MAXILLARY SUTURES AS AN INDICATOR OF ADULT AGE AT DEATH: REDUCING ERROR AND CODIFYING APPROACHES

By

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To Jacob and Isaac, for support and encouragement, but also for lots of laughs, and to Baby Wime, who made sure I got this done

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MAXILLARY SUTURES AS AN INDICATOR OF ADULT AGE AT DEATH: REDUCING ERROR AND CODIFYING APPROACHES

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This research examines the palate in terms of sutural fusion and age. The study sample is drawn from documented modern and historic U.S. and Japanese skeletal collections (*n*=762 individuals). The research design employed stratified random sampling in order to balance age, sex, and ancestry. Sutural fusion was examined via ordinal scoring systems and quantification through digital measurement; sutural complexity for each of the measured palatal sutures was also calculated. Summary fusion scores were compared to age, demographic groups, biomechanical proxy variables – wear, tooth loss, and sutural complexity – and palatal variants.

Results indicate that sutural fusion in terms of age is best summarized using a 15-section/4-phase summary score. Measurement of the sutures captures less variation in terms of age than a summary score based on ordinal scoring, likely due to the inability to measure the incisive suture. Palatal suture fusion is greater in males and individuals of African ancestry than females and individuals of Asian or European ancestry; Asian individuals have the lowest average fusion. No secular trends in palatal suture fusion are noted.

Fusion has positive associations with wear and tooth loss, and a negative association with sutural complexity. Complexity shows no association with wear, tooth loss, or age; wear and tooth loss are positively associated with age and each other. This indicates that sutural complexity affects fusion, but that sutural complexity is not influenced by age, wear, or tooth loss. Simpler sutures show a tendency to fuse before more complex ones, even across the sexes and ancestral groups. Very few palatal variants are associated with fusion or age, though almost all show significantly different frequencies by ancestry.

Multiple regression analyses for fusion and age indicate that age, sex, sutural complexity, palatine torus expression, and their interactions significantly affect fusion, while fusion, sex, ancestry, tooth loss, maxillary tori and exostoses, and their interactions affect the prediction of age from skeletal remains. For both models, 50% of the variation in the response variable is explained by variation in the predictor variables. A simplified multiple regression model indicates that age can be predicted with a standard error of 14.6 years.

CHAPTER 1
INTRODUCTION

Age estimation based on skeletal indicators is an important component of bioarchaeological, paleodemographical, and forensic anthropological analyses. It provides key information in describing demographic compositions of human groups, investigating the health of past populations, and contributing to the identification of missing persons. In order to be useful for these purposes, age estimates should be close to actual ages at death (accurate) and have small ranges (precise).

To estimate age, the biological anthropologist compares the skeletal and dental elements of an individual with relevant reference standards. The most commonly used methods rely on growth, development, and macroscopic bony changes in non-moveable joints, though microscopic methods are also available and anthropologists often consider the extent of age-related pathology and bone quality when estimating age (e.g., osteophytosis, osteopenia, and osteoporosis). Age estimation methods rely on a correlation between chronological and biological age – the actual amount of time a person has been alive and the individual's stage of physiological development and degeneration observed in the skeleton, respectively.

Complications in Skeletal Age Estimation

Skeletal age estimation is problematic due to an imperfect correlation between chronological and biological age, one that decreases further with advanced age (Christensen et al., 2014). This tendency to have increased inaccuracy for age estimates of older individuals is known as the trajectory effect (Nawrocki, 2010). With increased age, there is a coincident increase in the dispersion of values from a least-squares regression line that relates age at death to a skeletal indicator or method, producing a cone-shape that opens to the right. Since growth and developmental processes are well understood, relatively uniform across human populations, largely genetically controlled, and changes occur regularly and at small intervals, age estimation from the skeletal and dental remains of individuals under the age of 18 years is both accurate and precise. However, once growth and development is complete, age estimation must rely on processes of skeletal degeneration, which are far more variable and less well understood, resulting in larger age intervals. Larger age intervals can lead to decreased utility of age as a variable in anthropological studies.

Variation in the aging process is generally related to inter-individual variation. Environmental factors such as an individual's health, nutrition, and socioeconomic status contribute to the aging process, as do genetic factors such as an individual's ancestry (geographic origin of his or her ancestors) and sex (Kemkes-Grottenthaler, 2002). Other factors include individual rates of senescence, mechanical loading patterns, and developmental asymmetry (Kemkes-Grottenthaler, 2002). It is very difficult to segregate these variables and their effects since there is a complex and poorly understood interaction between genes and environment in terms of aging (Scheuer and Black, 2000). The longer a person lives, the more time he or she is subjected to myriad environmental factors, and an individual's susceptibly to certain environmental factors may be affected by his or her genetic make-up.

An additional effect on the estimation of age at death is secular change over time. Secular change refers to a non-evolutionary short- or long-term trend; when used in biological anthropology, it commonly refers to a change in skeletal dimensions or shapes or the rates of maturation over time. In the United States, secular trends in height, cranial size and shape, and maturational times are observed between the 19th and 20th centuries, with modern Americans generally being taller, having taller and longer cranial vaults but narrower vaults and faces, and maturing earlier than their historic counterparts (e.g., Angel, 1976; Jantz and Jantz, 1999; Jantz and Meadows Jantz, 2000; Langley-Shirley and Jantz, 2010). Thus methods that are developed on reference samples from a certain time period may potentially introduce bias when used for individuals from a different era. This is one of the issues underlying the problem of age mimicry, in which the underlying demographic structure of a method's reference sample artificially imposes this structure on samples aged with the reference method (Bocquet-Appel and Masset, 1982).

Variation in the aging process and imperfect methods mean that continued research in skeletal age estimation is necessary in order improve adult age estimation methods. This research entails collecting data on documented individuals while also carefully considering the demographic composition of the research sample to make it as balanced as possible (Bocquet-Appel and Masset, 1982; Hoppa and Vaupel, 2002a). It is important to note that skeletal collections may not accurately represent the populations from which they are drawn because the sample is most often biased in terms of sex, ancestry, age composition, and socioeconomic status (Hunt and Albanese, 2005; Komar and Buikstra, 2008; Komar and Grivas, 2008). The demographic information available for most documented skeletal collections commonly includes sex, ancestry, stature, birth and death dates, from which age at death and time period the individual lived can be calculated. Other variables, such as individual health and socioeconomic status, nutritional intake, developmental asymmetry, loading patterns, and populational rates of senescence are not variables that are typically recorded and are more challenging to investigate. One solution is to collect additional data that can serve to better elucidate these factors, even in the absence of specific documentation. Examples of this include: linear enamel hypoplasias for health, dental wear for mechanical loading, and observations from both left and right sides to investigate asymmetry. The fundamentals of the aging process and skeletal age estimation are discussed in greater detail in Chapter 2.

Sutures and Age Estimation

One of the earliest methods developed to estimate age for adult skeletal remains is cranial suture obliteration. Cranial suture age estimation is based on the age-progressive synostosis of cranial sutures, with older individuals exhibiting greater amounts of obliteration as compared to younger individuals, who exhibit largely patent sutures (Brooks, 1955; Meindl and Lovejoy, 1985). Though cranial suture age estimation is used as early as the 1500s, it is codified as a method employing the vault sutures in a documented skeletal collection in the 1920s (Todd and Lyon, 1924; Todd and Lyon, 1925a; Todd and Lyon, 1925b; Todd and Lyon, 1925c; Ashley-Montagu, 1938). Since that time, it has been one of the more controversial methods of age estimation due to concerns about accuracy, precision, and variables other than age affecting sutural fusion (Ashley-Montagu, 1938; Brooks, 1955; Hershkovitz et al., 1997; Kroman and Thompson, 2009). While the cranial sutures are not typically the first choice for skeletal age estimation, the cranial sutures are still used to estimate age, especially considering the skull is the most commonly recognized human element and thus encountered frequently by the biological anthropologist (Nawrocki, 1998; Garvin and Passalacqua, 2012).

Interest in improving cranial suture age estimation has extended examination of the sutures to other areas of the cranium (e.g., facial skeleton and hard palate). In the United States, age estimation using the sutures of the hard palate has largely followed the work of Mann and colleagues (1987; 1991) but has not been widely employed in skeletal age estimation (Brown, 2009). This may be related to general skepticism concerning the validity of suture closure as an indicator of age or more specifically to problems with applying the palatal method, such as the lack of a standardized protocol and confusion with the Mann et al. (1991) system (Brown, 2010). The Mann et al. (1991) maxillary suture age method estimates age with rates of inaccuracy and bias that are similar to methods using the vault sutures, sternal ends of the fourth rib, and the pubic symphysis (Ginter, 2005; Brown, 2009). Differing scoring methods and statistical procedures employed in numerous cranial suture closure methods only serve to further obfuscate the use of suture closure as a means of estimating age at death. Previous studies have been temporally and geographically limited (e.g., Mann et al., 1987; Mann et al., 1991; Ginter, 2005; Sakaue and Adachi, 2007; Beauthier et al., 2010; Apostolidou et al., 2011); there has been no comprehensive, large-scale project to examine palatal suture closure. Additional concerns include the unbalanced study samples employed in the reference method (i.e., unequal representation of age/sex/ancestral groups) and a paucity of research investigating how variables other than age affect closure of the palatal sutures.

Due to the delayed closure of facial sutures as compared to cranial vault sutures, palatal sutures may be useful in estimating age for older adults (Persson and Thilander, 1977; Wang et al., 2006). Given the trajectory effect, methods that can provide age estimates in the notoriously difficult period of advanced age are particularly useful. Though developed on American individuals of African and European ancestry, the maxillary suture method has also been shown to be useful for estimating minimum age at death in Japanese individuals (Sakaue and Adachi, 2007). Thus age estimation from the maxillary sutures could potentially be useful in biological anthropology, provided that certain limitations are addressed, such as: examination of sutural closure in a larger, more diverse, and balanced sample; consideration of factors besides age that affect palatal suture closure (e.g., ancestry, sex, secular trends, masticatory forces, or diet); and standardization of the method to enable its use by practitioners. Cranial and maxillary suture age estimation is discussed in greater detail in Chapter 2.

Biomechanical Considerations

The primary role of the palate is to support mastication. In fact, chewing-related activities account for the largest routine loads on the skull as a whole (Rogers, 1984). Because of the regular nature of feeding activity, the effect of mastication on palatal structure and sutural fusion should be considered when examining the relationship of sutural closure and age. However, like the imperfect correlation of skeletal age and chronological age, the form of the palate is not entirely correlated to loading and its biomechanical environment is challenging to characterize (Hotzman, 2010).

While it is useful to understand how function affects form, there are several issues with inferring function from form in the palate. Like many skeletal structures, the facial skeleton is constrained by growth, geometry, and material make-up, and its form does not represent optimization of the structure for solely feeding purposes (Thomas and Reif, 1993; Hylander and Johnson, 1997). The skull is a complex structure composed of skeletal elements of varying thicknesses and shapes, joined by fibrous sutures, and it does not exhibit an overall pattern of deformation (Herring and Teng, 2000; Herring and Ochareon, 2005). This means that unlike long bones and limbs, it is difficult to model the cranial biomechanical environment as a single structure, and isolated, regional approaches are recommended (Herring et al., 2001; Herring and Ochareon, 2005). Models are particularly beneficial in instances where experimentally obtained values are not possible or very difficult to obtain, such as in living human subjects (Koolstra, 2002; Herring and Ochareon, 2005; Koc et al., 2010), but they are imperfect representations of a complex and dynamic system. For example, modeling the palate as a shell, plate, and beam did not produce strain values comparable to those that were experimentally obtained (Hotzman, 2010).

Contributing further to the interpretive challenge of facial function and form are the masticatory muscles. These muscles are heterogeneous, architecturally complex, and mechanically redundant, and attach to cranial bone through aponeuroses with varying orientations rather than connecting directly to the bone (Koolstra, 2002; Herring, 2007). Occlusal forces from chewing and incising are transmitted to the alveolar bone not by direct muscle attachments, but via the periodontal ligament, which mediates force from the teeth to the skeletal structure. The only major joint of the masticatory system is the temporomandibular joint, and this joint is not located on the maxillae or palatines nor is it an efficient lever (Koolstra, 2002). Additionally, intra-individual variation in musculature and overall bite force contributes to difficulties in characterizing the mechanical environment of the palate and tooth loss can drastically alter the loads experience by the masticatory complex (Koc et al., 2010).

Despite these complications, facial morphology still reflects jaw movement, and the overall cranial strain pattern during mastication is shear or torsion (Daegling and Hylander, 1997; Herring, 2007). Generally, individuals who are subjected to greater masticatory loads have more robust muscles and skeletal structures than those who experience decreased loading during chewing. The skeletal components of the masticatory system are not static and can respond to altered function through bone remodeling. For example, in rats fed a soft diet, which reduces loading of the masticatory system, decreased growth rate and change in facial morphology is noted (Kiliaridis et al., 1985). American secular trends of decreased facial width and increased facial height can also be attributed at least in part to dietary change following the introduction of processed foods in the 1950s (Jantz and Meadows Jantz, 2000; Wescott and Jantz, 2005; Skorpinski, 2014). In evolutionary terms, the introduction of the secondary palate to the mammalian skull increases strength and stiffness during bending and torsion of the maxilla, as demonstrated in experiments on American opossum (*Dibelphis virginiana*) (Thomason and Russell, 1986).

Sutures, the fibrous joints of the cranium, are also an important component of the masticatory system as they allow for both strength and flexibility. Sutures have their own strain environment that differs from the cranium, largely due to differences in their material make-up. Like the craniofacial elements, sutures have regionally-specific loading regimes, and also lend themselves to regional approaches. The local loading environment also contributes to sutural morphology, with highly interdigitated (complex) sutures having greater energy absorption potential that straight (simple) sutures due to increased surface area along the sutural margin (Jaslow, 1990). Growth, loading environment, and sutural morphology are related, necessitating an understanding of all three to investigate potential effects on masticatory form but also sutural closure. Palatal growth, development, form, and function is discussed in greater detail in Chapter 3.

Research Goals

This research aims to refine adult age estimation based on the hard palate through the analysis of the fusion of its sutures and morphological traits that may relate to age or suture closure, and by providing a comprehensive, codified, and standardized approach to maxillary suture age estimation. It also attempts to relate the functional role of the palate to variation seen in fusion patterns and rates. In order to do so, maxillary suture age estimation methods developed to-date are investigated as are the statistical methods used in cranial suture age estimation, the growth and development of the human palate and its sutures, and the effects of function on this area of the skeleton. This research is certainly not the first in any of these areas, but it organizes approximately two decades of work pertaining to age estimation using the maxillary sutures, provides a comprehensive source for age estimation of the palate, incorporates a greater diversity of skeletal collections than has been previously employed, and accounts for potential covariates with palatal suture closure beyond age.

Given the small and temporally and geographically disjointed samples used in previous research, this research increases the sample size and diversity for the palatal age estimation method with data from multiple documented skeletal collections in the United States and Japan. The sample represents individuals from modern and historic time periods from all three major ancestral groups (African, Asian, and European), both sexes, and balanced age categories. Data are collected on the fusion of individual palatal and facial sutures and sections of palatal sutures, and three ordinal scoring methods are tested along with the quantification of sutural fusion. Additional data on palatal variants and data that serve as proxies for biomechanical forces, such as measures of sutural complexity and shape, antemortem tooth loss, and dental wear are also collected. The inherent interrelatedness of cranial traits and the inability to examine any trait in isolation requires the consideration of as many factors as possible to better elucidate the relationship, if present, of palatal suture closure and age.

Research Questions

1. What is the relationship between maxillary suture closure and age?

It is expected that there will be some degree of correlation between maxillary sutural fusion and age since this has been demonstrated in previous studies of the maxillary sutures as an isolated system and when used in conjunction with cranial vault sutures (Meindl and Lovejoy, 1985; Mann et al., 1987; Mann et al., 1991; Nawrocki, 1998). The strength of the relationship may vary depending on the number and/or length of locations scored and the way those locations are analyzed (e.g., as categorical-, ordinal-, interval-, or ratio-level variables). Wheatley (1996) found a lower correlation of sutures with age than Nawrocki (1998), but the former scored only 1 cm sections, while the latter scored the entire suture length. Age estimation using the palatal sutures has largely incorporated ordinal-level variables, with limited use of interval- or ratio-level data. In addition to scoring the four palatal sutures, two facial control sutures (nasofrontal and zygomaticomaxillary) are scored in order to examine the relationship between age and closure in other areas of the facial skeleton: one that is subjected to similar masticatory loading (zygomaticomaxillary) and one that undergoes less loading during mastication (nasofrontal) (Rogers, 1984; Wroe et al., 2007).

2. How does group affiliation influence maxillary suture closure?

Group affiliation includes sex, ancestry, and time period (historic or modern). Previous studies have found differences in suture fusion between males and females, with males undergoing sutural fusion earlier than females, although females exhibit a more regular fusion tempo (Ashley-Montagu, 1938; Mann et al., 1991; Nawrocki, 1998). Ancestral differences are less clear, with some studies finding no difference in cranial suture fusion between European and African Americans (Meindl and Lovejoy, 1985; Mann et al., 1991), while others find significant differences between these groups (Galera et al., 1998; Nawrocki, 1998). Testing the Mann revised method in a Japanese sample, Sakaue and Adachi (2007) did not find that it performed well, though it is useful for providing a minimum age. Likewise, secular trends are observed variably in suture closure, with Masset (1989) reporting earlier suture closure in modern individuals and Nawrocki (1998) reporting later closure for modern individuals. Zambrano (2005) does not find any systematic secular trends between historic and modern individuals for vault sutures using the equations provided by Nawrocki (1998). Because of the results of previous studies, it is unclear what differences, if any, might be present among groups in terms of palatal sutural fusion.

3. How do biomechanical factors influence maxillary suture closure?

In this research, the main biomechanical variable investigated is bite force, though other palatal variants that may affect the biomechanical environment of the palate are explored (see Research Question 4, below). As less masticatory loading occurs, sutures have the potential to exhibit osseous bridging and/or closure when sutural margins approach. Based on previous experimental studies that have found altered craniofacial form and increased fusion alongside decreased bite force (Engström et al., 1986; Hinton, 1988; Wheatley, 1996; Skorpinski, 2014), it is expected that sutural fusion will be seen more commonly in individuals with decreased bite force as measured by lower rates of dental wear and higher rates of antemortem tooth loss (AMTL). However, there is the potential that extreme dental wear that results in dentine exposure could lead to dental disease and tooth loss, so the relationship of dental wear and AMTL is also examined.

Sutural complexity can also be related to bite force and sutural fusion. Simpler sutures are more likely to be seen where loading is predominantly tensile, while more complex sutures are generally indicative of a compressive loading environment (Rafferty and Herring, 1999; Herring and Ochareon, 2005). Tensile sutures may resist fusion to some extent because of continuous growth at margins brought about by tensile forces. However, increased sutural complexity may reflect an adaptation to greater loading environments, resulting in similar strain regardless of observed sutural complexity. If this is the case, there should be no relationship of dental wear and sutural complexity, as sutures have adapted to account for greater loads. In terms of fusion, complexity may interact with force, producing results that suggest that there is less fusion in individuals with greater bite force, as measured by higher rates of dental wear and little to no AMTL. Fusion may also be more related to sutural morphology than force since diet has also been shown to be unrelated to midpalatal sutural complexity in certain primate species (Hotzman, 2004).

4. What are the relationships of palatal variants to age, demographic group, and palatal biomechanics?

Palatal variants have some degree of utility in assigning an individual's sex, ancestry, or age (Hauser and De Stefano, 1989). Because of this, they are often used in forensic anthropology, bioarchaeology, and paleodemography to support group membership. The relationship of palatal variants to biomechanical factors and palatal sutural fusion, however, is not currently well understood. For example, it has been hypothesized that the presence of a raised area of bone along the midpalatal suture (*torus palatinus*) is related to increased masticatory stresses resulting in the need for buttressing along the center portion of the palate (Hooton, 1946). This relationship is not universally agreed upon, with other researchers attributing expression to genes or a combination of genetic pre-programming and environmental stressors (Woo, 1950; Hassett, 2006). Additionally, multiple other palatal traits have been studied with only limited investigation of their relationship to masticatory forces or fusion of the palatal sutures. These traits include: transverse palatine suture and overall palate shape, palatine bridging, *crista marginalis*, lesser palatine foramina, and more generally, overall bone quality and porosity. This research investigates the frequencies of palatal variants across three ancestral groups and in both sexes, and the relationships of variants to age and certain biomechanical variables as discussed in Research Question 3, above. If a variant has demographic classificatory power, it is expected that it will occur with greater frequency in a certain group over another. If a variant is related to masticatory function, it is expected that it will be related to dental wear, sutural complexity, and/or AMTL, if those variables are shown to reflect masticatory stresses.

Chapter Outline

This dissertation is composed of seven chapters. Chapter 1 provides an introduction to the research and outlines research questions. Chapter 2 is an overview of the aging process and skeletal age estimation, with particular focus on the use of sutures to estimate age. Chapter 3 presents the growth, development, and function of the human palate, and ways in which palatal traits are employed for group assignment. Chapter 4 describes the materials and methods used in this research, and Chapter 5 presents results. Chapter 6 discusses these results and their implications, and Chapter 7 summarizes this research.

CHAPTER 2
SKELETAL AGE ESTIMATION

The estimation of age at death from skeletal remains is an important area of research in biological anthropology because it directly contributes to knowledge about human variation; however, it remains particularly challenging for adult individuals. Skeletal age-at-death estimation is employed in the sub-fields of forensic anthropology, paleodemography, and bioarchaeology to develop age profiles of individuals or groups. These age profiles contribute to the identification of skeletal remains, the understanding of past diseases through mortality profiles and life expectancies, and the reconstruction of past lifeways and demographic structures. In order to understand how skeletal biologists conduct age estimation and the inherent challenges in doing so, the aging process is outlined, followed by skeletal growth and development, skeletal age estimation, and the statistics used in estimating age at death from skeletal remains. The final section of this chapter deals exclusively with age estimation using the cranial sutures.

Age and Aging

Age is the length of time an organism has existed, and it can be described chronologically or biologically. Chronological age is measured by the time a person has lived since his or her day of birth (e.g., years, months, days), while biological age is the stage of physiological development of an individual irrespective of how long he or she has been alive. Aging in the strictest sense is the “progressive loss of function accompanied by decreased fertility and increasing mortality with advanced age” (Kirkwood and Austad, 2000: p 233), but it can broadly be defined as the process of getting older.

Aging is dictated by internal (genetic) and external (environmental [e.g., health, disease, trauma]) variables, which leads to great interpersonal heterogeneity in the environmental variables throughout his or her life, and the dissimilar genetic make-ups among individuals also contribute to variation. Additionally, the interaction between genes and environment is complex, and it is difficult to isolate single causal factors to explain inter-individual differences (Scheuer and Black, 2000). Aging also depends on a combination of genes unique to the individual (private) and genes shared among groups of individuals (public) (Kirkwood and Austad, 2000).

The human life cycle is comprised of multiple progressive stages, beginning with fertilization, and continuing through prenatal life, birth, postnatal life (infant, child, juvenile, adolescent, adult), maturity, senescence, and ending with death (Bogin, 1999). Within the human life cycle, the process of aging is generally divided into two distinct stages: growth/development and degeneration. A third stage, maintenance, may be added on the continuum between growth and development and degeneration, but no age-specific processes are seen in this stage (Garvin et al., 2012). Maintenance is the general upkeep of the mature organism on a day-to-day basis (i.e., maintaining stasis), and this is generally following growth and development when the organism or element undergoes no size or shape changes. During maintenance, the processes of repair and deterioration are balanced.

Growth describes a general increase in size and subsequent changes in shape and form (Scheuer and Black, 2000). Development involves a process of differentiation at cellular levels that leads to a more specialized and mature state (Bogin, 1999). The end result of growth and development is the adult form of an organism or element of that organism (Enlow and Hans, 1996). The processes of growth and development are tightly controlled genetically and generally less affected by extrinsic factors like environment and disease. Even in cases where growth is temporarily halted, children often display "catch-up" growth that returns the child to a normal growth pattern once the insult has been removed (Prader et al., 1963; Tanner, 1963). An exception to this is a disturbance that occurs during key developmental stages, which affects only the sites or processes active at that moment in time, but could cause adverse consequences for the organism as a whole depending on the severity of the insult and the sites or processes affected (Brodie, 1941). Additionally, children with access to good nutrition will display accelerated growth when compared to similar age cohorts with poor nutrition (Ferembach et al., 1980).

Degeneration involves the breakdown of structures and functions in an organism. It is highly variable, and its mechanisms are poorly understood (Crews, 1993). Senescence (the process of getting older) is not simply the end result of the degeneration of biological systems through accumulated effects on the organism. This process is complex, and the exact contributions of genes and environment are not yet clearly elucidated (Kenyon, 2010; Vaupel, 2010). While multiple genes influence senescence, specific genes programmed to increase longevity likely do not exist and environment certainly plays a key role (Kirkwood and Austad, 2000).

An interesting paradox emerges with increasing age. Individuals who are able to survive to very old ages may in fact appear biologically younger than individuals who did not survive to very old ages (Angel, 1984). Schmitt (2002) explains that individuals who live to a very old chronological age are likely people who experience a slower progression of biological age and thus have an increased life expectancy compared to those who undergo a faster progression of biological age. This results in a lag between biological and chronological age. Whether it is genes, environment, or an interaction of the two, something enables a protracted survival, and the key to longevity may in fact be that the organism does not undergo degeneration at the same rate as organisms with decreased relative lifespans. Degenerative processes may display greater variation among individuals not simply because they are more variable than the processes of growth and development, but also because senescence may depend on individual circumstances, such as health and prosperity. An exception to this is for individuals of extreme advanced age (e.g., 100+), who appear to undergo degeneration at the same rate (Vaupel, 2010).

