2012; Rohlf & Corti, 2000). The covariance between the paired axes (one from each block of landmarks / module) is called the singular value which is similar to the eigenvalue of a PCA but reflects the magnitude of covariance rather than variance as in a PCA. Scores for each specimen on the singular axes are calculated for each block and corresponding singular axes from each bock are visualized as bivariate plots (Mitteroecker et al., 2012).

Separate 2B-PLS analyses were performed on each human and chimpanzee dental developmental stage in part to avoid having between-species effects swamp out potential shared patterns of dental and facial development and a combined dental stage analyses was performed to detect patterns of integration from one dental stage to the next. A single GPA was performed on all of the landmarks in each dental stage, as opposed to a GPA on the facial and dental blocks separately for each stage, to retain information about the size, position and scale of the dental and facial blocks relative to one another, and to test if the pattern of integration is different between chimpanzees and humans (Baab, 2013; Klingenberg, 2009). 2B-PLS analyses were performed in the “geomorph” package version 3.0.2 (Adams & Otarola-Castillo, 2013) in R 3.3.1 (R Core Team, 2016). To visualize the pattern of shape covariation in the 2B-PLS analyses, wireframes and 3D visualizations were created to reflect the direction of shape change along the PLS axes.

To determine if the strength or magnitude of integration between the face and teeth changed throughout ontogeny, three statistical measures were utilized to quantify the magnitude of integration or modularity including the correlation coefficient for each pair of singular axes in the 2B-PLS, the covariance ratio, and the RV coefficient. The correlation coefficient (r-pls) between the scores for each pair of singular axes can be seen as a measure of integration for the sample along each corresponding pair of axes. A higher correlation indicates increased integration between the teeth and face for a particular pair of PLS axes (Rohlf & Corti, 2000). The correlation between the PLS scores for each specimen along each pair of singular axes was assessed for statistical significance using permutation tests (n= 1,000) with a null hypothesis of independence between the two blocks.

The covariance ratio (CR) was utilized to quantify the magnitude of integration or modularity (Adams, 2016). The CR is a ratio of the covariation between modules to the covariation within modules. The covariance ratio is unperturbed by sample size and landmark number, but has not been utilized extensively (Adams, 2016) The CR coefficient is a ratio of the overall covariation between predetermined modules compared to the overall covariation present within the modules. The null hypothesis of the method assumes that the landmark are randomly associated. A CR value between 0 and 1 characterizes a more modular structure where the degrees of covariation between modules is less than the covariation within the modules. A CR value greater than one reflects more covariation between modules than within the two modules, or more integration. The CR coefficient of the two predetermined modules is compared to a distribution of modules that contain randomly assigned landmarks. If the observed CR is less than the distribution, than there is more modularity in the dataset than predicted by chance. Confidence intervals were generated from 1000 iterations of the distribution.

The RV coefficient (Klingenberg, 2009) determines the overall strength of association between the blocks of variables. The RV coefficient is analogous to a multivariate squared correlation coefficient (R) and indicates the association between two vectors (v) (Escoufier, 1973). It is the sum of the squared covariances between the two sets of variables divided by the total amount of variation. It ranges from zero to one. A score of zero indicates complete independence between blocks, and one indicates perfect covariance between the blocks (Klingenberg, 2009). Therefore, larger RV coefficients indicate integration between two modules, whereas lower numbers indicate more modularity. The RV coefficient was assessed for statistical significance using permutation tests (n= 1,000) with a null hypothesis of independence between the two blocks. Several studies report that the RV coefficient is unreliable and sensitive to changes in sample size and landmark numbers (Adams, 2016; Fruciano et al., 2013; Smilde et al., 2009). They are reported here for comparison with other studies as it is widely used in the literature (e.g. Gomez-Robles & Polly, 2012; Jojic et al., 2012; Labonne et al., 2014; Miller et al., 2016). Although sample sizes are roughly similar in humans and chimpanzees and across dental stages, the number of landmarks vary and results should be interpreted cautiously.

Shape changes captured by a single dimension of the 2B-PLS analysis can be thought of as a multivariate vector. Just as we can measure the angle between any 2 dimensional vectors, we can likewise measure the angle between these multivariate vectors as a way of quantifying how similar the direction of shape change is between humans and chimpanzees for any given dimension (Cobb & O'Higgins, 2004; McNulty et al., 2006; Zelditch et al., 2012). The angle between two vectors was calculated as the dot product of the arccosine of the two vectors. An angle of 0 degrees, with a cosine of 1 indicates identical trajectories. An angle of 90 degrees indicates that the vectors are independent of each other and the shape variation is uncorrelated. Therefore, the smaller the angle, the more comparable the shape changes. Angles were computed from the combined lower face and teeth PLS1 shape change vectors from equivalent dental stages as well as the analysis of all four stages simultaneously. To test the statistical significance of a calculated angle, it was compared to a random distribution of vectors of similar size. Angle calculations and permutation tests were performed in R (Claude, 2008). It was hypothesized that there would be no difference between the pattern of integration of humans and chimpanzees.

In short, r-pls, CR and RV coefficients were calculated on all specimens and all landmarks utilizing the same dental and cranial landmarks with similar sample sizes, but some of these values (r-pls and RV) may be affected by the differing numbers of landmarks or disparate sample sizes in each analysis. Only the CR will be useful for comparison with other studies, but all three can be used as quantitative measures of the strength of integration across dental stages within the study. It is expected that the r-pls, CR, RV coefficient will decline with increasing age, especially after the complete eruption of the deciduous dentition. To compare the magnitude of integration between humans and chimpanzees throughout ontogeny, the CR, RV coefficients and r-pls were compared between the two taxa at each dental stage. Angles were computed from shape change vectors from equivalent dental stages as well from the analyses of all four stages simultaneously to compare patterns of shape changes between humans and chimpanzees. Analyses were performed using the morpho package version 2.4.1.1 (Schlager, 2016) and the "geomorph" package version 3.0.3 (Adams & Otarola-Castillo, 2013) in R 3.3.1 (R Core Team, 2016) and MorphoJ v1.06 (Klingenberg, 2011).

Results

Pattern of integration between the lower face and teeth

The 2B-PLS analyses were performed separately for humans and chimpanzees for each dental developmental stage but also for all four stages combined (full ontogenetic sequence). The well-known differences in dento-facial shape and dental eruption between the two genera are apparent in the wireframe diagrams (Figures 3.2 – 3.9). This, however, is not the focus of the study. Rather, it is pattern of shape change that we are analyzing. For example, it is possible to see in the wireframe diagrams an initial increase in size of the individual teeth and then their descent into occlusal position. In most dental stage for humans and chimpanzees, prognathism was associated with relatively more protruding incisors. Subnasal prognathism was not necessarily associated with a relatively shorter or broader palate where an increase in the lower subnasal clivus in DS4 and DS5 humans, was associated with a narrower and shallower palate. In both humans and chimpanzees, younger individuals with less developed teeth had relatively shorter and broader palates (Figures 3.2 – 3.9) which became narrower and more elongate as they aged. The angle between the shape change vectors of the lower face and dentition of comparable dental stages was statistically significant and moderate to large in degree of difference (Table 3.4). The pattern of shape changes throughout ontogeny were visually similar between human and chimpanzees, but there are distinct differences early in ontogeny, such as the breadth of the palate, height of the maxilla and angle of the subnasal clivus. Throughout ontogeny, human maxilla are relatively broader, taller and have a straighter subnasal clivus than chimpanzees at comparable dental stages. The smallest differences between shape vectors are in the adults (DS5) and the largest DS4, when many of the permanent teeth are erupting.

Table 3.4 Angle between human and chimpanzee PLS1 shape vectors for each ontogenetic dental stage in radians and degrees.

Dental Stage	Cosine	Radians	Degrees	p-value
DS2	0.44	1.12	64.02	< 0.001
DS3	0.46	1.09	62.46	< 0.001
DS4	0.21	1.36	77.80	0.02
DS5	0.69	0.81	46.67	< 0.001

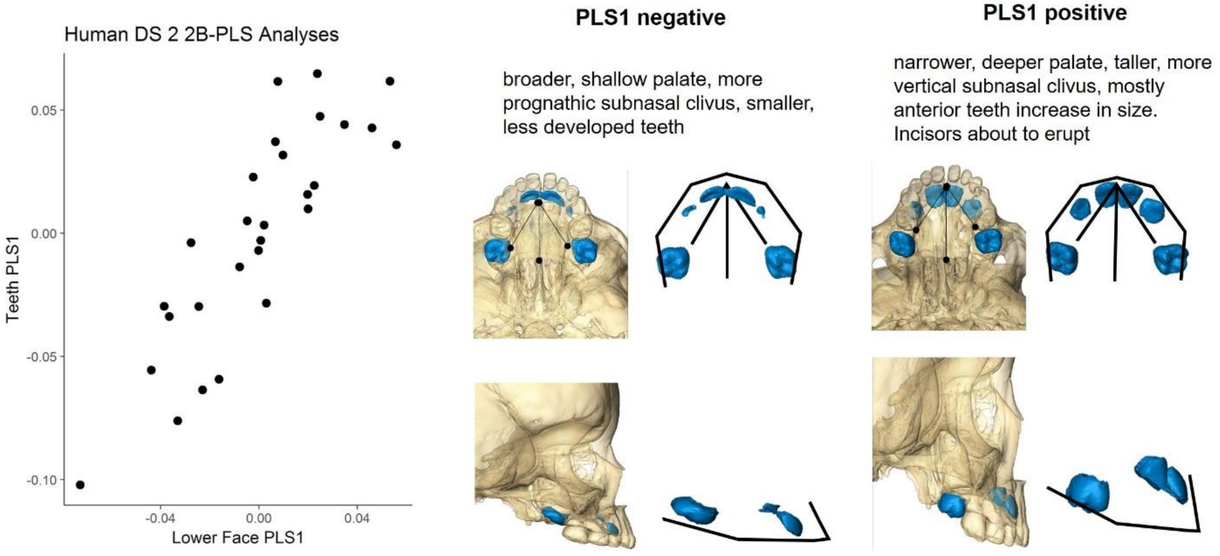

Figure 3.2 Human DS2 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D visualizations in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through time within each module.

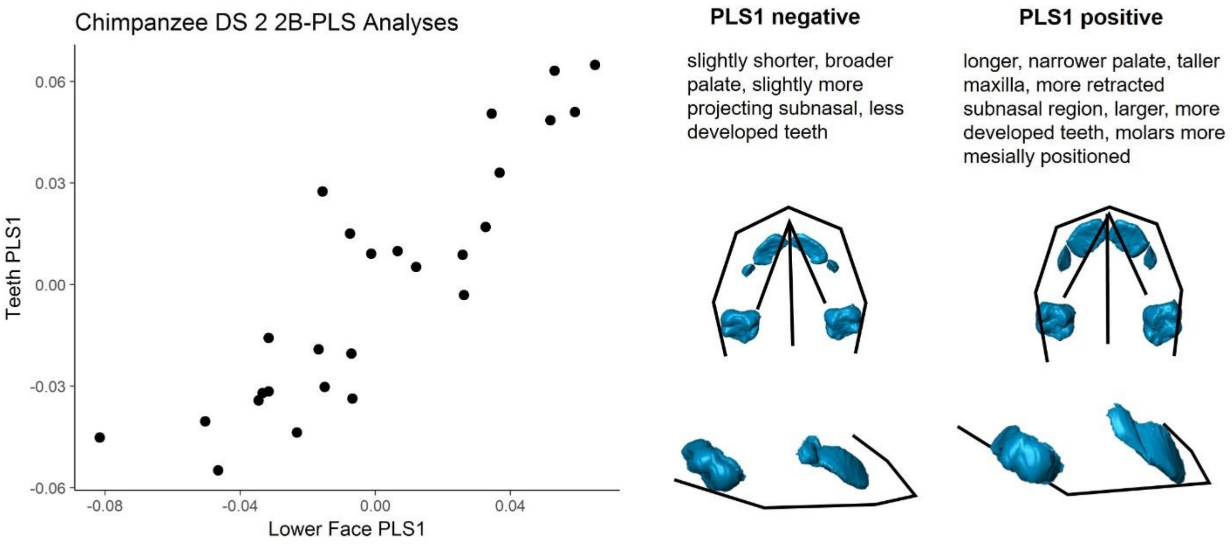

Figure 3.3 Chimpanzee DS2 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through time within each module.

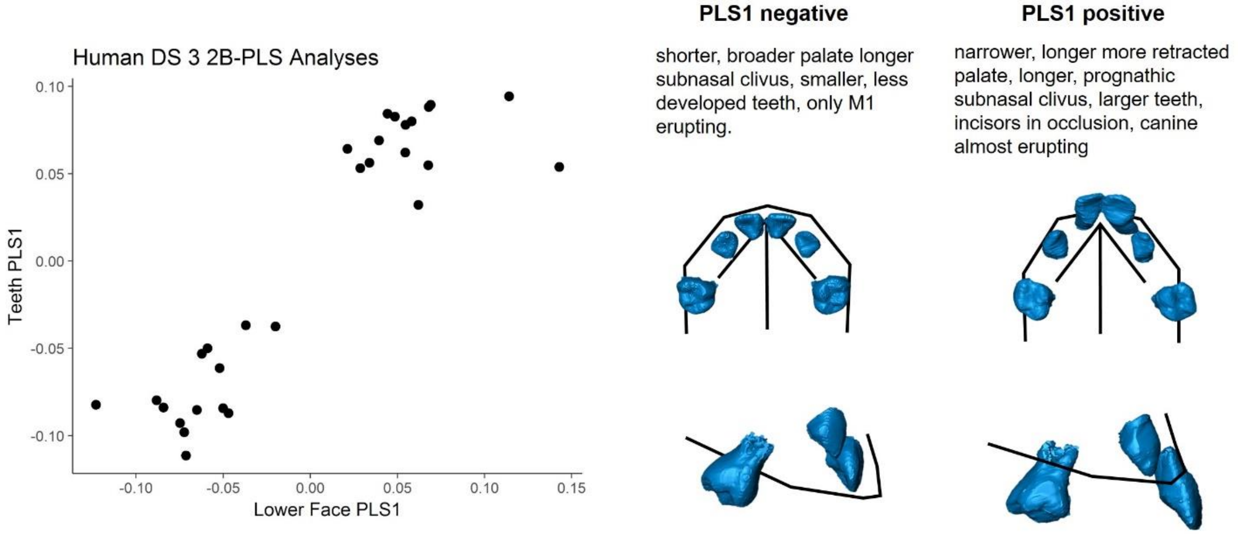

Figure 3.4 Human DS3 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through time within each module.

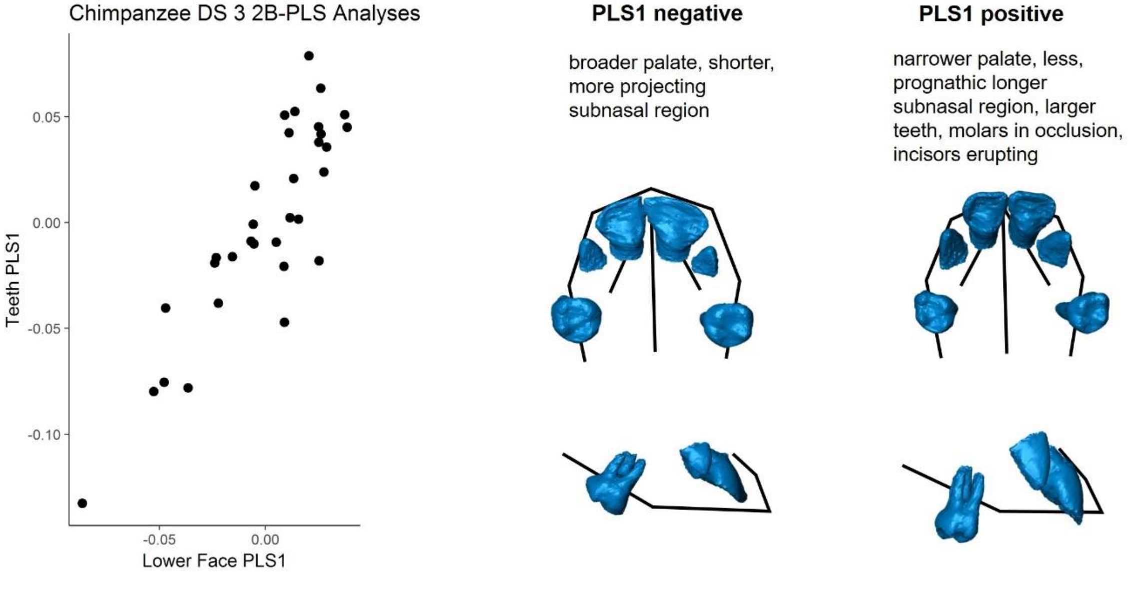

Figure 3.5 Chimpanzee DS3 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through time within each module.

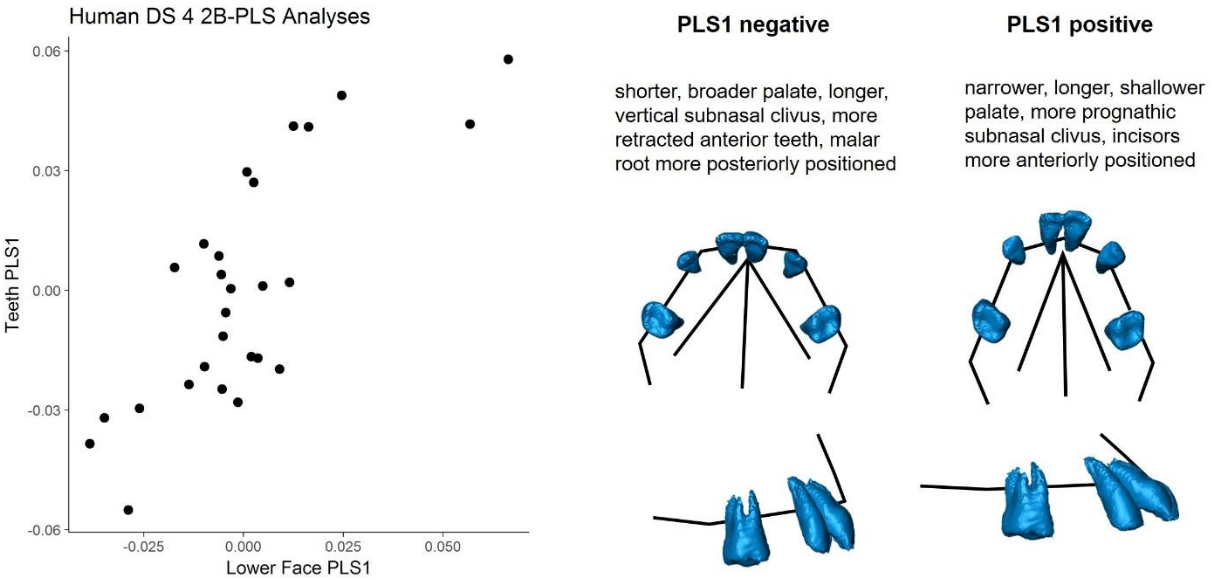

Figure 3.6 Human DS4 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through time within each module.