Evolutionary Theories of Aging: The mutation accumulation, antagonistic pleiotropy, and disposable soma evolutionary theories of aging rely on this basic underlying principle: the force of selection is progressively weakened with increasing age (Crews, 1993; Kirkwood and Austad, 2000). This means that the longer an individual organism has been alive, the less effect natural selection will have. The difference between mutation accumulation and antagonistic pleiotropy is whether deleterious genes simply accumulate over time via mutation due to a progressive reduction in the force of selection in older individuals (mutation accumulation; Medawar, 1952) or if aging is brought about by genes that are beneficial early in life but carry deleterious late life changes (antagonistic pleiotropy; Williams, 1957). The disposable soma theory posits that the organism can only allocate so many resources towards certain functions and that some organisms will preferentially allocate to reproduction at the cost of maintenance and repair, eventually leading to senescence (Kirkwood, 1977). The main problem with all three of these concepts is that aging itself can represent an adaptation, and as such is not just a side effect of selection for traits that maximize reproductive potential (Mitteldorf, 2004).

Humans present a special case since they not only live longer but also have an extended post-reproductive lifespan. In a strict Darwinian sense, life past reproduction is of no utility, yet humans continue to live well beyond reproductive years. The explanation for longevity following the reproductive years is often found in life-history theory. The large brain of humans, which is an adaptation that increases survival in many environments, represents a life history trade-off for delayed fecundity, a longer developmental timeframe, and increased longevity (Kirkwood and Austad, 2000). Kirkwood and Austad (2000) also suggest that humans live longer relative to many other species because they have decreased extrinsic mortality levels, due at least in part to their large brains. This reduced extrinsic mortality level allows for the accumulation of resources to maintain the organism beyond reproduction age (Kirkwood, 1977), yet it complicates age estimation as humans have a longer period of time to be exposed to detrimental environmental conditions that may affect rates of degeneration as well as live long enough to express late-life, deleterious genetic effects.

Skeletal Growth and Development

Bones grow through endochondral and intramembranous ossification and in response to genetic and environmental signals. Endochondral ossification is the development of osseous tissue from a cartilaginous precursor; this type of ossification characterizes the majority of the postcranial skeleton and some cranial elements such as the cranial base. Intramembranous ossification is the result of the combined processes of direct mineralization of mesenchymal connective tissue and osseous deposition; this type of ossification occurs in a majority of the cranial elements and a few postcranial elements. Both types of ossification involve the growth phases of initiation, proliferation, histodifferentiation, morphogenesis, and apposition (Brodie, 1941). The differentiation of precursor cells results in the formation of cells with specific functions for skeletal tissue. Osteoblasts are the cells that build bone through deposition, and osteoclasts destroy bone through resorption. Osteocytes are the third type of cell in skeletal tissue; they are mature osteoblasts. Osteocytes serve important regulatory roles in skeletal tissue, and while they cannot replicate or resorb/deposit bony matrix, they are crucial in signaling these processes to active osteoblasts and osteoclasts.

Ossification occurs at primary and secondary centers. The primary centers of ossification are the sites of initial bone development. The majority of the primary centers form prior to birth, and a single element can have multiple primary centers (Scheuer and Black, 2000). At these centers, osteoblasts deposit new bony tissue, which causes size increase. Once osteoblasts become “trapped” within the matrix they have formed, they develop into osteocytes, while osteoblasts continue to deposit new bone on the external surface. The outside surface of bones, the periosteum, remains osteogenic throughout life (Scheuer and Black, 2000). Secondary centers of ossification form after birth and are generally located at the extremities of forming bones. These centers allow for an increase in length during the growth period. During skeletal growth, deposition largely outpaces resorption; in the post-growth phase, deposition and resorption are balanced.

As new bone matrix is being deposited, skeletal elements increase in length and width and change in shape via modeling and remodeling. In closely related structures, growth in one element will cause changes in adjacent elements. The subtraction and addition of bone in modeling and remodeling allow skeletal elements to maintain consistent relationships with other skeletal elements and structures while they increase in size. Modeling affects the development and modification of primary lamellar bone, ‘while remodeling subtracts already deposited bone and adds new secondary cortical bone through complementary processes of deposition and resorption. During remodeling, deposition occurs on the external surface, while resorption is simultaneously occurring on the opposite side of the same surface (Enlow and Hans, 1996). Remodeling enables skeletal tissue to relocate and respond to functional demands or repair trauma (Enlow and Hans, 1996). The attainment of adulthood signals an end to large-scale skeletal growth and very little modeling takes place following skeletal maturation; remodeling continues to take place throughout adulthood although it occurs at a slower pace than in childhood.

When elements change in both size and shape, they change position within the soft tissue matrix. Drift is passive, small-scale relocation that results in the change in relative position of a structure within another structure (Thilander, 1995; Enlow and Hans, 1996). Displacement, or translation, is a large-scale process of drift where the entire bone actively moves to a new position, and the change in position is measured in relation to other bony elements. In primary displacement, the relocation is related to growth of the bone, while in secondary displacement, adjacent structures are the impetus for movement (Thilander, 1995). All relocation processes involve modeling in the early stages and remodeling throughout life.

Bone is a living and dynamic tissue that can alter its size and shape in response to mechanical, physiological, or other environmental factors. A developmental trajectory is defined both by intrinsic and extrinsic cues, during which a different combination of internal and external constraints operate to give rise to a certain form (Rasskin-Gutman and Izpisúa-Belmonte, 2004). A skeletal element will develop into a largely recognizable form in the absence of load-bearing, but it will not be structurally sound (Lanyon, 1984). A certain level of external loading is necessary for bone growth or bones will atrophy, and even *in utero* there are mechanical forces (Scheuer and Black, 2000).

The understanding of the process of skeletal modeling/remodeling during life based on external loads and mechanical needs has long been credited to Julius Wolff. Wolff's "law of bone transformation," simply stated, is that bone will be deposited where it is needed and removed (or resorbed) where it is not needed (White et al., 2012: p 28). Accordingly, a skeletal element can be expected to adapt over time in response to the presence or absence of external load(s): increased activity results in an osteogenic response, decreased activity results in bone loss (Lanyon, 1984). Using this principle, variation in size and shape among individuals or species can be assessed in terms of the ability carry out a function or action (e.g., the ability to withstand stresses generated in a particular activity or to describe mechanical relationships in elements of a system) (Swartz, 1991). Robust skeletal elements are assumed to be able to endure greater mechanical loading without failure, while gracile elements can endure less.

The skeletal response to mechanical loading is quite complex, and how much of the past mechanical environment that can be interpreted from skeletal elements is still a source of debate (see Ruff et al., 2006). The skeleton has other functions besides mechanical competence (Ruff et al., 2006). Each skeletal structure actually has three biological contexts: functional, developmental, and evolutionary (Wainwright, 1988). Therefore, no optimum level of adaptation or ideal fit of skeletal structure to loading can be assumed (Carter, 1984); although a context-specific "optimum customary strain level" is likely maintained (Ruff et al,. 2006: p 485). Growth is bounded, meaning that skeletal structures are constrained by geometric rules and growth and material properties, and they do not generally reach physical limits (Thomas and Reif, 1993). Genes, hormones, age, and disease can affect the skeletal response. The remodeling response also depends on the type of bone being subjected to the load (cortical versus trabecular), the type of load being applied (static versus dynamic), the frequency of application, the magnitude of application, the sense of application (tension versus compression), the location of the load (e.g., femoral midshaft versus femoral head), direct versus indirect loading, and other disturbance(s) to the skeletal tissue (e.g., trauma).

Determining functional adaptation can be difficult due to the properties of bone and theoretical and experimental limitations. Skeletal tissue is not a homogenous structure. Bone is anisotropic, meaning that it has different material properties in different orientations and even within a single element, responses to the same applied force can be markedly different (Swartz, 1991). It can also be difficult to define the load and to what forces the element is subjected. While the use of models eliminates many confounding variables, models may be too simplistic. Often, engineering models are based only a single function and cannot take into account the complex three-dimensional shapes seen in skeletal structures (Swartz, 1991). In experimental loading, the choice to conduct *in vivo* versus *in vitro* analysis, frequently based on feasibility, will dictate the types of assumptions that must be made and each is faced with certain limitations (e.g., for *in vitro* it may be difficult to simulate natural behaviors, while invasive procedures for *in vivo* may adversely impact muscle function and repair phenomena related to the procedure and not loading) (Bertram and Swartz, 1991; Swartz, 1991). The use of dry bone versus living skeletal tissue in experiments is also a concern. All of these factors indicate that adaptation to mechanical loads is contextual and site-specific (Carter, 1984) and that mechanical environments may not be easily interpreted from skeletal form, nor can shape be assumed to perfectly correlate with function or load.

With these limitations aside, the general concept of Wolff's law remains an important component of research in skeletal biology because it demonstrates that growth occurs not only because of genetic signals or progressing age but also due to mechanical constraints and physiological demands (Francillon-Vieillot et al., 1990). Ruff et al. (2006) recommend the term bone functional adaptation to describe the response of bone to its loading environment. Experimental research has shown that bone does indeed respond to its mechanical environment, and the consideration of multiple factors in the remodeling response is vital to successful research (e.g., Lanyon et al., 1982; O'Connor et al., 1982; Carter, 1984; Lanyon, 1984; Lanyon and Rubin, 1984; Meade et al., 1984; Rubin and Lanyon, 1985; Garman et al., 2007; Ozcivici et al., 2007).

Age Estimation Using Skeletal Indicators

In biological anthropology, age estimation relies on skeletal indicators that are correlated to biological age, using these biological indicators to predict chronological age. There are three requirements for a good skeletal age indicator: the traits show progressive and unidirectional change with advancing age, features can be reliably classified or measured, and changes occur at approximately the same time in all people (Milner and Boldsen, 2012b). If an indicator and its associated traits do not show the characteristics of the first requirement, age cannot be predicted from that indicator. The second requirement speaks to observer error; multiple observers should be able to classify or measure the given features. The third requirement is most often affected by populational and sex differences. Research in skeletal age estimation aims to find indicators that fulfill all three of these requirements, plus understand variation in the aging process as expressed by the skeleton.

Variability

The dissonance between chronological age and biological age as measured by the skeleton is the result of many factors. Broadly, differences among individuals are due to differences in genes and environment (Hoppa, 2000). Specifically, geographic origin; sex; health, nutritional, and socioeconomic status; secular trends (temporality); individual rates of senescence; mechanical loading patterns; and developmental asymmetry can contribute to these differences (Kemkes-Grottenthaler, 2002). Additionally, the correlation between biological age and chronological age decreases with increasing age – the trajectory effect (Nawrocki, 2010). This results in older individuals exhibiting greater variability in age-related processes (i.e., degeneration) than younger individuals and greater difficulty in estimating the age of older adults as compared to younger adults (Nawrocki, 1998).

Sex differences arise largely from sexual dimorphism, differences in size and shape between males and females, while regional differences are due to both genetic and environmental factors, (e.g., the adaptation of differing body proportions due to climate). For some age estimation methods, there is no variation in population or sex, for others there is variation in both, and for still others variation exists in only one (population or sex). Differences between the sexes and among regions have largely been dealt with by continued research and the development of sex- and regional-specific age estimation methods. However, large, varied samples can alleviate the need for many sex- and regionally-specific methods and will likely aid in reducing age mimicry, in which the estimated age distribution of sample becomes similar to the reference method even though it is actually very demographically different (Bocquet-Appel and Masset, 1982; Konigsberg et al., 2008).

Secular trends (variation in temporality) and their effects on age estimation have not been as thoroughly investigated as sex and regional variation (Milner and Boldsen, 2012a). Individuals living in different time periods but in the same general geographic area can display differences in body size and proportions, and secular trends in height and other skeletal dimensions have been well documented in biological anthropology (e.g., Jantz and Jantz, 1999; Jantz and Meadows Jantz, 2000). Langley-Shirley and Jantz (2010) find secular trends in fusion rates of the medial clavicle, with modern Americans commencing fusion four years earlier than Americans from the early 20th century. If earlier skeletal maturation in more modern populations occurs, it is important to recognize this temporal variation as standards developed using historic individuals may not be applicable to modern individuals (and vice versa); for age estimation this could result in over-estimation of age in skeletal remains (Langley-Shirley and Jantz, 2010). Additionally, maturation, like skeletal dimensions and shape, has both environmental and genetic components. If differences are observed between temporal groups, this suggests variation of an environmental nature; if differences are observed among ancestral groups, this suggests genetic variation.

Developmental and degenerative asymmetry is the differential progression of development/degeneration between the right and left sides of the body of one individual. Estimating age can be problematic when different sides of the same skeletal indicator produce dissimilar age estimates or when only a single element is present and asymmetry cannot be assessed. Asymmetry has not traditionally played a large role in explaining variability in skeletal age estimation, though methods do often make a recommendation on which side to use if differences are observed (e.g., older or younger side). Development and degeneration may progress asymmetrically due to individual and populational differences in biomechanical environments, physiological processes, or genetics, and if differences occur in the growth process, these may be further magnified later during degeneration (Overbury et al., 2009). Overbury et al. (2009) find asymmetry in pubic symphysis phase assignment using the Suchey-Brooks method (Katz and Suchey, 1986; Brooks and Suchey, 1990) for over 60% of the individuals in their sample, though accuracy is still maintained if age is estimated with the morphologically older side. McCormick and Kenyhercz (2015) also found side differences of age-related traits for the pubic symphyses and auricular surfaces and conclude that component-based methods including traits from both sides are preferable to phase-based methods. Conversely, Beresheim (2015) does not find statistically significant differences between left and right sides of the pubic symphysis, attributing observed asymmetry in Overbury et al. (2009) to observer error. The investigation of developmental and degenerative asymmetry is as important as understanding how other sources of error might contribute to conclusions about asymmetry.

Two parallel but complimentary forces have driven research aimed at understanding variability in age estimation: forensic science and paleodemography. Following the ruling in the *Daubert* case (1993) and the recommendations of the National Academy of Sciences' National Research Council (2009), the field of forensic science has been impelled to better understand how well methods perform and the error associated with their application. This includes methods contributing to the identification of human remains such as age estimation (e.g., Baccino et al., 1999; Martrille et al., 2007; Kimmerle et al., 2008). A powerful critique of anthropological demography in the 1980s focused on the perceived inability to ever estimate age with any certainty due to age mimicry and a low correlation between skeletal age indicators and chronological age (Bocquet-Appel and Masset, 1982; Hoppa, 2002). Reactions to this gloomy prediction served to improve not only single indicator methods, but to rethink the statistical basis for age estimation in anthropology and the ways in which to best combine estimates from multiple indicators (e.g., Van Gerven and Armelagos, 1983; Konigsberg and Frankenberg, 1992; Konigsberg and Frankenberg, 1994; Aykroyd et al., 1997; Aykroyd et al., 1999; Hoppa and Vaupel, 2002a).

Methods

Macroscopic methods are the most commonly employed since they represent the quickest and cheapest methods and are thus accessible to all osteologists (Falys and Lewis, 2011; Garvin and Passalacqua, 2012; Milner and Boldsen, 2012a). Microscopic methods are used, but they are often time-consuming, expensive, and destructive (e.g., histology). Methods are based on classificatory schemes (categorical data) or measurements of age indicators (continuous data) (Milner and Boldsen, 2012a). Classificatory methods include phase systems that use overall form to place an individual into a distinct phase (e.g., İşcan et al., 1984; İşcan et al., 1985; Lovejoy et al., 1985a; Brooks and Suchey, 1990) and component systems that score separate portions of a skeletal element to develop a summary score (e.g., McKern and Stewart, 1957; Gilbert and McKern, 1973; Meindl and Lovejoy, 1985; Boldsen et al., 2002; Buckberry and Chamberlain, 2002). Measurement-based age estimation methods include microscopic analyses of bone microstructure and measurement of long bone lengths for sub-adults.

Sub-adults exhibit active growth and development and are generally less than 20 years of age (Falys and Lewis, 2011). Since growth and development are tightly controlled genetically, methods of sub-adult estimation have the ability to consistently estimate age within a few years of known age. Sub-adult age estimation methods include: timing of the appearance of primary and secondary ossification centers, dental development and eruption, long bone length, and fusion of ossification centers (skeletal maturation). For young children (fetal age, infant, less than 10 years old), age estimation relies most on the development of the dentition, long bone length, and the appearance of primary growth centers. Still in childhood but prior to puberty (approximately 10-14 years), dental development and the appearance of secondary growth centers are employed. For individuals in their mid to late teen years (adolescents), age estimation relies heavily on the fusion of secondary ossification centers and the appearance of the third molars.

While an adult may exhibit some developmental changes such as the late-fusing epiphyses of the vertebrae, ilium, and clavicle, an adult is an individual who has completed growth and development. Adult age estimation is based largely on processes of degeneration, making it markedly more difficult, less accurate, and less precise than the age estimation of sub-adults. General degenerative processes (e.g., edentulism, osteoarthritis at joint surfaces) can be used to place an individual into broad age categories (e.g., young, middle, older; Listi and Manhein, 2012), but these lack specificity. Methods employing the pubic symphyses, auricular surfaces, sternal ends of the ribs, and cranial sutures are employed for adult age estimation (e.g., McKern and Stewart, 1957; İşcan et al., 1984; Lovejoy et al., 1985a; Meindl and Lovejoy, 1985; Brooks and Suchey, 1990; Mann et al., 1991; Buckberry and Chamberlain, 2002; Osborne et al., 2004). No adult age estimation methods offer particularly small intervals, and most methods produce age intervals that span several decades. The large age intervals provided by adult age estimation methods likely do not reflect scientific or statistical limitations, but rather are a true indicator of the biological reality of the highly variable aging process (Nawrocki, 1998; Kirkwood and Austadl 2000). Research also includes modifying existing methods to age very old adults (e.g., Berg, 2008; Beauthier et al., 2010).

Adult single indicator methods

The most reliable and most commonly employed single age indicator for adults is the pubic symphysis phase method developed by Suchey and colleagues (Brooks and Suchey, 1990; Buikstra and Ubelaker, 1994). This method was developed from a large and diverse modern sample and, with the use of standardized casts for each of six phases, represents the current "best case" scenario for adult age estimation. A component system for the pubic symphysis is also available, though it is generally far less employed by practitioners (McKern and Stewart, 1957; Gilbert and McKern, 1973). The pubic symphysis may be so useful because it exhibits delayed development, well into the middle-aged adult years, though the method also considers degenerative changes. However, the pubic symphysis, especially in archaeological remains, is often damaged or not present.

Other adult age estimation methods also employ a combination of late development and degenerative changes, with the emphasis mainly on degenerative changes after about 30 years of age. Because of preservational problems with the pubic symphysis, Lovejoy and colleagues develop a similar phase system to estimate age from the auricular surface of the ilium because it is often more well-preserved and exhibits age-associated changes (Lovejoy et al., 1985a). This system is modified by Osborne and colleagues (Osborne et al., 2004) in order to provide statistically viable age ranges. Buckberry and Chamberlain (2002) developed a component system for the auricular surface (the "revised" method), but the method suffers from small sample sizes in the younger age stages, resulting in poor performance for these groups and does not demonstrate broad applicability across many samples (Mulhern and Jones, 2005; Falys and Lewis, 2011). A phase system is also employed for the sternal end of the fourth rib

(İşcan et al., 1984; İşcan et al., 1985), but this too suffers from the same preservational issues as the pubic symphysis and the statistical validity of the small age intervals for each of the phases is questionable (Nawrocki, N.D.). Cranial sutures are discussed in greater detail below. These methods do not represent the only ways to estimate adult age at death, but they are the most commonly employed macroscopic indicators in anthropological skeletal analysis (Garvin and Passalacqua, 2012).

Adult multiple indicator methods

The multifactoriality of the aging process suggests that a single age indicator or bone does not adequately reflect chronological or biological age nor can any one indicator be truly predictive (Kemkes-Grottenthaler, 2002). More age indicators are certainly better, especially when considering the imperfect correlation between chronological and biological age and the variability of the aging process (Houck et al., 1996). However, there is currently no consensus on how to best combine multiple age indicators (Uhl and Nawrocki, 2010; Garvin and Passalacqua, 2012). For example, if the pubic symphysis is considered to be the most reliable indicator and it is present, how much weight is given to other age indicators? What if age indicators produce different estimates for the same individual? How are the indicators that are present best combined? The difficulty in constructing a final age estimate is reflected in Buikstra and Ubelaker (1994) where the recommendation is to use these three broad age categories: 20-34 years (young adult), 35-49 years (middle adult), or 50+ years (old adult) based on the observer's overall assessment of available age indicators. For cases that do not fit into one of the three age categories, the recommendation is that more weight be given to postcranial indicators than cranial.

In a survey of practicing forensic anthropologists, Garvin and Passalacqua (2012) find that the manners of constructing a final age estimate based on multiple indicators are highly varied, experience-based, and often include statistically invalid assumptions. One of the more objective techniques indicated was the use of the lower end of the interval from the method that provided the oldest age and the higher end of the interval from the method that provided the lowest age (colloquially referred to as "highest of the low, lowest of the high"). Even this method presents statistical challenges since many of the reference articles do not use the same statistical information (e.g., standard deviations versus standard errors) (Garvin and Passalacqua, 2012).

More statistically rigorous ways of combining multiple indicators include those methods classified as multifactorial (e.g., McKern and Stewart, 1957; Acsádi and Nemeskéri, 1970; Lovejoy et al., 1985b; Martrille et al., 2007). Three main approaches are currently available for estimating age from multiple indicators: the complex method (Acsádi and Nemeskéri, 1970); the multifactorial summary age method (Lovejoy et al., 1985b); and transition analysis[1] (Boldsen et al., 2002). While analytically different, all three have the ability to collect data on more than one age indicator and then it to develop a summary age.

The Acsádi and Nemeskéri (1970) complex method, employed primarily by European anthropologists, bases age on the average of the ages given by the pubic symphysis, trabecular structure of the humeral and femoral heads, and endocranial

[1] Here transition analysis refers to the specific method to combine multiple indicators developed by Boldsen and colleagues. Transition analysis is also a generalized statistical approach in age estimation (see The Statistical Basis of Age Estimation, below).

suture closure. Concerns raised with this method include the averaging of indicators without weighting and the need for the same age indicators as the reference method (Lovejoy et al., 1985b; Brooks and Suchey, 1990). While this method is widely used in Europe following the recommendations of the Workshop of European anthropologists (Ferembach et al., 1980), it is less frequently employed in other regions.

The original multifactorial summary age method employs the auricular surface, pubic symphysis, cranial sutures, and radiographic analysis of the proximal femur and clavicle, though any combination of methods can be used as long as the entire sample is seriated by method prior to data collection (Lovejoy et al., 1985b). Data on each indicator is collected and then principal components analysis (PCA) is run to weight the indicators employed for the sample. The final age estimate for an individual is the weighted average of the available age indicators (Lovejoy et al., 1985b). The need to seriate biases this method towards paleodemographic usage, though with some modifications it can be used in forensic identification. Martrille et al. (2007) propose running the PCA on a single case using the individual age indicators collected and then the correlation between the first principal component and the age indicators as the weights. These authors conclude that as many skeletal and/or dental indicators as possible should be used, with particular attention to methods that have higher accuracy for a certain age range when producing the final age estimate (Martrille et al., 2007).

Multiple indicator transition analysis employs scoring of separate components of the pubic symphysis (five characteristics), iliac portion of the sacroiliac joint (nine characteristics), and cranial sutures (five segments) (Boldsen et al., 2002). This method computes the likelihood of death estimates occurring at different ages for each character by looking at the age of transition from a particular stage to the next for each indicator and calculating the probability that an individual died at a particular age given certain observed skeletal traits (Boldsen et al., 2002). One of the particularly useful facets of transition analysis is that it allows for the estimation of age from incomplete or fragmentary remains and does not require seriation of the sample. However, transition analysis, like other Bayesian statistical methods, requires knowledge of an independent but appropriate prior age distribution or the use of uniform priors.

Tests of multifactorial methods are equivocal. Saunders et al. (1992) do not find that the Lovejoy et al. (1985b) multifactorial method outperforms single indicators in their unseriated sample but that a simple average of the estimates produced from single indicators is more effective. Conversely, Bedford et al. (1993) find that the multifactorial method is superior to any single indicator in their seriated sample. Martrille et al., (2007), in examining the pubic symphysis (Brooks and Suchey, 1990), fourth rib end sternal extremity (İşcan et al., 1984; İşcan et al., 1985), auricular surface (Lovejoy et al., 1985a), and the anterior teeth (Lamendin et al., 1992) find that the use of multiple indicators (through PCA) has the lowest inaccuracy for all groups, but if the sample is broken down by young (25-40), middle (41-60), and old (>60) age groups, single indicators (different for each group) are more accurate than PCA. Bethard (2005) finds that the method of transition analysis proposed by Boldsen et al. (2002) does not perform as well as the authors claim, though a subsequent application of transition analysis by Milner and Boldsen (2012b) produces more favorable results. Uhl and Nawrocki (2010) test various individual indicators (pubic symphysis, auricular surface, sternal end of the rib, and cranial sutures) and three ways of combining them (average of point estimates, range of spatial overlap of four confidence intervals, and multiple linear regression with forward stepwise selection) and find that combining multiple indicators is always more effective than simply using single indicators. Their results favor the use of linear regression, which has similar inaccuracy values to other methods but offers the advantage of producing both a point estimate and an interval.

The continuing development of multifactorial approaches and the best way to combine multiple age indicators necessitates continued research on single age indicators and subsequent research on the most accurate way(s) to combine information from these single indicators. The continued refinement of single indicator methods is important because it leads to more accurate, precise, and reliable estimates of age at death. As eloquently stated by Milner and Boldsen (2012a: p 99), "overall composite estimates…are arguably no better than the individual indicators of age they are based on." Also important in this process is an investigation of analytical methods for both single and multiple skeletal age indicators. To date there has been little consensus among anthropologists on ways to measure the effectiveness of age estimation methods (Uhl and Nawrocki, 2010).

The Statistical Basis of Age Estimation

The estimation of age at death from skeletal remains necessitates the conversion of observable skeletal age indicators into chronological ages, which is accomplished via statistical inference. The two main schools of statistical inference in skeletal age estimation are frequentist and Bayesian. Anthropologists have traditionally relied on frequency statistics for calculating age at death, but the use of Bayesian methods is becoming more common. The preference of one over the other is not clear in biological anthropology, and often the anthropologist will blur the line between the two approaches in order to best interpret the data (Klepinger and Giles, 1998).

Frequency-based inference comprises the statistics and analytical procedures that are most familiar (e.g., ANOVA, Student's *t*-test, regression). These tests are based on the assumption that the population from which the sample is drawn is normally distributed. The sampled data are assumed to be a repeatable, random sample from an unchanging underlying population that has specified parameters. For a frequentist, probability describes the frequency of a specific outcome over many trials (Klepinger and Giles, 1998). This type of statistical inference closely mimics the desired scenario in scientific testing (objective, controlled, replicable experiments), and hypotheses are rejected based on the evidence presented, but they are never proven to be true. Sampling error is a very large component of frequentist inference, meaning that experimental design is an important part of the experiment itself (e.g., adequate sample sizes, appropriate sampling procedures) (Nawrocki, 2010). The strength of frequency-based approaches is in their use of relatively simple calculations, straightforward, unvarying procedures, and the ability to apply the same formulae in subsequent analyses.

Bayesian statistical inference does not rely on predefined parameters but instead assumes fixed data with parameters that can be probabilistically determined from experiential observation. Bayesian inference incorporates known facts about the universe (or testing population), and this *a priori* knowledge is then used in hypothesis testing and to update subsequent test iterations. Probability is not based on repeated trials but is the measure of the outcome of a hypothesis (Jefferys and Berger, 1992).

Hypothesis testing in Bayesian inference produces a probabilistic statement about the strength of the hypothesis, in the form of a posterior probability or likelihood ratio. Bayesian statistical inference can be quite complex and time-consuming; however with the advent of powerful computing capabilities, Bayesian inference has become more common. Many researchers have recognized that data, especially those of a biological nature, do not always conform to stringent assumptions, and the support for Bayesian inference has grown. The underlying distribution, a problem that can affect the outcome of hypothesis testing in frequentist inference, is not a problem in Bayesian inference because the parameters are always updated to reflect the data.

Another distinction that can be made in statistical inference is between parametric and nonparametric options; frequency statistics and Bayesian statistics have both parametric and nonparametric options. A parametric statistical method employs certain assumptions about the shape or form of the data's underlying probability distribution (e.g., a normal distribution for the population; probability distribution as determined by the data) or a fixed model structure. Nonparametric methods make no such assumptions about underlying probability distributions or fixed model structures. Nonparametric tests are less powerful (meaning they have less ability to find a real effect or an association) than parametric procedures when the population follows an expected distribution or model structure (either normal or defined by priors), but they can be particularly useful for small sample sizes and when the data do not follow an expected distribution because nonparametric tests are more robust (resistant to outliers). The choice of statistical paradigm (frequency or Bayesian inference) and methods (parametric or nonparametric) are generally left to the practitioner, though some choices are more commonly seen in biological anthropology than others (e.g., frequentist inference using parametric methods).

The development of age estimation methods based on skeletal indicators starts with data collection from documented samples. A certain indicator or several indicators are observed to be age-related, and these traits are compared in terms of their relationship with known ages at death in the reference sample. Observations can then be lumped into discrete descriptive categories as in phase systems or assigned individual numbers that are summed as in component systems. There are currently no standards for reporting results, though most age estimation methods will commonly include at least the age ranges, means (or other measure of central tendency), standard deviation (or other measure of dispersion), and sample sizes per phase, stage, or score (Nawrocki, 2010). Age ranges are variably presented, to include prediction or confidence intervals, or are constructed through the use of adding one or two standard deviations to the mean age.

Measures of method effectiveness include: calculations of inaccuracy (the absolute difference between estimated and actual age per individual, phase, or sample), bias (the positive or negative difference between estimated and actual age per individual, phase, or sample), the correlation coefficient (r; strength and direction of the linear relationship between two variables), the coefficient of determination (r^2; the amount of variation in one variable that can be explained by variance in another variable), and the percentage of correct classification using published data, which can include individuals correctly classified by phase or stage, by one or two standard deviation ranges, or by true age “category” (Murray and Murray, 1991; Uhl and

Nawrocki, 2010). Measures of bias, inaccuracy, and covariance (*r* and R^2) average the total error in a method or phase (or other grouping category), but it is also important to include information on the overall pattern of error for a particular study. For example, Lovejoy et al. (1985b) include the largest absolute differences between predicted and actual ages, which inform on how much a method over- or underestimates age. An additional consideration in testing methods following their development is the inclusion of data on inter- and intraobserver error to address method reliability.

Regression-based methods estimate age (the dependent variable) from the age indicator (s) (the independent variable[s]). While this is not entirely biologically realistic – the indicator does not actually cause a person's age, rather age is what dictates morphology – age is the unknown variable in skeletal analyses and must be predicted from observed traits. The success of regression depends on a strong linear relationship between dependent and independent variables and continuous data that is independent where multiple predictor variables are employed (Adler, 2012). If the independent variables are categorical rather than continuous, ANOVA is employed in the same way as regression (Crawley, 2013).

The use of regression in age estimation is not without problems. Because regression aims to reduce individual deviations from a particular line, age estimates for extrema points tend to regress to the mean, referred to as "attraction of the middle" (Masset, 1989). There is often a non-linear relationship between indicator and age, and morphological traits are discrete rather than continuous (Kemkes-Grottenthaler, 2002). When there is a relationship, the minimum acceptable value of the correlation coefficient is not agreed upon (Bocquet-Appel and Masset, 1982; Lovejoy et al., 1985b). Additionally, independence among different age indicators cannot be assumed.

Transition analysis, based in Bayesian inference, does not require data to meet the assumptions of regression, nor does it require a normally distributed population. This analysis models the passage of individuals from a given developmental stage to the next stage in an ordered sequence using a prior distribution (Konigsberg et al., 2008). Rather than predict age from skeletal traits, transition analysis takes a more biologically realistic approach by conditioning all indicators on age and giving the probability that a set of skeletal remains are from a person who died at a certain age (Hoppa and Vaupel, 2002b). While frequency-based statistics assign fixed intervals per stage, Bayesian inference allows for the use of prior knowledge to adjust the intervals.

Theoretically, Bayesian inference appears to be well suited to the statistical needs of biological anthropology, but it has yet to see significant incorporation into the most commonly used age estimation methods. Bayesian statistics are believed to solve problems of age mimicry, independence, inaccurate representations of estimation uncertainty, and open-ended upper age intervals, but methods like transition analysis still only work as well as their associated reference samples and scoring systems (Garvin et al., 2012). Since analysis is based on the estimated age of transition between adjacent phases of a method, it requires discrete stage or phases that are age progressive as well as a known-age reference sample that has been previously scored using the same method (i.e., informed priors) (Garvin et al., 2012). Prior distributions have the capability to negatively affect age estimates if they are not appropriately developed, and the selection of priors can be highly subjective. For continuous data, frequentist approaches are better, and with appropriate experimental design are highly effective.

Cranial Suture Age Estimation

The use of cranial sutures in age estimation is based on a positive correlation between suture fusion and age. Older individuals tend to exhibit more sutural obliteration than younger individuals, who retain largely patent sutures. Unlike epiphyseal fusion, complete obliteration of the cranial sutures rarely occurs, though complete fusion of the endocranial aspect of sutures is more likely (Ashley-Montagu, 1938). Because they fuse earlier, endocranial aspects of sutures have the potential to more accurately predict the ages of younger adults, while the ectocranial portions of the sutures may be preferable for older adults (Perizonius, 1984). Craniofacial sutures, most notably the external portions, show an even greater delay in fusion than vault sutures and because of this have great potential for age estimation in older adults (Wang et al., 2006). According to Kokich (1976), facial sutures often remain open until the eighth decade of life, and facial sutures may be able to distinguish between old and very old adults (Beauthier et al., 2010).

Sutural age estimation methods most often examine sections of sutures or degrees of fusion along a suture in order to develop an overall picture of sutural fusion and assign an age (e.g., Meindl and Lovejoy, 1985; Mann et al., 1991). Methods that employ the ectocranial portions of the sutures are more common than those that examine endocranial aspects, largely because the external surfaces of sutures are easier to observe than the internal surfaces, especially for the facial sutures (Wang et al., 2006; Falys and Lewis, 2011). Macroscopic cranial suture age estimation methods are easy to apply and generally have low rates of interobserver error (Zambrano, 2005; Milner and Boldsen, 2012a).

Cranial suture age estimation also has several challenges, several of which are related to the variability of sutural fusion. The complexity of the skull means that sutural fusion cannot be interpreted as a simple linear relationship between only fusion and age. Although sutural growth is related to growth of the brain and facial structures, it is unclear why sutures fuse since patency enables the skull to retain flexibility (Herring, 2008). Variation in fusion rates are observed between the sexes, with males fusing earlier than females while the pace of obliteration is more regular in females (Ashley-Montagu, 1938). Fusion rates may, or may not differ among ancestral groups. Galera and colleagues (1998) and Nawrocki (1998) found statistically significant differences between ancestral groups, but Meindl and Lovejoy (1985) did not. Secular trends may also contribute to variation in sutural fusion, and given earlier maturity in more recent cohorts, more modern individuals may also exhibit greater suture closure at a given age than prehistoric or historic individuals (Masset, 1989; Langley-Shirley and Jantz, 2010). Conversely, Nawrocki (1998) finds that synostosis occurs at a slightly slower rate in modern individuals, so that for any given level of suture closure the modern sample is actually aged younger than the historic. Zambrano (2005) finds that the equations given in Nawrocki (1998), while based on a historic sample, perform well for modern individuals and that there is no systematic secular trend observed when these equations are applied to individual forensic cases. Somatic dysfunction (e.g., sacroiliac fusion, ankylosing spondylitis, and scoliosis) has also been found to have a stronger correlation with cranial suture fusion than documented age (Kroman and Thompson, 2009). The effect of fusion on cranial strain pattern and the effects of mastication on fusion have also been recently considered (Wang et al. 2006) and offer a potential avenue to quantify qualitative criteria, such as thinning or thickening of the vault and bone density changes, which have been used in past to make inferences about age estimation based on the cranium (Krogman and İşcan, 1986; Henderson et al., 2005; Wang et al., 2006).

Beyond the inherent variability of sutural fusion among individuals and populations, cranial suture age estimation methods themselves also contribute to challenges in age estimation from the sutures. There is a lack of consensus in scoring cranial suture obliteration, including the number of sites observed, the amount of sutures examined (full suture versus 1-cm sections), and the number of stages. The distinction between different stages can be difficult to identify and intra- and interobserver error increases with greater subdivision of stages (Scheuer and Black, 2000). In the history of cranial suture age estimation, analytical techniques have been rudimentary, disjointed, and lacking in statistical complexity (Nawrocki, 1998). While many studies compare sets of certain sutures (e.g., frontosphenoidal sutures: Dorandeu et al., 2008; maxillary sutures: Mann et al., 1987; Mann et al., 1991; vault sutures: Meindl and Lovejoy, 1985; squamous and parietomastoid sutures: Saito et al., 2002), studies that incorporate many different sutural sites or sutures into multifactorial methods are less common (Nawrocki, 1998; Boldsen et al., 2002).

Vault Sutures

Age estimation using the sutures of the cranial vault is one of the oldest and most deliberated methods (Ashley-Montagu, 1938). Methods of age estimation from the vault sutures are based on the work of Todd and Lyon, who adapted Broca's work from the 19th century (Broca, 1875; Todd and Lyon, 1924; Todd and Lyon, 1925a; Todd and

Lyon, 1925b; Todd and Lyon, 1925c). The Todd and Lyon method scores obliteration of endocranial and ectocranial sutures on a five-stage scale: 0 – none, 1 – one-quarter, 2 – one-half, and 3 – three-quarters, 4 – complete. Interestingly, Todd and Lyon do not find that their work supports the use of cranial sutures as an accurate age estimation method due to the highly variable nature of sutural fusion.

Further research in the 1950s and 1960s agrees with Todd and Lyon's conclusions about the ability of cranial suture fusion to predict age (e.g., Ashley-Montagu, 1938; Singer ,1953; Brooks, 1955; McKern and Stewart, 1957; Powers, 1962). These critiques point out that cranial sutures are unable to estimate age within 10 years of known age at death. However, further research in the 1970s and 1980s revives cranial suture age estimation, not because the methods are able to produce more precise intervals, but because the anthropological field begins to embrace more robust statistical analyses and come to terms with the lack of a single "perfect" skeletal age indicator (Meindl and Lovejoy 1985). At this time, vault sutures are also incorporated into multifactorial methods (e.g., Acsádi and Nemeskéri, 1970; Lovejoy et al., 1985b).

Of methods currently employed, Meindl and Lovejoy (1985) is the most common for ectocranial methods and Acsádi and Nemeskéri (1970) is the most common for endocranial methods (Falys and Lewis, 2011). The Meindl and Lovejoy (1985) system omits one of Todd and Lyon's categories, reducing scoring to a four-stage system to remove the potential ambiguity of three intermediate phases: 0 – open, 1 – 1-50% union, 2 – 51-99% union, and 3 – complete. This system also uses predefined landmarks on specific sutures, divides the skull into vault and lateral-anterior systems, and does not include any endocranial suture sites. A sum of all landmark scores is used to estimate age, and the lateral-anterior system is preferred since the fusion pattern is more regular in these sutures (Meindl and Lovejoy, 1985). This differs from the methods used by European anthropologists, who continue to employ the five-phase system of Broca, score endo- and ectocranial sutures, and calculate a suture coefficient (sum of all obliteration scores divided by total number of observation points) (Ferembach et al., 1980; Masset, 1989). Both European and North American anthropologists employ linear regression to predict age at death from closure of the vault sutures.

Yet the utility of cranial vault suture estimation is still debated. Some practitioners routinely include cranial fusion as a component of age estimation while others utilize it in a “last resort” or “only indicator available” capacity (Buikstra and Ubelaker, 1994; Nawrocki, 1998; Garvin and Passalacqua, 2012; Warren, personal communication). In fact, the standards given in Buikstra and Ubelaker (1994) advise that suture closure is only useful when other criteria are not available or when the information is used in conjunction with other skeletal age indicators. Practicing forensic anthropologists, regardless of experience, rank cranial vault sutures as one of the least preferred age estimation methods (Garvin and Passalacqua, 2012). Conversely, Nawrocki (1998) asserts that the use of sophisticated statistical methods, ones that include models which incorporate multiple suture sites based on their ability to predict age and the proper construction of error intervals, makes cranial suture age estimation comparable to other adult age estimation techniques.

Palatal Sutures

Age and palatal suture closure are first investigated in the dental and orthodontic fields as related to clinical practices of mid-palatal expansion (e.g., Latham, 1971; Persson and Thilander, 1977). A positive correlation between suture closure and age is noted, and much of this research focuses on sutural microstructure and employs histological methods (e.g., Persson and Thilander, 1977). In anthropological research, the fusion of the palatal sutures is summarized by Mann and colleagues, who publish two versions of their method: original (Mann et al., 1987) and revised (Mann et al., 1991). Of these two methods, the revised one is cited more frequently than the original (Wheatley, 1996; Sakaue and Adachi, 2007; Brown, 2009; Beauthier et al., 2010; Brown, 2010; Apostolidou et al., 2011; Siegel and Passalacqua, 2012;). Table 2-1 compares the samples for the published original and revised methods, subsequent test samples, and newly developed methods. Age estimation from the maxillary sutures has yet to be widely employed for adult age estimation (Brown, 2010; Garvin and Passalacqua, 2012).

The palatal sutures are: incisive (IN), transverse palatine (TP), and median palatine, which is divided into anterior and posterior sections based on location in relation to the TP suture (AMP and PMP, respectively); Chapter 3 discusses the structure of the palate and its sutures in greater detail. Like other vault sutural age estimation methods, the sutures of the hard palate are examined for fusion, and age is estimated based on the varying states of fusion seen throughout the palate. The conversion of observed obliteration to age depends on the particular method employed. Sutural obliteration most often proceeds in this order: IN, PMP, TP in the greater palatine foramen (GPF), TP, and AMP.

In the original method, based on Mann's master's thesis (1987), suture obliteration is measured for each of the four maxillary sutures and the percent of obliteration present per suture is calculated (Mann et al., 1987). These percentages are added and converted to an obliteration score value between 0 and 4, with the percent of obliteration associated with each value as follows: 0=0%, 1=1-25%, 2=26-50%, 3=51-75%, 4=76-100% (Mann et al., 1987). A more detailed age prediction model is presented in Mann (1987), where linear inverse prediction formulae are given in order to produce an age estimate from a given obliteration score, regressing age on suture closure. While Mann (1987) and Mann et al. (1987) are largely similar, the published study bases scoring on the half of the maxilla with the least amount of obliteration, while the thesis employs the side with the most obliteration.

Gruspier and Mullen (1991) find the original method to be 27-28% accurate within 10 years and 55-71% accurate within 20 years, based on two observers. These authors caution that the Mann et al. (1987) method may appear to work well because higher correlations of age and suture closure in the younger group mask lower correlations in the older group, causing an overall significant linear regression when in fact one does not exist. Following the testing of the original method by Gruspier and Mullen (1991) and the publication of the revised method (Mann et al., 1991), the original method does not appear to have gained much traction in the anthropological literature.

The revised method is based solely on visual examination for any amount of obliteration along each of the four sutures as well as the TP suture within the GPF (Mann et al., 1991). For sutures expressed bilaterally, the side with the most obliteration is used. Age is estimated based on the last suture to see any degree of obliteration, using the ages given in Figure 2 of the reference article (Table 2-2). For example, if the incisive, posterior median palatine, and transverse palatine sutures show at least one area of obliteration but the anterior median palatine does not, the individual is estimated to be between 35 and 50 years of age. If the same general progression of suture fusion is always observed, this technique is straightforward, albeit lacking in statistical robusticity. However, where the observed pattern differs from the expected, it is less clear how to estimate age since Mann et al. (1991) only provide the earliest age of fusion per suture seen in their sample. The age estimate can also include the assessment of other subjective palatal traits, such as bone condition, edentulism, and alveolar resorption. However, these traits are not defined, no codified measurement system is provided, and it is unclear how these traits should be assessed in relation to fusion (i.e., how are traits versus fusion prioritized?).

Tests and modifications of the revised method include: Wheatley (1996), Ginter (2005), Sakaue and Adachi (2007), Beauthier et al. (2010), Brown (2010), Apostolidou et al. (2011), and Siegel and Passalacqua (2012). Results of these studies are equivocal, with some suggesting the method performs with high enough accuracy to be employed for age estimation (Ginter, 2005; Beauthier et al., 2010; Brown, 2010; Apostolidou et al., 2011) while others caution against its use due to low accuracy and precision in age estimates as compared to known ages at death (Wheatley, 1996; Sakaue and Adachi, 2007; Siegel and Passalacqua, 2012). What all of the studies do agree on is the general relationship of palatal suture closure to age, the progression of palatal suture fusion outlined by Mann and colleagues, and that palatal sutures can be used, at a minimum to place individuals into broad age categories (e.g., young, middle-aged, old). However, the methods employed vary greatly and even where a similar method has been applied, the results seem to be contradictory (e.g., Wheatley, 1996 versus Beauthier et al., 2010). No standard exists for palatal suture age estimation, and, even in studies that cite the revised method, application varies.

Palatal suture fusion is also included in more multifactorial approaches: Nawrocki (1998) and Vodanović et al. (2011). Nawrocki (1998) finds that the correlation of age and all palatal sutures is 0.55, as compared to positive correlations of 0.66 and 0.67 for age and all ectocranial and all endocranial sutures, respectively. In using median palatine suture as one of four methods to estimate age in a Croatian archaeological sample, Vodanović et al. (2011) find that closure of this suture and dental wear show high degrees of association. Compared to more complex methods that require extensive training such as tooth root translucency and pulp/tooth area ratio, the use of the palatal suture method for age estimation results in less accurate age estimations but is easier to apply (Vodanović et al., 2011). The use of a single suture and an archaeological sample (where actual ages at death cannot be verified) differs from the Mann method and other tests of this method, but the potential relationship of tooth wear and midpalatal suture closure is interesting.

Wheatley (1996) and Beauthier et al. (2010) both employ systems that score smaller sections of each palatal suture and use multiple regression to relate fusion at each site to age. Though neither study offers vastly improved accuracy as compared to the revised method, Wheatley's (1996) results suggest the palatal sutures have only limited utility in estimating age at death, while Beauthier et al. (2010) suggest the method is promising, especially for individuals of advanced age since palatine fusion progresses more slowly and starts later than vault fusion. They also find that there is agreement between age estimates from palatal and vault suture closure, and there is good agreement between age estimates produced from their method and the revised method. Interestingly, Wheatley (1996) finds that individuals with partial to complete tooth loss actually display premature fusion of the sutures, resulting in overestimation of their ages, and the presence of a large number of edentulous individuals in her sample may affect method performance.

Variation in palatal suture fusion by sex is also not consistent among studies. Mann et al. (1991) and Apostolidou et al. (2011) find greater obliteration in males as compared to females of the same age, while Wheatley (1996) does not find that sex significantly affects the rate of suture closure. Ginter (2005) finds no statistically significant differences in the accuracy of age estimation between the sexes for either the original or revised methods, though age is more often correctly predicted for males than females. This trend of higher correct classification rates for males is also found by Mann et al. (1991), Sakaue and Adachi (2007), and Apostolidou et al. (2011).

Populational differences in palatal suture closure are harder to assess because test samples often examine individuals from one major group or a small sample from a second group (Table 2-1). Mann et al. (1991) find minor ancestral differences in palatal suture closure, but this study includes only individuals of African and European ancestry. The study by Ginter (2005) offers a more complete picture of revised method performance in different groups. Ginter (2005) found lower correct classification rates for “black” individuals and individuals from the ancestrally diverse sample group as compared to “white” individuals, though no statistically significant differences exist among these groups. Using the original method, Ginter (2005) finds that individuals from the ancestrally diverse sample group have slightly higher correct classifications than “white” and “black” individuals, but these differences also are not statistically significant. In a Japanese sample, age is estimated correctly for only 36.9% of males and 25.7% of females, but since ages are not often over estimated Sakaue and Adachi (2007) state that palatal suture closure is useful as an indicator of minimum age in Japanese individuals. In a Greek sample, correct classification is much higher, with an overall rate of 87% correct (89% for males, 84% for females). When combining palatal sutures with vault sutures, palatine sutures are more heavily selected in models for individuals of African ancestry versus European ancestry (Nawrocki, 1998).

The effects of secular trends on palatal suture closure are unknown. Examining the samples given in Table 2-1 it can be seen that only three studies include samples from both historic and modern time periods. Even in these samples, only one has sample sizes balanced and large enough for comparison between historic and modern individuals (Wheatley, 1996).

Improving palatal suture closure as an age indicator

The large-scale applicability of maxillary suture age estimation remains uncertain because of the inability to compare methods due to differences in sample composition, the various ways that palatal suture closure has been scored and analyzed, and skepticism concerning the validity of sutural closure to estimate age. In order to improve palatal suture closure as an age indicator and reduce error in estimating age from palatal suture fusion, these challenges must be addressed. While a poor correlation between age and palatal suture fusion could be contributing to poor method performance, without the investigation of other variables that potentially relate to age and/or fusion it cannot solely be attributed to this.

Investigation of the maxillary sutures has been conducted in samples composed largely of individuals of European ancestry, some individuals of African ancestry, and only a limited number of individuals of Asian ancestry. No one study includes adequate sample sizes from all three major ancestral groups, and most samples to-date are not balanced in terms of age, sex, ancestry or time period (Table 2-1). Poorly distributed samples with small sizes introduce unnecessary error (Nawrocki, 1998).

There are also methodological inconsistencies in suture scoring and how those scores are translated into age estimates. An interobserver error study conducted by Brown (2010) indicated that while practitioners show high concordance in observing and recording obliteration of the palatal sutures, there is little agreement on how to develop an age interval from these observations. Being able to apply the method with little error for many observers is important, and the inability to do so introduces error. Efforts to standardize the method by scoring pre-defined suture sites have not always been successful (e.g., Wheatley, 1996) and actually result in lower correct classification rates than the solely visual method that takes into account the entire length of a single suture.