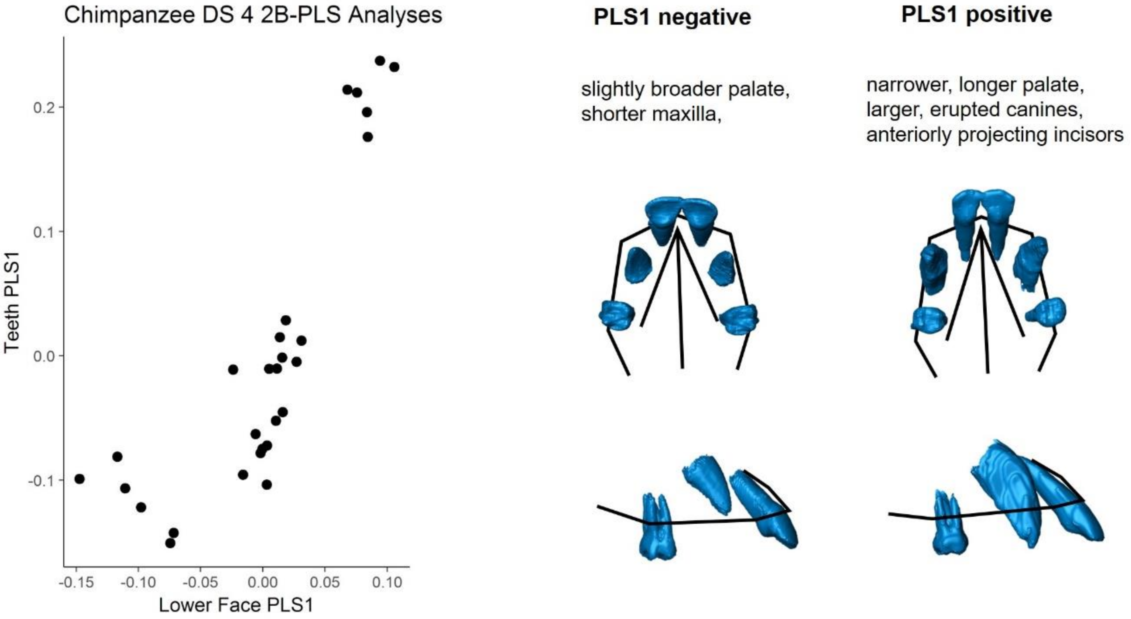

Figure 3.7 Chimpanzee DS4 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through time within each module.

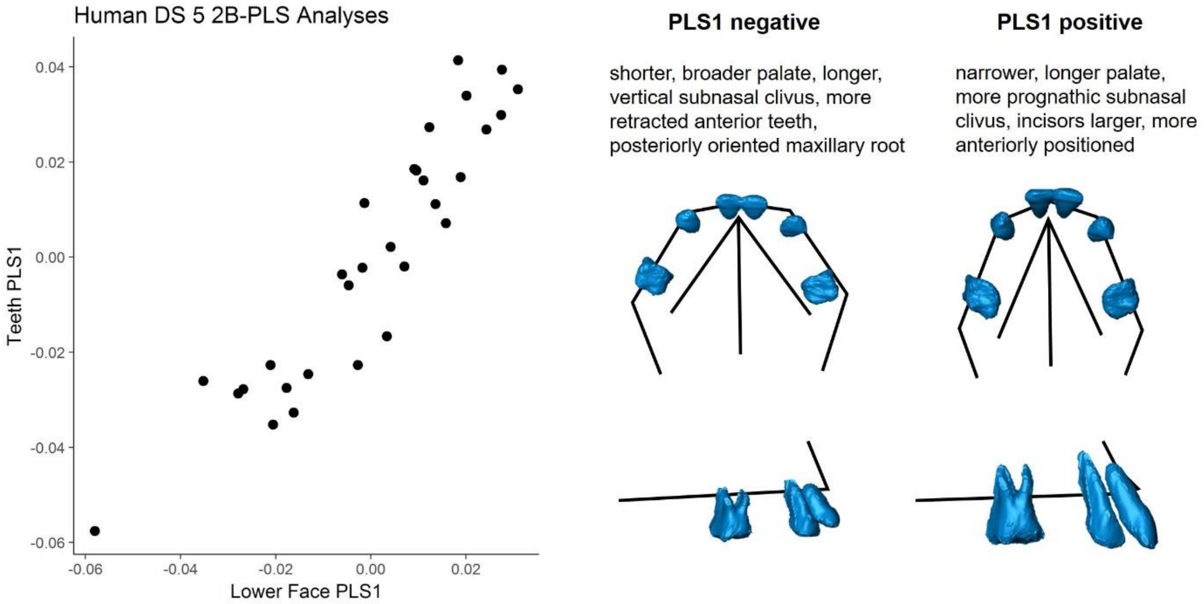

Figure 3.8 Human DS5 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate shape changes within DS5.

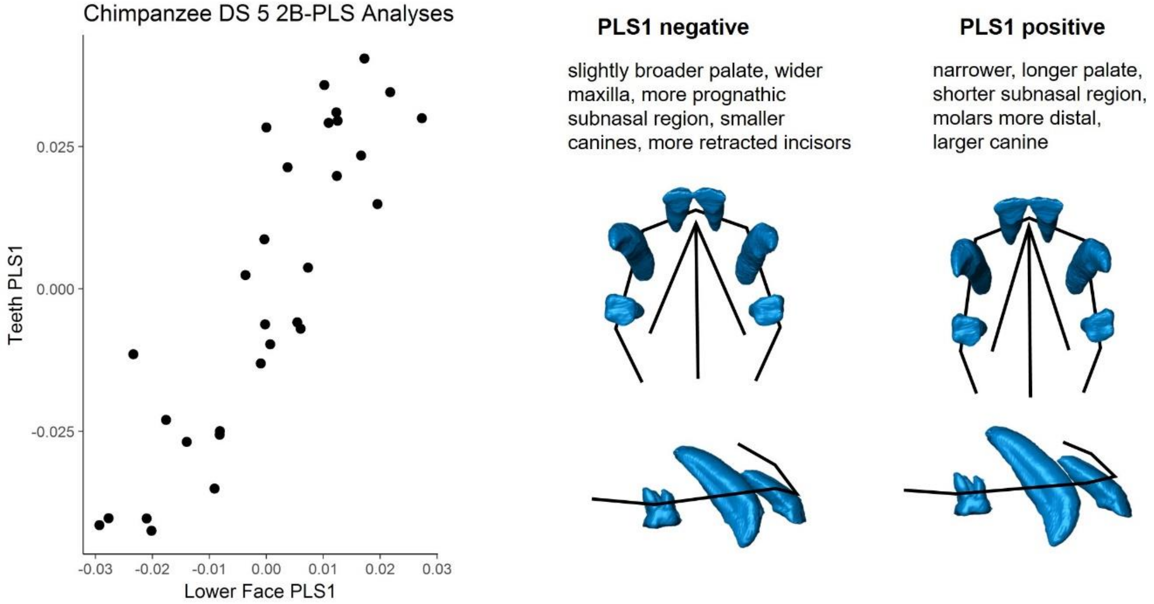

Figure 3.9 Chimpanzee DS5 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate shape changes within DS5.

The analyses of all four stages simultaneously, which captured a longer period of ontogeny, have patterns of shape change that are similar to the individual dental stage analyses (Figures 3.10 - 3.11). Overall, the palate is relatively wider and shorter in earlier dental stages with no erupted permanent dentition, while older individuals have relatively longer, narrower, more prognathic and anteriorly positioned maxillae and anterior dentition. In addition, DS3 in humans and DS4 in chimpanzees have more variation than the other dental stages (Figures 3.10 – 3.11). The angle between the DS2-5 shape change vectors including all four dental stages is much smaller (10°, $p < 0.001$) than the individual dental stage analyses and reflects these comparable overall shape changes.

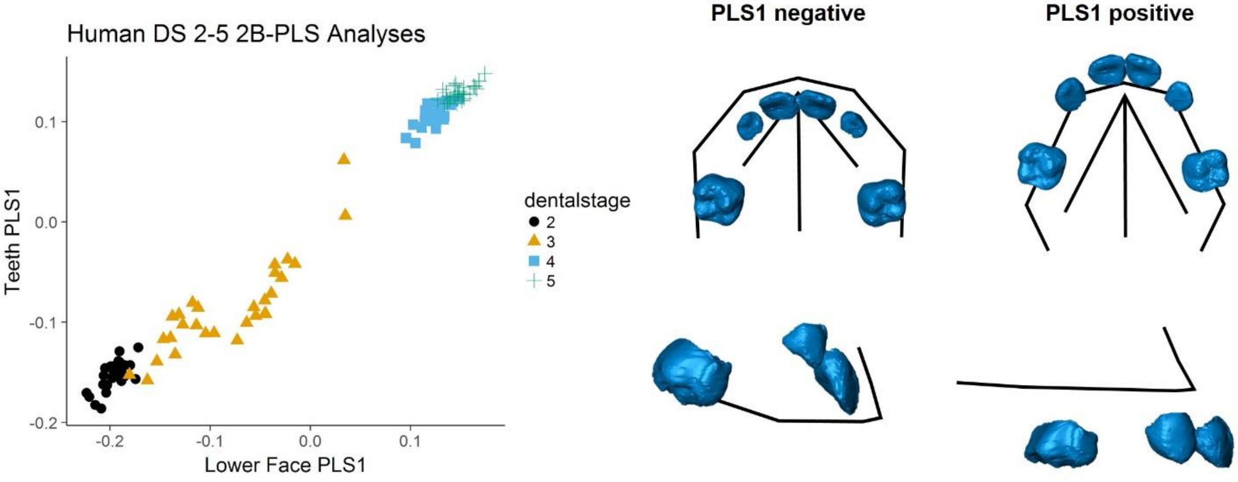

Figure 3.10 Human DS 2-5 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through ontogeny.

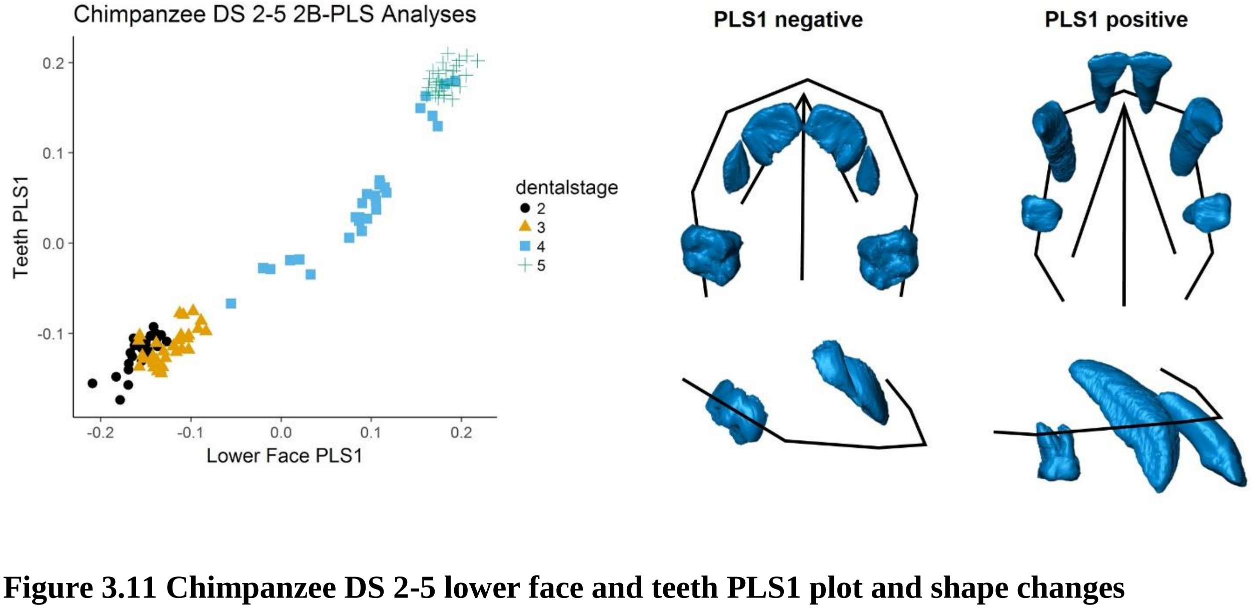

Figure 3.11 Chimpanzee DS 2-5 lower face and teeth PLS1 plot and shape changes visualized as wireframes and 3D morphs in inferior (top row) and lateral (bottom row) views. Negative to positive changes illustrate chronological change and dental development through ontogeny.

Magnitude of integration or modularity for all landmarks

The magnitude of integration was measured as the correlation coefficient (r-pls) from the scores for each pair of singular axes in the 2B-PLS (Rohlf & Corti, 2000), the RV coefficient (Klingenberg, 2009), and the covariance ratio (Adams, 2016). Each value was calculated for each dental stage and species. Contrary to the prediction, the magnitude of integration between the lower face and teeth did not decline continuously throughout ontogeny. Although the different measures do not correspond perfectly, a basic pattern emerges: in humans and chimpanzees, integration between the lower face and the permanent teeth is higher in the early part (DS2) and later (DS5) part of ontogeny and more moderate during the middle (DS3 and 4) (Table 3.5). Integration seems to increase in DS3, when the canines are moving into position just prior to eruption and the incisors are moving into occlusion. However, it is the facial variation that is particularly great in this stage for humans and two clusters of individuals are visible on the plot in this dataset (Fig 3.6). In chimpanzees, integration is fairly constant DS1 through DS5, with a slight decline in DS3 and DS4. In DS4, chimpanzees have both deciduous dentition and erupted first and second molars and, as is apparent from Fig. 3.7, the canines are erupting, which may contributed to increased variation. In DS5, the magnitude of integration in chimpanzees increased with the eruption of the third molars and the shift of the canine into occlusion (Fig. 3.9). For most stages, the actual magnitudes of integration between humans and chimpanzees were fairly similar, with both increasing at DS5 compared to DS2 and 3, but diverged sharply at DS4 when the humans experienced a larger decline in integration. In the combined dental stage analyses (DS2-5) the magnitudes of integration were similar for human and chimpanzee dental stages 2-5 (human r-pls = 0.99, p-value < 0.001; chimpanzee r-pls = 0.98, p <0.001).

Table 3.5 Magnitudes of integration for the lower face and teeth. Correlation coefficient (r-pls), Covariance ratio (CR), Covariance ratio confidence interval (CR CI) and RV coefficient values (RV). Permutation tests for significance of each integration test indicate $p < 0.05$.

	Human				Chimpanzee			
	r-pls	**CR**	**CR CI**	**RV**	**r-pls**	**CR**	**CR CI**	**RV**
DS2	0.85	0.81	0.78 – 0.94	0.51	0.89	0.85	0.82 - 0.96	0.55
DS3	0.92	0.86	0.80 – 0.96	0.67	0.87	0.78	0.74 - 0.92	0.49
DS4	0.78	0.76	0.77 - 0.91	0.45	0.83	0.8	0.71 - 0.92	0.56
DS5	0.92	0.91	0.89 – 0.97	0.64	0.88	0.81	0.79 - 0.94	0.49

Discussion

The goals of this study were to evaluate and characterize ontogenetic integration between the lower face and permanent dentition in humans and chimpanzees, how it varied throughout ontogeny and determine if the pattern and magnitude was different between the two genera. There is significant covariation throughout ontogeny between the lower face and permanent dentition in humans and chimpanzees. Humans and chimpanzees exhibit shared patterns of integration. For instance, increased subnasal prognathism was associated with more protruding incisor crowns and likely, more angled roots. In addition, more immature individuals with less developed dentition had relatively broader and shorter palates compared to older individuals with larger teeth and longer, more elongated palates. Chimpanzees and humans have similar magnitudes of integration in the earliest dental stage evaluated here, DS2, when no permanent teeth are erupted, and again in DS5 when M3 has erupted. Integration magnitudes in chimpanzees decline during the dental stages characterized by the eruptions of the first and second molars where the canine is developing and erupting, while integration between the lower face and teeth is consistent throughout ontogeny in humans, except during the eruption of the second molar.

The pattern of integration between the lower face and teeth is similar in humans and chimpanzees, particularly in the early dental stages (DS2 and DS3). Visually, the relative palatal breadth and length shape changes along PLS1 are similar, but the angles between the two shape vectors indicate only moderately correlated shape change at earlier dental stages (Table 3.5). This moderately correlated shape change may be a result of the different shape or positon of the teeth at the corresponding dental stages. The largest angle is between the DS4 shape vectors for each species. Dental stage 4 is the least integrated stage for chimpanzees and humans (Figure 3.7, Table 3.5). In the chimpanzee DS4, both deciduous and permanent teeth are present, the incisor is in full occlusion and the canine is erupting. The amount of variation in dental shape is higher in this stage than in other stages, most likely because of the changing position of the canine. There is also little change in palatal breadth, shape or subnasal angle during chimpanzee DS4 compared to DS3. This implies that there is some decoupling of coordinated dental and facial skeletal shape change during this time. In contrast, during human DS4 there is more facial shape variation than dental shape variation. In the human DS4, almost all of the permanent teeth, except the third molar have erupted. The contrasting patterns of shape variation would produce a larger angle between the shape vectors in DS4. The smallest angle is between DS5 shape vectors suggesting that human and chimpanzee adults have similar patterns of covariation compared to the other ontogenetic stages, which is similar to Ackermann (2005) who found adults of different species have more similar covariance patterns.

Human DS3 also displays increased variation compared to DS2, and is marked by more facial shape variation than dental shape variation when the axes of the 2B-PLS are compared. This stage is characterized by the eruption of the first molars, but the first incisors are also erupting as the anterior deciduous dentition is shed (Fig 3.4). Dental stages were defined primarily by permanent molar eruption to include the most specimens in each analysis and because molar eruption is a reliable marker for growth and development (Smith, 1989), but more subtle changes in development of other teeth may be missed. In this study, the dental stages in humans and chimpanzees with the most variation (DS3 and DS4) are characterized by more complex dental changes. For instance, the incisors and canines are coming into occlusion in both of these dental stages (Figs. 3.4 - 3.7). While, the chimpanzee molars erupt twice as fast as the human first molars, the chimpanzee first incisors are half as fast in erupting as modern humans (Conroy & Mahoney, 1991; Smith et al., 1994). Variation in palatal and maxillary morphology may be impacted by the delayed canine eruption in chimpanzees contributes to the variation, as well the orientation, shape change and timing of incisor eruption. In addition during human DS3, the second molar is developing and erupting during DS4. Sardi and Rozzi (2007) postulate that an change in what they characterized as the alveolar component in the cranium later in ontogeny may be linked to the development of M2 and M3. Using molar eruption as a marker and the limited tooth analyses of the first incisor, canine and first molar, may have concealed changes in the palate due to other teeth such as the second incisors, second molars or premolars.

Based on adult and ontogenetic mandibular and dental studies, the magnitude of integration was expected to decline throughout ontogeny (Boughner & Hallgrimsson, 2008; Coquerelle et al., 2010; Plavcan & Daegling, 2006; Polychronis & Halazonetis, 2014). Yet, a smaller number of integration studies have found an increase in integration throughout development (Ackermann, 2005; Adams, 2016; Zelditch & Carmichael, 1989) or change in covariance structure throughout ontogeny (Mitteroecker & Bookstein, 2009). In the present study, covariation between the face and teeth changed in humans throughout ontogeny, with the exception of DS4 relative to DS3. The difference in growth rate and timing could explain the differences in integration results between the maxilla and mandible (Boughner & Hallgrimsson, 2008; Coquerelle et al., 2010; Plavcan & Daegling, 2006; Polychronis & Halazonetis, 2014). Facial growth in humans is delayed in comparison to neurocranial growth (Humphrey, 1998). The human frontal, occipital and mandible bones reach most of their maximum heights and breadth by the eruption of the second molar, followed by the growth of the face with the onset of puberty (Humphrey, 1998). In addition, in some individuals, the cranial growth could be accelerated or the dental growth is delayed, which would result in some individuals with relatively greater face change than shape change in a particular dental stage. Ackermann (2005) used matrix correlation of size-adjusted linear measurements to assess morphological integration and reported that humans and chimpanzees have common patterns of facial integration, but the magnitudes of integration are different throughout ontogeny. Of the various modules analyzed, the oral integration remained high throughout ontogeny compared to the zygomatic, nasal or orbit groups (Ackermann, 2005). In this current study, the magnitudes of integration also changed throughout ontogeny. In contrast, Polychronis and Halazonetis (2014) found no statistical significance between the maxillary first molar occlusal surface and the craniomandibular complex in prepubertal (younger than 12) or adult analyses. These authors reported significant weak craniomandibular covariations (utilizing the RV coefficient) with the mandibular M1 and a decline in covariation from prepubertal to adult age groups. The age groups were broad, such that the human prepubertal groups would encompass DS2 and DS3 of this study (Polychronis & Halazonetis, 2014). These broad age groups and the comparison of the entire craniofacial complex to the occlusal surface of one tooth could explain the low integration values, and make it difficult to compare results to this study. While the increase or decrease of integration across ontogeny in primates varies by analysis, what is consistent is that the magnitude of integration changes throughout ontogeny. This is apparent in humans and chimpanzee in this study (Table 3.5).

The decline in integration in DS4 corresponds to the eruption of the second molar and approximate sexual maturity or puberty in humans and chimpanzees (Smith, 1989, 1992). While skull growth in humans overall slows (Bastir & Rosas, 2004a) during and after M2 eruption compared to pre-M1 eruption, the human face continues to grow (Humphrey, 1998) and become sexually dimorphic (Bulygina, Mitteroecker, & Aiello, 2006). In humans, during this stage there is increased facial variation while for chimpanzees it is mostly dental variation. This increased variation in face and dentition would impact the magnitude of covariation and allow for morphological change during those dental stages.

Adults with third molar eruption were analyzed in both Chapters 2 and 3. A smaller sample size of thirty was utilized in this chapter to have balanced sample design with the other dental stages. In addition, only the first incisors, canines and first molars were analyzed in this chapter because these teeth are present in each dental stage whereas all of the dentition was analyzed in Chapter 2. The pattern and magnitude of integration results were similar in both studies and the reduced sample size did not impact the covariation analyses. While a larger sample size gives a study more statistical power, the comparable adult results indicate that a sample size of approximately thirty individuals was sufficient to detect the pattern of integration. Furthermore, when a limited number of landmarks are analyzed, 30-40 individuals can reliably estimate the magnitude of integration (Haber, 2011). Grabowski and Porto (2016) recommend a sample size of 108, to detect magnitude of integration for ten traits, but this sample size is not feasible for within-dental stage ontogenetic analyses. Another difference between the two sets of adult analyses was the choice of 2B-PLS analyses. In Chapter 2, pooled 2B-PLS analyses for the chimpanzee and the combined human and chimpanzee sample were performed in which the centroid size of each sex or species, respectively, determined and the differences from the mean were calculated and used in the 2B-PLS analyses. These pooled analyses eliminated mean shape differences due to sex or species. Although the Chapter 2 chimpanzee 2B-PLS was pooled, the adult human and chimpanzee analyses in both chapters had similar patterns of integration between the lower face and teeth. A relatively shorter, broader palate with a longer more vertical subnasal clivus was associated with retracted teeth, while more prognathic specimens with narrower palates had relatively larger and more projecting incisors and canines. The most noticeable shape change difference in the sex-pooled analyses of chimpanzees in Chapter 2 compared to the unpooled analyses in this chapter was the reduction in the size dimorphism of the canine.

In this study, the morphological integration between the lower face and the permanent first molars, canines and first incisors was evaluated. There is significant covariation between the lower face and permanent dentition in humans and chimpanzees throughout ontogeny. Humans and chimpanzees have similar patterns of integration, such that younger individuals have broader, shorter plates while older individuals have longer, narrower and slightly more prognathic subnasal regions. Humans and chimpanzees also have similar magnitudes of integration, but the magnitude of integration declines during dental stages with complex dental eruption patterns such as around the second molar eruption in humans and chimpanzees.

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Chapter 4 Subnasal height, prognathism and the anterior dentition

Introduction

Subnasal prognathism describes the angular relationship of the lower face (positioned, below the nasal aperture and housing the maxillary dentition*)*, in reference to the upper face (the region superior to the nasal aperture around the orbits) (Bilsborough & Wood, 1988; Lieberman, 2011). Prognathism in the subnasal region is distinguished from facial projection that describes the anterior protrusion of the face in relationship to the anterior cranial base (Lieberman et al., 2000) and mid-facial prognathism, which describes the protrusion of the region around the nasal aperture and zygomatic bones in relation to the rest of the face (Bilsborough & Wood, 1988; Harvati, Hublin, & Gunz, 2010). The orthognathic modern human face contrasts to the subnasal prognathism of the great apes and the midfacial prognathism of Neanderthals. The morphological variation of the subnasal region and dentition are used to characterize and describe modern humans, great apes and fossil hominins. Patterns of variation in the size and shape of the dental arcade, the premaxilla, position of the dentition, and subnasal prognathism differentiate humans from great apes and fossil hominins. These subnasal traits are likely associated and variation in these traits produce different cranial and dental shapes.

Björk (1951) proposed that evolutionary changes to the human face are a result of the increase in neurocranial size and the widening of the face which leads to a shorter, broader jaw and flatter face. There are molecular and morphological mechanisms that produce covariation between the brain and the face (Boughner et al., 2008; Marcucio, Young, Hu, & Hallgrimsson, 2011; Parsons et al., 2011), and an increase in basicranial flexion is hypothesized to rotate the face downward, and decrease prognathism (Lieberman, 2011; McCarthy & Lieberman, 2001). The less prognathic face of *Australopithecus afarensis* when compared to chimpanzees may be a consequence of a shorter more flexed cranial base (Kimbel et al., 2004), while in adult humans, a relatively wider cranial base with a wide middle cranial fossa and elongated anterior cranial fossa is associated with a smaller, narrower face with subnasal prognathism (Bastir & Rosas, 2016).

Internal and external features of the subnasal regions, including the shape of the dental arcade, depth of the palate, subnasal prognathism, and incisor procumbancy are related characters utilized to describe and classify taxa (Asfaw et al., 1999; Berger et al., 2010; Kimbel et al., 1997; Rae, 1997). A vertically oriented premaxilla contributes to the orthognathic face of modern humans (Cobb, 2008), while the length of the palate or relative positon of the palate in relationship to the orbits may contribute to prognathism in fossil hominins (Rak, 1983). The articulation and vertical relief between the premaxillae and maxillae of the hard palate distinguish among hominins (McCollum, 2000; McCollum, Grine, Ward, & Kimbel, 1993; McCollum & Ward, 1997; Robinson, 1953, 1954; Ward & Kimbel, 1983). *Australopithecus anamensis, A. afarensis* and *A. africanus* resemble *Pan troglodytes* and have subnasal morphology with some vertical relief between the premaxilla and maxillary palatine process. In contrast, *Paranthropus boisei*, *P. robustus* and *P. aethiopicus,* early *Homo, Homo erectus* and modern humans have a smoother and continuous transition between the premaxilla and maxilla (McCollum, 2000; McCollum et al., 1993; McCollum & Ward, 1997). The internal subnasal morphology also mirrors the various subnasal shapes and subnasal prognathism among hominins. Modern humans are defined by a derived reduction of subnasal prognathism compared to chimpanzees that retain a prognathic subnasal region in which the incisors protrude from the premaxilla (Cobb, 2008). The retention of a prognathic subnasal region in apes and some fossil hominins is a primitive condition (Kimbel et al., 1997). Of the major fossil genera, *Australopithecus* has a relatively curved, prognathic subnasal region, while *Paranthropus, Kenyanthropus,* and *Ardipithecus* have flatter, orthognathic subnasal regions (Spoor et al., 2010; Suwa et al., 2009). Similar to modern humans, *Homo habilis* and *H. rudolfensis* have moderate subnasal prognathism that is less than *Australopithecus* (Kimbel, 2009).

Descriptions and hypotheses about the variation in craniodental morphology of extant and fossil hominins assume an association between features of the subnasal region and the anterior dentition. These hypotheses have been proposed in humans, chimpanzees and fossil hominins and assume a relationship between orthognathism, palatal length, maxillary height or depth and the incisors or canines. Several hypotheses state that as a result of palatal shape, the size and shape of the anterior dentition changes (Björk, 1951; Simpson, Lovejoy, & Meindl, 1991). With a change in palate shape and size, the incisors become more vertically oriented and the dentition becomes smaller or more crowded (Björk, 1951) or orthognathism and reduced palatal length may lead to the decrease in canine size (Simpson et al., 1991). In contrast, there have been various hypotheses that propose that changes in the dentition impact the prognathism of the subnasal region. Larger incisors and canines have longer roots and larger root cross sections that enlarge the alveolar region of the lower face. As a result, the subnasal region of hominins with procumbent incisors tends to be curved or convex and prognathic (Lieberman, 2011). In *A. afarensis,* the curved prognathic maxillae is influenced by the robust, curved roots of the anterior dentition, while *A. africanus* has a flatter nasoalveolar clivus and straighter incisor roots (White, Johanson, & Kimbel, 1981). Kimbel et al. (2004), further stated that the canine root influenced the shape of the *Australopithecus afarensis* maxillae. Species such as *A. afarensis* or *A. garhi* that exhibit subnasal prognathism also have procumbent incisors, whereas the flatter face of *Paranthropus robustus* and *P. boisei* is associated with vertically oriented incisors (Asfaw et al., 1999; Berger et al., 2010). In *Homo habilis*, Tobias (1991) hypothesized that enlarging the tooth roots led to an increase in height of the maxilla and deeper alveolar process. Suwa et al. (2009) stated that the anterior displacement of the dental arcade and increased prognathism was related to an increase in canine size in chimpanzees. In addition to the association between tooth size and prognathism, incisor alveoli and incisor root and crown fragments have been used to assess subnasal prognathism (Suwa et al., 2009) assuming a positive correlation between root angle and subnasal prognathism. Villmoare, Kuykendall, Rae, and Brimacombe (2013), analyzed the root length and inclination of the incisor roots of great apes and fossil hominins to investigate the orientation of the short roots of the Sts 5 *Australopithecus africanus* cranium. Results indicate a negative correlation between incisor root inclination and relative root length (or the root length scaled by the nasoalveolar clivus length), but the authors did not investigate the correlation between root inclination and prognathism. The assumptions about the relationship between subnasal region and the anterior dentition have rarely been tested.

These evolutionary hypotheses involving the subnasal region assume that the morphological traits of the maxilla and anterior dentition are not independent. The majority of assessments of subnasal prognathism and its relationship with the anterior dentition have been qualitative, rather than quantitative, and include very few juveniles. In the previous chapter (Chapter 3), subnasal prognathism increased throughout ontogeny and was associated with relatively more projecting permanent central incisors as part of a larger complex of facial variation. Because the dental roots are not present in all dental stages, the incisor or canine roots were not analyzed in the previous chapter. Given that the anterior dentition is located within the alveolar bone of the subnasal regions, a correlation between root length, root angle, subnasal height and subnasal prognathism might be expected. This paper combines traditional linear and angular measurements with measurements of tooth root angles, a key variable that has not been fully evaluated with its relationship with subnasal morphology. This will allow for the comparison of the previous 3D geometric morphometric results to traditional linear and angular measurements.

This study will analyze the association between the anterior dentition and subnasal prognathism in adult and juvenile human and chimpanzee specimens and test several hypotheses about the subnasal region and the anterior dentition. Firstly, the study will quantitatively assess whether prognathism increases throughout ontogeny to confirm the geometric palatal shape changes observed in Chapter 3. It is predicted that the degree of prognathism will increase throughout ontogeny. Secondly, it is hypothesized that the first permanent and deciduous incisor root lengths will be correlated with subnasal height of the maxilla. Taller subnasal regions will have longer incisor roots. A similar correlation is expected between the deciduous and permanent first incisors in chimpanzees and humans, because the permanent and deciduous roots are in similar locations in the nasoalveolar clivus. Incisor root angles have been used to assess subnasal prognathism in fossil hominins (Suwa et al., 2009) and subnasal prognathism is associated with enlarged incisors and canines (Kimbel et al., 2004; Lieberman, 2011; Tobias, 1991). Thus, incisor and canine root inclination is predicted to be positively correlated with subnasal prognathism.

Materials and Methods

Immature and adult humans and chimpanzees of mixed sex were utilized (n=245) in this study. Human and chimpanzee specimens and computed tomography (CT) scans were acquired from a variety of museums and repositories (Table 4.1). Due to the limited availability of complete crania with mostly complete dentition, different subspecies of *Pan troglodytes* were combined in the analyses. Specimens were classified as *Pan t. troglodytes, Pan t. verus,* and *Pan t. schweinfurthii.* Sex was generally unknown for all of the immature specimens and is difficult to accurately estimate prior to puberty. Sex for some of the adult human and juvenile specimens was collected from museum or researcher records, otherwise sex was classified as unknown. The sample of *Homo* and *Pan* has previously been divided into four dental stage groups for analyses (Chapter 3). Three of these dental stages were subdivided into two groups, one group with the youngest individuals that still retain their deciduous anterior dentition (“deciduous”) and an older group (“permanent”) with erupted first and second incisors and permanent canines (Table 4.2). The anterior root inclination will be analyzed in the “deciduous group” within species and then in the “permanent group” within species. Dental stage 3 was not analyzed in the “deciduous” or “permanent” group analyses because many specimens did not have deciduous central incisors.

Table 4.1 Museum collections and digital archives of *Homo* and *Pan* crania

Collection	**Genus**
American Museum of Natural History	*Homo, Pan*
Hull York Medical School	*Homo, Pan*
Raymond A. Dart Collection of Human Skeletons, University of Witwatersrand	*Homo*
Museum of Comparative Zoology, Harvard University	*Pan*
National Museum of Bloemfontein	*Homo*
National Museum of Natural History	*Homo*
Peabody Museum of Archaeology and Ethnology, Harvard University	*Pan*
Pennsylvania State University	*Homo, Pan*
Pennsylvania State University, National Museum of Natural History	*Homo*
Primate Research Center Digital Morphology Museum	*Pan*
Royal Museum of Central Africa	*Pan*
South African Museum	*Homo*
Stony Brook University	*Pan*
University of Cape Town	*Homo*
University College of London	*Homo, Pan*
University of Liverpool	*Homo, Pan*

Table 4.2 Dental stage description, sample size and anterior tooth analyses subgroups

Dental stage	Dental stage description	Human	Chimpanzee	Anterior tooth analyses
DS2	any deciduous teeth erupted	30	30	Deciduous
DS3	permanent first molar (M1) eruption	30	33	*Not analyzed**
DS4	permanent second molar (M2) eruption	32	30	Permanent
DS5	permanent third molar (M3) eruption	30	30	Permanent

*Dental stage 3 was not analyzed in the “deciduous” or “permanent” group analyses because many of the specimens did not have deciduous central incisors.

Three dimensional visualization and landmark acquisition

Three-dimensional landmarks of the crania and dentition were placed on the 3D reconstructions of the crania and permanent and deciduous dentition using Avizo 8.1 (Figure 4.1 for adult landmarks). I scanned specimens from the AMNH at the Stony Brook Hospital on a GE VCT Lightspeed CT scanner in the Department of Radiology and specimens from the MCZ and PMAE on an X-Trek HMST 225 microCT at Harvard University’s Center for Nanoscale Systems. Specimens scanned at Stony Brook were scanned at 140 kV and 200 mA and have an isometric voxel size ranging from 0.187-0.33. The parameters of the CT scans obtained from other museums and researchers varied, but slice intervals were no more than 1 millimeter. Avizo 8.1 visualization software was used to segment the teeth and crania from all specimens using a combination of manual and semi-automated approaches. 3D surfaces of the crania and teeth were generated using the constrained smoothing algorithmic software function.

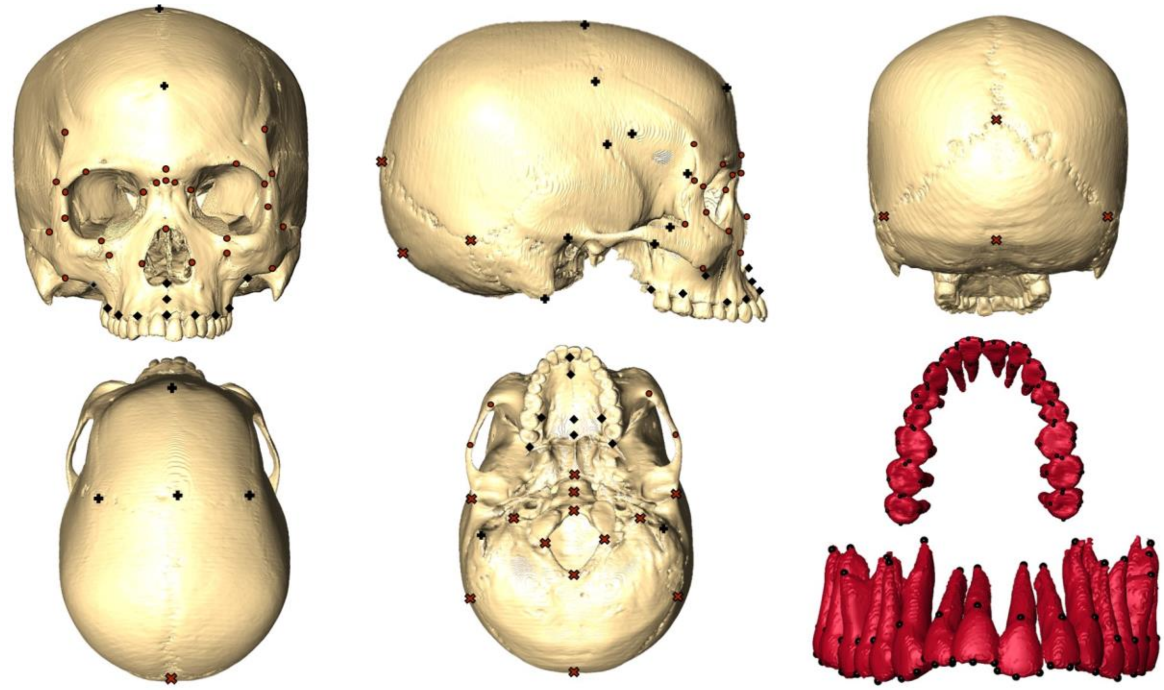

Figure 4.1 Adult cranial and dental landmarks. Red circle- upper face landmarks, black diamonds-lower face landmarks, black cross- vault landmarks, red "X"- occipital landmarks, black circles- tooth landmarks.

Metrics and Angles

Incisor and canine tooth root lengths were calculated from the 3D landmarks to assess the relationship between the anterior tooth root height and the subnasal region. The 3D landmarks were converted to interlandmark distances by calculating the Euclidean distance (d) between two landmark points (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) using the following formula: d = $\sqrt{(X1 - X2)^2 + (Y1 - Y2)^2 + (Z1 - Z2)^2}$. Subnasal height was calculated as the distance from nasospinale to prosthion. Root length was calculated as the distance from the root apex to the most superior point in the midline of each crown.

Angles between vectors connecting landmarks were calculated to assess root inclination and subnasal prognathism. All cranial and dental 3D landmarks were imported into MorphoJ and subjected to a Generalized Procrustes Analysis and aligned to the mid-sagittal plane. Using the "align using specific landmarks" function, opisthion and prosthion were used to define the x-axis and glabella to define the y-axis (Klingenberg, 2011). The x-coordinates of the superimposed landmark coordinates represent the anteroposterior variation in landmark position, the y-coordinates represent the supero-inferior variation and z-coordinates represent the mediolateral deviations relative to the midsagittal plane (Figure 4.2). The symmetric component of the superimposed landmark coordinates was exported and the z-coordinate deleted. This procedure projected all of the coordinates into the midsagittal plane. Two-dimensional (2D) angles representing subnasal prognathism and incisor and canine root inclination were then calculated, making these angles comparable to 2D angles measured from photographs (Spoor, Leakey, & Leakey, 2005). Subnasal prognathism was calculated as the angle between the nasospinale – prosthion line and the prosthion-ectomolare line which is similar to Spoor et al. (2005). Incisor and canine root angles were calculated between the root apex-superior midline crown point line to the superior midline crown point-ectomolare line (Figure 4.3). This subnasal angle of prognathism was utilized to approximate an angle that corresponds to a visual estimation of the degree of subnasal prognathism.