Based on tests of the original and revised methods, there is still some confusion that exists on the different approaches presented in each method. The two methods differ significantly in not only the ages assigned per state of fusion (Table 2-2), but how fusion is scored. The original method requires measurement of the sutures, though the technique is not clearly outlined, and the revised method uses a visual, quantitative method, though some continue to use the summary score from the original method.

These differences are poorly defined between the two methods, and subsequent tests of the methods reflect this difficulty, contributing to error when applying either method.

The improper application of statistics, or the absence of statistical analysis altogether, also contributes to difficulties in estimating age from the palatal sutures. Very few of the above methods employ robust statistical analysis or selection procedures, and the revised method, which subsequent studies use as a guide, does not even provide descriptive statistics for stages of observed suture fusion. There is a clear lack of predictive models for age estimation.

Even with the general trend of increasing fusion with increasing age, confounding variables, especially in an area as complex as the palate, are important considerations. None of the above studies have truly examined the relationship of sutural fusion, age, masticatory function, and other palatal traits. Equally as important is the investigation of other facial sutures as controls in order to better understand maxillary suture fusion patterns. While multiple studies show a general relationship between maxillary suture fusion and age, in a study of the frontonasal suture, Alesbury et al. (2013) found that fusion of this suture is poorly correlated with age and that no regular pattern of fusion occurs. Secular trends may also affect age estimation based on the palatal sutures if individuals in more recent decades are in fact maturing earlier than their historical counterparts, and, as with other age estimation methods, this should be investigated.

Summary

This chapter presented descriptions of age and aging, processes of skeletal growth and remodeling, and how anthropologists estimate age from skeletal indicators, including a consideration of the statistics employed and how cranial and palatal sutures are used for age estimation. The next chapter provides a detailed discussion of the human palate and its growth, development, and function. It also includes a consideration of how the palate is used in biological anthropology.

Table 2-1. A comparison of anthropological studies of age estimation based on all of the palatal sutures. The order is chronological based on publication date. Information in parentheses further describe the sample.

Reference	*n*	Ancestry	Sex	Time period	Age range
Mann et al. (1987)	36	"White" (30) "Black" (6)	Males (14) Females (22)	Modern	22-73 (males) 13-79 (females)
Mann et al. (1991)	186	"White" (78) "Black" (108)	Males (110) Females (76)	Historic (171) Modern (15)	Not given
Gruspier and Mullen (1991)	83	"White"	Males	Historic	29-87
Wheatley (1996)	346	Not given	Males (177) Females (169)	Historic (146) Modern (200)	13-101
Ginter (2005)	155	"Black" (11) "White" (112) "Diverse" (23) "Unknown" (9)[a]	Males (96) Females (59)	Modern	26-100 (both)
Sakaue and Adachi (2007)	375	Asian (Japanese)	274 males 101 females	Not given	~15-80 (both)
Beauthier et al. (2010)	134	European (French, Belgian)	78 males 56 females	Modern (100) Historic (34)	19-96 (males) 19-101 (females)
Apostolidou et al. (2011)	271	European (Greek)	150 males 121 females	Modern	20-64+
Siegel and Passalacqua (2012)	200	European African	Not given	Historic	10-82 (both)

[a]Classified according to social classification categories in use at time of collection; "white" is European, "diverse" includes East Asian and Khoisan, "black" is African.

Table 2-2. Comparison of age estimates for the original (Mann et al., 1987) and revised (Mann et al., 1991) maxillary suture methods.

Suture fusion observed	Age interval – Original	Age interval – Revised
IN	<25	20-24
PMP	25-42	25-29
TP in GPF	N/A	30-34
TP	43-60	35-50
AMP	60+	50+

CHAPTER 3
THE HUMAN PALATE

The human craniofacial skeleton, which includes the palate, exhibits a complex developmental history and biomechanical environment. As a part of this structure, the palate is intrinsically related to the growth, development, maturation, form, and function of the skull, facial skeleton, and dentition. Besides it role in alimentation, the palate is also important in biological anthropology because morphological traits can be used for individuation or placement within a specific group (e.g., sex, ancestry, and age). This section discusses facial and palatal growth, development, and maturation; palatal function; and uses of the palate in biological anthropology. More general processes of skeletal growth and aging are discussed in Chapter 2.

Palatal Form

The human palate is composed of hard and soft tissue, and it serves as a divider between the alimentary and respiratory tracts. The hard palate is made up of the left and right maxillae and palatines, though considerable debate exists on the presence of a separate premaxilla in humans (Scheuer and Black, 2000)[1]. The anterior two-thirds of the hard palate is composed of the palatine processes of the right and left maxillae, and the posterior one-third is composed of the horizontal plates of the right and left palatines. The soft palate is made up of the aponeuroses and fibers of the *tensor veli palatini*, *levator veli palatini*, and *uvulae* muscles (Scheuer and Black, 2000); the

[1] The premaxilla debate can be traced as far back as Vesalius in 1543 (Ashley-Montagu, 1938). Since that time, the literature is divided between those that confirm the presence of a separate premaxilla in humans, similar to other primates, and those who deny its presence, setting humans apart from non-human primates. This debate is only pertinent here in how it relates to the incisive suture, and whether or not this suture is functionally and developmentally the same as the other sutures of the hard palate or is simply a fissure in the maxilla. For this research, the incisive suture is considered as a sutural junction between the maxillae and premaxillae.

muscles of the soft palate are listed and described in Table 3-2. The only muscles that connect to the hard palate do so via the soft palate at the posterior palatines; no muscles have direct origins or insertions on the hard palate.

The maxillae are paired bones that form the floors of the eye orbits, the floor and lateral walls of the nasal cavity, and the roof of the mouth. The maxillae also house sinuses (one on each side) and the upper dentition - 10 deciduous teeth and 16 permanent teeth. The left and right maxillae form the majority of the hard palate, joining with each other at the anterior median palatine (AMP) suture and with the palatines at the transverse palatine (TP) suture (Figure 3-1). The maxillae also articulate with the frontal, nasals, lacrimals, ethmoid, inferior nasal conchae, vomer, zygomatici, and sphenoid. The anterior portions of the maxillae articulate with the premaxillae at the incisive (IN) suture, though this suture is often fused and not externally visible in adults.

The palatines are paired bones that form the posterior portion of the roof of the mouth and walls and floors of the nasal cavity. The left and right palatines are joined with each other at the posterior median palatine (PMP) suture and with the maxillae at the TP suture (see Figure 3-1). The TP suture descends into the greater palatine foramen (GPF), which is formed at the lateral junction of the alveolar process of the maxilla and the horizontal plate of the palatine on each side. The palatines also articulate with the vomer, inferior nasal conchae, ethmoid, and sphenoid.

Sutures are the fibrous joints that interlock to form tight connections between adjacent bones in the hard palate, permitting flexibility in growth, maximum durability in adulthood, and simultaneous movement and cohesion (Rogers, 1984; Thilander, 1995). Palatal sutures change in morphology during growth, generally progressing from, wide and straight to narrow and more sinuous. In adulthood, the two main sutures of the palate are the median palatine and transverse palatine (see Figure 3-1); the incisive suture is less prominent as it has a tendency to fuse in late adolescence or early adulthood (Mann et al., 1991).

Facial Growth and Development

The facial skeleton supports the orbits, nose, jaw, and soft tissues of the face, as well as vision, olfaction, respiration, and alimentation. The face is composed of fourteen bones that are formed via intramembranous ossification and joined by sutures. Six of the bones are paired –maxillae, lacrimals, nasals, inferior nasal conchae, zygomatics, palatines, and two are unpaired – vomer and mandible.

The growth of the face is complex and highly integrated (Hinrichsen and Storey, 1968; Enlow and Hans, 1996). None of the elements that make up the facial skeleton grow or exist in isolation, and growth is related to complex biological and mechanical demands in the entire cranial system. Growth is a composite change of all components in this system, although some areas of the cranium and face contribute greater percentages to total growth than others (Enlow and Hans, 1996). An increase in size is connected to complex remodeling changes that ensure that craniofacial shape, proportions, and relationships among elements are maintained (Enlow, 1966). The timing of facial growth is covered below as well as the growth of the elements of the palate.

The coordinated growth of multiple elements of the skull is important in maintaining the functional integrity of the entire system. The face itself is built on the cranial base, thus the growth of the face is intrinsically linked with the growth of the neurocranium. The human brain is a powerful driving factor in facial growth because it is the most rapid growing organ in infancy (Bogin, 1999: p 72). Additionally, the coordinated growth of teeth and the craniofacial complex is important in maintaining the functional integrity of the masticatory system. Without this harmony between teeth and bone growth, an individual would not survive (Bogin, 1999).

There are important size and shape differences between prenatal, infant, child, and adult facial forms, and the relative positions of facial structures change with age (Feik and Glover, 1998); the adult face is not simply a larger infant face. An example of these size and shape differences can be seen in the changing relationship of the inferior borders of the nasal cavity and the eye orbit. At birth, these two landmarks are at approximately the same level. Displacement and drift during childhood and adolescence steadily increases the distance between these landmarks. This results in the transition of a short, small, and round neonate face to an elongated, larger, and more rectangular adult face. Growth of the facial skeleton is dominated by increases in height, followed by depth, and then width.

Overall, the face appears to grow downward and outward as unit, but this only describes the direction that the face moves in relation to the rest of the cranium, not the direction of growth (Brodie, 1941). Facial bones have surfaces that are resorptive in nature, which are complemented by depository surfaces, meaning that the face actually grows from behind and above, displacing elements down and to the front (Enlow, 1966). The location of these paired surfaces allows for integrated remodeling and growth of the face. Because of the varied regional orientations of the face and the complex relationships of shape and dimensions among the skeletal elements, the pairing of resorptive and depository surfaces is not easily summarized directionally. Each bone grows in specific ways in order to compensate for size and shape changes in the growing face.

The V-principle describes the general progression of skeletal growth through both remodeling and displacement (Enlow and Hans, 1996) (Figure 3-2). For facial elements, deposition occurs on the internal surface of the V (+ symbols), and resorption occurs on the outer surface (- symbols). Together, these deposition and resorption events represent the process of remodeling. The gray V-shapes depict the former locations of the element and indicate displacement during growth. The direction of growth is from the narrow end of the V to the wider end (indicated by the solid black arrow). In the facial elements, it is not simply the anterior surface that is resorptive and the posterior surface that is depository; even a single element can exhibit multiple orientations for resorptive and depository surfaces. However, the V-principle provides a descriptive framework for interpreting skeletal growth; in the face, the surface that points the same direction as growth is depositional, while the surface that points away from the direction of growth is resorptive.

Craniofacial Growth Models

Disagreements on the number of facial ossification centers and how craniofacial growth progresses highlight some of the difficulties in modeling craniofacial growth (Woo, 1949; Scheuer and Black, 2000). There are two main, competing models of craniofacial growth: nasal septum (Scott, 1953; Scott, 1954) and functional matrix (Moss 1968; Moss and Salentijn, 1969). These models describe what happens during growth and offer explanations of some growth stimuli, but neither addresses the influence of genes or the impact of the interaction of genes and environment on the growth process. While these are integral to the growth and development of any organism and cannot be separated from what happens during these processes, much like age is the result of complex gene and environmental interactions (see Chapter 2), an investigation of the cellular and genetic mechanisms of facial growth is beyond the scope of this research.

Prior to the development of the nasal septum and functional matrix models, the predominant idea was that sutures were intrinsic growth sites, pushing apart cranial elements as they grew, similar to the growth plates seen in long bones (Moss, 1969). It is now understood that the stimulus for bone growth/remodeling along a suture is actually related to tension that is produced by displacement of the bone where the suture is located and not by the suture itself. In fact, compression at a sutural junction actually leads to resorption of the bone, not bony deposition (Enlow and Hans, 1996). While sutures are sites of osteogenesis and major growth centers of the cranium, they are not the driving force of displacement in the cranium nor are they independent and self-initiating growth sites (Lenton et al., 2005).

The nasal septum model is based on the displacement of the maxilla, which leads to bony growth/remodeling (Scott, 1953; Scott, 1954). The observation of abnormal growth in the midface following the removal of or damage to the nasal septal cartilage forms the basis for this model (Scott, 1953). Growth of cartilage in the nasal region causes tension in adjacent sutures, resulting in the anterior and inferior movement of facial bones from the cranial base and one another, with the exception of the mandible. This is possible because cartilage is adapted to pressure-related growth sites, and it can allow growth in compression (Enlow and Hans, 1996). In this model, cartilage has intrinsic growth potential (i.e., it is a growth center).

Opponents of this theory argue that this is a singular explanation for a multifactorial process, and it does not account for the remainder of craniofacial growth (Enlow and Hans, 1996). For example, the cartilage of the mandibular condyle is not a growth center even though it participates in growth early in life and has the ability to absorb pressure forces later in life (Thilander, 1995). Unlike the calvaria, the facial skeleton does not have a major organ like the brain to drive growth, and although the nasal septum theory attempts to adapt this concept to the facial skeleton, it really only applies to the nasal region. In the absence of the nasal septum, while the nose does not grow, maxillary development is still fairly normal (Feik and Glover, 1998).

The functional matrix model states that bones react to changes in the functional units they support, and it places the initiation of growth on the enclosing soft tissues of the cranium, with the skeletal components following suit (Moss, 1968; Moss, 1969; Moss and Salentijn, 1969). In the cranium, multiple functions take place, and each function is carried out by a particular functional matrix and protected or supported by a skeletal unit (Moss and Salentijn, 1969). For example, midfacial growth is driven by respiratory function, and growth of the masticatory apparatus drives growth of the mandible and parts of the maxilla. In this model, the nasal septal cartilage is a locus of secondary, compensatory, and mechanical growth rather than an initiator of growth (Thilander, 1995). The concept of the functional matrix is an important component of functional morphology and the interpretation of function from form.

One of the points of opposition to the functional matrix theory is that functional forces do not operate *in utero* and therefore have no effect on growth during this time (Mooney et al., 1989). The nasal septal cartilage theory purportedly accounts for this prenatal growth. However, studies have found that there are fetal facial and mastication functions that are carried out, albeit small (Humphrey, 1969). Furthermore, nasal septal cartilage, while important in prenatal growth, shows less clear contributions to postnatal growth, though it does play a significant biomechanical role in maintaining normal midfacial form (Thilander, 1995).

Both the nasal septum and functional matrix models posit that passive skeletal changes of the face are related to active growth of adjacent soft tissues (Mooney et al., 1989). Where they differ is the role played by the nasal septum versus the functioning spaces of the face (e.g., respiration, alimentation) and what is causing the force that leads to tissue separation (soft tissue matrix or cartilage) (Mooney et al., 1989). There may also be a difference in growth during the prenatal and postnatal time periods, which would result in a better model fit based on what material is being studied. However, both models demonstrate that facial skeletal growth is the result of the growth of other structures and is not mediated by an intrinsic force.

Timing of Craniofacial Growth

Normal craniofacial growth patterns are studied in order to better understand the patterns themselves, their timing, and deviations from the norm. Studying human craniofacial growth presents several challenges, one being access to study material because the initiation of growth centers commences *in utero*. Histological, cephalometric, radiographic, and other types of studies contribute to the knowledge of growth timing and patterns pre- and postnatally and form the basis for current knowledge in this area. The timing of growth and growth patterns for the face are outlined temporally below, starting with the prenatal period.

Prenatal craniofacial growth

Prenatal growth of the face involves the coordination of multiple specialized tissues. Facial growth begins with neural crest cells from the brain, which migrate to form the facial growth centers and later to form connective tissue (cartilage, bone, and ligaments). These growth centers are located first in the pharyngeal (branchial) arches, which are composed of mesenchyme covered externally by ectoderm and internally by endoderm. The pharyngeal arches provide the framework for future development, and each of the five bilateral pairs of pharyngeal arches gives rise to specific facial bones with all of their associated veins, arteries, nerves and muscles.

The first pharyngeal arch is the origin for the maxilla and mandible and all muscles for mastication. The facial growth centers from the first pharyngeal arch form around the stomodeum (the primitive mouth). These growth centers give rise to the frontonasal, maxillary, and mandibular prominences, which grow and later fuse to form the face. At four weeks *in utero* the stomodeum marks the future location of the mouth, the entire head is composed mainly of brain with thin layers of ectoderm and mesoderm, and the eyes are located on the lateral surfaces of the head (Enlow and Hans, 1996). By the end of the fourth week and into the fifth week of intrauterine life, the basic organization of the face commences, as the frontonasal prominence and the paired maxillary and mandibular prominences from the pharyngeal arches come together (Barnes, 2012).

Skeletal growth is initiated in the facial skeleton following the appearance and fusion of facial growth centers that lay the framework for the basic form of the face. The appearance of ossification centers *in utero*, taken from Enlow and Hans (1996), is: maxilla – end of week six; premaxilla – seven weeks; mandible – six to eight weeks;

zygomatic – eight weeks; nasal – eight weeks; lacrimal – eight and a half weeks. The facial bones then enlarge from their ossification centers. The greatest period of growth of the facial bones is from 24 mm to 36 mm crown-rump length stage (approximately 9 to 10 weeks gestational age) (Avery and Devine, 1959). During this time, growth is greatest in the antero-posterior plane, with limited vertical growth (Avery and Devine, 1959). The form of the face is visible between four and ten weeks *in utero* (Scheuer and Black, 2000).

Prior to 14 weeks *in utero*, facial bones grow from their ossification centers, but no significant remodeling takes place (Enlow and Hans, 1996). Prenatal remodeling does occur, but the majority will not take place until morphologically definitive skeletal elements appear, which is at or after 14 weeks (Enlow and Hans, 1996). Some remodeling may occur as early as week 10, but it is limited to two locations: bone around tooth buds and the endocranial surface of the frontal bone (Enlow and Hans, 1996). From week 14 onward, growth entails enlargement and remodeling, although large-scale growth and development of the facial skeleton, with the exception of the eyes, is related to dental and masticatory muscle development. These functions are not given priority in fetal development, resulting in the large head and eyes to small face proportions seen in human newborns (Scheuer and Black, 2000).

Postnatal craniofacial growth

While prenatal growth is important in establishing a baseline form, work by Richtsmeier and colleagues (1993) demonstrates that postnatal growth patterns contribute significantly to adult form, and the majority of facial growth occurs postnatally. At birth the skull as a unit is closer to adult size and proportions than any other skeletal element, but the calvarium is six to eight times the size of the face due to a difference in growth rates between the neurocranium and viscerocranium (Brodie, 1941). Elements that make up the neurocranium follow a neural growth curve, which preferentially accommodates rapid growth required by the large brain of human infants (Briggs and Martakis, 1998; Feik and Glover, 1998). The elements of the viscerocranium follow an S-shaped somatic growth curve, displaying slow prenatal growth followed by a period of rapid growth postnatally, similar to growth of the postcranial elements (Feik and Glover 1998). By birth, the craniofacial skeleton has completed 30-60% of its total growth; following birth the size of the neurocranium increases by about 50%, as compared to a 200% increase in height and a 75% increase in width of the facial skeleton (Thilander, 1995). Growth of the face is most rapid during the first three years of life (Feik and Glover, 1998).

The development of the dentition and masticatory muscles greatly influences postnatal facial growth and development. The emphasis on brain development at the expense of facial development in the infant skull precludes the early development of adult-sized dentition, thus two sets of teeth are found in humans: deciduous and permanent (Rogers, 1984). There are four distinct time periods of dental eruption that are related to facial growth and development: deciduous teeth during the second year of life; permanent incisors and first permanent molars between six and eight years; permanent canines, premolars, and second molars between ten to twelve years; and third molars around eighteen years (White et al., 2012). At each of these stages, the facial skeleton must accommodate these new additions by increasing in size and altering in shape.

At or around the time of puberty, the facial skeleton also undergoes changes that are related to the acquisition of secondary sex characteristics. Adult female faces are smaller and have a more rounded contour than males (Rogers, 1984). Changes in brow and chin shape related to greater robusticity in males as compared to females also occur. The face is considered to have reached skeletal maturity between 12 to 15 years in males and 10 to 13 years in females (Feik and Glover, 1998).

Adult craniofacial growth

Facial growth and development does not cease in adults, though the pace is greatly decreased, and changes in the adult face may also be related to degeneration, disease, loss of the teeth, and the accumulated effects of masticatory stresses, rather than growth. Much of the aging of the face has been discussed in terms of soft tissue change (e.g., wrinkling) but adult facial growth still occurs for skeletal components and dentition. While growth as a process is generally attributed to subadults, growth of the head and face do occur in adulthood, with changes in facial size and shape occurring largely between 16-30 years (Albert et al., 2007; Behrents, 1985). Changes in facial form can continue into the fifth and sixth decades of life, though the rate of change is much slower than that of children and adolescents, as is the order of magnitude (1-2 mm over several years to several decades) (Behrents, 1985). Displacement no longer occurs, but the craniofacial skeleton changes in horizontal, vertical, and sagittal dimensions via remodeling (Albert et al., 2007). While changes are small, they can be clinically significant, especially for the implantation of prosthetic devices. A sexually dimorphic trend exists, with female faces exhibiting increased vertical growth over time as compared to males, who exhibit increased horizontal growth (Albert et al., 2007).

Females also show greater shape changes, perhaps due to hormonal changes associated with menopause (Doual et al., 1997; Albert et al., 2007).

Secular Changes in Craniofacial Growth

In the United States, secular changes in cranial and craniofacial morphology include an increase in cranial capacity, vault height, base length, and total length, and a decrease in vault and facial width and cranial vault thickness (Angel, 1976; Nawrocki, 1995; Jantz and Meadows Jantz, 2000; Jantz, 2001; Wescott and Jantz, 2005). Shape changes of the vault are more pronounced than those of the face, but facial dimensions do show a trend of narrowing and becoming higher over time (Jantz and Meadows Jantz, 2000). Additionally, cranial shape changes are more pronounced than size changes.

Change is often attributed to improvements in health and nutrition, such as access to better healthcare, decreased prevalence of diseases, and increased caloric intake. However, while these environmental factors can certainly contribute to taller stature and cranial height in U.S. populations, they do not explain the narrowing seen in the cranium and face (Skorpinski, 2014). It is possible that changes of the face are related to changes in the cranial base, since an increase in cranial capacity does result in inferior movement of the cranial base (Jantz, 2001; Wescott and Jantz, 2005), but this is not the only explanation.

There are intrinsic difficulties in interpreting the effects of better nutrition and health on secular change in the United States. While ample information is available for documented skeletal collections, information on nutrition was not routinely collected and is thus not available. Many skeletal collections, and specifically those considered to be historic (individuals born in the 19th century), are composed of individuals of low socioeconomic status (Hunt and Albanese, 2005). These individuals may exhibit less positive growth changes as they likely had decreased access to improvements in health care and alimentation when compared to individuals of higher socioeconomic status. The composition of the reference samples therefore may bias the interpretation of potential secular trends if these trends are rooted in improved health and nutrition.

Another alternative explanation for secular change in cranial shape and size is a change in the consistency of food consumed and not in its nutritional value (Jantz and Meadows Jantz, 2000; Wescott and Jantz, 2005; Skorpinski, 2014). With the introduction of processed foods to the American diet in the mid-20th century, the overall quality of food has decreased, as has its toughness. More nutrition, including overnutrition, does not necessarily mean better nutrition, and changes in size and shape could be related to eating less tough or gritty foods, which represents a biomechanical, dietary explanation (Wescott and Jantz, 2005; Skorpinski, 2014). In fact, Kiliaridis et al. (1985) find that rats fed food with a softer consistency did show changes in craniofacial morphology as compared to the control group, which was fed a standard laboratory diet of pellets. The effect of diet on palatal form is discussed in further detail below.

The above explanations for secular change are purely environmental. However, there is also a genetic component to growth and development, and Jantz (2001) attributes observable secular trends to a combination of phenotypic plasticity and genetic change over time. With the improved health hypothesis, individuals growing up in the same environment should exhibit the same change even among different ancestral groups. Yet, secular changes in facial dimensions are not the same between European and African Americans. The increase in facial height over time is only significant in Europeans, and facial depth, the anterior to posterior dimension of the palate, shows an increase in European Americans and a decrease in African Americans (Angel, 1976; Jantz and Meadows Jantz, 2000; Jantz, 2001). American “Blacks” and “Whites” continue to have different cranial dimensions and shapes and do not exhibit similar morphology even though they are largely living in the same environments with similar access to better food and healthcare (Jantz and Meadows Jantz, 2000).

Sparks and Jantz (2002), performing a reanalysis of cranial and facial measurements from Boas’s seminal work on cranial form (Boas, 1910), find that environmental factors on cranial form are minimal when compared to differences seen among ancestral groups (i.e., there is less difference between a European-born immigrant and his/her American-born child in terms of cranial measurements than there is between individuals from different ancestral backgrounds). Their study suggests a high heritability of cranial form traits and not a large amount of phenotypic plasticity, as Boas claimed. Conversely, Gravlee et al. (2003a; 2003b), in their own reanalysis of Boas’s data, suggest that differences in cranial form can be attributed to environmental plasticity and not the high heritability of cranial traits, though they do not argue against the heritability of cranial form. Thus differences in cranial form, of the lack thereof, may be interpreted differently, though what these studies do suggest is that multiple variables are likely contributing to cranial form, rather than solely heredity or environment.

The investigation of secular trends in craniofacial growth needs to adequately address multiple variables, which is challenging. However, by collecting data that reflects genetic contributions to size and shape, such as the sex and ancestry of individuals, and environmental factors, such as dental wear as a proxy for changes in food consistency, it is possible to better understand observed trends in terms of secular change. These changes do not occur in isolation and, much like growth and development, are the result of complex interactions of genes and environment.