To calculate subnasal prognathism and root inclinations from the three landmarks (nasospinale, prosthion and ectomolare or root apex, superior crown, ectomolare), vector analysis was utilized (Figure 4.3). The cosine of the angle between two vectors (V1, V2) is equal to the dot product of the two vectors divided by the product of the vector magnitudes. First, the magnitude of the two vectors was calculated by subtracting the coordinates of the terminal point of the vector (ns or ecmL) from the initial vector point (pr) to create two vectors. Then, the angle (θ) between two vectors was calculated as the arccosine of the sum of the product of the two vectors divided by the product of the vector magnitudes utilizing the following formula:

$$\theta = \cos^{-1}\left(\frac{V1_xV2_x + V1_yV2_y}{\sqrt{V1_x^2 + V1_y^2} * \sqrt{V2_x^2 + V2_y^2}}\right).$$

The root lengths and root angles of the left deciduous and permanent first incisors, second incisors and canines were analyzed. Interlandmark distances were calculated using PAST 2.17c (Hammer, Harper, & Ryan, 2001) and angles were calculated in R v3.3.3 (R Core Team, 2017) using a modified “angle.calc” function of the “Morpho” package (Schlager, 2016).

The mean subnasal angles for each chimpanzee and dental stage were calculated and unpaired t-tests were performed between the youngest (DS2) and oldest individuals (DS5) with the null hypothesis that DS2 and DS5 have the same mean subnasal angles. Pearson’s correlation coefficients were calculated within species and by “deciduous” or “permanent” dental groupings to assess the association between the root length and root angles, the subnasal angle, and the anterior teeth. A combined human and chimpanzee correlation analysis was performed to determine the association between incisor and canine root length and root angles with subnasal prognathism across species. Correlations were computed between the linear and angular measurements in R v3.3.3 (R Core Team, 2017).

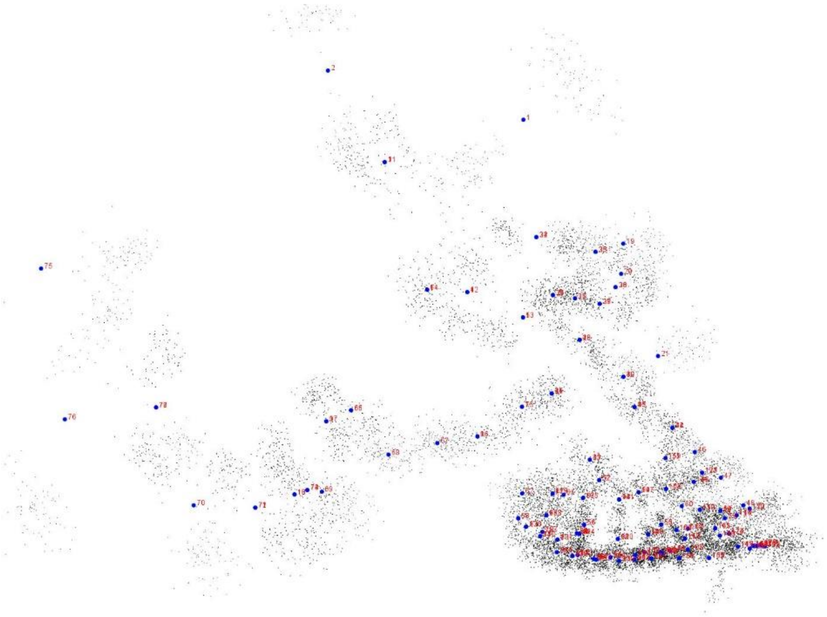

Figure 4.2 The mean symmetric shape from a generalized Procrustes analysis aligned of human and chimpanzee DS4 and DS5 cranial and dental landmarks. The GPA was aligned using opisthion, prosthion and glabella.

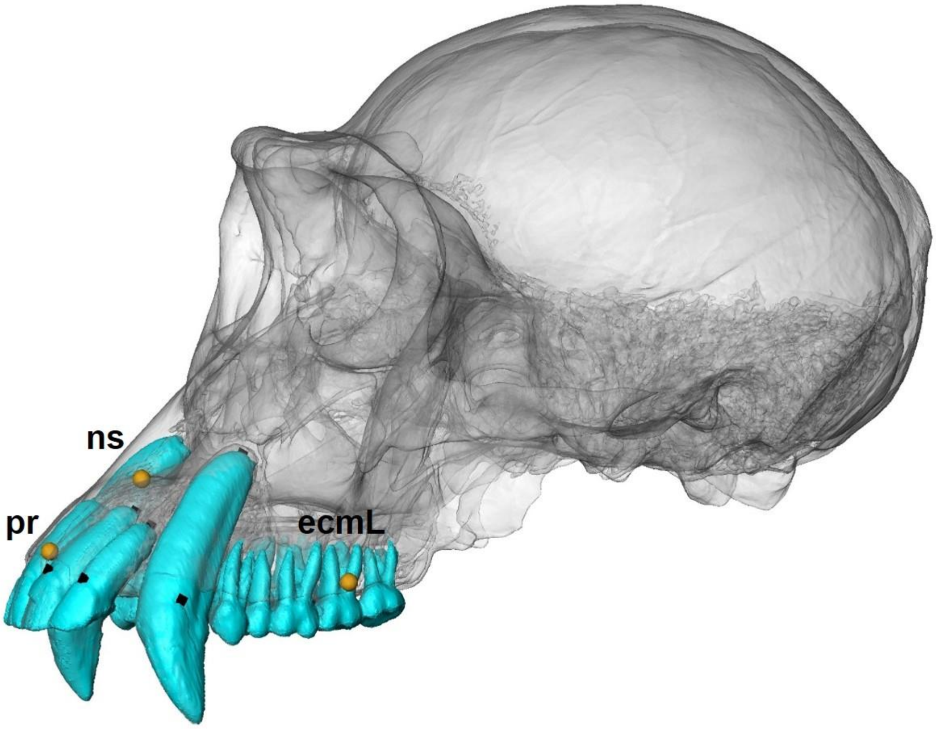

Figure 4.3 Subnasal prognathism and root angle landmarks. Yellow circles represent the landmarks used to calculate subnasal prognathism (nasospinale = ns, prosthion = pr, ectomolare left = ecmL). The black square landmarks are the root apex and superior midline crown landmarks of the left first and second incisors and canine. The root apex, superior crown landmarks and ecmL were the landmarks used to calculate root angle.

Results

Subnasal prognathism throughout ontogeny

Subnasal prognathism increased throughout ontogeny after DS3 in chimpanzees and in humans, as seen by the decrease in magnitude of the subnasal angle (Table 4.3). A subnasal angle closer to 90° represents a vertical or orthognathic subnasal region, while a smaller angle such as 45° describes a more prognathic subnasal region. The mean subnasal angles from the earliest dental stage (DS2) and the latest (DS5) are statistically different in chimpanzees ($t = 5.57$, $p < 0.001$), but not quite so in humans ($t = 2.22$, $p = 0.06$). In humans and chimpanzees, the most orthognathic angle occurs in DS3.

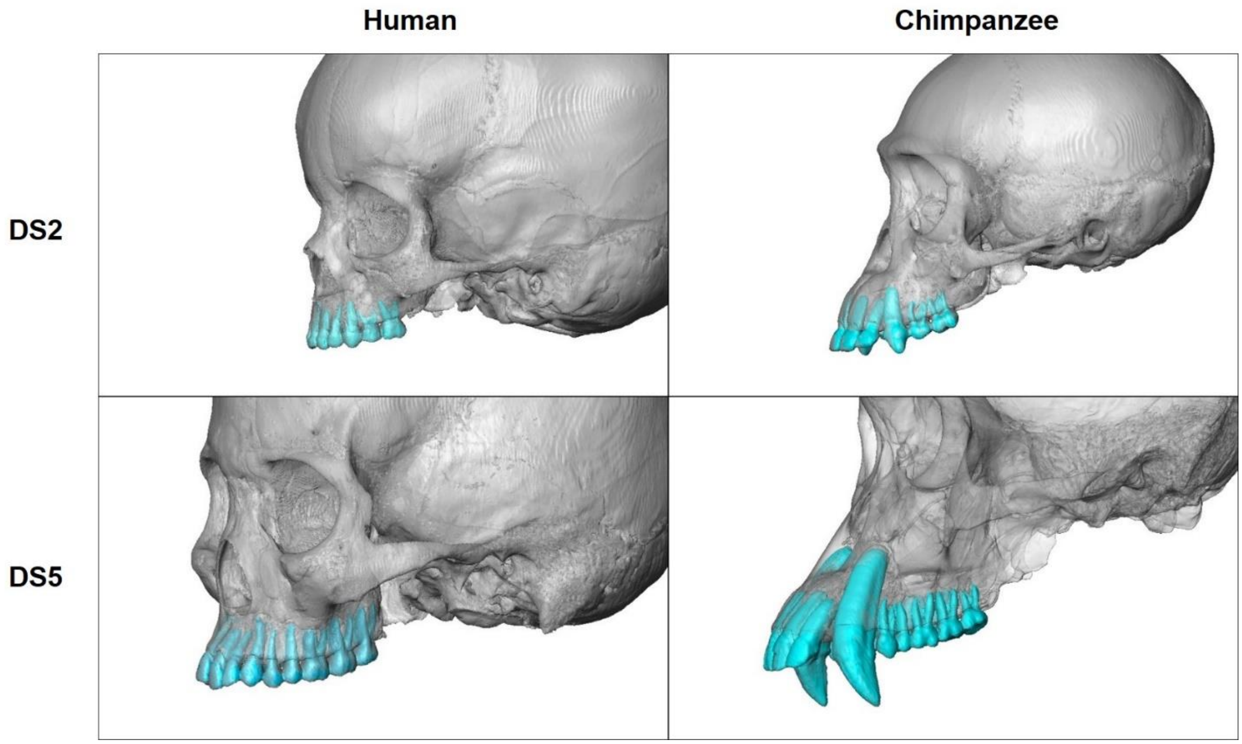

Figure 4.4 Root angle and root length and subnasal height and subnasal prognathism. Transparent images of human and chimpanzee DS2 and DS5 crania with deciduous or permanent dentition in teal. In human DS2, the deciduous incisors extend to the margin of the nasal aperture, while in the chimpanzees DS2 they do not. The root inclination in the adult human anterior teeth and deciduous incisors are correlated with subnasal prognathism

Table 4.3 Mean and standard deviations of subnasal angles by dental stage

	Homo sapiens		***Pan***	
	Mean	**SD**	**Mean**	**SD**
DS2	71.4°	8.3	54.4°	6.3
DS3	73.4°	9.9	56.2°	5.1
DS4	64.6°	8.6	48.4°	6.1
DS5	67.4°	8.2	47.4°	3.4

Central incisor root length and subnasal height correlation

The human deciduous central incisor root length is moderately correlated with subnasal height (r = 0.56, p<0.05), the first human central incisor is weakly correlated with subnasal height, while a significant and slightly stronger relationship exists between the permanent central incisors root length of chimpanzees and the subnasal height (Table 4.4). There are no significant correlations with subnasal height and the deciduous central incisor of *Pan*. In the combined human and chimpanzee correlation analyses, there is a positive, moderate correlation between the deciduous first incisor root length and subnasal height and a strong positive correlation between the permanent first incisor root length and subnasal height.

Table 4.4 Correlation coefficients and p-values between subnasal height and the deciduous and permanent central incisors.

		Homo	*Pan*	*Homo + Pan*
di1L root length	Subnasal height	**0.56 (p = 0.002)**	0.23 (p =0.266)	**0.53 (p<0.001)**
LI1 length	Subnasal height	**0.36 (p = 0.004)**	**0.67 (p<0.001)**	**0.85 (p<0.001)**

Bold numbers are significant at p<0.05.

Root angle and subnasal prognathism

In *Homo,* a positive significant relationship exists between the permanent incisor and canine root angles and subnasal prognathism. In addition, the human deciduous canine angle is moderately correlated with subnasal root angle. In *Pan,* the deciduous incisors are strongly and significantly correlated with the subnasal angle, but the deciduous canine root angle and permanent tooth root angles are not correlated with the angle of subnasal prognathism (Table 4.5, Figure 4.5). When the chimpanzee and humans are combined, the deciduous and permanent incisors are moderately and positively correlated with subnasal angle, where more inclined incisor roots are associated with more subnasal prognathism (Table 4.6). In contrast, the combined human and chimpanzee deciduous and permanent canine root angles are negatively and weakly correlated with subnasal angle. There is a weak association present between more inclined deciduous or permanent canine roots and less prognathic subnasal regions in the human and chimpanzee combined analyses (Table 4.6).

Table 4.5 Incisor and canine root angles and subnasal prognathism angle correlations.

		Homo		***Pan***	
		Deciduous	Permanent	Deciduous	Permanent
Incisor 1 root angle	Subnasal angle	0.34 (p = 0.08)	**0.71** (p < 0.001)	**0.79** (p < 0.001)	0.09 (p = 0.54)
Incisor 2 root angle	Subnasal angle	0.37 (p = 0.06)	**0.63** (p < 0.001)	**0.73** (p < 0.001)	0.05 (p = 0.75)
Canine root angle	Subnasal angle	**0.54** **(p = 0.004)**	**0.52** (p < 0.001)	0.20 (p = 0.33)	0.11 (p = 0.46)

Bold numbers are significant at p<0.05.

Table 4.6 Combined human and chimpanzee root angle and subnasal prognathism angle correlations.

		Combined *Homo* and *Pan*	
		Deciduous teeth	Permanent teeth
Incisor 1 root angle	Subnasal angle	**0.61** (p < 0.001)	**0.60** (p < 0.001)
Incisor 2 root angle	Subnasal angle	**0.65** (p < 0.001)	**0.55** (p < 0.001)
Canine root angle	Subnasal angle	**-0.40** (p = 0.003)	**-0.28** (p = 0.003)

Bold numbers are significant at p<0.05.

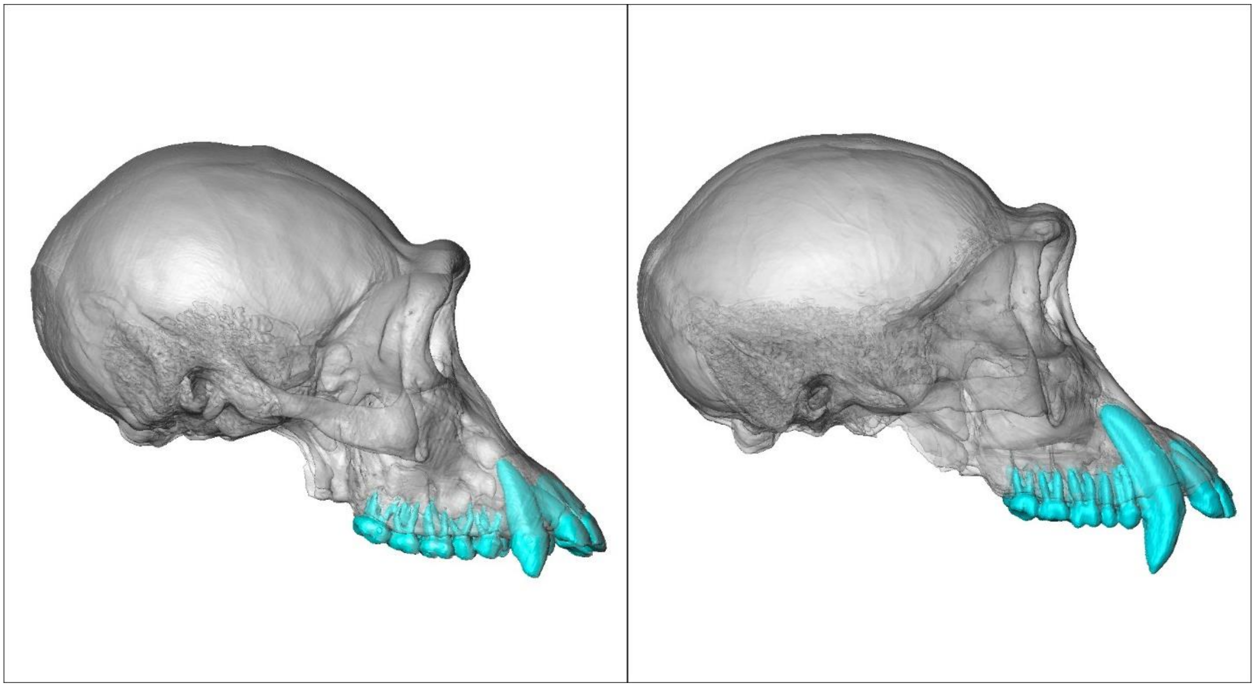

Figure 4.5 Relative prognathism in the adult chimpanzee. Transparent images of adult chimpanzee crania with the permanent dentition in teal. The left cranium (USNM-282763) is one of the more orthognathic in the sample and the cranium on the right (USNM-599172) is one of the more prognathic specimens. In chimpanzees, the canine root extends beyond the subnasal region to the lateral margin of the nasal aperture in the maxilla.

Discussion

In hominin evolution, the reduction of subnasal prognathism and the flattening of the lower face are defining traits that are assumed to be correlated with the anterior dentition (Björk, 1951; Simpson et al., 1991; White et al., 1981). The goal of this paper was to assess the relationship between the anterior dentition, the subnasal region and subnasal prognathism. From the earliest age groups to adulthood, the subnasal angle generally decreased and humans and chimpanzees become more prognathic throughout ontogeny (Viðarsdóttir, O'Higgins, & Stringer, 2002). These results present a pattern where in humans, prognathism increases, but not significantly throughout ontogeny; the deciduous first incisor is correlated with subnasal height; and the permanent anterior tooth root angles are correlated with subnasal prognathism. In chimpanzees, subnasal prognathism significantly increases throughout ontogeny; the permanent first incisor root length is correlated with subnasal height; and the deciduous anterior incisors are correlated with subnasal angle.

Morphometric analyses (Viðarsdóttir et al., 2002) and visual comparison of human fetal and adult crania reveal that prognathism increases throughout ontogeny, but this study quantified subnasal prognathism and compared it across dental stages (Table 4.3). As expected, humans are less prognathic, and have more vertical subnasal regions compared to chimpanzees. In humans, there is a slight decrease in prognathism from DS2 to DS3, and then a large increase in prognathism in DS4 (Table 4.11). These results are similar to the 3D visualizations in Chapter 3 (Figures 3.2, 3.4., 3.6). The decrease in subnasal prognathism from DS2 to DS3 may be related to the increase in subnasal height to accommodate the permanent incisors. In DS4, all of the permanent anterior teeth have erupted, but this is the approximate time that puberty begins and secondary sexual characteristics are expressed (Smith, 1992). In chimpanzees, the increase in prognathism in DS4 may be related to the eruption of the incisors and canines and the developing incisor roots or it may be related to the eruption of the permanent premolars. Spoor et al. (2005) analyzed the facial and mandibular prognathism across a range of primates and fossil hominins. The subnasal angles calculated in this study for adult humans and chimpanzees are comparable to Spoor et al. (2005) and any differences are mostly likely due to orientation during measurement or sample composition. In this study, humans and chimpanzees had a subnasal angle of 67.4°/47.4° compared to 60°/43° in Spoor et al. (2005). The Spoor et al. (2005) human sample is composed of anatomical crania and a pre-industrial sample that includes crania from indigenous populations of six continents. The adult human sample in this study originates solely from South Africa and is likely more prognathic because sub-Saharan African populations are characterized by increased subnasal prognathism compared to Europeans populations (Gill & Rhine, 1990; Lahr, 1996).

The correlation between subnasal morphology and incisor root lengths and root angles varied between species. For instance, the permanent chimpanzee central incisor was correlated with subnasal height (r =0.67), which reflects that the permanent central incisors extend to the margin of the nasal aperture (Villmoare et al., 2013). Thus, the central incisor of chimpanzees can reasonably estimate the subnasal height, but there is some variation that is remains unexplained. In contrast, there is more space between the root apex and the nasal aperture in the adult human subnasal region and very week correlation between incisor root heights and subnasal height. In the shorter, less prognathic face of juvenile humans, there is a moderate correlation between the central deciduous incisor root length and subnasal height. It might be assumed that there would be no correlation among the human deciduous tooth root length and subnasal height because of the developing permanent incisors in the maxilla would produce a taller maxilla, but the developing dental crypts are located postero-superior to the central incisor roots in the maxillae, as opposed to directly superior. It would also be likely that the permanent incisor crowns would also moderately to strongly correlate with subnasal height in the "deciduous" group.

A different pattern was found between the deciduous root inclination, permanent root inclination and the angle of subnasal prognathism in chimpanzees and humans. The correlation between the deciduous chimpanzee incisors and the subnasal angle, and the lack of a correlation between the permeant incisor root angles and the subnasal angle could be explained by the vertical inclination of the chimpanzee incisors with wear. As the incisors wear, the angle of the tooth becomes more vertical to maintain occlusion with the lower dentition and due to the buildup of cementum, a dental tissue that repairs and maintains tooth positon, and the alveolar region becomes slightly more protruding (Villmoare et al., 2013). In this study, severely worn teeth were not analyzed, but teeth with slight to moderate wear were used to increase the craniodental sample size, and this condition of vertical inclination of the incisor is most likely present. Permanent human incisors do not appear to show this pattern, and the incisor root angle of humans is correlated with subnasal angle. In contrast, the human deciduous root angles are not correlated with subnasal angle. This may be a result of the coexistence of deciduous incisor roots and developing permanent crowns in the more orthognathic human subnasal region. From the pattern seen in humans and chimpanzees, incisor root angles should be used cautiously to estimate subnasal angle, particularly if the tooth is worn or there is no crown. The incisor inclination of orthognathic hominins, such as modern humans, *Ardipithecus* and *Paranthropus* may reflect subnasal angle. However, if *Australopithecus* or other prognathic hominin incisors reorient like chimpanzee incisors, then neither the incisor nor the canine root inclination would be a substitute to assess subnasal prognathism.

This study analyzed root angles and incisor and canine root length, but several hypotheses of tooth size and subnasal prognathism relate to the robusticity or enlargement of the anterior teeth roots (Lieberman, 2011; Tobias, 1991). The volume or surface area of the anterior teeth, and not the root length, may strongly correlate to prognathism and subnasal height. The canine also extends lateral to the nasal aperture in chimpanzees and an assessment of maxillary height or a different measure of prognathism may capture the impact of the canine on maxillary form. Although there is a relationship between the teeth and maxilla, researchers debate the directionality of this influence. Incisor crowding (Howe, McNamara, & O'Connor, 1983) and the agenesis or impaction of the third molar (Anderson, Thompson, & Popovich, 1975) are said to be a result of lack of space in the palate and decreased palatal length. Some researchers argue that reduced palate length also contribute to smaller canines and incisors (Björk, 1951; Simpson et al., 1991), while others predict that the dentition influences the subnasal region of modern humans and fossil hominins (Kimbel et al., 2004; Tobias, 1991). This paper and the dissertation indicate that the dentition and subnasal region are integrated, but it is difficult to determine if one or both would direct morphological change as a response to development, masticatory stress, palatal spatial demands, or some other contributing factor.

The orthognathism that characterizes the *Homo* lineage is most likely a result of a combination of factors including the size and shape of the teeth, cranial breadth, basicranial flexion, and changes in the growth of the face. The increase in basicranial flexion in hominins causes the face to rotate under the braincase and the face to be less prognathic (Lieberman, Hallgrímsson, Liu, Parsons, & Jamniczky, 2008; Lieberman et al., 2000), while more robust crania are also more prognathic (Baab, Freidline, Wang, & Hanson, 2010). In addition, alterations to the facial growth and pattern of bone remodeling have been hypothesized to produce prognathism. *Australopithecus* and early *Homo* have similar bone remodeling patterns that produce a more prognathic face while *Paranthropus* and modern humans have a different derived pattern of facial growth that leads to a more orthognathic face (Bromage, 1987, 1989; Lacruz, Bromage, O'Higgins, et al., 2015; Lacruz, Bromage, O’Higgins, et al., 2015). Due to the complex nature of the crania, it is likely that a variety of changes to craniofacial form produced the orthognathic faces of modern humans. There is likely a relationship between the anterior detention and subnasal region in hominins, which reflects the difference in prognathism and orthognathism between humans and chimpanzees. In humans, the first permanent incisor root is correlated with subnasal height and the incisor and canine root angles are correlated with subnasal prognathism. This pattern would be expected in orthognathic hominins, while more prognathic hominins would exhibit a relationship between increased root length, tooth size and subnasal height.

Conclusion

This study analyzed the relationship between subnasal prognathism, subnasal height and the anterior dentition. Subnasal prognathism increased in humans and chimpanzees throughout ontogeny, and different correlation patterns were present in humans and chimpanzees. In humans, the deciduous first incisor was correlated with subnasal height and the permanent incisors root angles roots were strongly correlated with subnasal prognathism. In chimpanzees, the permanent first incisor root length was correlated with subnasal height, the incisor root angles are more vertically inclined and the deciduous incisor root angles are correlated with subnasal angle. In fossil specimens, the use of root angle, or subnasal height may not provide a good estimation of prognathism or the orientation of the subnasal region.

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Chapter 5 Conclusion and synthesis

Summary

The objective of this dissertation was to determine if the face and dentition are two separate modules that can evolve independently or if the face and teeth are tightly integrated in humans and chimpanzees, the closest living phylogenetic relatives of extinct hominins. Whereas pervasive craniodental integration and strong modularity are quite distinct, there is also much "middle ground" between them; this study suggests that while there is some modular structure between the lower face and dentition, these modules strongly covary and cannot be considered independent. The project was divided into three data chapters to accomplish this objective and 3D geometric multivariate analyses and univariate analyses of traditional linear measurements of the crania and dentition were performed to address the research questions.

In the second chapter, the covariation between the lower face and the permanent dentition in adult *Homo* and *Pan* was analyzed in comparison to other paired cranial regions to compare the lower face and teeth to a baseline of integration within the cranium. Humans and chimpanzees have similar patterns of integration between the lower face and the teeth. Individuals with relatively more prognathic lower faces, and taller and longer palates have more protruding, larger anterior teeth. Individuals with relatively broader midfaces, shorter palates, and less prognathic lower faces have more retracted, smaller and shorter anterior teeth. To assess the relative magnitude of integration among cranial regions, pairwise integration magnitudes were calculated among the upper face, lower face, occipital, and dental modules. These results indicate that the pattern and magnitude of integration are similar between adult humans and chimpanzees, suggesting a conservation of covariance throughout evolution (Ackermann & Cheverud, 2000, 2004b; Cheverud, 1996; Marroig & Cheverud, 2001; Marroig et al., 2004; Neaux, 2017; Singh et al., 2012; Villmoare et al., 2014). The magnitude of integration between the lower face and teeth was higher than other pairs of developmentally, functionally or spatially related modules, such as the lower face and upper face, but less integrated than the right and left sides of the dentition. When compared to these other cranial and dental regions, the lower face and teeth are absolutely and relatively more integrated. These results provide additional support to the hypothesis that the lower face and teeth are strongly integrated and demonstrate the range of integration present within the cranium.

Chapter 2 also highlighted several methodological issues that arise in the statistical assessment of the magnitude of morphological integration. For instance, the RV coefficient is sensitive to changes in the sample size and the number of landmarks. Large sample sizes lower the RV coefficient and a higher number of variables increase the RV coefficient (Adams, 2016; Fruciano et al., 2013; Smilde et al., 2009). In Chapter 2, analyses with a large number of landmarks, such as the analyses of integration between the occipital and teeth, had larger than expected RV coefficients and correlation coefficients. Analyses utilizing a large number of landmarks with a small sample will produce inflated magnitudes of integration that aren't comparable to other analyses. This study compared integration magnitudes of humans and chimpanzees with similar sample sizes and landmark numbers and utilized a subset of the landmarks when comparing magnitudes of integration among cranial regions. When each set of paired modules had equivalent sample sizes and landmark numbers, the correlation coefficient, RV coefficient and CR value produced similar integration results. Equivalent landmark numbers and samples sizes were then used to test the relative integration of the lower face and teeth and corroborate the earlier finding that the teeth and lower face are strongly integrated relative to other pairs of craniodental modules.

In Chapter 3, integration throughout ontogeny was analyzed within each human and chimpanzee dental stage and across all dental stages. The goals of this chapter were to analyze the pattern of covariation between the lower face and teeth throughout ontogeny in humans and chimpanzees, determine the magnitude and pattern of integration between the dentition and maxilla, and assess whether the pattern and magnitude changed throughout ontogeny. There was significant shape covariation found between the lower face and permanent teeth throughout ontogeny in humans and chimpanzees. In the combined dental stage analyses of humans and chimpanzees, the maxilla was broader, shorter and relatively taller before and during the eruption for the first molar, while later ontogenetic stages were marked by narrower, more prognathic, shorter palates with more projecting anterior teeth. Integration was also assessed in each dental stage within each species. The magnitudes of integration between the two genera at equivalent stages were similar. The degree of integration was initially high, then declined around the eruption of the first and second molars and finally increased again in adulthood. In the dental stages containing individuals with mixed deciduous and permanent dentition, different patterns of shape change were present in humans and chimpanzees. In the human DS3, integration increased slightly as the incisors and first molars erupted and moved into occlusion which produced more facial shape variation than dental variation. Integration in humans, then declined with the eruption of the second molars and permanent canines (DS4). In chimpanzee DS3 and DS4, integration declined slightly relative to DS2. With the eruption of the permanent second molars and canines during DS4, chimpanzees exhibit slightly more dental than cranial shape variation and some individuals retain the deciduous dentition. In DS4, the magnitude of integration declined in chimpanzees and humans during the eruption of the second permanent molar. During this dental stage, sex hormones and sexual dimorphism are expressed with the onset of puberty, and facial growth continues (Bulygina et al., 2006; Smith, 1992; Smith et al., 1989).

In addition to the juvenile specimens, adult integration was analyzed in Chapter 3 to assess the integration throughout ontogeny. Compared to the Chapter 2 analyses, the general patterns of shape change were similar in Chapter 3. A relatively shorter, broader palate with a longer more vertical subnasal clivus was associated with retracted teeth, while more prognathic specimens with narrower palates had larger more projecting incisors and canines. In Chapter 2, pooled 2B-PLS analyses of the chimpanzee and combined human and chimpanzee sample were performed to eliminate mean shape differences due to sex or species in the analyses. Although the Chapter 2 chimpanzee 2B-PLS was pooled, the adult human and chimpanzee analyses in both chapters had similar patterns of integration. In the sex-pooled analyses of chimpanzees in Chapter 2, the most noticeable visual shape difference compared to the unpooled analyses in Chapter 3 was the reduction in the dimorphism of the canine.

To test hypotheses about the coordinated relationship between the anterior tooth roots and the subnasal region, the fourth chapter analyzed the relationship between the subnasal height and prognathism with anterior root length and inclination. Similar to the ontogeny chapter, increase in prognathism (decrease in subnasal angle) was found throughout ontogeny and chimpanzees were more prognathic than humans. Different patterns of correlation were found between the anterior permanent and deciduous teeth in humans and chimpanzees and subnasal height or prognathism, reflecting differences in the size and orientation of the dentition and subnasal region that are not necessarily apparent in the 3D analyses. For instance, root angles of the permanent human dentition were correlated with subnasal prognathism, while deciduous teeth root were correlated with subnasal prognathism in chimpanzees. In fossil specimens, the use of root angle, or subnasal height may not provide a good estimation of prognathism or the configuration of the subnasal region.

Pattern of shape change

In this dissertation, the lower face and the dentition are strongly integrated. A majority of the covariation and visual shape changes were between the anterior dentition (the incisors and canines) and the subnasal region, palatal breadth and palatal length. In the PLS1 axes in all dental stages, little shape covariation was present between the molars and incisors or the molars and palate. This may also indicate some modularity within the dentition or the presence of submodules within the dentition where the incisors and molars are more modular in the adult sample and across the ontogenetic sample. In addition, the covariance ratio values in chapter 2 and 3 indicate that some modular structure (CR < 1) was present between the face and teeth. Directional selection as a response to new environmental or dietary demands of early fossil hominins like *Paranthropus* may have created submodules within the face and dentition that allowed additional evolutionary change within the dentition. Therefore, a more modular structure between the incisors and molars could explain the relative size differences in teeth such as those in *Paranthropus* (Hlusko et al., 2011). The increased molar size would be unrelated to the relatively small anterior incisors of *Paranthropus*, which would covary with a flat, broad maxilla. The covariation between the lower face and molars, could be further explored by analyzing the development and eruption of all three molars over ontogeny and investigating modularity between the molars and incisors. In this study, the anterior dentition was defined as the incisor and canine, but several studies have reported weak covariation and modularity between incisor and canine size (Delezene, 2015; Grieco et al., 2013). Many of the evolutionary hypotheses about the morphology of the subnasal region of *A. anamensis* (Ward et al., 2010) and *A. afarensis* (Kimbel et al., 2004; Ward et al., 2010) were related to the canine root or canine size. The covariation between the lower face and canine was not explicitly analyzed, but the correlation between the subnasal angle and canine root angle was moderately strong in humans and weak and not statistically significant in chimpanzees. In chimpanzees, other dimensions of the maxilla or measures of prognathism not quantified in these studies may covary with the canines such as facial projection from the zygomatic or maxillary height from the orbits to the alveolar region.

The patterns of shape change between the lower face and teeth were similar, but not identical, between chimps and humans over ontogeny and in the adult only analyses. Humans are less prognathic than chimpanzees and have broader and shorter palates, but with increased age, humans and chimpanzees transition from broader, shorter palates to longer, taller and narrower palates. In both humans and chimpanzees, increased subnasal prognathism was associated with more protruding incisor crowns. In DS3 and DS4, humans and chimpanzees have different patterns of dental eruption, and the differences in length and breadth of the palate are visually apparent, but the coordinated patterns of shape change between humans and chimpanzees are similar. The conservation of patterns of integration across evolutionary time has previously been demonstrated in primates (Ackermann, 2005; Ackermann & Cheverud, 2004b; Singh et al., 2012) and more broadly in mammals (Goswami, 2006b).

If the patterns and magnitudes of integration between the face and teeth have been maintained in humans and chimpanzees, this indicates *Homo* and *Pan* also have similar covariance. Fossil hominins, such as *Paranthropus* or early *Homo,* may also exhibit similar patterns of covariation. Stabilizing selection has been proposed as a mechanism to maintain covariance or correlation structures between traits within a module (Cheverud, 1982; Jamniczky & Hallgrimsson, 2009; Lande, 1980; Melo & Marroig, 2015; Wagner, 1996). Through integration, selection for shared function between traits produces pleiotropy between the selected traits and shared development (Hallgrímsson et al., 2009). With time, stabilizing selection and the conservation of mutation patterns produces stability around an optimum phenotype (Lande, 1980) and stabilizing selection and developmental constraints maintain covariance structure within an organism (Jamniczky & Hallgrimsson, 2009). In humans and chimpanzees, and likely fossil hominins, stabilizing selection may maintain the integration and covariance structure within the face for traits of the lower face and teeth.

While stabilizing selection has maintained the pattern of integration between the teeth and the face, directional selection increases the correlation or magnitude of integration among selected traits and creates modules (Assis, Patton, Hubbe, & Marroig, 2016; Melo & Marroig, 2015; Pavlicev, Cheverud, & Wagner, 2011). Goswami et al. (2014) reported morphological integration may impact the direction of evolution, but does not influence the rates of evolution. In their simulations with carnivoran crania, integration concentrated variation in limited directions, which constrained morphological evolution in certain directions and occasionally produced extreme morphologies (Goswami et al., 2014). If integration constrains morphologies in certain morphospaces, variation only occurs along a single axis, which can produce a large range of phenotypes along this single axis of covariation (Goswami et al., 2014; Klingenberg, 2014). For instance, a cranium with large canines and a prognathic maxilla and a cranium with small incisors and an orthognathic lower face could be two extremes of the lower face and dentition morphospace. The evolutionary change of the dentition and face might also be restricted due to covariation with other modules in the cranium, such as the neurocranium or basicranium. In addition, if the number of cranial morphologies are limited, multiple occurrences of similar cranial morphologies would be possible. For instance, the similar morphological patterns of smaller anterior dentition and reduced prognathism of *Paranthropus,* and *Homo* may be a result of the constrained cranial morphologies due to integration. Alternatively, the similar patterns of integration and morphological similarities between *Paranthropus* and *Homo* may be homoplastic due to similar responses to selection (Ackermann & Cheverud, 2004a).

Morphological integration and modularity arise through selection and genetic drift (Wagner, Pavlicev, & Cheverud, 2007). The strong covariation between the lower face and teeth in this study, the integration within the oral module of the face (Ackermann, 2005; Ackermann & Cheverud, 2004b) and integration among adjacent modules of the dentition, such as the molar and premolars (Gomez-Robles & Polly, 2012; Grieco et al., 2013; Hlusko & Mahaney, 2009; Hlusko et al., 2011) suggest directional selection created the face module and its associated phenotypes, while stabilizing selection maintains the covariation within the face. These results correspond with several studies that report adaptations to the face and maxilla due to natural selection in hominin fossils (Ackermann & Cheverud, 2004a; Schroeder & Ackermann, 2017) and modern humans (Roseman, 2004; Roseman & Weaver, 2004). The derived morphology of *Paranthropus,* facial differences among *Australopithecus,* and the divergence of *Homo* were primarily driven by selection (Ackermann & Cheverud, 2004a) and positive selection is hypothesized to create new maxillary morphologies among paired fossils in the *Homo* lineage, such as between A.L. 666-1 and the Dmanisi *H. erectus* and *H. habilis* to *H. erectus* (Schroeder

& Ackermann, 2017). Many of the same studies of hominin cranial evolution and modern human cranial morphological diversity also report that neutral evolution is a mechanism driving evolutionary change, particularly in the neurocranium (Ackermann & Cheverud, 2004a; Harvati & Weaver, 2006; Roseman, 2004; Roseman & Weaver, 2004; Schroeder & Ackermann, 2017; Schroeder, Roseman, Cheverud, & Ackermann, 2014; Weaver, Roseman, & Stringer, 2007). In neutral evolution, most evolutionary changes are selectively neutral and increase or decrease by genetic drift, or random changes in genotype frequency, and not natural selection (Kimura, 1968). Yet, no one evolutionary process describes human cranial evolution (Roseman, 2016) and the phenotypes in modern and fossil hominins are a result of genetic drift, natural selection, gene flow, and mutation. Selection most likely contributed to the development of new maxillary morphologies, due to environmental or dietary changes, while within species or population craniofacial changes, such as within *Homo,* might be due to genetic drift.