Palatal Growth and Development

This section discusses the growth and development of the hard tissue components of the palate as well as the aspects of the dentition that directly contribute to growth and development of the palate. The timing of palatal growth and development, including some key events in dental development that affect the hard palate, is given in Table 3-1, compiled from Scheuer and Black (2000). Like the study of craniofacial growth, palatal growth is often studied to inform abnormal growth patterns, such as cleft palate.

Prenatal Palatal Growth and Development

The first maxillary and palatine ossification centers appear early in intrauterine life and are located at the anterior and medial aspects of the nasal capsule, respectively. The primary palate, also described as the premaxilla, is visible by the end of the fourth week *in utero*. Another ossification center in the premaxilla appears between nine and ten weeks. Woo (1949) identifies three ossification centers for each maxilla (six total), with one of these for the maxilla itself and the other two for the premaxilla, and research by Avery and Devine (1959) confirms the presence of at least two premaxillary growth centers based on histological observation of normal and cleft palate embryos.

The palatal shelves form from the maxillary processes at four to six weeks *in utero*. At this point, the palatal shelves are vertical (i.e., they do not form the "roof" of the oral cavity, but run alongside it), and the tongue is located in between them because of the small size of the oral cavity. The transition from vertical to horizontal shelves occurs between seven and eight weeks *in utero*, and is related, in part, to the expansion of the inferior portion of the lower face. Mouth opening reflexes commence prior to palatal shelf elevation and have also been shown to significantly affect tongue withdrawal from the vertical shelf via traction from mandibular depression (Humphrey, 1969), though the growth of Meckel's cartilage and the mandible also plays a role. With the movement of the tongue inferiorly, a vacuum is created that then draws the shelves towards midline; this also results in a larger oral cavity.

Once the tongue has descended, the palatal shelves expand horizontally and join at midline. Bone then forms at this location, which becomes the secondary palate. The secondary palate displays an antero-posterior gradient of palatal closure[2] beginning at the primary palate (Burdi and Faist, 1967). During the time of palatal shelf elevation and closure, there is also a significant increase in overall depth and height of the facial region, and the palate moves into a position that is approximately 90 degrees relative to the cranial base, similar to its postnatal position (Diewert, 1983). At the time of midline closure, the maxillary processes fuse with the nasal septum and posterior portion of the primary palate. Cleft palate anomalies often occur during this time frame (see Palatal Developmental Anomalies, below). The palatine processes meet in the midline later than the maxillary processes at about 18 weeks *in utero*.

The maxilla does not completely ossify until late fetal life nor does it attain adult form or proportions by birth, and the premaxilla remains separate from the maxilla until

[2] Note that closure here refers to the joining of the adjacent sides of the secondary palate, not the obliteration of the sutural junctions at this location.

about month four or five *in utero*. By the sixth month *in utero* the facial aspect of the incisive suture is closed. During fetal life, deposition of bone occurs mainly on the anterior maxilla (labial surface), and the fetal maxillary arch lengthens horizontally in posterior and anterior directions (Enlow and Hans, 1996). The palatine reaches adult form by mid-fetal life, although it does not reach adult proportions until later (i.e., the perpendicular plate ends up being much greater in height due to changes in the size of the face and nasal cavity).

Fetal palatal growth is tied very closely with fetal dental development (Table 3-1). While *in utero*, tooth germs develop. As the teeth begin to form, bone also forms around them. This bone extends on the buccal and lingual surfaces and between the teeth in the form of thin walls. This bone growth is the foundation for the alveoli.

Sutural growth is also an important component of prenatal palatal growth and development. In a histological examination of the mid-palatal suture, Latham (1971) finds that the interpremaxillary suture develops almost coincident with the premaxillary ossification centers and is definitively established no later than seven weeks *in utero*. Sutural formation along the maxillary mid-palate is present at 10.5 weeks, with definitive formation of an intermaxillary suture by 12 weeks (Latham, 1971). The difference in timing of sutural appearance is likely related to union of the separate right and left halves of the premaxillae and maxillae, with the former occurring several weeks prior to the latter. Following sutural formation, sutural growth occurs until 16 weeks *in utero*, with growth and remodeling occurring together after this time and continuing postnatally. Based on macroscopic examination of the premaxillary area, Sejrsen et al. (1993)

conclude that the development of the incisive suture is most likely related to the development of the anterior teeth.

Postnatal Palatal Growth and Development

At birth, there is no longer any evidence of a separate premaxilla on the facial aspect of the cranium, though the internal surface of the palate often shows evidence of this separation (the incisive suture or fissure). Also at birth, only one primary center of ossification is still present on each side of the maxilla, the maxilla has a small body with tooth germs close to the orbital floor, and the maxillary sinuses are small (Scheuer and Black, 2000). The infant palate is composed mainly of fine cancellous bone that quickly remodels in conjunction with changes in the dentition, nasal cavity, and eye orbits, contributing to rapid growth.

In the immediate postnatal period, the fine cancellous bone of the palate is replaced by cortical bone with medullary spaces, and the medial ends of the palatal processes gradually thicken (Latham, 1971). During the first two years of life the inferior cortical layer of the palate remains cancellous due to deposition on this surface, the intermaxillary suture increases in height while also narrowing, and the sutural margins become parallel and exhibit continuous cortical bone (Latham, 1971). At around three years of age compact cortical bone and clear medullary spaces are seen in the thickened medial area with sutural tissue composed of fiber bundles running parallel to the sutural bone margins (Latham, 1971). Between years two and four midpalatal sutural growth slows and then stops. Also within the first two and a half years following birth, the deciduous dentition erupts (Hillson, 1996). The maxillary dentition emerges slightly later than the mandibular.

The maxilla has the appearance of growing out and down, but it is actually the superior and posterior appositional growth of this element that causes both the lowering of the nasal floor and the continued anterior projection of the alveoli and nasal spine in childhood, resulting in a downward and forward pattern of displacement (Brodie, 1941). The postnatal palate, largely dominated by the maxilla, grows in three dimensions: length (anterior to posterior), width (transverse), and height (superior to inferior). Growth of the palate takes place via paired processes of deposition and resorption that involve different facial components for each dimension. Transverse growth occurs via expansion of the midpalatal suture through deposition with some resorption, remodeling and resorption along the labial and buccal surfaces of the alveolar border, and deposition along the lingual surface of the maxillary alveolar bone. Bony deposition on the buccal surface of the maxillary tuberosity (posterior alveolar border) also affects width. Growth in length occurs via expansion and bony deposition at the transverse palatine suture and maxillary tuberosities, as well as remodeling of the maxillary tuberosity, while the anterior (labial) surface of the maxilla is resorptive. Growth in height occurs via remodeling and resorption of the nasal side of the hard palate with coincident bony deposition on the oral side of the palate; dental eruption also plays a large role in height growth. While growth of the face is largely affected by facial structures, the expansion of the middle cranial fossa of the neurocranium also affects growth in all three dimensions. Growth in width via deposition at the alveolar margins generally ceases around age 7, growth in height generally stops after age 9, and growth in length occurs largely in adolescence until adult life, mainly driven by dental development (i.e., the emergence of the third molars).

Dental development and eruption affects palatal growth and development because of the close relationship between teeth and bone. Eruption is the process by which teeth move towards the occlusal plane, and it concludes when the tooth reaches that plane. All maxillary permanent teeth develop superior to the deciduous dentition, with the exception of the second and third molars. The eruption of the permanent teeth therefore serves to displace the deciduous dentition and alter the alveolar bone. Alveolar bone is also altered by root growth since the roots continue to grow after the tooth has erupted. Continued eruption of the teeth results in mesial drift, where the teeth “move” towards the front of the mouth as the palate grows in length, freeing up space in the back of the mouth for more teeth. The combined processes of eruption and drift result in adjustment of the dentition in relation to the face, which is permitted by the periodontal ligament. The relationship between the periodontal ligament and the alveolar bone is also important because it allows the bone to remodel in order to adapt to changing forces in the mouth (see also Mastication, below).

In the period from childhood to adolescence, palatal sutures changes from simple straight lines to lines of increased complexity. The transverse palatine suture develops into a squamous suture, while the median palatine becomes sinuous and interdigitated (Melsen, 1975). The palate also changes from flat to increasingly concave on its interior surface. The palatal surfaces of younger individuals tend to have rough, bumpy surfaces that smooth with increasing age (Bass, 2005), and Mann et al. (1987) find that in advanced age the maxilla has a flat and smooth lingual surface. Growth generally ceases once the palate has attained adult size and shape, which is most often around the age of 18 (Scheuer and Black, 2000).

Palatal Developmental Anomalies

Cleft palate is one of the most commonly researched developmental anomalies of the palate, and it is the failure of one or both maxillary prominences to merge with the fused nasal prominences. This anomaly is associated with problems prior to cell differentiation and the disruption of growth processes following this stage (Scheuer and Black, 2000). Growth disruption can result in clefts of the soft palate only, clefts of the soft and hard palate, complete unilateral clefts of the lip and palate, and complete bilateral clefts of the lip and palate and can affect the primary and secondary palate (Kirschner and LaRossa, 2000). Palatal clefts are troublesome because they can lead to problems with alimentation and respiration, as well as issues with hearing, dentition, speech, and midfacial growth.

A cleft palate indicates a disruption to normal palatal development and can be attributed to a number of different factors. Most often the problem occurs at the time of elevation of the palatal shelves (see Prenatal Palatal Growth and Development, above). During this time period, the following things can occur to result in cleft palate: inhibition of cell division/migration, which means the palatal shelves are too small to meet at midline; failure of shelf elevation at correct time; excessive head width, which is also related to sex differences since females palate elevation occurs approximately one week later than males; failure of shelf fusion; or post-fusion rupture (Ferguson, 1987). A failure to displace the tongue can also cause a cleft.

The etiology of cleft palate is not entirely understood. There can be environmental factors that affect palatal growth, and certain types of clefts can be associated with genetic disorders. However, most clefts are multifactorial in origin or result from a mutation or change at a major single-gene locus (Kirschner and LaRossa, 2000). There are also demographic differences in the occurrence and frequency of cleft palate. According to Kirschner and LaRossa (2000), Asians are most likely to exhibit cleft lip and palate, followed by Whites, then African Americans, and cleft palate occurs more commonly in females (Barnes, 2012).

The hard palate can also exhibit developmental cysts. There are three types of cysts seen in the hard palate: median anterior maxillary – in or near the incisive foramen; median palatal – between the palatal processes (in the vicinity of *staurion*); and globulomaxillary – at the lateral junction of the premaxilla and maxilla between the lateral incisor and canine (Barnes, 1994). These cysts form when there is a delay in the retraction of overlying ectodermal tissue during development or, in the case of the globulomaxillary cyst, in relation to odontogenesis (Little and Jakobsen, 1973; Barnes, 1994). A retraction delay results in the retention of epithelial tissue between skeletal elements as they unite, forming a cyst that is lined with epithelium and contains either a fluid or semisolid substance (Little and Jakobsen, 1973). Cysts are generally rounded or oval, although some can be irregular in shape, and may or may not have sclerotic margins. They are not associated with any significant functional problems and appear to be largely asymptomatic (Stafne, 1969).

Palatal Function

When describing and measuring loads there are two basic concepts employed: stress and strain. Stress is the normalized intensity of a force, and it is measured as the load per unit area (Swartz, 1991). Strain is the physical change in dimension of a loaded body, and it is quantified by measuring the deformation of a given body when a load is applied (Swartz, 1991). Stress is often much more difficult to measure, especially in biology, so strain is more commonly used. Strain can be predicted theoretically via engineering models or measured in extant and extinct organisms through strain gage analysis. In strain gage analysis, small gages measure the amount of deformation of a material, such as a skeletal element, when loaded.

The cranium protects the brain and other organs from impact loads, and the craniofacial region as a whole is subjected to a wide variety of loading factors. These factors are difficult to measure or describe due to the irregular shapes and thicknesses of cranial elements, presence of fibrous joints (sutures), varied muscular and occlusal loads, and cross-bracing in the skull (Herring and Ochareon 2005). There is no overall pattern of cranial deformation, making it difficult to study the skull as a single mechanical entity (Herring and Ochareon, 2005), a uniform and optimal strain environment cannot be assumed, and regional or single element approaches are very important when investigating form and function in the skull since strain regimes can be region- and element-specific (Hylander and Johnson, 1997; Herring et al., 2001).

Functional loading refers to routine activities rather than infrequent traumatic loads, though infrequent traumatic loads are certainly a consideration when it comes to resisting damage to tissue (Lanyon and Rubin, 1985). Based on *in vivo* studies, most craniofacial bones experience a level of strain comparable to limb elements, but the strain pattern differs from long bones because the most common pattern of strain is shear or torsion, rather than bending, and strain magnitudes are very different depending on the location of the skeletal element and applied force (Herring and Ochareon, 2005). Additionally, the orientation of maximum stiffness in cranial cortical bone and the anatomical axis of the structure are not coincident (Herring and Ochareon, 2005; Wang and Dechow, 2006), and the assumption that craniofacial bones do not receive heavy loading is a false one (Hylander and Johnson, 1997; Herring and Ochareon, 2005). In examining loads in the cranial region, it is important to consider not only the type of force and load, but also the frequency and magnitude of that load. Mechanical loading is also imperative for bone growth and maintenance, and loss of muscle function will also lead to altered loading (Herring, 2007) (See Chapter 2, Mechanics in Bone Growth).

Mastication

While the skeletal elements of the maxillae and palatines support alimentation, respiration, and sight, the primary function of the palate is to provide structural support for mastication. The main loading on the palate and the cranium as a whole is from chewing-related activities - mastication and incision, which are largely cyclic in nature (as opposed to static). During mastication, the elevator muscles of the mandible pull it superiorly, while depressors perform the opposite function. These loads also twist the mandible and maxillae, and cause shear in the maxillae, tension in the palate, and compression in the nasals (Herring, 2008; Herring and Ochareon, 2005). Loading on the maxilla is indirect since it occurs primarily on the teeth. Outside of the palate, the masseter muscle pulls downward on the zygomatic arch, creating vertical tensile strains at its origin, and the downward pull of the masseter plus the upward force on the teeth creates sheering stress under the eye orbits (Rogers, 1984). Strain is minimal in the brow ridge (forehead) and higher in the zygomatic arches, mandible, and around the eye orbit (Rogers, 1984; Wroe et al., 2007). The facial skeleton also undergoes torsion during mastication, and strain depends on which side is loaded (i.e., which side the individual chews on). The muscles involved in mastication are listed in Table 3-3.

The maxilla is structurally and morphologically very different from the mandible, even though both house the dentition. The palate is braced by the zygomatic and temporal bones in order to match in strength the impact applied by the mandible via the masticatory muscles (Rogers, 1984), and no masticatory muscles attach directly to the hard palate (Table 3-3). Compared to the mandible, the bone of the maxilla is actually less stiff, and the maxilla is subjected to less stress during mastication and incision (Hotzman, 2010). Values for mandibular bone mineral density are twice as high as compared to the maxilla, and the maxilla has thinner and less cortical bone than the mandible (Devlin et al., 1998).

Even though there are no direct masticatory muscle attachment sites on the bone of the hard palate, the periodontal ligament plays a crucial role in mastication. This ligament is the connection between the teeth, where direct bite force is applied, and the alveolar bone. Bite force is a result of the jaw elevator muscles and is modified by jaw biomechanics and reflex mechanisms (Koc et al., 2010). While the masseter muscle is a large source of maxillary strain, tooth contact is also important (Herring et al., 2001). When biting occurs, force is transmitted from the occlusal surface of the teeth to the alveolar bone via the periodontal ligament. This occlusal contact is an important part of mastication, and loads transmitted via the periodontal ligament dictate bone remodeling in the maxillary structure, providing a type of feedback loop between the teeth and alveolar bone. The application of force to the tooth and root is important in maintaining alveolar bone, growth and development, and signaling bite reflexes that stop the chewing motion when a particularly hard substance is encountered.

The palate is part of a complex mechanical environment that Hotzman (2010) finds difficult to characterize. Attempting to model the palate as a shell, beam, and plate, Hotzman (2010) does not find that any of these models accurately predict experimentally obtained strain values. One of the reasons the mechanical environment of the maxilla is so difficult to characterize is because no direct forces are applied to the maxilla via muscle attachments, and it exhibits no direct articulation with the temporomandibular joint (Hotzman, 2010). An additional complication is that bite force can vary depending on several factors, such as individual variation in sex, age, craniofacial morphology, dental disease, dental restorations, and occlusion, and bite force values can vary depending on the recording method and device (Koc et al. 2010). For example, aging might lead to loss of muscle force, though the effect of age on bite force is presumed to be small (Koc et al., 2010). Strain gage analysis is also particularly challenging in the palate, and measuring compressive and tensile forces on the internal and external surfaces of skeletal material for *in vivo* studies is less than perfect (Herring and Ochareon, 2005; Wang et al., 2010).

An additional concern in the relationship of form and function in the palate is that the facial skeleton may also be over-adapted for routine food processing and therefore form may not fully reflect these behaviors (Daegling and Hylander, 1997; Hylander and Johnson, 1997). Humans exhibit low strains even during powerful biting, which when considered with the thick dental enamel that protects the teeth, may indicate that normal mechanical loads sustained during mastication may not have a large effect on facial form (Swartz, 1991; Hylander and Johnson, 1997). Based on their work with macaques, Hylander and Johnson (1997) find that the high-strain areas of the zygomatic arch are not exclusively correlated with thick layers of dense cortical bone, though the geometry and bone mass density in this area are related to countering loading from mastication. An optimized facial structure should display maximum strength with minimal material (e.g., robust bone structure in areas of high strain and decreased robusticity in areas of low strain; Hylander and Johnson, 1997). However, as with many skeletal structures that are limited by other factors such as growth restraints, the facial skeleton does not display an optimized structure for the sole purpose of feeding. This can make the inference of function from form challenging.

Though facial form and mastication are not perfectly correlated, facial morphology still reflects jaw movement (Herring, 2007). Changes in jaw movement are transferred to muscles via ligaments and/or aponeuroses, which are transferred to the osseous structure, influencing, at least in part, its morphology. In fact, feeding is an important part of skeletal growth and development. In experiments on American opossum crania, Thomason and Russell (1986) find that the secondary palate contributes significantly to torsional strength and stiffness of the rostrum and maxillae in latero-medial bending. Once the palatal shelves meet in the midline, they detect a notable increase in torsional strength and stiffness and conclude that the secondary palate is important to resisting forces exerted on the upper dentition during mastication. Therefore while the facial skeleton may not be optimally adapted to resist masticatory forces, its form is related at least in part to function.

Given the difficulty in interpreting the strain environment of the palate from experimental studies, theoretical models, and palatal morphology, it is useful to examine other variables that have the potential to serve as proxies and provide information on forces in this skeletal structure. For example, since bite force and mandibular bone strain are highly correlated, mandibular strain measurements are informative for indicating bite force in the maxilla (Swartz, 1991). However this still does not entirely describe the strain environment of the palate, which is structurally very different from the mandible.

The contribution of diet

Since the human masticatory system is responsive to changes in food texture (Lucas et al., 2002), dietary changes have the ability to alter the cranial skeleton. For example, decreased bite force, such as that seen when softer foods are consumed, may result in a less robust craniofacial structure, a narrower palate, sutural fusion, and decreased dental wear. This is because softer foods require less force to process. Sutural fusion is discussed in further detail below.

In an experiment comparing rats fed a soft diet and those fed a standard laboratory diet of hard pellets, Kiliaridis et al. (1985) find that the softer diet leads to a changes in cranial shape that include more anteriorly direct facial growth and increased facial height, though no overall difference in skull size are found. The soft diet group also displays a decreased growth rate in the gonial angle. Kiliaridis et al. (1985) conclude that masticatory muscles influence both local and overall cranial growth/remodeling and softer foods produce a narrower palate.

Since the teeth come into direct contact with food and transmit bite force to alveolar bone, dental wear is potentially informative for interpreting the biomechanical environment of the masticatory system as well as looking at dietary change over time (Skorpinski, 2014). Greater dental wear could potentially be related to greater bite forces. For historic and prehistoric populations extensive wear may be related to large bite force, required to process tough or gritty foods. In modern populations eating less tough or gritty foods, dental wear could be reduced.

Altered Function through Tooth Loss

Tooth loss is generally interpreted as a sign of advanced age, although it can occur at any age due to infection or extreme wear, leading to disease and eventual tooth loss. Because of the relationship of the teeth, periodontal ligament, and alveolar bone in transmitting forces during mastication, the partial to complete loss of the dentition alters the biomechanical environment of the masticatory system. Most notably, the loss of teeth means a loss of direct loading on the occlusal surface of the teeth, which leads to a loss of loading on the periodontal ligament and the alveolar bone. Since osteoblasts reside in the lining of the tooth roots, the loss of teeth means the eventual loss of alveolar bone due to the absence of loading via the periodontal ligament. However, if only the crown of the tooth is lost, it is possible to maintain alveoli as long as the root is present. Tooth loss also can entail dietary changes, including the decreased ability to process tough foods and a transition to a softer diet, which brings about decreased bite force.

For those individuals who live past tooth loss, remodeling and eventual resorption of the alveolar bone occurs, with the alveolar process reducing in height and becoming rounded or even sharp in advanced stages (Scheuer and Black, 2000). Overall, the maxilla reduces in size. Morphological changes also result in a relaxation of the tongue to fill in areas where bone once filled and the approximation of alveolar bone margins in occlusion, changing the way the jaw moves.

The loss of teeth can also weaken bone by decreasing bone density, especially in individuals with osteoporosis or osteopenia. Devlin et al. (1998) find a significant negative correlation between bone mineral density and age in the anterior maxilla and mandible. Bone mineral density changes whether due to increasing age, edentulism, or a possible interaction of the two will in turn impact the sustainable loads on the jaw, with decreased bone density leading to earlier failure as bone is less able to resist loads of larger magnitudes. There may be coincident structural changes in the palate to account for this loss of strength. These structural changes could include increased instances of fusion to increase strength or a lack of fusion to ensure flexibility in brittle bone. Stiffness of the bone could also be affected, with a decrease in bone density leading to less stiff bone and again a decreased ability to sustain the cyclic, high magnitude forces resulting from mastication (Herring, 2008). The maxilla is more regionally variable than the mandible in elastic properties when alveolar cortical bone, maxillary body cortical bone, and palatal cortical bone are compared (Peterson et al., 2006). Therefore, it is unclear to what degree changes in bone mineral density will actually affect the structure.

Another consideration is the implantation or use of devices to aid edentulous individuals. In modern populations where dental care is practiced, the installation of dentures, implants, or other prosthetic devices is common. Dentures or prosthetic devices affect maxillary form because they alter the mechanical environment and loading to both the alveolar region and the palate. Dentures "lay" on top of the alveolar bone, while implants are inserted into the alveolar bone. For dentures, loading is still a cyclic force on bone during mastication, but one that differs from forces experienced during occlusion of the dental arcade due to differences in material properties between the structure of teeth and that of the dentures. In the case of implants, the desired effect is one of osteointegration with bone that will closely mimic the missing teeth, but it still does not perfectly imitate these structures since implants lack periodontal ligaments (Yacoub et al., 2002). Yacoub et al. (2002) investigate bone strain in craniofacial bone adjacent to and distant from dental implants in order to determine the effect of implants on the maxilla and other craniofacial bones. Their results indicate that implants affect an area much greater than just that adjacent to them, including the zygomaticotemporal suture and supraincisor cortical bone (Yacoub et al., 2002). Strain is transmitted through multiple routes from the implant site, and while no comparisons were made with non-edentulous individuals in this study, it demonstrates that complex strain patterns are produced via dental implant loading (Yacoub et al., 2002).

The Role of Sutures

Sutures allow for a combination of strength and flexibility in the palate, and they play a key role in growth and mastication. Cranial sutures largely withstand cyclic forces of mastication and to a lesser extent soft tissue and organ growth (Jasinoski et al., 2010). The design of the cranium as a whole in terms of sutures, bone, and remodeling capability allows for rigidity while maintaining a structure that is not overly cumbersome (Yu et al., 2004). While sutures do not have intrinsic growth potential, they do allow for expansion of the palate, with growth occurring along sutural margins. During mastication, patent palatal sutures also enable movement of the hard palate in response to loading. Loading of the sutures is not possible until the sutural margins approach one another, thus linking growth and function (Herring, 2008; Zollikofer and Weissmann, 2011).

The presence of sutures is one of the main reasons the skull cannot be considered as a single functional entity because loading in one area of the cranium is not necessarily transmitted efficiently to other areas (Herring et al., 2001; Herring and

Ochareon, 2005). Sutures are irregular structures that have a lower Young's modulus than bone, meaning they are more flexible and deform at lower stress/strain than bone (Linge, 1970; Jasinoski et al., 2010). Sutures are also anisotropic, meaning that their mechanical response is dependent on orientation (Yu et al., 2004). Energy absorption is complex and may be related to sutural morphology, fiber orientation, and loading rate (Jaslow, 1990; Rafferty and Herring, 1999; Jasinoski et al., 2010). It has been suggested that sutures damp force transmission or absorb energy (Jaslow, 1990; Herring and Teng, 2000; Herring and Ochareon, 2005).

Like force transmission in bone, force transmission in sutures is also regionally-specific and affected by local muscle actions and signals rather than overall cranial loading (Herring and Teng, 2000; Herring et al., 2001; Herring and Ochareon, 2005; Zollikofer and Weissmann, 2011). Specific sutures display specific strain regimes, and sutures rarely alternate between regimes (e.g., the midpalatal suture has a tensile strain regime; Herring and Ochareon, 2005). The presence of the midpalatal suture bisecting the palate also may mean that force is not effectively transmitted across the entire palate during mastication. However, Herring et al. (2001) find that in pigs strains are not significantly different by side for left- versus right-side chewing pigs.

The local strain regime determines the structure of the suture, with compressed sutures being interdigitated and tensed sutures displaying a flat (beveled or straight) form (Herring and Ochareon, 2005). These shapes related to the ways in which the collagen fibers of the suture attach to bone: in tensed sutures fibers are straight or cruciate and in compressed sutures the arrangement is oblique (Herring and Ochareon, 2005). Even if the suture as a whole has a particular strain regime, it should be noted that because of the arrangement of sutural fibers, the load on the sutural margins is always tensile; without a tensile load on the margin, the bone would actually resorb (Enlow and Hans, 1996; Herring and Ochareon, 2005). Therefore, even in a behavior like mastication that would intuitively seem to produce compressive forces, the sutural margins do not sustain this compression. If sutures removed from particular strain environment, they have shown the ability to adapt to new environment, and the fibers will arrange so they are subjected to tensile stresses (Herring, 2008; Jasinoski et al., 2010).

Sutural fusion

Sutural fusion is not well understood from a functional perspective (Wang et al., 2006). In humans, palatal sutures show a tendency to fuse, but usually do not completely obliterate even in old age. Most often, fusion consists of small areas of bony bridging rather than entire sections of a suture. This means that some degree of patency is generally maintained throughout life. Patent sutures serve to segregate certain regions and result in a structure that is less rigid and not mechanically integrated (Wang et al., 2010). Experimental data from pigs indicate loaded patent sutures exhibit strains an order of magnitude greater than adjacent bone (Herring and Teng, 2000; Herring et al., 2001; Herring and Ochareon, 2005), though fused sutures do not appear to have a significant effect on bite force (Wang et al., 2010). There is an expectation that the strain environment where sutures are fused should be more unified since synostosed sutures are still less stiff and less mineralized than surrounding bone and thus differ in mechanical properties (Herring et al., 2001; Grau et al., 2006). Thus there is a basic structural difference between elements that are fused together and act as a single element versus elements that maintain separation but are connected via a fibrous joint (Herring, 1972). While fusion may strengthen skull structure, often the tradeoff is reduced flexibility Herring (1972).

One functional hypothesis for sutural fusion posits that it is directly affected by loading. Osteogenesis along sutural margins via applied tensile force is the basis for orthodontic practices like midpalatal expansion, and Linge (1970) finds that expansion increases bony deposition at the midpalatal suture in rhesus macaques. Because tension at the sutural margins is required to maintain bone and stimulate bone growth, and cyclic loading has been shown to increase osteogenesis along sutural margins (Kopher and Mao, 2003), a lack of loading could result in growth cessation and narrowing of the sutural margin. It is important to note that while tensile forces are osteogenic along sutural margins, there is a difference between growth at the margins, resulting in expansion, and fusion of the suture itself, effectively halting expansion.

Narrowing can be the result of reduced masticatory function; for example, the consumption of softer foods, injury, or the loss of the dentition (edentulism). Comparing rats fed a soft diet with rats fed a standard laboratory diet of hard pellets, Engström et al. (1986) find that in the soft diet group the internasal, nasopremaxillary suture, and interpremaxillary sutures exhibit narrowing, a decrease in bony spicules, and for the internasal suture, significant obliteration. From these results, Engström et al. (1986) conclude that decreased masticatory function, which alters the tension placed on bone from sutural and periosteal fibers, leads to sutural fusion. Hinton (1988) also finds that decreased masticatory loading via consumption of a soft diet or incisor clipping leads to decreased cartilage growth in the intermaxillary suture in rats, with the suture becoming largely fibrous rather than maintaining secondary cartilage.

Experimental studies do not point unequivocally to a decrease in loading as an explanation for sutural fusion. Actual strain levels sustained in sutures may actually be far too small to induce osteogenesis in the first place (Henderson et al., 2004), and there are likely myriad factors contributing to fusion beyond functional necessity. Additionally, and counter to reduced loading inducing fusion, Heller et al. (2007) find that applying mechanical stress to fusing posterior frontal and patent sagittal rat sutures results in significantly more fusion at locations subjected to oscillating compressive and tensile stress as compared to a static control. Finally, movement of the skeletal elements may be what retains patency. Latham (1971) suggests that the lack of synostosis in the mid-palatal suture could be due to the slight movement of bones caused by the range of motion in mastication. However, in humans there is not a wholesale lack of fusion in palatal sutures (e.g., Mann, 1987; Mann et al., 1991; Gruspier and Mullen, 1991; Wheatley, 1996; Ginter, 2005) so movement does not entirely account for sutural patency.

If sutural fusion is related to function, partial to complete loss of the dentition or low rates of dental wear could alter the process of sutural fusion, possibly resulting in premature fusion, absence of fusion, or abnormal sequences of fusion. Wheatley (1996) finds that individuals with partial to complete edentulism also displayed premature fusion of the palatal sutures, resulting in overestimation of those individuals' ages. Thus, edentulism may affect function but also the ability to accurately predict age from palatal suture closure.

Sutural complexity

Sutures are sinuous structures with varying levels of complexity. A complex suture is one that displays numerous interdigitations, resulting in a total length longer than its straight-line (chord) length. A simple suture is one that has nearly equivalent total and chord lengths. Sutural interdigitations can play a role in transmitting force from one bone to another (Herring, 1972). Increased interdigitations of sutures creates increased surface area of the sutural margin and increased collagen along those margins, giving greater energy absorption potential to more complex sutures and strength during bending (Jaslow, 1990).

Sutural morphology is affected by stress during ontogeny (Herring, 1972), but growth is not enough to cause interdigitations. A suture must be loaded in order for these to develop, and greater loading results in greater bone growth (Herring, 2008). Thus, complexity is related to growth processes and individual variations in strain environment (Zollikofer and Weissmann, 2011). Interdigitations are seen both parallel and perpendicular to the main direction of applied force, but a suture can adapt for multiple loading scenarios by modifying the number of interdigitations and the directions of its fibers (Herring, 1972). This means that sutural morphology is not perfectly correlated with a specific loading scenario or strain environment. Since growth and loading are linked in terms of sutural morphology, with increasing age, sutures may also increase in complexity (Zollikofer and Weissmann, 2011).

Bony shape is related in part to the collagen fibers that make up the sutures themselves. In sutures where the dominant loading regime is tensile, fibers are straight or cruciate. For compressed sutures, oblique fibers are present. Sutures with numerous interdigitations are associated with compressive loads, while butt-ended, shallow, beveled, and straight (i.e., simple) sutures are associated with tensile loads (Rafferty and Herring, 1999; Herring and Ochareon, 2005). In examining butt-ended, moderately interdigitated, and complexly interdigitated sutures, Jasinoski and Reddy (2012) find that strain energy is highest in the butt-ended sutures and lowest in the complexly interdigitated sutures, indicating that a more complex sutural morphology may be better at dissipating strain. However, regardless of the strain regime of the suture or portion thereof, the sutural margins must always be in tension so that the bone at this area does not resorb (Enlow and Hans, 1996). This means that describing overall strain regimes of sutures are likely overly simplistic summaries of loading as it relates to sutural morphology.

Because of the relationship of force and sutural morphology, complexity has also been examined in terms of diet. In individuals or species who routinely chew harder foods, these loads may lead to increased sutural complexity as sutures become more interdigitated to increase the surface area of the suture and prevent the disarticulation of cranial elements with greater loading (Herring, 1993). However, Hotzman (2004) does not find that species who consume harder foods have a significantly higher mid-palatal suture complexity than those species who consume softer foods, and complexity is likely related to other factors than just diet, such as age.

Increased loads associated with harder foods or greater masticatory loading may also impact sutural fusion. Herring (1972) finds that fusion begins in the more complex portion of the intermaxillary suture in pigs, but that this trend is not the same in other species, where fusion begins along the less complex portion. In the palate, sutures are not generally very complex, with more complex regions usually located in the posterior median palatine suture. Human palatal sutures rarely completely fuse, lending support to the concept that simple sutures may resist fusion, perhaps due to their tendency to be subjected to mainly tensile loads. However, because complex sutures can withstand greater loading, stress and strain may not play a major role in sutural fusion, with fusion related more to sutural morphology than how it is loaded.

Palatal Variants

The understanding of growth, development, form, and function of the palate translates into the ability to use certain morphological traits to draw conclusions about the age, sex, and population origin (ancestry) of individuals and groups. Skeletal non-metric traits generally fall into one of the following categories: (1) bone shape, (2) bony feature morphology, (3) suture shape, (4) presence/absence of trait, and (5) feature prominence/protrusion (Hefner, 2009). These traits do not generally appear in isolation, and certain groups may share similar suites of traits, enabling the anthropologist to "match" an individual to a group that also shares those same characteristics. However, even when suites of traits are found together, indicating a certain level of inter-trait association, just how much association exists is not well understood (Hauser and De Stefano, 1989). As with processes of aging (see Chapter 2), skeletal traits are also the result of complex interactions between genes and environment, and it is still largely unknown why certain traits arise in some but not others and how function or group affiliation may or may not affect their expression.

The palatal variants discussed below have been used with varying degrees of success to differentiate individuals and groups by age, sex, and/or ancestry. A brief description is provided along with the utility of the trait for differentiation. Not all palatal traits are included – only those that are most commonly referenced or employed for differentiation based on group membership. While certain generalizations are provided for group assignment based on trait expression, it is important to note that single traits are rarely informative for group assignment due to their variable expression across multiple groups. Additionally, traditional scoring techniques are largely based on visual assessment, rather than metric methods.

Transverse Palatine Suture Shape

The medial portion of the TP suture displays varying forms, as can be seen in Hauser and De Stefano (1989). Anthropologists commonly condense these categories and score the appearance of the suture as straight, bulging/arched (anteriorly or posteriorly), and jagged/M-shaped, (Rhine, 1990; Gill, 1998; Hefner, 2009). These shapes are depicted in Figure 3-3. The straight shape is generally associated with individuals of Asian ancestry, the anterior bulging/arching with individuals of African ancestry, and the jagged/M-shaped with individuals of European ancestry. There are no known sex or age differences in TP suture shape. Shape of the TP suture may be affected by the presence of prognathism, in which the mid- or lower-face projects anteriorly, thereby "pulling" the TP suture anteriorly as well. However, the possible explanation for an M-shaped suture is less clear, as individuals with this shape suture do not usually display pronounced prognathism (i.e., individuals of European ancestry).

Palate Shape

Palate shape refers to the shape of the alveoli, to include the dental arcade. This shape can generally be divided into three categories: parabolic, hyperbolic, and elliptic (Rhine, 1990; Gill, 1998). More specifically, Rhine (1990: p 20) defines the categories as follows: parabolic – "narrower and tapering"; elliptic – "wider and smoothly curving"; hyperbolic – "approaching rectangular." These shapes are depicted in Figure 3-4. As with TP suture shape, palatal shape is scored based on visual assessment and associated with ancestral groups as follows: parabolic – European, hyperbolic –

African, elliptic – Asian. Palatal shape is largely tied to ancestral differences, though females and males may also differ in palatal shape, which may be tied to sizes due to sexual dimorphism (Rogers, 1984). Rogers (1984) offers general differences between the sexes, with males displaying larger/U-shaped palates as compared to smaller and more parabolic female palates. However, no frequencies are given. It is unclear whether or not age affects palatal shape.

Subjective descriptions of palatal shape are potentially problematic when considering replicability and interobserver error (Maier, 2013). Examination of palatal shapes via three-dimensional digitization and machine-learning methods shows that the previously used shape categories of parabolic, hyperbolic, and elliptic are discrete from one another, and that shape alone is accurate in classifying ancestry in only 58% of cases (Maier, 2013; Maier et al., 2015). Maier (2013) did not note a secular change in palatal shape with digitization of shape.

Tori

In the masticatory complex, a torus is a rounded prominence or ridge along the median palatine suture (*torus palatinus*), the lingual side of the maxillary alveolar bone usually in the molar region (*torus maxillaris*), or the lingual side of the mandible below the alveolar margin and generally in the vicinity of the second premolar (*torus mandibularis*) (Figure 3-5; Hauser and De Stefano, 1989; Rogers, 1984). Bony growths along the buccal aspect of the dentition, generally in the vicinity of the molars, are maxillary exostoses. The majority of research on tori in the maxilla has focused on palatine tori, with relatively little investigation of maxillary tori and exostoses, and the summary that follows largely pertains to the former.

Tori are normal, non-pathological variants of the human skull composed of spongy bone (Miller and Roth, 1940; Woo, 1950). In the palate, this spongy bone is a result of an inferior enlargement of the diploe of the maxillary and palatine bones, with no associated “bending” or distortion of the underlying bones (Miller and Roth, 1940; Woo, 1950). Tori may be present in isolation or a single individual may display multiple tori. Suzuki and Sakai (1960) find a statistically significant correlation of palatine and mandibular tori in 309 living Japanese patients, and Woo (1950) reports that skulls with maxillary and mandibular tori are present in higher percentages in skulls with palatine tori versus those where palatine tori are absent.

The etiology of tori is largely unknown and continues to be debated (Hassett, 2006). The growth of tori is hypothesized to be genetically determined, the result of greater masticatory forces requiring buttressing of the masticatory system, or a combination of genes and forces – genetic signals triggered in people with greater masticatory stresses, what Hassett (2006) refers to as a threshold trait. Hooton (1946) attributes the development of the palatal torus to “excessive” development of the masticatory apparatus, which produces pressure in the median palatine area. Because of this pressure, bone on either side of the suture adapts by thickening, to serve as a type of buttress for resisting pressure. Woo (1950) disagrees with this, citing greater masticatory stress on the molar teeth and the anterior to posterior arrangement of lamellae in palatine tori that do not configure to the expected lateral medial arrangement for a structure adapted to countering mid-palatal masticatory stress. Thus, Woo (1950) attributes tori presence to heredity as does more recent, clinical literature (e.g., Eversole, 2011). Suzuki and Sakai (1960) find a higher percentage of tori occurrences in children whose parents also have tori.

Tori are present in various forms, and the form of the *torus palatinus* can vary from a small ridge along the median palatine suture to a massive structure that occupies the majority of the hard palate and may even inhibit speech or mastication. Woo (1950) states that the palatine torus generally tapers gradually anteriorly, with a more abrupt end posteriorly, and it can be restricted to only one area of the palate. The palatine torus can also be symmetrical or asymmetrical, as well as “mounded” on either side of the median palatine suture, with a deep groove down the center. Hooton (1946) describes the various forms of the palatine torus as mound, ridge, or lump, and Woo (1950) further categorizes them as ridge – narrow and nearly uniform in width, mound – wide with anterior and posterior tapering, lump – irregular shape. Smaller palatine tori are more common than large (Woo, 1950).

Varying frequencies of tori have been reported across populations. Clinical dental literature reports that palatal tori are most common in individuals of Asian ancestry (Eversole, 2011), though Chohayeb and Volpe (2001) find the highest frequencies of palatal tori in African American women as compared to Caucasian, Hispanic, Asian, and Native American women in the Washington, DC area. Miller and Roth (1940) report the overall occurrence of any degree of expression of *torus palatinus* in their sample of 1040 New York dental patients to be 24.2%. Studies on skeletal materials range from a single instance of a palatine torus out of 600 skulls of varying geographic origins (skull from British Columbia; Berry and Berry, 1967)[3], to 10%

[3] Nor did they report any instances of maxillary tori in the same study.

expression of some amount of palatal torus in British skulls (Brothwell, 1981), to a high of 69.94% in “Eskimo” females in a study of 2246 skulls from “Eskimos,” Asian, and American Indians, “Whites,” and “Blacks” (Woo, 1950). In this same study, American Indians and Asians followed “Eskimos” in frequency of palatine tori, with the lowest frequencies observed in American “Whites” and “Blacks.” Data for maxillary tori are limited, though Brothwell (1981) reports frequencies from 2.5 to 17%, with no ancestral group specified.

The frequency of tori by sex is les ambivalent than ancestry, with most research agreeing that females are more likely to display palatine tori than males (Miller and Roth, 1940; Woo, 1950; Eversole, 2011). In their patients, Miller and Roth (1940) observe twice as many females as males with some degree of expression. Woo’s (1950) research agrees with greater expression in females but at a lower frequency than reported by Miller and Roth (1940).

Clinical literature states that tori develop following puberty (Eversole, 2011), but a more specific relationship of tori presence and age is not clear. Miller and Roth (1940) find that a palatine torus was rarely seen before the age of five years, and the average age of occurrence for any degree of expression was 35.9 years. In their sample, Miller and Roth (1940) find that increased expression is seen with increased age, from which they conclude that development of a palatine torus is gradual, progressive, and associated with increasing age (i.e., slight tori are seen more often in younger individuals while moderate to marked tori are seen in older individuals). However, Woo (1950) finds that the torus does not increase with age, and attributes this difference with Miller and Roth (1940) to a statistical error. Woo (1950) concludes that growth of the palatine torus stops at age 20 years, along with skeletal growth, and does not increase with age. Chohayeb and Volpe (2001) also find no relationship between age and the presence of a palatine torus.

These results bring into question the ways in which this trait has been measured, and the irregular form of tori may lead to difficulty in standardizing observations. Scoring ranges from simple absence/presence (Berry and Berry, 1967) to more complex systems including elevation, width, length, size, and shape (Miller and Roth, 1940; Hooton, 1946; Woo, 1950; Hauser and De Stefano, 1989). Suzuki and Sakai (1960) measure the palatine torus in living patients as trace – palpation only, not visible by sight; slight – visible by sight; and marked; if asymmetrical, the side with a greater degree of expression is scored. Since shape is so variable, systems that take into account relative size as compared to the overall masticatory complex or certain skeletal elements may be more effective at summarizing tori expression.

Palatine Bridging

Grooves that serve as passage for vessels and nerves originate from the greater palatine foramen. The lateral palatine groove (*sulcus palatinus lateralis*) runs along the alveolar border to the canine and is larger than the medial palatine groove (*sulcus palatinus medialis*), which can have the appearance of bifurcating from the lateral groove (Hauser and De Stefano, 1989). If the lateral groove bifurcates anteriorly, an alveolar groove may also be present along the alveolar border and lateral to the lateral groove. Palatine grooves can exhibit tubercles and/or spines along their borders, and then when these tubercles or spines connect, they form bridges. Scoring of palatine bridging can follow degree of completeness, position, and number (Hauser and De Stefano, 1989). Degrees of expression of palatine bridging are depicted in Figure 3-6.

There is limited research concerning the demographic distribution of palatine bridging. There is no conclusive sex incidence or relationship of age and bridging frequency (summarized in Hauser and De Stefano, 1989). Zivanović (1980) reports the presence of bridging in fetal and newborn skulls, but other studies show no relationship with age, an increase in frequency with age, and a decrease with age (summarized in Hauser and De Stefano, 1989).

Marginal Crest

Stieda (1891) describes an osseous crest along the posterior end of the horizontal lamina of the palatine bone – marginal crest or *crista marginalis*. At this location the palatine can exhibit spicules or variably expressed ridges of bone. The location of this crest is depicted in Figure 3-7. No demographic frequencies have been reported for this trait (Hauser and De Stefano, 1989).

Lesser Palatine Foramina

Lesser palatine foramina can lie on both sides of the posterior border of the hard palate posterior to the greater palatine foramen (Berry and Berry, 1967). Absence of lesser palatine foramina is infrequent (Hauser and De Stefano, 1989). Scoring lesser palatine foramina can be done by presence/absence of any number of foramina greater than 1 (Berry and Berry, 1967) or by more detailed means that include number, shape, size, and position in relation to the marginal crest (Hauser and De Stefano, 1989). Expression is usually symmetrical though in cases of asymmetry there is no pronounced side difference (Hauser and De Stefano, 1989). Lesser palatine foramina are visible in Figures 3-6 and 3-7.

Hauser and De Stefano (1989) report low heritability estimates and the following frequency of the trait in eight human populations: Egypt (all eras)=48.6%, Nigeria

(Ashanti)=41.0%, Palestine (Lachish)=13.2%, Palestine (modern)=23.3%, India (Punjab)=48.0%, Burma = 32.0%, North America (British Columbia)=71.0%, South America (Peru)=59.4%. Males may exhibit greater than one lesser palatine more frequently than females, and the trait appears more frequently in older adults as opposed to younger ones, though this trait is visible at birth (Hauser and De Stefano, 1989).

Bone Quality and Porosity

Bone quality generally decreases with advanced age, meaning that bone density decreases and bone may appear more porous and lightweight. Devlin et al. (1998) find that bone mineral densities in the anterior maxilla and the mandibular body are significantly correlated with age, though the posterior maxilla and hard palate are not found to have a significant relationship. Cortical bone has greater porosity with increased age, but trabecular bone does not show the same effects (von Wowern and Stoltze, 1978). Therefore, decreased bone quality and increased porosity in the maxilla may be indicative of old age, even if only generally.

Summary

This chapter presented growth and development of the facial skeleton and palate, the form and function of the palate, and how palatal traits are employed by biological anthropologists to classify individuals. It is important to understand the complex developmental and biomechanical environment of the palate in order to investigate the relationship of age on this region of the skeleton. The next chapter outlines the research methods and materials used in this study.

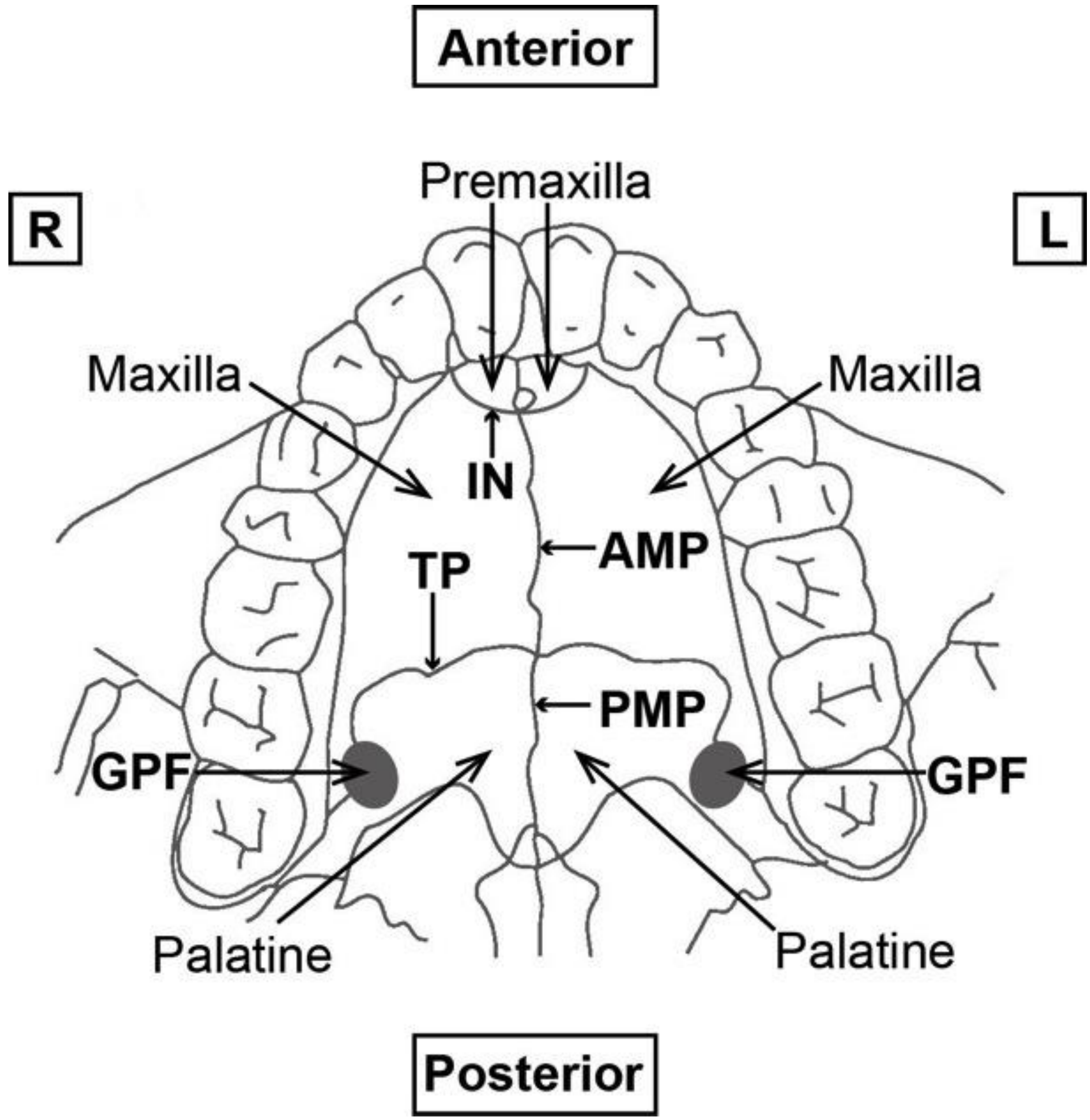


Figure 3-1. Diagram of the skeletal elements of the hard palate and its sutures. Note: this diagram depicts an adult with all permanent dentition; the incisive suture and premaxillae are depicted to show location only since an adult is unlikely to display a completely open incisive suture and separation of the maxilla at the region of the central incisors. IN = incisive, AMP = anterior median palatine, TP = transverse palatine, PMP = posterior median palatine, GPF = greater palatine foramen. This diagram is not to scale.