Magnitude of integration

In this study, the magnitude of integration declined during ontogeny in humans and chimpanzees during the eruption of the first and second molars and increased in adults. In previous studies of the crania, integration increased throughout development (Ackermann, 2005; Adams & Collyer, 2016; Zelditch & Carmichael, 1989), the covariance structure continuously changed throughout ontogeny (Mitteroecker & Bookstein, 2009), or integration declined throughout ontogeny (Coquerelle et al., 2010; Polychronis & Halazonetis, 2014). The different integration magnitude results could be explained by the utilization of different methods and calculated magnitudes of integration. Alternatively, the results indicate that integration changes throughout ontogeny, declines in some samples, and increases in other samples depending on the modules that are analyzed. The increase in integration in this study in adults compared to the subadult and juvenile stages (Chapter 3) and the high magnitudes of integration reported in adults (Chapter 2) indicate a maintenance of integration values in the most stable dental stages with evenly distributed variance. Similar magnitudes of integration were present in the stage marked by only deciduous dentition (DS2) and permanent dentition (DS5) where the overall facial or dental shape changes were consistent. The magnitude of integration would most likely be similarly high in adult fossil specimens, as it is in humans and chimpanzees. Evolutionary changes in craniofacial form are due to mutations and increased variation upon which selection can act. If selection acts on variation when there is a decrease in integration during an ontogenetic event like sexual maturity, then craniofacial form can change producing new phenotypes. Studies have reported that the change in magnitude of integration is variance dependent (Hallgrímsson et al., 2009). An increase in variance produces an increase in morphological integration (Gonzalez, Oyhenart, & Hallgrímsson, 2011; Hallgrímsson et al., 2009). In the dental stages with decreased integration (DS3, DS4), the specimens were clustered by dental development, and the variance was limited to certain regions within the larger dental stage. In humans DS3, the eruption of the first incisors impacted the facial shape change, and in chimpanzee DS4, the permanent canine eruption characterized palatal shape changes. This lack of continuous variance may reduce the overall variance and integration within the sample. Due to the nature of museum specimens, it is difficult to find a continuous series of dental eruptions of each tooth. A longitudinal study may reveal more specific timing of the decline in integration and produce more distributed variance. In addition, other factors such as sexual maturity could be compared to the magnitude of integration in a longitudinal study. In Chapter 3, the decline in human and chimpanzee integration occurred in the dental stage characterized by the eruption of the second molar, which is also associated with the approximate time of sexual maturity in chimpanzees and humans (Smith, 1989).

Implications for human evolution

Humans and chimpanzees have similar patterns and magnitudes of integration throughout ontogeny, and this suggests that a correlated response between the dentition and lower face would be expected in fossil hominins. *A. afarensis* has strong subnasal prognathism, a convex nasoalveolar clivus and large, procumbent incisors, with large canines relative to the molar size (Kimbel et al., 2004). If the relatively smaller, non-projecting incisors of *Paranthropus* (McCollum, 1999) evolved from *A. afarensis*, you would expect to see reduced prognathism of the nasoalveolar clivus and perhaps even the taller, broader maxillae, which *Paranthropus* exhibits. These shape changes of the lower face were observed in the combined human and chimpanzee analyses (Fig 2.4). Early *Homo* crania are broadly characterized by a relatively straighter nasoalveolar clivus and weak subnasal prognathism, a more parabolic dental arcade shape, and relatively smaller and vertical anterior dentition (Lieberman et al., 1996). With a reduction in the crowns and roots of the incisors and canines, the lower face would also become less prognathic in *Homo.* The relationships between orthognathism and dental reduction or prognathism and larger anterior dentition throughout the hominin lineage demonstrate strongly integrated traits that are a result of similar masticatory functions (Gunz, 2012; Lieberman et al., 1996) and a restricted range of possible cranial morphologies (Goswami et al., 2014; Klingenberg, 2014).

Future directions

This dissertation primarily focused on the integration between the permanent first incisor, canine and first molar teeth and the lower face throughout ontogeny. While the dental stages were characterized by molar eruption for consistency and comparison to other ontogenetic studies, the molar shape did not covary strongly with shape changes to the lower face. In the anterior face, the canines and incisors strongly covaried with the subnasal region. Perhaps the breadth and length of the palate would covary with the eruption of the molars and premolars and analyzing all of the permanent teeth may reveal more subtle patterns of facial shape change. In addition, integration of the developing dentition in fetal or perinatal crania, or the eruption of the deciduous dentition with the lower face was not quantified or described. Integration could be strongest during fetal growth and up to the eruption of the first molar. Due to my decision to used broad dental stages, these patterns could not be quantified with an appropriate sample size. Furthermore, this dissertation treated the dentition as one unit, but based on the results of this study and other studies that indicate modularity within the dentition (Delezene, 2015; Gomez-Robles & Polly, 2012; Grieco et al., 2013), the integration between individual dental classes and the lower face could be assessed. These analyses would test if the incisor, canine or molar shapes covary with the lower face and if these patterns vary between humans and chimps or sexes. These 2B-PLS analyses would be performed with separate generalized Procrustes analyses for each module to test for complete independence between the two modules analyzed. Separate GPAs are in contrast to the single superimposition utilized in this study that contained the relative covariance between the teeth and the face and defined the shape of the teeth by the landmark configuration of the dentition and the spatial arrangement of the teeth within the maxilla. Preliminary analyses of separate superimpositions have been completed. In adults, 2B-PLS analyses of separate superimpositions of all landmarks of the paired cranial regions from Chapter 2 indicate that the lower face and teeth and the right and left halves of the dentition have similar magnitudes of integration when compared to the single superimpositions, while the other cranial regions have lower magnitudes of integration (Table A.15). Magnitudes of integration of all of the landmarks of the face and teeth were similar to analyses of the lower face and teeth (Table A.15-A.16). When the dental regions were divided into smaller modules in adults, the magnitudes of integration between the lower face and these dental submodules, such as the anterior dentition, were lower in the separate superimpositions than in the single superimpositions and chimpanzees had lower magnitudes of integration than humans (Table A.16). In analyses of smaller subsets of landmarks, the lower face and teeth were relatively as integrated as the upper face and teeth (Table A.17-A.19), but additional subsets should be explored. In the juvenile dental stages, the lower face and teeth magnitudes of integration were lower with separate superimpositions (and often not significant) than with a single GPA. The separate superimpositions of the lower face and teeth contain shape information independent of the orientation and scaling of the two modules relative to each other. This suggests the modules were more integrated in the single GPA as a result of the relative positions and scaling of the lower face and teeth (Table A.20). However, in adults the magnitudes of integration are still high when using a separate or single GPA, and there is a relationship between the lower face and teeth. These results will be explored in the various cranial modules and within the dentition in adults and juveniles to establish a baseline of covariance in the cranium with separate superimpositions of the modules. In the 2B-PLS analyses in Chapters 2 and 3, PLS1 often explained a large portion of the covariance in the analyses. To assess the proportion of variance in the teeth and lower face explained by the lower face and teeth PLS1, the variance of the lower face scores from PLS1, the variance of the teeth scores from PLS1, the total lower face variance, and the total teeth variance were calculated (Table A.21, A.22). In chimpanzees, DS4 had the largest ratios of variance explained by PLS1 for the lower face and teeth (Table A.21), while in humans DS3 had the largest teeth and lower face ratios. The predominance of shape variance in chimpanzee DS4 and human DS3 is consistent with the ontogenetic results in Chapter 3. This distribution of the dental and lower face variance will be explored more in future analyses. Additionally, the inclusion of the entire face or maxilla with the lower face in the previous analyses may indicate slightly different patterns of facial prognathism and shape change in the midface. The large chimpanzee canine roots are often positioned lateral to the nasal aperture, and maxillary height and other facial shape changes may be apparent in those regions. Finally, humans and chimpanzees were utilized in this study to estimate evolutionary patterns of integration. The inclusion of subadult and adult fossils would directly test the association between canine and incisor root and tooth size and the subnasal region.

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Appendix

Table A.1 Chimpanzee lower face and teeth limited landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Lower face	**Teeth**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
ns, pr, ecmLR, ol, mtLR, pm	LR M1 and M2 crown height	0.63	**<0.0001**	0.00048021	**<0.0001**	78.49	0.93	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LR M1, M2 tooth ht	0.58	**<0.0001**	0.00052123	**<0.0001**	70.84	0.93	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LM2 LM1 crown	0.51	**<0.0001**	0.00036678	**<0.0001**	60.95	0.92	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	RM2, RM1 crown	0.50	**<0.0001**	0.00035117	**<0.0001**	57.61	0.91	**<0.0001**
ns, pr, ecmLR, ol, mtLR, sta	LM2 LM1 crown	0.55	**<0.0001**	0.00036473	**<0.0001**	61.04	0.93	**<0.0001**
ns, pr, P3P4LR, mtLR, ol, sta	LR M1 and M2 crown height	0.67	**<0.0001**	0.00045883	**<0.0001**	69.80	0.91	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LR M1, C inf & sup crown; crown ht	0.48	**<0.0001**	0.00034904	**<0.0001**	45.81	0.84	**0.0001**
ns, pr, P3P4LR, mtLR, ol, sta	LR M1, C inf & sup crown; crown ht	0.44	**<0.0001**	0.00036439	**0.0001**	45.92	0.81	**0.0003**
ns, pr, ecmLR, ol, mtLR, pm	LR M1, C inf crown & root tooth ht	0.37	**<0.0001**	0.00075614	**<0.0001**	69.36	0.74	**0.0120**
ns, pr, ecmLR, ol, mtLR, pm	L M1 C crown	0.36	**<0.0001**	0.00035702	**0.004**	37.38	0.76	**0.0007**
ns, pr, ecmLR, ol, mtLR, pm	LR I1,I2 crown height	0.37	**0.0006**	0.00029553	**0.0028**	50.44	0.82	**0.0279**
ns, pr, ecmLR, ol, mtLR, sta	LR I1,I2 crown height	0.42	**<0.0001**	0.00036316	**0.0001**	61.28	0.80	**0.0180**
ns, pr, ecmLR, ol, mtLR, pm	LR I1, I2 inf crown and root; tooth ht	0.47	**<0.0001**	0.00055905	**<0.0001**	65.47	0.80	**0.0009**
ns, pr, ecmLR, ol, mtLR, sta	LR I1, I2 inf crown and root; tooth ht	0.43	**<0.0001**	0.00056099	**<0.0001**	69.00	0.80	**0.0005**
ns, pr, ecmLR, ol, mtLR, pm	LI1, LI2 crown lmks	0.54	**<0.0001**	0.0003543	**<0.0001**	49.40	0.87	**0.0146**
ns, pr, ecmLR, ol, mtLR, pm	RI1, RI2 crown lmks	0.50	**<0.0001**	0.00035353	**<0.0001**	56.22	0.89	**0.0013**
ns, pr, ecmLR, ol, mtLR, sta	LI1, LI2 crown lmks	0.53	**<0.0001**	0.0003298	**<0.0001**	46.76	0.87	**0.0026**
ns, pr, ecmLR, ol, mtLR, pm	LR M2, P4crown ht	0.60	**<0.0001**	0.0004503	**<0.0001**	69.58	0.93	**<0.0001**
ns, pr, ecmLR, ol, mtLR, sta	LR M2, P4crown ht	0.65	**<0.0001**	0.00043784	**<0.0001**	65.86	0.93	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LR M2, P4 tooth ht	0.48	**<0.0001**	0.00039048	**<0.0001**	47.82	0.89	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LM2, LP4 crown lmks	0.44	**<0.0001**	0.00031362	**0.0001**	43.63	0.88	**0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LR I1 C1 crown ht	0.39	**<0.0001**	0.00039089	**0.0074**	38.93	0.75	**0.014**
ns, pr, ecmLR, ol, mtLR, sta	LR I1 C1 tooth ht	0.47	**<0.0001**	0.00063961	**<0.0001**	60.90	0.78	**0.023**
ns, pr, ecmLR, ol, mtLR, pm	LI1, LC crown	0.39	**<0.0001**	0.00044504	**0.0004**	45.04	0.81	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	RL M2 I1 crown ht	0.58	**<0.0001**	0.00043607	**<0.0001**	53.73	0.88	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LM2 LI1 crown	0.70	**<0.0001**	0.00046472	**<0.0001**	55.37	0.93	**<0.0001**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.1 Adult human lower face and teeth landmark subset analyses

***Homo* Module 1**	**Homo Module 2**							
Lower face landmarks	**Teeth landmarks**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
ns, pr, ecmLR, ol, mtLR, pm	LR M1 and M2 crown height	0.60	**<0.0001**	0.00037591	**<0.0001**	43.79	0.88	**0.0174**
ns, pr, ecmLR, ol, mtLR, pm	LR M1, M2 tooth ht	0.47	**<0.0001**	0.00036229	**0.0003**	31.46	0.81	**0.0111**
ns, pr, ecmLR, ol, mtLR, pm	LM2 LM1 crown	0.59	**<0.0001**	0.00049436	**<0.0001**	47.02	0.90	**0.0001**
ns, pr, ecmLR, ol, mtLR, pm	RM2, RM1 crown	0.53	**<0.0001**	0.00039337	**<0.0001**	39.00	0.85	**0.0008**
ns, pr, ecmLR, ol, mtLR, sta	LM2 LM1 crown	0.61	**<0.0001**	0.00048193	**<0.0001**	47.29	0.91	**<0.0001**
ns, pr, P3P4LR, mtLR, ol, sta	LR M1 and M2 crown height	0.60	**<0.0001**	0.00033723	**<0.0001**	36.34	0.87	**0.0226**
ns, pr, ecmLR, ol, mtLR, pm	LR M1, C inf & sup crown; crown ht	0.53	**<0.0001**	0.00048947	**<0.0001**	51.85	0.84	**0.0023**
ns, pr, P3P4LR, mtLR, ol, sta	LR M1, C inf & sup crown; crown ht	0.48	**<0.0001**	0.00031131	**0.0001**	30.22	0.93	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LR M1, C inf crown & root tooth ht	0.39	**<0.0001**	0.00035399	**0.0094**	29.69	0.86	**0.0001**
ns, pr, ecmLR, ol, mtLR, pm	L M1 C crown	0.54	**<0.0001**	0.00059917	**<0.0001**	51.01	0.84	**0.0008**
ns, pr, ecmLR, ol, mtLR, pm	LR I1,I2 crown height	0.40	**<0.0001**	0.00049015	**0.0001**	51.44	0.80	**0.0058**
ns, pr, ecmLR, ol, mtLR, sta	LR I1,I2 crown height	0.40	**<0.0001**	0.0004599	**<0.0001**	52.63	0.80	**0.0255**
ns, pr, ecmLR, ol, mtLR, pm	LR I1, I2 inf crown and root; tooth ht	0.33	**0.0004**	0.00047895	**0.0109**	39.43	0.85	**<0.0001**
ns, pr, ecmLR, ol, mtLR, sta	LR I1, I2 inf crown and root; tooth ht	0.34	**0.0001**	0.00043486	**0.0208**	37.07	0.85	**0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LI1, LI2 crown lmks	0.47	**<0.0001**	0.0005187	**<0.0001**	58.14	0.89	**0.0001**
ns, pr, ecmLR, ol, mtLR, pm	RI1, RI2 crown lmks	0.44	**<0.0001**	0.0005258	**<0.0001**	55.25	0.84	**0.0115**
ns, pr, ecmLR, ol, mtLR, sta	LI1, LI2 crown lmks	0.48	**<0.0001**	0.00048689	**<0.0001**	57.34	0.89	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LR M2, P4crown ht	0.59	**<0.0001**	0.00046782	**<0.0001**	51.47	0.85	**0.0021**
ns, pr, ecmLR, ol, mtLR, sta	LR M2, P4crown ht	0.61	**<0.0001**	0.00045284	**<0.0001**	51.38	0.86	**0.0009**
ns, pr, ecmLR, ol, mtLR, pm	LR M2, P4 tooth ht	0.44	**<0.0001**	0.00038471	**0.0001**	32.30	0.79	**0.0138**
ns, pr, ecmLR, ol, mtLR, pm	LM2, LP4 crown lmks	0.51	**<0.0001**	0.00048071	**<0.0001**	41.40	0.85	**0.0011**
ns, pr, ecmLR, ol, mtLR, pm	LR I1 C1 crown ht	0.40	**<0.0001**	0.00046447	**0.0001**	49.49	0.80	**0.0006**
ns, pr, ecmLR, ol, mtLR, sta	LR I1 C1 tooth ht	0.33	**0.001**	0.00037459	**0.0863**	29.40	0.85	**<0.0001**
ns, pr, ecmLR, ol, mtLR, pm	LI1, LC crown	0.44	**<0.0001**	0.00052197	**<0.0001**	51.90	0.84	**0.0063**
ns, pr, ecmLR, ol, mtLR, pm	LR M2 I1 crown ht	0.51	**<0.0001**	0.00060062	**<0.0001**	58.68	0.82	**0.0014**
ns, pr, ecmLR, ol, mtLR, pm	LM2 LI1 crown	0.63	**<0.0001**	0.00066433	**<0.0001**	59.43	0.89	**<0.0001**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.3 Chimpanzee lower face and teeth limited random landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Lower face random landmarks	**Teeth random landmarks**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
enmR, ecmL, pr, P3P4R, mcli, I2CL, pm, P3P4R	LM1l, RCd, LM2d, RP4l, RI2root, Rcsup, LM3root, LCd	0.4732	**<0.0001**	0.00031387	**<0.0001**	38.148	0.84389	**<0.0001**
pr, enmR, enmL, mtR, mroR, ol, sta, mcli	LM1m, RI1root, RM3sup, RM2inf, Rcinf, LM2inf, LI1root, LCinf	0.5116	**<0.0001**	0.00052847	**<0.0001**	57.537	0.89674	**<0.0001**
mtR, I2CL, ecmL, mtR, mroR, ol, sta, mcli	LM3 inf, LCd, LCm, LP3d, RP4d, LM3sup, LI1inf, LM3l	0.5421	**<0.0001**	0.00039041	**<0.0001**	51.233	0.89607	**<0.0001**
ol, mroR, mtR, enmL, enmR, pr, mcli, I2CR	LM2root, RM1s, LI1root, RP4sup, RCsup, RCd, LP3m, RI1sup	0.5934	**<0.0001**	0.00041052	**<0.0001**	50.453	0.89149	**<0.0001**
ol, mroL, I2CR, enmL, pm, sta, mroL, ecmR, exmR	LM3d, LP4root, LM3l, LP4d, RM2inf, RM1inf, RI1root, RM2m	0.5481	**<0.0001**	0.0005818	**<0.0001**	65.89	0.86059	**<0.0001**
ol, pm, I2CR, mroL, mtR, pr, I2DL, P3P4L	RM1root, RP3sup, RM1m, LM1sup, RM3d, RI1m, RM2sup, LM1l	0.6447	**<0.0001**	0.0006177	**<0.0001**	56.064	0.88958	**<0.0001**
ecmR, mtL, sta, P3P4L, mroL, ol, mtR, I2CR	LCm, LM3root, LP4m, RI2m, LM3sup, LM2inf, LCsup, RP3root	0.5146	**<0.0001**	0.00037506	**<0.0001**	48.684	0.87625	**<0.0001**
mroR, pm, P3P4R, I2CL, mroL, ecmR, ns, pr	RP3root, RP3sup, RI2l, LCm, LI2d, RI1l, LM3d, RM1m	0.5672	**<0.0001**	0.00058911	**<0.0001**	65.104	0.88716	**<0.0001**
enmR, mtL, pm, ecmL, ms, ol, ecmR, P3P4R	RP3root,LM3inf, RM1root, RP4m, RM2inf, LP3root, LM3sup, LM2sup	0.4723	**<0.0001**	0.00040433	**<0.0001**	55.841	0.82421	**0.0008**
enmL, enmR, P3P4R, ecmR, ecmL, mcli, ol, mroL	RM3root, RI1l, RCm, LP3l, RCd, LM3root, RM3inf	0.5605	**<0.0001**	0.00042407	**<0.0001**	56.712	0.89123	**<0.0001**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.4. Human lower face and teeth limited random landmark analyses

***Homo* Module 1**	**Homo Module 2**							
Lower face random landmarks	**Teeth random landmarks**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
ol, ns, enmR, sta, inc, mtR, enmL, P3P4R	RM1sup, RM2sup, Lcsup, LM3sup, RI2sup, RI2m, Rcinf, LI2inf	0.45	**<0.0001**	0.00049017	0.0001	43.58	0.83	**0.0007**
enmL, pr, I2CL, I2CR, inc, mtR, enmL, P3P4R	LM3inf, LI2root, RP4l, RM1root, LI2inf, RM3l, RM2root, RI1inf	0.52	**<0.0001**	0.00059789	<0.0001	48.01	0.89	**<0.0001**
sta, mcli, I2CL, mtL, mtR, pm, P3P4R, pr	LM2root, LI2root, LI1l, RM2inf, RM2m, LM1d, LI2m, RI1root	0.37	**<0.0001**	0.00040091	0.001	41.80	0.75	**0.0031**
I2CL, mcli, enmR, P3P4L, ns, mtL, I2CR, enmL	RM2sup, LM2l, LCd, LP4m, LI2d, RI2root, LCinf, LP3d	0.57	**<0.0001**	0.00050987	<0.0001	45.30	0.91	**<0.0001**
mtR, pr, ns, I2CR, ecmR, P3P4R, enmL, mcli	RM3sup, RCd, RM3l, RCinf, RM3d, LI2m, LP4inf, LM3d	0.53	**<0.0001**	0.00057031	<0.0001	67.12	0.86	**<0.0001**
mtL, I2CR, enmL, mroR, mcli, P3P4L, ol, mroL	LI1d, RI2sup, RM2l, LCroot, RI1l, RCroot, LCsup, RI2d	0.52	**<0.0001**	0.00048281	<0.0001	34.90	0.85	**0.0002**
ns, pm, mroR, I2CR, I2CL, mtR, enmR, ecmR	RI2m, LCl, LM1m, LP3root, RM1inf, LI1sup, LM1sup, RP4d	0.47	**<0.0001**	0.00040563	0.0002	36.60	0.82	**0.0012**
enmR, P3P4L, I2CL, ol, pr, ecmR, mcli, sta	LM2l, RP3inf, LP4inf, RP4root, RI1m, RM2l, LP4root, RM2sup	0.49	**<0.0001**	0.00064789	<0.0001	58.02	0.83	**0.0004**
enmR, P3P4L, I2CL, ol, pr, ecmR,	LM2l, RP3inf, LP4inf, RP4root, RI1m,	0.53	**<0.0001**	0.0004882	<0.0001	48.25	0.89	**0.0001**
mtR, inc, ecmL, mtL, mroR, mroL, ol, ns	RP4m, RI2d, LM1inf, LCinf, LI2l, LP4m, RP4root, LM3root	0.52	**<0.0001**	0.000533	<0.0001	44.36	0.90	**0.0019**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.5 Chimpanzee upper face and lower face limited landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Upper face	**Lower face**	**RV**	**P-value**	**PLS1 SV**	**SV p**	**% cov**	**r PLS1**	**r-PLS1 p**
Eye LR: osup, d, ec, zo,	ns, pr, ecmLR, ol, mtLR, pm	0.31	**0.002**	0.00031129	**0.003**	46.59	0.83	**0.001**
Eye LR: osup, d, ec, zo,	ns, pr, ecmLR, ol, mtLR, sta	0.35	**0.000**	0.00032904	**0.001**	47.57	0.84	**0.002**
nose: n, rhi, inLR, alLR	ns, pr, ecmLR, ol, pm	0.44	**<0.0001**	0.00050317	**0.000**	50.07	0.87	**<0.0001**
nose: n, rhi, inLR, alLR ifLR	ns, pr, ecmLR, ol, mtLR, sta	0.54	**<0.0001**	0.00043063	**0.000**	36.79	0.83	**0.000**
g, n, fmtLR, zoLR, zmLR	ns, pr, ecmLR, ol, mtLR, sta	0.38	**<0.0001**	0.00033381	**0.000**	40.05	0.82	**0.001**
face: n, rhi, zoLR, zmLR	ns, pr, ecmLR, ol, pm	0.38	**<0.0001**	0.00050444	**0.000**	47.13	0.76	**0.030**
n, rhi osup, dL, ecL, zoL, zmL, alL	ns, pr, ecmLR, ol, mtLR, sta	0.44	**<0.0001**	0.00043383	**<0.0001**	49.98	0.87	**<0.0001**
LR fmt, zo, zm, ju	ns, pr, ecmLR, ol, mtLR, pm	0.47	**<0.0001**	0.00040541	**<0.0001**	45.93	0.83	**0.004**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.6 Human upper face and lower face limited landmark analyses

***Homo* Module 1**	**Homo Module 2**							
Upper face	**Lower face**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
Eye LR: osup, d, ec, zo	ns, pr, ecmLR, ol, mtLR, pm	0.42	**0.0001**	0.00038629	**<0.0001**	57.70	0.91	**0.02**
Eye LR: osup, d, ec, zo	ns, pr, ecmLR, ol, mtLR, sta	0.44	**<0.0001**	0.00038074	**<0.0001**	57.80	0.92	**0.03**
nose: n, rhi, inLR, alLR ifLR	ns, pr, ecmLR, ol, mtLR, pm	0.35	**<0.0001**	0.00047329	**0.0001**	42.62	0.71	**0.04**
nose: n, rhi, inLR, alLR ifLR	ns, pr, ecmLR, ol, mtLR, sta	0.35	**<0.0001**	0.00045917	**<0.0001**	43.46	0.73	**0.02**
g, n, fmtLR, zoLR, zmLR	ns, pr, ecmLR, ol, mtLR, sta	0.47	**<0.0001**	0.0003836	**<0.0001**	51.21	0.91	**0.01**
g, n, fmtLR, zoLR, zmLR	ns, pr, ecmLR, ol, mtLR, pm	0.47	**<0.0001**	0.00038785	**<0.0001**	49.51	0.90	**0.01**
n, rhi, osupL, dL, ecL, zoL, zmL, alL	ns, pr, ecmLR, ol, mtLR, sta	0.33	**0.0002**	0.00035022	**0.0064**	38.45	0.75	**0.01**
LR fmt, zo, zm, ju	ns, pr, ecmLR, ol, mtLR, pm	0.46	**<0.0001**	0.00025828	**<0.0001**	33.10	0.89	**0.00**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.7 Chimpanzee upper face and teeth limited landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Upper face	**Teeth**	**RV**	**P-value**	**PLS1 SV**	**SV p**	**% cov**	**r PLS1**	**r-PLS1 p**
Eye LR: osup, d, ec, zo	LR M1 and M2 crown height	0.22	0.1483	0.00010891	0.1678	40.11	0.59	0.52
Eye LR: osup, d, ec, zo	LM2 LM1 crown	0.33	**0.0007**	0.00011452	**0.0004**	49.62	0.89	0.25
Eye LR: osup, d, ec, zo	LR M1, M2 tooth ht	0.30	**0.0067**	0.00018477	**0.0008**	52.72	0.74	0.11
Eye LR: osup, d, ec, zo	LR I1,I2 crown height	0.29	**0.0122**	0.00022928	**0.0021**	70.04	0.79	0.52
Eye LR: osup, d, ec, zo	teeth I1, I2 inf crown and root; tooth ht	0.28	**0.0015**	0.00039446	**0.0003**	74.43	0.72	0.06
Eye LR: osup, d, ec, zo	LI1, LI2 crown lmks	0.38	**0.002**	0.00018704	**0.0005**	64.53	0.90	0.53
Eye LR: osup, d, ec, zo	LR M1, C inf & sup crown; crown ht	0.23	0.0862	0.00018245	0.1672	42.62	0.76	**0.005**
Eye LR: osup, d, ec, zo	LR M1, C inf crown & root tooth ht	0.24	**0.0126**	0.00031441	**0.0304**	52.31	0.71	**0.011**
Eye LR: osup, d, ec, zo	L M1 C crown	0.26	**0.0055**	0.00018749	**0.0414**	41.33	0.75	**0.003**
nose: n, rhi, inLR, alLR ifLR	LM2 LM1 crown	0.59	**0.000264**	0.00026359	**<0.0001**	73.42	0.97	0.05
nose: n, rhi, inLR, alLR ifLR	LRM1 and LRM2 crown height	0.35	0.067	0.00019528	**0.0277**	50.07	0.90	0.23
nose: n, rhi, inLR, alLR ifLR	LR M1, M2 tooth ht	0.35	**0.0067**	0.00023742	**0.012**	44.37	0.82	0.27
nose: n, rhi, inLR, alLR ifLR	LR I1,I2 crown height	0.42	**0.001**	0.00049414	**0.0004**	78.52	0.84	0.66
nose: n, rhi, inLR, alLR ifLR	teeth I1, I2 inf crown and root; tooth ht	0.47	**<0.0001**	0.00090351	**<0.0001**	83.20	0.78	0.31
nose: n, rhi, inLR, alLR ifLR	LI1, LI2 crown lmks	0.62	**<0.0001**	0.00045851	**<0.0001**	78.25	0.92	0.70
g, n, fmtLR, zoLR, zmLR	LR M1 and M2 crown height	0.31	**0.0024**	0.00014782	**0.0126**	38.40	0.69	0.30
g, n, fmtLR, zoLR, zmLR	LR M1, C inf & sup crown; crown ht	0.34	**0.0002**	0.00027497	**0.0002**	52.03	0.74	**0.03**
g, n, fmtLR, zoLR, zmLR	LR I1,I2 crown height	0.46	**0.0001**	0.00034812	**0.0001**	72.57	0.95	0.18

Values in bold are statistically significant at $p \leq 0.05$.

Table A.8 Human upper face and teeth limited landmark analyses

***Homo* Module 1**	**Homo Module 2**							
Upper face	**Teeth**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
Eye LR: osup, d, ec, zo	LR M1 and M2 crown height	0.52	**0.0004**	0.0004284	**<0.0001**	84.68	0.85	0.334
Eye LR: osup, d, ec, zo	LM2 LM1 crown	0.64	**<0.0001**	0.00029241	**<0.0001**	80.24	0.98	**0.0001**
Eye LR: osup, d, ec, zo	LR M1, M2 tooth ht	0.53	**<0.0001**	0.00046226	**<0.0001**	77.99	0.90	0.278
Eye LR: osup, d, ec, zo	LR I1,I2 crown height	0.63	**<0.0001**	0.00040122	**<0.0001**	83.21	0.97	0.172
Eye LR: osup, d, ec, zo	teeth I1, I2 inf crown and root; tooth ht	0.50	**<0.0001**	0.00052125	**<0.0001**	77.33	0.95	0.270
Eye LR: osup, d, ec, zo	LI1, LI2 crown lmks	0.70	**<0.0001**	0.00035955	**<0.0001**	86.33	0.98	**0.001**
Eye LR: osup, d, ec, zo	LR M1, C inf & sup crown; crown ht	0.52	**0.0001**	0.00041885	**<0.0001**	80.92	0.89	0.627
Eye LR: osup, d, ec, zo	LR M1, C inf crown & root tooth ht	0.55	**<0.0001**	0.00051446	**<0.0001**	77.61	0.91	0.502
Eye LR: osup, d, ec, zo	L M1 C crown	0.64	**<0.0001**	0.0004	<.0001	86.17	0.97	0.333
nose: n, rhi, inLR, alLR ifLR	LM2 LM1 crown	0.36	**0.0001**	0.00019287	**<0.0001**	47.63	0.86	0.172
nose: n, rhi, inLR, alLR ifLR	LRM1 and LM2 crown height	0.41	**0.0003**	0.00047607	**<0.0001**	84.06	0.82	0.500
nose: n, rhi, inLR, alLR ifLR	LR M1, M2 tooth ht	0.39	**0.0005**	0.00043375	**<0.0001**	67.13	0.83	0.157
nose: n, rhi, inLR, alLR ifLR	LR I1,I2 crown height	0.35	**0.0002**	0.00042047	**<0.0001**	63.62	0.85	0.138
nose: n, rhi, inLR, alLR ifLR	LR I1, I2 tooth ht	0.34	**0.0013**	0.00063793	**0.0001**	66.16	0.80	0.211
nose: n, rhi, inLR, alLR ifLR	LI1, LI2 crown lmks	0.37	**0.0008**	0.00029595	**<0.0001**	62.53	0.93	0.047
g, n, fmtLR, zoLR, zmLR	LR M1 and M2 crown height	0.59	**<0.0001**	0.00048427	**<0.0001**	76.22	0.90	0.142
g, n, fmtLR, zoLR, zmLR	LR M1, C inf & sup crown; crown ht	0.53	**<0.0001**	0.00042526	**<0.0001**	73.18	0.93	0.076
g, n, fmtLR, zoLR, zmLR	LR I1,I2 crown height	0.68	**<0.0001**	0.00052599	**<0.0001**	81.30	0.97	**<0.0001**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.9 Chimpanzee lower face and occipital limited landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Lower face	**Occipital**	**RV**	**P-value**	**PLS1 SV**	**SV p**	**% cov**	**r PLS1**	**r-PLS1 p**
ns, pr, ecmLR, ol, mtLR, pm	spba, ba, op, jfLR, l, asLR	0.33	**<0.0001**	0.00021358	**<0.0001**	57.86	0.73	**0.008**
ns, pr, ecmLR, ol, mtLR, sta	spba, ba, op, fmlLR, l, asLR	0.30	**<0.0001**	0.00020126	**0.000**	59.26	0.71	**0.008**
ns, pr, ecmLR, ol, mtLR, sta	ba, op, jflLR, l, in, asLR	0.32	**<0.0001**	0.00020953	**<0.0001**	61.22	0.72	**0.014**
ns, pr, P3P4LR, mtLR, ol, sta	ba, op, jflLR, l, in, asLR	0.36	**<0.0001**	0.00019462	**<0.0001**	60.11	0.77	**0.002**
ns, pr, P3P4LR, mtLR, ol, sta	spba, ba, op, fmlLR, l, asLR	0.31	**0.000**	0.00017897	**0.000**	56.46	0.73	**0.003**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.10 Human lower face and occipital limited landmark analyses

***Homo* Module 1**	**Homo Module 2**							
Lower face	**Occipital**	**RV**	**RV pval**	**PLS1 SV**	**SV p**	**% cov**	**r-pls1**	**r-pls1 p**
ns, pr, ecmLR, ol, mtLR, pm	spba, ba, op, jfLR, l, asLR	0.41	**<0.0001**	0.00021455	**<0.0001**	39.14	0.79	0.179
ns, pr, ecmLR, ol, mtLR, sta	spba, ba, op, fmlLR, l, asLR	0.41	**<0.0001**	0.000215	**0.0002**	38.67	0.76	0.392
ns, pr, ecmLR, ol, mtLR, sta	ba, op, jflLR, l, in, asLR	0.35	**0.0001**	0.00017778	**0.0095**	32.29	0.77	0.057
ns, pr, P3P4LR, mtLR, ol, sta	ba, op, jflLR, l, in, asLR	0.37	**<0.0001**	0.00014614	**0.0054**	32.73	0.81	**0.026**
ns, pr, P3P4LR, mtLR, ol, sta	spba, ba, op, fmlLR, l, asLR	0.44	**<0.0001**	0.00018764	**0.0001**	37.52	0.84	**0.018**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.11 Chimpanzee upper face and occipital limited landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Upper face	**Occipital**	**RV**	**P-value**	**PLS1 SV**	**SV p**	**% cov**	**r PLS1**	**r-PLS1 p**
Eye LR: osup, d, ec, zo	spba, ba, op, jfLR, l, asLR	0.36	**<0.0001**	0.0002356	**<0.0001**	53.90	0.77	**0.002**
nose: n, rhi, inLR, alLR ifLR	spba, ba, op, jfLR, l, asLR	0.27	**0.0078**	0.00017081	**0.006**	51.34	0.68	0.070
g, n, fmtLR, zoLR, zmLR	spba, ba, op, jfLR, l, asLR	0.37	**0.0001**	0.00025379	**<0.0001**	53.98	0.76	**0.007**
n, rhi osup, dL, ecL, zoL, zmL, alL	spba, ba, op, jfLR, l, asLR	0.33	**<0.0001**	0.00022633	**0.0009**	46.97	0.73	**0.016**
LR fmt, zo, zm, ju	spba, ba, op, jfLR, l, asLR	0.42	**<0.0001**	0.00030768	**<0.0001**	62.04	0.79	**0.030**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.12 Human upper face and occipital limited landmark analyses

***Homo* Module 1**	**Homo Module 2**							
Upper face	**Occipital**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
Eye LR: osup, d, ec, zo	spba, ba, op, jfLR, l, asLR	0.30	**0.0146**	0.00012812	0.1802	29.56	0.60	0.768
nose: n, rhi, inLR, alLR ifLR	spba, ba, op, jfLR, l, asLR	0.34	**0.0001**	0.00016458	**0.0031**	40.13	0.77	0.088
g, n, fmtLR, zoLR, zmLR	spba, ba, op, jfLR, l, asLR	0.30	**0.0073**	0.00016301	**0.0235**	35.19	0.72	0.285
n, rhi osup, dL, ecL, zoL, zmL, alL	spba, ba, op, jfLR, l, asLR	0.32	**0.0014**	0.0001685	**0.0058**	39.46	0.77	0.057
LR fmt, zo, zm, ju	spba, ba, op, jfLR, l, asLR	0.32	**0.0045**	0.00017725	**0.0035**	38.79	0.74	0.225

Values in bold are statistically significant at $p \leq 0.05$.

Table A.13 Chimpanzee occipital and teeth limited landmark analyses

***Pan* Module 1**	***Pan* Module 2**							
Occipital	**Teeth**	**RV**	**P-value**	**PLS1 SV**	**SV p**	**% cov**	**r PLS1**	**r-PLS1 p**
spba, ba, op, jfLR, l, asLR	LR M1 and M2 crown height	0.33	**0.0005**	0.00015435	**0.0007**	60.53	0.71	0.265
spba, ba, op, jfLR, l, asLR	RM2, RM1 crown	0.47	**<0.0001**	0.00009248	**<0.0001**	49.70	0.88	0.933
spba, ba, op, jfLR, l, asLR	LR M1, M2 tooth ht	0.34	**0.0004**	0.0001477	**0.0014**	51.36	0.74	0.453
spba, ba, op, jfLR, l, asLR	LR M1, C inf & sup crown crown ht	0.23	**0.0291**	0.0001191	0.0552	46.56	0.72	**0.010**
spba, ba, op, jfLR, l, asLR	LR M1, C inf crown & root tooth ht	0.17	0.2811	0.00013192	0.5507	38.59	0.57	0.204
spba, ba, op, jfLR, l, asLR	L M1 C crown	0.17	0.461	0.00007972	0.6201	35.80	0.54	0.525
spba, ba, op, jfLR, l, asLR	teeth I1 and I2 crown height	0.27	**0.0057**	0.00007623	**0.0136**	51.34	0.77	**0.044**
spba, ba, op, jfLR, l, asLR	teeth I1, I2 inf crown and root; tooth ht	0.31	**<0.0001**	0.00016591	**<0.0001**	72.76	0.68	**0.006**
spba, ba, op, jfLR, l, asLR	LI1, LI2 crown lmks	0.42	**<0.0001**	0.00008223	**<0.0001**	57.48	0.80	0.203
spba, ba, op, jfLR, l, asLR	LR M2, P4crown ht	0.34	**0.0003**	0.00014259	**0.0011**	53.93	0.71	0.259
spba, ba, op, jfLR, l, asLR	LR M2, P4 tooth ht	0.33	**0.001**	0.00013663	**0.0066**	43.92	0.73	0.431
spba, ba, op, jfLR, l, asLR	LR M2, P4 tooth ht	0.31	**0.0015**	0.00013318	**0.0024**	48.30	0.68	0.376
spba, ba, op, jfLR, l, asLR	LM2, LP4 crown lmks	0.41	**<0.0001**	0.00010612	**0.0005**	47.57	0.74	0.655
spba, ba, op, jfLR, l, asLR	LR I1 C1 crown ht	0.30	**0.0002**	0.00013811	**0.0008**	61.02	0.66	**0.025**
spba, ba, op, jfLR, l, asLR	LR I1 C1 tooth ht	0.18	0.1491	0.00014018	0.4185	42.42	0.61	0.170
spba, ba, op, jfLR, l, asLR	LI1, LC crown	0.25	**0.0067**	0.00012247	**0.0045**	58.51	0.67	**0.030**

Values in bold are statistically significant at $p \leq 0.05$.