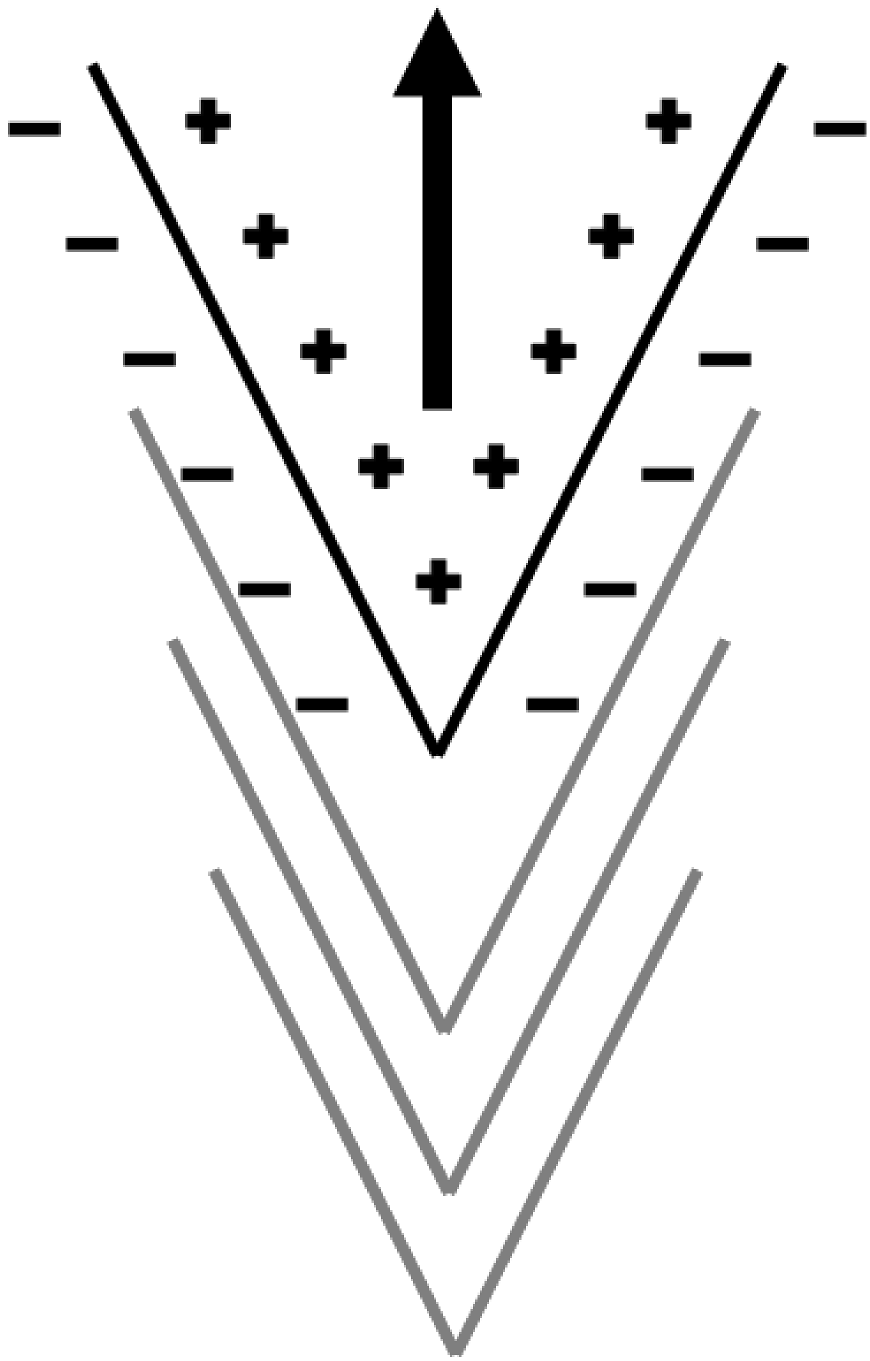


Figure 3-2. Diagrammatic representation of the V-principle of growth, following Enlow and Hans (1996). The solid black V represents the current location of the element; the gray Vs represent the former location and the process of displacement; the plus and minus symbols indicate deposition and resorption, respectively, which, when combined result in remodeling; and the direction of growth is represented by the solid black arrow.

Table 3-1. Timing of palatal growth and development, compiled from Scheuer and Black (2000: p 134, 138, 151). This table includes some key dental development and eruption events.

Stage	Timing/Age	Event
Fetal (*in utero*)	Week 6	Maxillary ossification centers appear
	Weeks 7-8	Palatine perpendicular plate ossification centers appear
	By Week 8	Maxillary body and 4 processes identifiable
	Weeks 9-10	Appearance of premaxillary ossification centers
	Week 10	Palatine orbital and sphenoidal processes begin development
	Weeks 10-12	Maxillary sinuses begin development
	Week 11	Maxillary deciduous dentition crypts begin formation
	Weeks 14-16	Maxillary deciduous tooth germs begin formation
	Weeks 17-18	Maxillary deciduous crypts complete
	Week 18	Palatine palatal processes fuse
	Mid-fetal life	Palatine adult form attained but not proportions
At birth (neonate)	0 years	Maxilla: main parts of bone and rudimentary sinuses present Palatine: adult form except horizontal and perpendicular plates are of equal width and height, orbital process has no air cells Dental: crowns of deciduous maxillary dentition in crypts, roots of deciduous teeth start to form
Infancy/ Childhood	0-12 years	Maxillary body and sinus size increase gradually, eruption/replacement of deciduous dentition
	0-1 year	Permanent first molar and anterior teeth begin formation/mineralization
	2-4 years	Mineralization of premolars and second molars
	By 3 years	Deciduous dentition emerged, completed root formation
Childhood	3+ years	Palatine perpendicular plane increases in height
	6-8 years	First permanent molar erupts posterior to second deciduous molar, deciduous incisors lost, permanent incisors erupt; formation of third molar begins
Juvenile	10-12 years	Deciduous canines and molars lost; permanent canines, premolars, and second permanent molars erupt; formation of third molar continues (crown mineralization complete 4 years following formation commencement)
Puberty	~10 years for girls/~12 years for boys	Palatine attains adult proportions
Adolescence	No later than 12-14 years	All permanent teeth erupted (except M3s)
	~18 years	Eruption of third permanent molars

Table 3-2. Muscles of the soft palate.

Muscle name	Function(s)	Origin	Insertion
Elevators			
Levator veli palatini	Elevates soft palate posteriorly and superiorly towards pharyngeal plate Contracts during swallowing to avoid food entering nasopharynx Provides velopharyngeal closure during speech	Inferior surface of the petrous portion of the temporal bone	Palatal aponeurosis
Musculus uvulae	Shortens/broadens uvula Helps close nasopharynx during swallowing Role in speech	Nasal spine on palatine	Near uvula
Depressors			
Palatoglossus	Elevates posterior tongue Aids in swallowing Maintains palatoglossal arch	Palatal aponeurosis	Lateral portions of the posterior tongue
Palatopharyngeus	Tenses to pull pharynx over food bolus Aids in swallowing and breathing Lowers palate	Lower surface of palatal aponeurosis	Lateral wall of pharynx, posterior border of thyroid cartilage
Other			
Tensor veli palatini	Assists in opening or swallowing to equalize air pressure in Eustachian (auditory) tube	Medial pterygoid plate of sphenoid, cartilage of Eustachian tube	Palatal aponeurosis, horizontal portion of the palatine

Table 3-3. Muscles of the masticatory system, compiled from White et al. (2012: p 99).

Muscle name	Function	Origin	Insertion
Temporalis	Elevates the mandible Closes the mouth	Lateral cranial vault inferior to the superior temporal line	Lateral sides, apex, and anterior surface of the coronoid process of the mandible
Masseter	Elevates the mandible Closes the mouth	Inferior surface of the zygomatic arch	Lateral surface of the mandibular ramus and the gonial angle of mandible
Medial pterygoideus	Elevates the mandible Closes the mouth	Superior head: postero-superior maxilla Inferior head: Medial surface of the lateral pterygoid plate of the sphenoid	Medial surface of the mandibular gonial angle
Lateral pterygoideus	Protracts the mandible Assists in depressing the mandible Pushes jaw forward Allows for lateral-medial movement of mandible	Superior head: sphenoid greater wing Inferior head: lateral pterygoid plate of the sphenoid	Neck of the condyloid process of the mandible and the articular disc and fibrous capsule of the temporomandibular joint

A

B

C

D

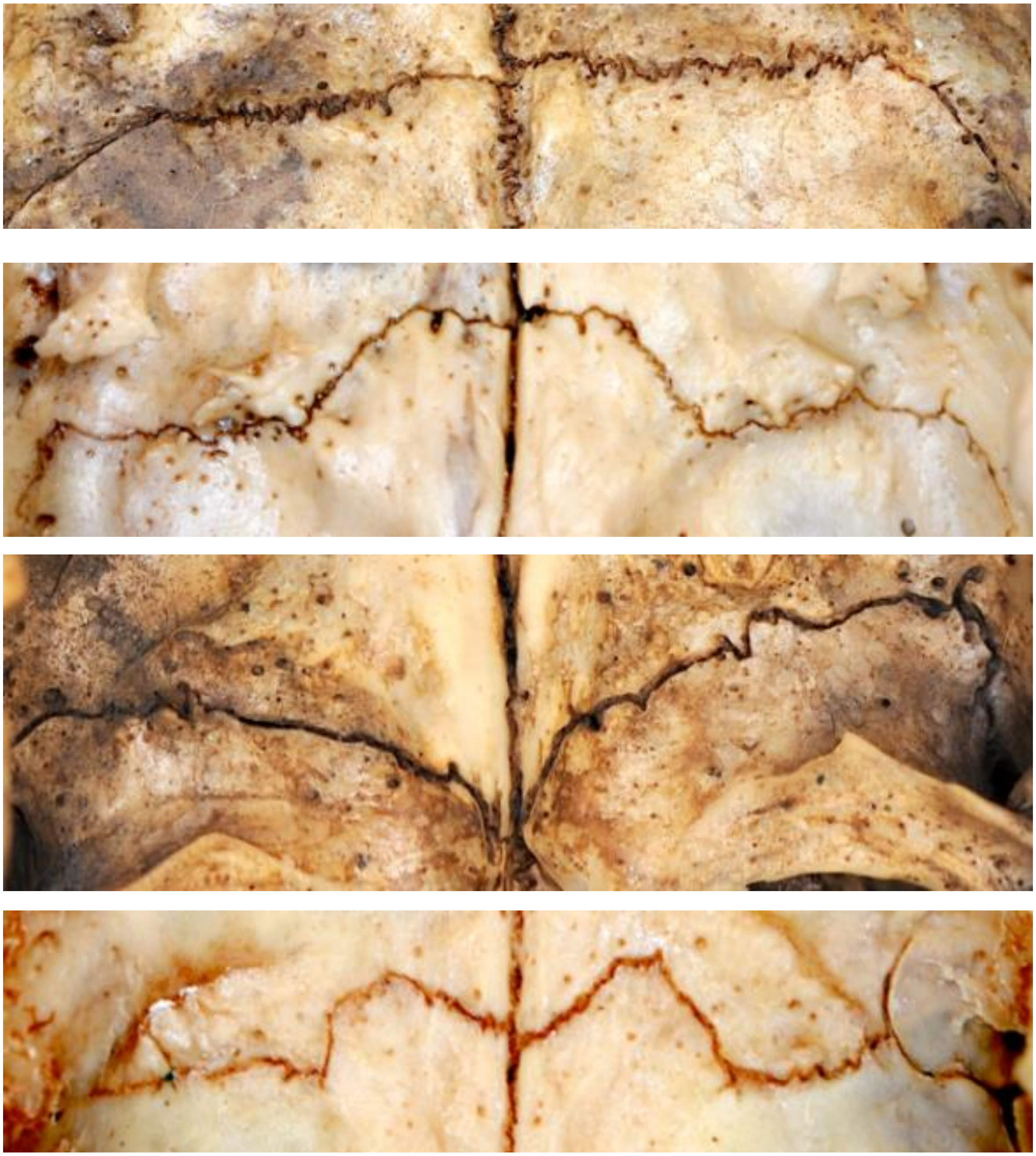


Figure 3-3. Transverse palatine suture shape. A) Straight, B) anterior deviation/bulging, C) posterior deviation/bulging, D) jagged/M-shaped. Photographs courtesy of Carrie A. Brown.

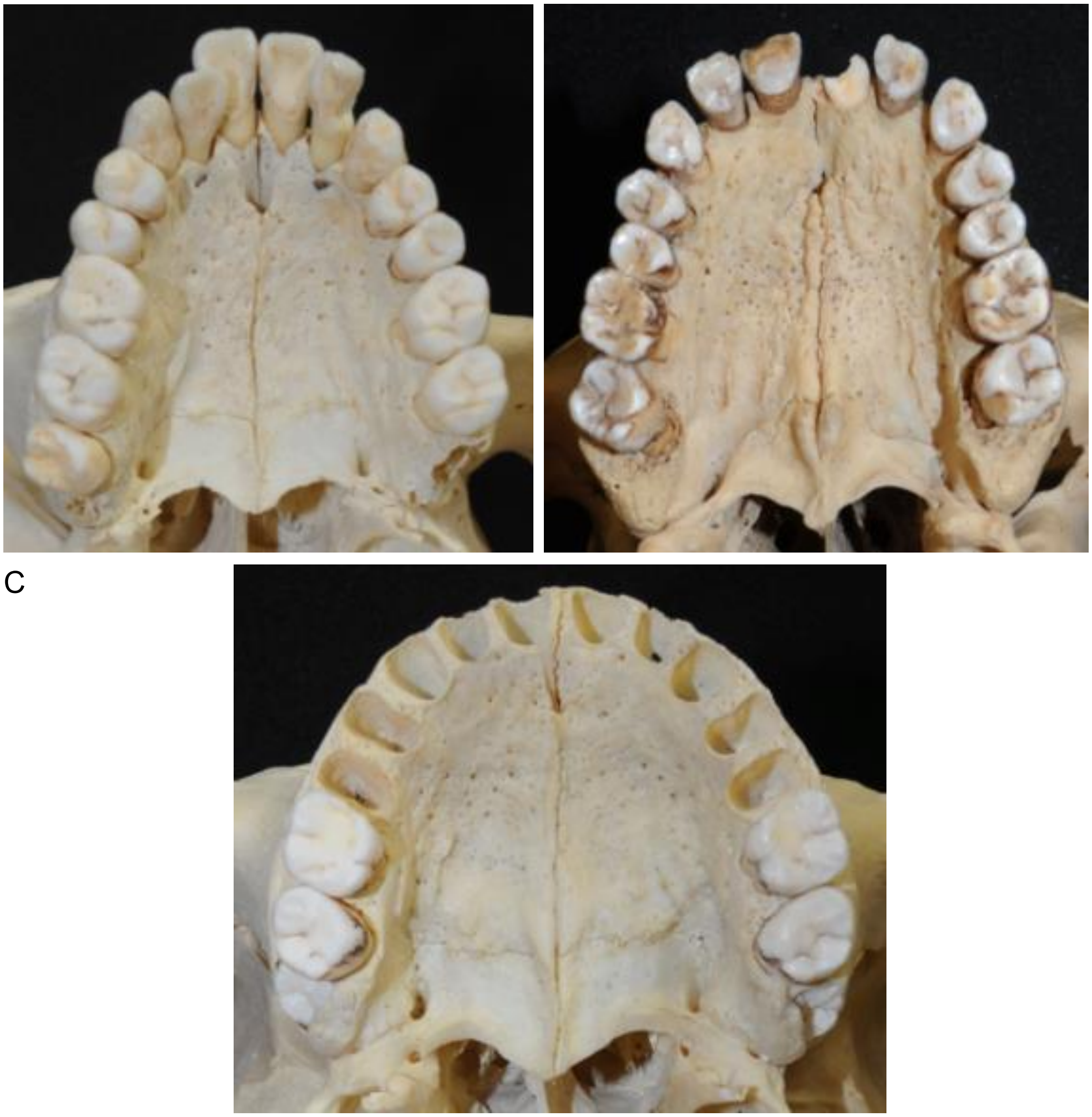


Figure 3-4. Palate shape. A) Parabolic, B) hyperbolic, C) elliptic. Photographs courtesy of Carrie A. Brown.

A

B

Figure 3-5. Tori. A) Small palatine torus, B) large palatine and bilateral maxillary tori and small to medium maxillary exostoses. Photographs courtesy of Carrie A. Brown.

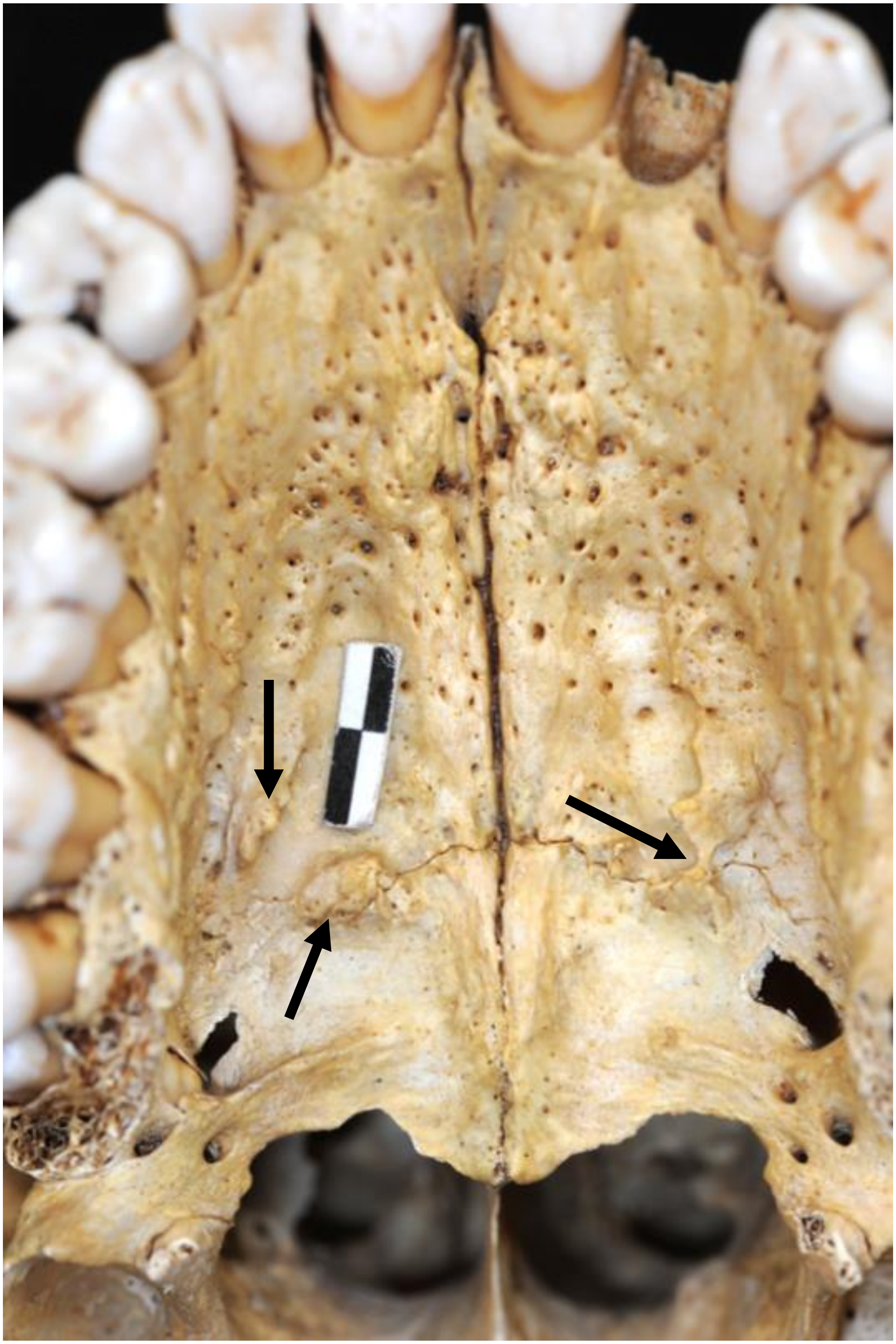


Figure 3-6. Palatine bridging; spines, left; bridging, right. Photograph courtesy of Carrie A. Brown.

A

B

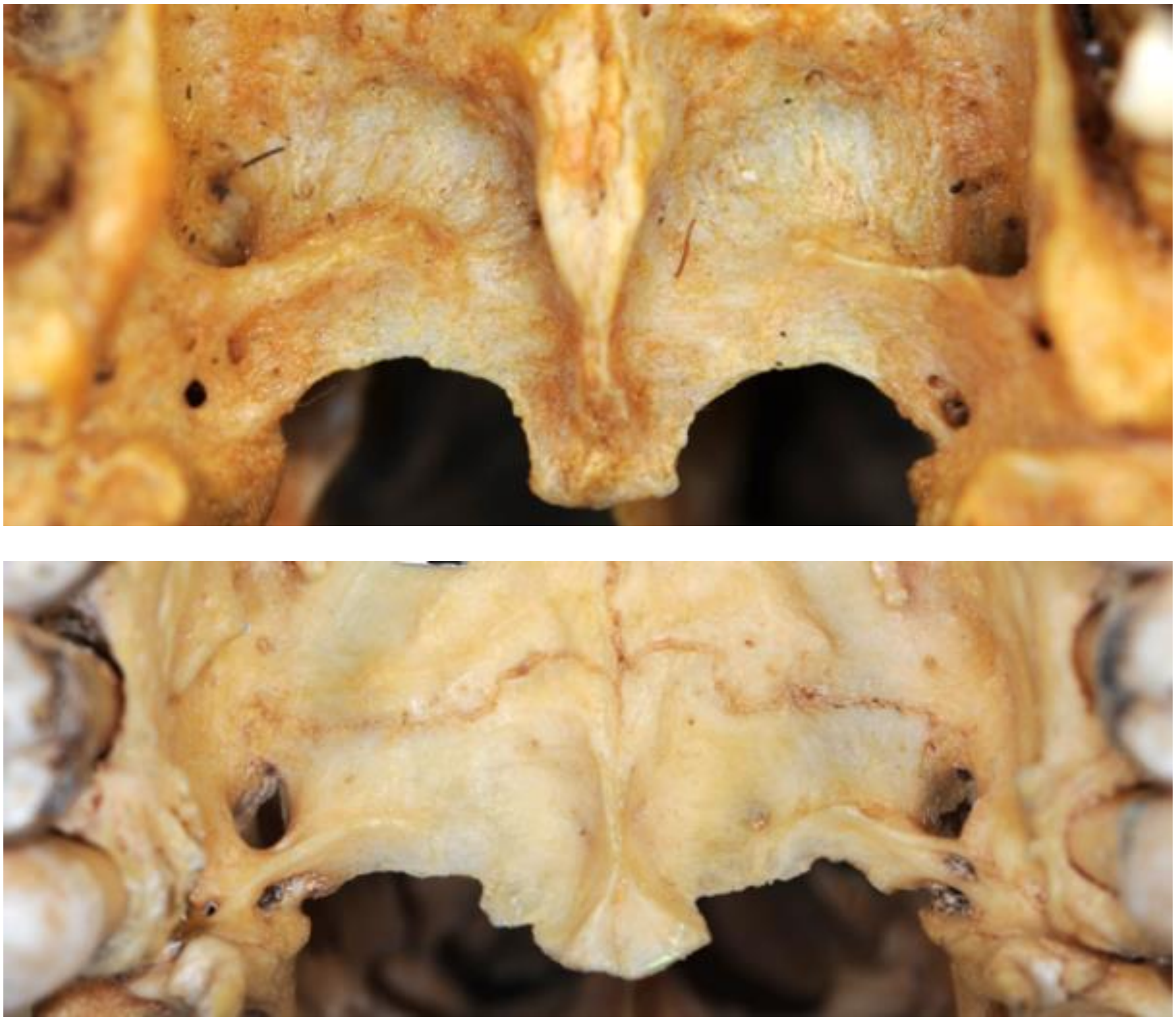


Figure 3-7. Marginal crest. A) Anteriorly positioned ridge, B) posteriorly positioned ridge. Photographs courtesy of Carrie A. Brown.

CHAPTER 4
MATERIALS AND METHODS

Sampling Strategy

Power analyses were first conducted to develop a sampling strategy prior to data collection. This type of analysis examines the relationship among sample size (n), significance or confidence level (α), power (β), and population effect size and is used to predict one of these variables given the other three (Cohen, 1992). One of the most common uses of power analysis in research is finding the sample size required in order to obtain a significant effect if one is present, given a specified degree of confidence and power (Cohen, 1992; Adler, 2012; Crawley, 2013). A test's confidence (α) speaks to the risk of committing a Type I error, which occurs when the null hypothesis is mistakenly rejected; generally, $\alpha = 0.05$ is used unless a more or less stringent test is desired (Cohen, 1992). A test's power is the probability of rejecting a false null hypothesis (Type II error), with β representing the probability of accepting a false null hypothesis (Crawley, 2013). Effect size is a statistic that quantifies the degree that the null hypothesis is believed to be false (Cohen, 1992; Vacha-Haase and Thompson, 2004). For example, in a two-sided t-test an effect size of zero indicates that there is no difference between group means (Vacha-Haase and Thompson, 2004). Effect size is more challenging to determine in experimental design and is dependent on what statistical test is chosen for data analysis (Cohen, 1992).