Table A.14 Human occipital and teeth limited landmark analyses

***Homo* Module 1**	**Homo Module 2**							
Occipital	**Teeth**	**RV**	**RV p**	**PLS1 SV**	**SV p**	**% cov**	**r-PLS1**	**r-PLS1 p**
spba, ba, op, jfLR, l, asLR	LR M1 and M2 crown height	0.39	**0.0002**	0.00022001	**0.0006**	49.55	0.83	0.477
spba, ba, op, jfLR, l, asLR	RM2, RM1 crown	0.63	**<0.0001**	0.00018297	**<0.0001**	49.58	0.93	0.089
spba, ba, op, jfLR, l, asLR	LR M1, M2 tooth ht	0.39	**0.0001**	0.00020085	**0.0028**	39.89	0.75	0.362
spba, ba, op, jfLR, l, asLR	LR M1, C inf & sup crown	0.39	**0.0004**	0.00017101	**0.0008**	46.45	0.94	0.051
spba, ba, op, jfLR, l, asLR	LR M1, C inf crown & root tooth ht	0.42	**<0.0001**	0.00017993	**0.0001**	42.94	0.90	0.055
spba, ba, op, jfLR, l, asLR	L M1 C crown	0.54	**<0.0001**	0.00018633	**<0.0001**	56.51	0.92	0.490
spba, ba, op, jfLR, l, asLR	LR I1,I2 crown height	0.54	**<0.0001**	0.00013721	**<0.0001**	51.93	0.95	0.202
spba, ba, op, jfLR, l, asLR	teeth I1, I2 inf crown and root; tooth ht	0.38	**<0.0001**	0.00016952	**<0.0001**	52.79	0.82	0.484
spba, ba, op, jfLR, l, asLR	teeth I1, I2 inf crown and root; tooth ht	0.32	**0.0085**	0.0001109	**0.0815**	37.13	0.91	0.052
spba, ba, op, jfLR, l, asLR	LI1, LI2 crown lmks	0.61	**<0.0001**	0.00012023	**<0.0001**	51.57	0.93	0.646
spba, ba, op, jfLR, l, asLR	LR M2, P4crown ht	0.40	**0.0002**	0.00021273	**0.0001**	50.28	0.85	0.384
spba, ba, op, jfLR, l, asLR	LR M2, P4 tooth ht	0.39	**<0.0001**	0.00019588	**0.0008**	40.70	0.83	0.186
spba, ba, op, jfLR, l, asLR	LM2, LP4 crown lmks	0.49	**<0.0001**	0.00016751	**<0.0001**	46.64	0.91	0.058
spba, ba, op, jfLR, l, asLR	LR I1 C1 crown ht	0.45	**<0.0001**	0.00014399	**0.0001**	51.43	0.94	0.160
spba, ba, op, jfLR, l, asLR	LR I1 C1 tooth ht	0.40	**<0.0001**	0.00017121	**<0.0001**	51.45	0.82	0.539
spba, ba, op, jfLR, l, asLR	LI1, LC crown	0.59	**<0.0001**	0.00014385	**<0.0001**	53.44	0.97	**0.005**

Values in bold are statistically significant at $p \leq 0.0$

Table A.75 Adult chimpanzee and human magnitudes of integration of paired cranial regions of all landmarks in analyses with separate GPAs for each module compared to a single GPA for each module. Abbreviations: r-PLS1 is the correlation coefficient of the first paired axes of the 2B-PLS, CR = Covariance ratio, p = p-value. Magnitudes of integration are lower in the separate GPA analyses and often nonsignificant compared to the single GPA analyses. All landmarks were used and this may overestimate the relationship between modules with large number of landmarks, such as the occipital and teeth. The separate GPA of the lower face and teeth modules have similar magnitudes of integration to the single GPA. Lower face and teeth magnitudes of integration utilizing all landmarks are relatively very high.

			Separate GPA				**Single GPA**						
Module 1	**Module 2**	**Species**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**CR**	**CR p**	**CR Confidence Interval**
Lower Face	Teeth	*Chimp*	0.94	**<.0001**	0.64	**<.0001**	0.92	**<0.001**	0.60	**<0.0001**	0.95	**0.042**	0.934 - 0.987
		Human	0.94	**0.001**	0.60	**0.001**	0.85	**0.0003**	0.53	**<0.0001**	0.90	**0.001**	0.878 - 0.967
Upper Face	Lower Face	*Chimp*	0.70	0.046	0.36	**<.0001**	0.86	**<0.001**	0.49	**<0.0001**	0.83	**0.002**	0.820 - 0.926
		Human	0.78	0.098	0.37	**0.034**	0.92	**<0.001**	0.55	**<0.0001**	0.73	**0.001**	0.710 - 0.870
Upper Face	Teeth	*Chimp*	0.74	**0.004**	0.32	**0.005**	0.93	**<0.001**	0.56	**<0.0001**	0.74	**0.001**	0.735 - 0.864
		Human	0.63	0.488	0.29	0.460	0.84	**0.0281**	0.46	**0.0004**	0.75	**0.001**	0.719 - 0.865
Lower Face	Occipital	*Chimp*	0.68	**0.038**	0.28	**0.009**	0.75	**0.0011**	0.36	**0.0001**	0.67	**0.001**	0.661 - 0.831
		Human	0.73	0.101	0.25	0.377	0.75	0.083	0.36	**0.0024**	0.74	**0.001**	0.731 - 0.893
Upper Face	Occipital	*Chimp*	0.69	**0.029**	0.26	**0.02**	0.86	**0.029**	0.40	**<0.001**	0.71	**0.001**	0.708 - 0.838
		Human	0.68	0.42	0.28	0.189	0.75	0.1308	0.35	**0.002**	0.76	**0.001**	0.725 - 0.887
Occipital	Teeth	*Chimp*	0.68	**0.032**	0.28	**0.005**	0.93	**<0.001**	0.57	**<0.001**	0.60	**0.001**	0.601 - 0.769
		Human	0.55	0.603	0.21	0.674	0.88	**0.0006**	0.44	**<0.0001**	0.77	**0.001**	0.743 - 0.892
Teeth Left	Teeth Right	*Chimp*	0.96	**<.0001**	0.82	**<.0001**	0.97	**<0.001**	0.88	**<0.001**	1.00	0.243	0.981 - 1.104
		Human	0.91	**0.001**	0.72	**0.001**	0.97	**<0.001**	0.87	**<0.001**	0.91	**0.001**	0.896 - 0.952

Values in bold are statistically significant at $p \leq 0.05$.

Table A.16 Adult human and chimpanzee magnitudes of integration of the face and teeth with separate GPAs for each module compared to a single GPA for both modules. Abbreviations: r-PLS1 is the correlation coefficient of the first paired axes of the 2bB-PLS, CR = Covariance ratio, p = p-value. The chimpanzee analyses with separate GPAs have been sex mean centered in MorphoJ. Only the human analyses r-PLS1 and RV were performed with a single GPA. When analyzing all landmarks of the lower face and different classes of the dentition, the r-PLS1 of separate GPAs were not necessarily lower in humans compared to the single GPA. The RV of separate GPAs was similar or lower in humans. The analyses of the anterior dentition, incisors, canines and lower face had lower magnitudes of integration in the separate GPA analyses. Magnitudes of integration (r-PLS1) were lower in chimpanzees compared to humans, except in the analyses of the entire face and dentition and the lower face and anterior dentition.

			Separate GPA				**Single GPA**						
Module 1	**Module 2**	**Species**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**CR**	**CR p**	**CR Confidence Interval**
Face	Teeth	*Chimp*	0.96	**<.0001**	0.82	**<.0001**					0.83	**0.001**	0.824 - 0.912
		Human	0.87	**0.001**	0.42	**0.002**	0.90	**0.001**	0.54	**0.001**	0.82	**0.001**	0.795 - 0.908
Lower face	Teeth anterior	*Chimp*	0.81	**0.001**	0.44	**<.0001**					0.92	**0.011**	0.887 - 0.972
		Human	0.78	**0.006**	0.40	**0.001**	0.86	**0.001**	0.50	**0.001**	0.80	**0.001**	0.768 - 0.907
Lower face	Teeth posterior	*Chimp*	0.77	**0.004**	0.45	**<.0001**					0.85	**0.001**	0.828 - 0.930
		Human	0.89	**0.001**	0.54	**0.001**	0.86	**0.001**	0.56	**0.001**	0.83	**0.001**	0.816 - 0.922
Lower face	Incisors	*Chimp*	0.68	0.092	0.32	**0.003**					0.92	**0.001**	0.870 - 0.961
		Human	0.78	**0.005**	0.36	**0.003**	0.85	**0.001**	0.47	**0.001**	0.78	**0.001**	0.727 - 0.890
Lower face	Canines	*Chimp*	0.57	0.279	0.19	0.046					0.57	**0.001**	0.580 - 0.753
		Human	0.68	0.133	0.23	0.167	0.83	**0.001**	0.45	**0.001**	0.80	**0.001**	0.787- 0.918
Lower face	Premolars	*Chimp*	0.67	0.126	0.35	**<.0001**					0.74	**0.001**	0.741 - 0.868
		Human	0.84	**0.002**	0.39	**0.001**	0.76	**0.029**	0.41	**0.001**	0.74	**0.001**	0.746 - 0.867
Lower face	Molars-M2, M1	*Chimp*	0.73	**0.004**	0.36	**<.0001**					0.85	**0.001**	0.813 - 0.927
		Human	0.86	**0.001**	0.48	**0.001**	0.89	**0.001**	0.58	**0.001**	0.84	**0.001**	0.779 - 0.924

Values in bold are statistically significant at $p \leq 0.05$.

Table A.17 Summary of adult human subset magnitude of integration analyses. Separate GPA magnitudes are lower than single GPA analyses.

		Separate GPA				Single GPA			
Module 1	**Module 2**	**Avg r-pls**	**Range r-pls**	**Avg RV**	**Range RV**	**Avg r-pls**	**Range r-pls**	**Avg RV**	**Range RV**
Lower Face	**Teeth**	0.65	0.55 - 0.85	0.26	0.20 - 0.41	0.80	0.54 - 0.89	0.56	0.4 - 0.63
Upper Face	**Lower Face**	0.61	0.19 - 0.24	0.21	0.19 - 0.24	0.84	0.74 - 0.91	0.46	0.33 - 0.47

Table A.18 Adult human magnitudes of integration of upper face-lower face subsets. The analyses with separate GPAs have lower magnitudes of integration and many are not significant (p > 0.05).

		Separate GPA				Single GPA			
Upper face landmarks	**Lower face landmarks**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**
g, n, fmtLR, zoLR, zmLR	ns, pr, ecmLR, ol, mtLR, pm	0.56	0.721	0.21	0.196	0.90	**0.0127**	0.47	**<.0001**
"	ns, pr, ecmLR, ol, mtLR, sta	0.60	0.459	0.21	0.182	0.91	**0.0071**	0.47	**<.0001**
n, rhi, osupL, dL, ecL, zoL, zmL, alL	ns, pr, ecmLR, ol, mtLR, pm	0.65	0.199	0.24	**0.037**	0.74	**0.0097**	0.36	**<.0001**
"	ns, pr, ecmLR, ol, mtLR, sta	0.68	0.127	0.24	0.045	0.75	0.0064	0.33	**0.0002**
LR fmt, zo, zm, ju	ns, pr, ecmLR, ol, mtLR, pm	0.62	0.308	0.20	0.212	0.89	**0.0016**	0.46	**<.0001**
"	ns, pr, ecmLR, ol, mtLR, sta	0.58	0.598	0.19	0.432				

Values in bold are statistically significant at $p \leq 0.05$.

Table A.19 Adult human magnitudes of integration of lower face and teeth subsets. Landmarks were limited to eight in each module. The analyses with separate GPAs have lower magnitudes of integration and many are not significant. Analyses using the crown heights have higher magnitudes of integration and similar values in separate and single GPAs.

		Separate GPA				Single GPA			
Lower face landmarks	**Teeth landmarks**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**
ns, pr, ecmLR, ol, mtLR, pm	LM1, LC crown	0.55	0.765	0.22	0.176	0.54	**<.0001**	0.84	**0.0008**
"	LR M1, C crown height	0.75	**0.002**	0.34	**0.001**	0.53	**<.0001**	0.84	**0.0023**
"	LR M2, P4 crown height	0.80	**0.002**	0.34	**0.001**	0.85	**0.0021**	0.59	**<.0001**
"	LM2, LP4 crown	0.56	0.642	0.24	0.053	0.85	**0.0011**	0.51	**<.0001**
"	LR I1, C1 crown height	0.70	**0.007**	0.22	**0.018**	0.80	**0.0006**	0.40	**<.0001**
"	LI1, LC crown	0.69	0.109	0.22	0.241	0.84	**0.0063**	0.44	**<.0001**
"	LM2, LM1 crown	0.58	0.68	0.29	**0.001**	0.90	**0.0001**	0.59	**<.0001**
"	RM2, RM1 crown	0.68	0.062	0.30	**0.001**	0.85	**0.0008**	0.53	**<.0001**
"	LI1, LI2 crown	0.56	0.569	0.18	0.395	0.89	**0.0001**	0.47	**<.0001**
"	LR I1, I2 crown height	0.60	0.084	0.20	**0.036**	0.80	**0.0058**	0.40	**<.0001**
"	LI1, RI1 crown	0.58	0.527	0.22	0.1				
"	LC, RC crown	0.55	0.553	0.20	0.145				
"	LR M2, I1 crown height	0.85	**0.001**	0.41	**0.001**	0.82	**0.0014**	0.51	**<.0001**
"	LM2, LI1 crown	0.60	0.556	0.26	**0.016**	0.89	**<.0001**	0.63	**<.0001**
"	LM1, LI1 crown	0.67	0.165	0.25	0.062				
"	RM1, RI1 crown	0.63	0.293	0.24	0.058				

Values in bold are statistically significant at $p \leq 0.05$.

Table A.20 Lower face and teeth magnitudes of integration throughout ontogeny in chimpanzee and humans. Analyses performed with a separate GPA and single GPA of the lower face and dental landmarks. All landmarks in each module were utilized. The RV coefficients in the separate GPA analyses are lower than in the single GPA analyses. The r-PLS1 of chimpanzee DS2, 3 and 4, and human DS3 and DS4 are lower and have p-vales greater than 0.05. In adults, the magnitudes of integration between the lower face and teeth are similar in both analyses. In humans in the separate GPA, DS3 has the lowest magnitude compared to DS4 in the single GPA. Chimpanzee DS2-5 has a much lower r-PLS1 (less integrated) in the separate GPA than in the single GPA analysis.

	Chimpanzee separate GPA				**Chimpanzee single GPA**						
	r-PLS1	**r-PLS1 p**	**RV**	**RV p**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**CR**	**CR p**	**CR Confidence Interval**
DS2	0.66	0.765	0.40	**0.029**	0.89	**0.002**	0.55	**0.001**	0.85	**0.001**	0.817 - 0.961
DS3	0.68	0.048	0.27	**0.043**	0.87	**0.001**	0.49	**0.001**	0.78	**0.001**	0.741 - 0.921
DS4	0.54	0.064	0.22	**0.016**	0.83	**0.001**	0.56	**0.001**	0.80	**0.001**	0.711 - 0.926
DS5	0.86	**0.002**	0.47	**<.0001**	0.88	**0.001**	0.49	**0.001**	0.81	**0.002**	0.794 - 0.936
DS2-5	0.51	**<.0001**	0.87	**<.0001**	0.98	**<.0001**					

	Human separate GPA				**Human single GPA**						
	r-PLS1	**r-PLS1 p**	**RV**	**RV p**	**r-PLS1**	**r-PLS1 p**	**RV**	**RV p**	**CR**	**CR p**	**CR Confidence Interval**
DS2	0.84	**0.034**	0.51	**0.003**	0.85	**0.018**	0.51	**0.001**	0.81	**0.001**	0.776 - 0.943
DS3	0.65	0.275	0.17	0.842	0.92	**0.001**	0.68	**0.001**	0.86	**0.001**	0.799 - 0.961
DS4	0.74	0.176	0.37	**0.031**	0.78	0.089	0.46	**0.004**	0.76	**0.001**	0.768 - 0.905
DS5	0.92	**<.0001**	0.55	**<.0001**	0.92	**0.001**	0.64	**0.001**	0.91	**0.012**	0.895 - 0.974
DS2-5	0.89	**<.0001**	0.73	**<.0001**	0.99	**<.0001**					

Values in bold are statistically significant at $p \leq 0.05$.

Table A.21 Proportion of variance explained by the lower face and teeth in chimpanzees. To assess the proportion of variance in the teeth and lower face explained by the lower face and teeth PLS1, the variance of the lower face scores from PLS1, the variance of the teeth scores from PLS1, the total lower face variance, and the total teeth variance were calculated. The total lower face variance and total teeth variance were calculated from separate principal component analyses of the lower face and teeth. The proportion was calculated as the variance of the PLS1 scores for a module to the total variance of that module. DS4 has the largest ratios of variance explained by PLS1 for the lower face and teeth.

DS	Variance LF PLS1 scores	VarianceTeeth PLS1 scores	LF variance	Teeth variance	Ratio LF	Ratio Teeth
DS2	0.001100	0.001478	0.008616	0.016225	0.128	0.098
DS3	0.000912	0.002247	0.007539	0.011207	0.121	0.200
DS4	0.004071	0.014060	0.016729	0.029685	0.243	0.507
DS5	0.000233	0.000785	0.004428	0.005508	0.053	0.143

Table A.22 Proportion of variance explained by the lower face and teeth in humans. To assess the proportion of variance in the teeth and lower face explained by PLS1, the variance of the lower face scores from PLS1, the variance of the teeth scores from PLS1, the total lower face variance, and the total teeth variance were calculated. The total lower face variance and total teeth variance were calculated from separate principal component analyses of the lower face and teeth. The proportion was calculated as the variance of the PLS1 scores for a module to the total variance of the module. In humans, DS3 has the largest ratios of variance explained by PLS1 for the lower face and teeth.

DS	Variance LF PLS1 scores	Variance Teeth PLS1 scores	LF variance	Teeth variance	Ratio LF	Ratio Teeth
DS2	0.000975	0.001809	0.008032	0.017914	0.121	0.101
DS3	0.004467	0.005812	0.010749	0.019130	0.416	0.304
DS4	0.000555	0.000828	0.006983	0.007114	0.080	0.116
DS5	0.000435	0.000701	0.006355	0.004163	0.068	0.168