For this research the significance level and power were set at conventional standards ($\alpha = 0.05$ and $1\text{-}\beta = 0.8$ [$\beta = 0.2$], respectively) (Cohen, 1992; Crawley, 2013). Effect size was based on previously published values for sutural closure or recommended values for small, medium, and large effect sizes taken from

Cohen (1992) when no such values were available. All predicted sample sizes were rounded up to next highest full integer since it is not possible to collect a portion of a sample (i.e., 322.157 is rounded to 323 since 0.157 of an individual is not a valid amount). Power analyses were conducted in *R* version 3.0.0 (RCoreTeam, 2014).

In the investigation of age and suture closure, correlation can be used to talk about the strength of that relationship. Correlation values for suture closure and age were drawn from previous research by Nawrocki (1998) and Wheatley (1996). Using the value of $r = 0.55$ given by Nawrocki (1998) for the correlation between age and all palatine sutural fusion, power analysis indicated that a minimum of 23 samples should be collected. As a comparison, values drawn from Wheatley (1996), which are correlations between age and specific palatal sutures, range from $r = 0.271$ for the left lateral incisive suture to $r = 0.494$ for the posterior median palatine suture. For the lower value, power analysis indicated that a minimum of 105 samples should be collected, while for the higher value a minimum of 30 samples. The correlation value provided by Nawrocki (1998) is preferred as it takes into account all palatal sutures, not just the relationship between single sutures and age. These power analyses are summarized in Table 4-1.

Power analyses were also conducted to find the sample sizes needed to find significant differences if they exist in sutural closure due to sex, ancestry, and temporality (i.e., secular trends). These differences are investigated via t-tests for two groups or the analysis of variance (ANOVA) for more than two groups. Both tests compare differences in mean values among groups. For ease of comparison, ANOVA power analyses were conducted for all groups (sex, ancestry, and secular trends) using *k* = 2 for sex (male or female) and secular trends (historic or modern) and *k* = 3 for ancestry (African, Asian, European); *k* indicates the number of groups being compared. In these analyses effect sizes of 0.10 (small), 0.25 (medium), and 0.40 (large) were employed (Cohen, 1992); the effect sizes are denoted by *f*. The results of these analyses are given in Table 4-2.

Power analyses for biomechanical variables and palatal variants and their relationship to both age and sutural closure are complicated by myriad variables to be investigated and the lack of published *r*-values for many of these statistical tests. For example, while increased loading in the palate may lead to more complex sutural morphology, and more complex sutures could potentially delay fusion (see Chapter 3), there are currently no published *r*-values for the relationship of sutural complexity and fusion. The same limitation is true for *r*-values for the relationship of palatal variants, antemortem tooth loss, and dental wear to age and palatal suture closure. These relationships can be tested through correlation and regression analysis, but without known *r*-values, it is not possible to estimate effect size. Additionally, several of these variables necessitate the use of nonparametric statistical tests as they are categorical- or ordinal-level variables. Since a certain distribution is not assumed when using a nonparametric test, the more straightforward power analyses described above for parametric tests cannot be applied. Therefore, no power analyses were conducted for biomechanical variables and palatal variants, and the assumption was made that the previously described power analyses and sample sizes are more than adequate for these additional variables.

Beyond determining the sample size needed to find a significant effect if one is present, the knowledge of required sample size also ensures that the sample can be evenly distributed in terms of demographic variables. In age estimation studies this is particularly germane since the underlying reference sample structure can affect method performance (see Chapter 2). The desired goal of the sampling strategy is to have groups of relatively equal size so that the entire sample is balanced.

Power analysis identifies the number of samples to be collected but does not specify possible interactions among variables or sample group compositions (e.g., Asian females between the ages of 30 and 39 years). In order to maintain a conservative approach, a group was designated as being age-, sex-, and ancestry-specific for data collection purposes. In this manner, larger samples are available for factor-specific analyses (e.g., ancestry and sutural closure), and by collecting the recommended sample size for the most specific group – age, sex, and ancestry together – sample sizes for all factors are more than adequate when examined on an individual basis. Ages were broken down into 10-year intervals, starting at age 20 and ending with a terminal category of 70+ years, for a total of 6 age groups – 20-29 years, 30-39 years, 40-49 years, 50-59 years, 60-69 years, and 70+ years. No individuals under the age of 20 years were included as other methods of age estimation are more accurate for these ages (see Chapter 2), and skeletal collections often do not include large numbers of sub-adult individuals. Sex is a binary category – male or female, and ancestry is divided into the three major ancestral groups – African, Asian, and European. While time of birth and/or death is also considered, it is not used in group assignment due to the composition of the skeletal collections. Collections with individuals born during the 19th or early part of the 20th centuries (generally pre-1940) were designated as historic, while collections with individuals born during the second half of the 20th century (generally post-1940) are designated as modern. These designations serve to aid in the investigation of potential secular trends.

The highest *r*- and *f*-values produced needed sample sizes between 22 and 26 individuals (Tables 4-2 and 4-3). Therefore, the ideal sample size to be collected per age-, sex-, and ancestry- specific group was set at 22 individuals, with the understanding that sutural closure or other variables may not differ significantly for some groups. This ideal sample size is limited by the availability of samples in and the demographic composition of the skeletal collections, but almost all groups have sample sizes at or very close to this number. The only group not meeting this threshold is European females between the ages of 20 and 29 years. Even examining four large U.S. collections, only 12 samples from this group were obtained, and 10 were viable following data scrubbing (see below). Data were also collected on individuals from other groups or mixed ancestral groups (i.e., Hispanic, European/Native American), but because of the limited number of these individuals overall, they were not included in further data analyses.

If demographic information about the documented collections could be collected ahead of time, a sampling strategy was devised prior to arrival (Hamann-Todd, Chiba, Bass); if the sample composition was not available to the researcher prior to data collection, a sampling strategy was devised upon arrival to the collection (Maxwell, Terry, Jikei). In general, a stratified random sampling strategy was preferred; this entailed choosing individuals at random from within the pre-defined age, ancestry, and sex groups. Ancestry largely led the decision on what collections to visit (e.g., the Terry Collection has some of the only documented individuals of African ancestry in the U.S., and the Bass Collection has very few non-“White” individuals), though obtaining a well-balanced sample overall was also important.

Documented Skeletal Collections

Table 4-3 summarizes information about the collections visited for this research and the total number of samples collected. These numbers reflect all samples examined for this research, but not the total sample number analyzed due to subsequent data scrubbing (see below). All skeletal collections contain both male and female individuals, although the general trend is that they contain more males than females. This is why the sampling strategy detailed above is used. Data was collected from both historic and modern collections, as it was impossible to collect a large enough sample size using only one time period. For example, in the U.S., neither of the largest modern collections have a substantial number of individuals of African ancestry while over 50% of the historic Terry Collection is comprised of individuals of African ancestry (classified as “Black” in the collection).

The Maxwell Museum’s Documented Collection represents almost exclusively residents of New Mexico and is housed at the Maxwell Museum of Anthropology at the University of New Mexico in Albuquerque. Collection of documented human remains began in 1975 and continues to date (Komar and Grivas, 2008). Documentation for the individuals in this collection is self/next-of-kin-reported or obtained from the medical examiner/Department of Anatomy, but not all of the individuals in the collection are documented (Komar and Grivas, 2008). Individuals with unknown demographic information are excluded from this study. The majority of individuals in this collection are of European ancestry, and both sexes are represented. This is a modern collection; all individuals have a documented year of death within the last 30 years.

The William M. Bass Donated Skeletal Collection, housed at the University of Tennessee, Knoxville, represents a collection of individuals from the donated body program, established by Dr. Bass in 1981. The majority of individuals in this collection are from Tennessee and the southeastern U.S. (University of Tennessee, Knoxville, N.D.). Documentation is self-, next-of-kin-, or medical examiner-reported. Collection and curation continues to this day, and most individuals in this collection have birth years post-1940 (University of Tennessee, Knoxville, N.D.). The majority of individuals in this collection are of European ancestry, though there are a larger number of non-European individuals than the Maxwell Collection.

The Robert J. Terry Anatomical Skeletal Collection, housed at the Smithsonian National Museum of Natural History in Washington, DC and Suitland, MD, contains skeletons from medical school cadavers collected by Dr. Robert Terry from 1898 to 1941 and continued by Dr. Mildred Trotter until 1967 (Hunt and Albanese, 2005). Documentation for the skeletons in this collection is from morgue records. Individuals in this collection have birth years between 1828 and 1943, and the majority of individuals died between ages 20 and 80 years (Hunt and Albanese, 2005). The collection is composed of a relatively similar number of male and female individuals of African and European ancestry. This is considered a historic collection based on the birth years for the majority of the individuals in this collection.

The Hamann-Todd Osteological Collection contains skeletons retained from cadavers used by medical students, and collection began in 1912 by Dr. T. Wingate

Todd. It is housed at the Cleveland Museum of Natural History in Cleveland, OH. The collection represents individuals who were born in the 19th century (Komar and Buikstra, 2008). Like the Terry Collection, the Hamann-Todd collection is historic and is composed of males and females of African and European ancestry. Documentation is available for the majority of the skeletons; however some ages are given as intervals rather than specific numbers, and in some cases it is unclear exactly how documentation was obtained. White et al. (2012) state that only about 16% of the individuals in this collection have reliable enough age data for skeletal aging studies. Due to this and the presence of mid-sagittal sectioning in some of the cranial remains, the sample obtained from this collection is small and only represents individuals for which a single, known age is recorded.

The Chiba Documented Collection consists of skeletons obtained from individuals who died while incarcerated and is composed solely of individuals of Asian ancestry. This collection is housed at the Chiba University School of Medicine in Chiba, Japan. The majority of the individuals in this collection are Japanese, although a few individuals with a birthplace of Korea are included. This collection represents individuals born during the 19th and earlier part of the 20th centuries (birth years of 1851 to 1923) and is therefore considered to be historic. Individuals whose documentation does not include age at death are not included in this research.

The Jikei Documented Collection, housed at the Jikei University School of Medicine in Tokyo, Japan, consists of full skeletal remains and isolated skulls obtained from individuals who donated their bodies to the medical school. This collection is more recent that the one housed at Chiba University, with dates of death in the second half of the 20th century, and represents modern individuals. Individuals with unknown or approximate ages at death are not included in this research.

Data Collection

A data sheet, designed prior to data collection and tested at the Stanford Collection, University of Iowa, prior to visiting other collections, was used to manually record data for each individual (Appendix A). Once data was collected, it was input into a Microsoft Excel spreadsheet. Both sides of the sheet contain a header that includes the specimen identification number, who collected the data, whether the data are collected by in-person examination or via photograph, and the date of data collection. No one other than the researcher (Carrie A. Brown) collected data for this project, and all skulls were examined in-person. The Excel worksheet also includes a log page where dates of data collection, photography, collection of biological profile information, digitization, and additional notes are recorded. Age, ancestry, sex, and any other biological information were unknown at the time of data collection. Additionally, no other areas of the skeleton were examined in order to avoid introducing bias from other age indicators; only the maxillae, select facial sutures, and dentition were inspected.

Each skull was examined first for the presence of items that obscure observation of the sutures, dentition, or palatal variants. This included: postmortem breakage of skeletal material, sampling, midpalatal or other sectioning, and incomplete processing that results in the retention of soft tissue or adipocere. Individuals without intact palates or craniofacial skeletons were excluded, though individuals were scored that did not have all observable traits. No individuals were excluded based on damage or trauma to other parts of the skull or palatal/facial abnormalities (e.g., disease, unusual growth).

Qualitative Data

Data were collected for each individual following the order on the worksheet (Appendix A). Closure of the palatal sutures and two facial control sutures was scored using a 4-phase ordinal variable system following Meindl and Lovejoy (1985): 0 – open, 1 – 1-50% union, 2 – 51-99% union, 3 – complete. The palate was initially scored in 15 sections (Wheatley, 1996; Beauthier et al.2010) (Figure 4-1 and Table 4-4), and then each of the four palatal sutures was scored in its entirety (Nawrocki, 1998) (Figure 4-2). Additionally, the right and left halves of the TP suture and the right and left TP suture within the greater palatine foramen were also scored to examine potential side differences in sutural fusion. The closure per suture and for sides of the TP suture was further converted to a binary score: 0 – no fusion or 1 – any fusion. This binary system represents the Mann et al. (1991) method, which requires only the recognition of any amount of closure along a suture. The TP suture within the GPF was scored separately from the TP suture as a whole due to age differences noted in timing of fusion at this location versus the entirety of the TP suture (see Chapter 2). The facial control sutures were scored for degree of closure following Meindl and Lovejoy (1985) and in their entirety, not by section, due to their smaller overall length.

For each of the three systems (15-section/4-phase, full suture/4-phase, and full suture/binary) a summary score was also calculated. The summary score for the 15-section system ranges from 0 to 45, for the 4-phase full suture system from 0 to 12, and for the binary full sutures system from 0 to 4; neither of these full suture system summary scores include the TP suture within the GPF. Therefore, for the 4-phase full suture and binary full suture systems, a second summary score that includes the TP suture within the GPF was produced. To determine which side to use for these second summary scores, the right and left fusion scores for the TP suture within the GPF were statistically compared for both the 4-phase and binary scoring systems using Mann-Whitney U-tests, the nonparametric equivalent of the t-test. Nonparametric tests were used because the suture fusion scores are ordinal-level variables. There were no significant differences between right and left fusion scores of the TP suture within the GPF for either the four-phase ($p = 0.437$) or binary ($p = 0.259$) scoring systems. Given these results, Spearman's *rho*, a nonparametric method for measuring the relationship between two variables, was calculated for age and fusion score for both the right and left TP sutures in the GPF in the 4-phase and binary scoring systems. The right TP suture in the GPF scores have slightly higher positive correlations with age than the left for both 4-phase and binary scoring systems (four-phase: right = 0.316, left = 0.291; binary: right = 0.321, left = 0.303). Therefore, the right side is used in the second summary score that includes the TP suture in the GPF. The summary scores that include the TP suture in the GPF range from 0 to 15 for the 4-phase system and from 0 to 5 for the binary system.

Palatal variants were scored based on Hauser and De Stefano (1989, and references therein), Gill (1998), and Hefner (2009); descriptions of these traits and their use in biological anthropology are given in Chapter 3. Table 4-5 gives the specific scoring system used in this research. Some of the referenced scoring systems were modified for this research, while the scoring of other variables was developed during this data collection due to absence of scoring systems for these variables in the relevant literature. Shapes of the transverse palatine and zygomaticomaxillary sutures were scored on initial examination, while palatal shape, lateral and medial groove bridging, marginal crest, accessory lesser palatine foramina, maxillary and palatine bone quality, porosity, tori, and exostoses were scored using notes made during initial observation and a re-examination of the photographs. The zygomaticomaxillary suture shape was scored because its shape may influence closure of this suture; it is included in the palatal variants table for ease of reference.

The dentition was inventoried following a modified version of the inventory categories presented by Buikstra and Ubelaker (1994: p 49) (Table 4-6, see also Appendix A). The first five categories were maintained, while category 6 was combined with category 8 since no radiographic examination was conducted as part of this research. The new category 6 indicates a tooth with intact and non-resorbed alveolar bone that was unobservable, either due to congenital absence or because the tooth was unerupted. Additional observations, including dental restorations and the presence of dentures, were noted on the dental diagram and in the “Notes” section.

Wear for each tooth present was recorded following Smith (1984) for the incisors, canines, and premolars, Scott (1979) for the molars, and general recommendations by Buikstra and Ubelaker (1994). Tables 4-7 to 4-9 outline the dental wear scoring systems. In order to summarize the total wear per individual, regardless of the number of teeth present, wear was summed and divided by the total number of teeth present for the entire dentition, the posterior dentition (molars and premolars), and the anterior dentition (canines and incisors). The overall mean wear score gives a picture of wear per individual and the mean posterior and anterior wear scores serve to analyze teeth that have contact surfaces of different sizes.

Because of the difficulty of determining if a tooth was congenitally absent or lost prior to death for the third molars and, in more limited circumstances, other teeth, an AMTL index was developed to compare antemortem tooth loss among all individuals without relying on simple counts of teeth lost. This index gives a standardized amount of AMTL per person, and it is calculated as follows:

$$([\text{Total teeth possible} - \text{Teeth no AMTL}]/\text{Total teeth possible})*100 \quad (4\text{-}1)$$

The total number of teeth possible per individual is a count of all inventory scores except 3 (missing, no associated alveolar bone) and 6 (unobservable, either due to congenital absence or non-eruption), for a total number of teeth no greater than 16 (the number of teeth in the maxillary arch if all teeth are present). For the AMTL Index, values of 0 indicate an individual with no tooth loss, while values of 100 indicate complete tooth loss (totally edentulous). Values may fall anywhere on the continuum from 0 to 100.

Photographs of the cranium were taken using a Nikon D700 digital camera, AF-S DX Nikkor 18-55mm lens (overview), AF-S micro Nikkor 105mm lens (close-up), and a Sigma EM-140 DG ring flash. In general, 10 photographs were taken per cranium: documentary containing the specimen identification number, overview in anterior view, overview in inferior view, detail of the entire palate, detail of each of the greater palatine foramina, detail of each of the zygomaticomaxillary sutures, and two details of the nasofrontal suture. One detail of the frontonasal suture was taken without a scale to record presence or absence of the supranasal suture, to be used in future research. All of these photographs were taken with a scale and with the lens parallel to the surface being documented so that there was no distortion of the image to enable accurate digital measuring. Additional photographs were taken as needed, to include documenting trauma or variants and the use of different camera settings to improve detail/lighting for certain samples. Photographs were documented as taken by marking the appropriate box on page 2 of the data collection worksheet and then burned directly to a disk for transfer to a computer.

Quantitative Data

Suture closure and character state variables, as described above, are qualitative summaries of the available data and either categorical- or ordinal-level variables. These types of variables can limit the ability to conduct parametric statistical tests and potentially obscure smaller-scale variation. In order to compare these variables quantitatively and capture more precise information, interval- and ratio-level variables were developed based on detailed photographs of the palate. To prepare for digitization, all images were sorted into digital folders by specimen number and then labeled sequentially with specimen number. Each detail photograph of the palate was copied into a separate folder containing only palate photographs in order to enable ease of reference when working in ImageJ (Rasband, 1997-2014). Digitally measuring sutures was chosen as a technique due to time constraints at the skeletal collections and the ability to more accurately measure total sutural length and fusion in the digital realm because of the sinuous nature of sutures. Digitally measuring the sutures of the hard palate in human adult skulls based on images does not significantly differ from the traditional caliper method (Moreira et al., 2006).

Landmarks used for measurement in this study are based on features of the palate or extrema points. Table 4-10 lists and defines the landmarks used in this study, and Figure 4-3 depicts these landmarks on the palate and in relation to other palatal features. These landmarks were chosen from reference materials or developed for this study based on their ability to best quantify sutural chords and total lengths. No landmarks incorporating the TP suture within the GPF were employed due to the difficulty of photographing this region without distortion.

The antero-lateral transverse palatine (altp) landmark was used in order to best quantify deviations along the length of the TP suture prior to its descent into the greater palatine foramen. While Szrkat et al. (2003) measure the length of the transverse palatine suture using *summi palati* on both sides, similar to the way that altp is defined for this study, the definition for this landmark is not entirely clear. It is also possible to take the length of the TP suture from a defined feature – the most anterior point on the greater palatine foramen, where the suture descends into the foramen, but this potentially artificially increases measures of complexity since in most palates the TP suture exits the GPF anteriorly in the sagittal plane for several millimeters before making an abrupt 90 degree turn medially. Therefore, the altp marks the most antero-lateral point on the TP suture on both right and left sides and does not include any portion of the TP suture that enters into the GPF or the abrupt deviation of this suture.

Incisulare (inc), described by Skrzat et al. (2003), was chosen over *orale* (Bass, 2005) for the measurement of the AMP suture because inc is located on the posterior border of the incisive foramen. *Orale*, defined as the midline of the hard palate where a line drawn tangentially to the posterior margins of the central incisor alveoli crosses the midline (Bass 2005), can also be difficult to locate where antemortem and/or postmortem tooth loss is present. Additionally, in the majority of palates examined, no suture was visible either within or anterior to the incisive foramen, making the choice of *incisulare* over *orale* the logical one for this research.

The landmark employed for the most posterior portion of the PMP suture was the posterior nasal spine (pns) (Bass, 2005). Neither *staphylion* nor *alveolon* was used as the posterior landmark for the PMP suture because they both are defined in relation to the posterior or alveolar border of the palate rather than the most posterior point on this suture (Steele and Bramblett, 1988). The choice of the posterior nasal spine enabled the complete measurement of the PMP suture since the use of the aforementioned points could result in artificial truncation of the suture in cases where these points are found anterior to the most posterior point of the intersection of the palatine bones. It is also impossible to precisely locate *staphylion* and/or *alveolon* in individuals with alveolar bone loss. In cases where the posterior nasal spine and the posterior edge of the PMP suture did not correspond, the suture was measured to the posterior edge of the PMP suture rather than the posterior nasal spine.

Finally, the standard landmark of *staurion* (sr), the intersection of the median and transverse sutures of the hard palate, was employed with no modifications. In cases where the right and left TP sutures asymmetrically intersected the median palatine suture, the more posterior point of intersection was used for the AMP suture measurement. This results in slightly truncated PMP suture measurements, but the truncation is standardized across the entire sample.

Using these landmarks, the total length (including all oscillations), total amount of suture closure, and sutural chord (shortest distance from point A to point B) per suture were digitally measured in ImageJ (Rasband, 1997-2014) using photographs of the palate and a Wacom Tablet touchscreen monitor and stylus (Figure 4-4). Measurements were taken in centimeters, to the one-thousandth decimal place. Prior to any measurement, the scale was set in ImageJ (Rasband, 1997-2014) by using the 1-cm scale in the photograph and the "set scale" function, which converts pixels to a known distance (Figure 4-5). The scale was set for each sample prior to digitization. If necessary, image brightness and/or contrast were adjusted to optimal levels for viewing or distinguishing sutures (Figure 4-6). Measurements and their corresponding landmarks are given in Table 4-11, and the order the measurements are taken for each individual is given in Table 4-12. Landmarks can be referenced in Figure 4-3, and Figures 4-7 to 4-10 show examples of measurements of sutures and fusion.

Ordinal observations (see above, Qualitative Data) were not referenced at any time during the digital measuring process. The incisive suture was excluded from the digitization process since most individuals in this sample displayed nearly or completely obliterated incisive sutures, which made it impossible to measure total sutural and chord lengths. In individuals where fusion was not continuous (i.e., multiple sites of closure present along the length of suture with breaks in between fusion sites), each separate instance of fusion was measured and then summed to produce a total fusion score for that suture (see Figure 4-10). The length, chord, and fusion of the TP suture were measured separately for right and left sides, and these scores were then summed to create total length, chord, and fusion variables for this suture. Specifically for the chord measurement, this strategy was used to avoid incorporating large-scale anterior or posterior deviations of the entire course of the suture since this is a different variable, which is described qualitatively using the categorical scale for transverse palatine suture shape (Table 4-5).

From these measurements, ratio-level variables were produced to standardize measurements for comparison among individuals. These variables are: sutural complexity and the degree of suture closure for the AMP, PMP, and TP sutures. Sutural complexity was calculated using the suture length ratio (Rafferty and Herring, 1999):

$$\text{Total Suture Length/Suture Chord} \tag{4-2}$$

Lower ratio values (close to 1) indicate sutures that are less complex, while larger ratio values (greater than 1) indicate sutures that are more complex. Suture length ratio was used since it does not require sutures to qualify as fractals, is more straightforward than fractal analysis, and is found to better quantify sutural complexity when compared to fractal dimension analysis (Hotzman, 2010). The fusion ratio was calculated by dividing the amount of fusion by the total length of the suture. A higher fusion ratio (closer to 1) indicates more fusion; while a smaller value (closer to 0) indicates less fusion. Scores of 1 indicate full fusion of the suture; scores of 0 indicate the absence of any degree of fusion. A summary score for the fusion ratio was calculated by adding fusion for the PMP, TP, and AMP sutures, and dividing this number by the sum of the total lengths of these sutures:

$$\text{(PMP.fus+TP.fus+AMP.fus) / (PMP.len+TP.len+AMP.len)} \tag{4-3}$$

Data Analysis

This study uses frequentist statistics due to the structure of the data and certain limitations that limit the application of Bayesian-based inference. Because of the previous scoring systems used in cranial suture age estimation, there are no discrete, age-progressive phases or stages in the methods developed to-date for palatal sutures, nor is there a single reference sample that has been scored using that method (Garvin et al., 2012). Additionally, prior distributions, which are required for Bayesian methods, are not easily obtainable for samples derived from skeletal collections (Konigsberg et al., 2008). Bayesian-based methods may be a possibility in the future, if discrete phases of palatal suture closure can be defined. The research design and sampling strategy outlined above provide a balanced sample, which supports the use of frequency statistics at this stage (Nawrocki, 2010).

Following data collection, the total sample was scrubbed to eliminate individuals not classified into one of the three major ancestral groups and individuals who had missing data points for one or more suture fusion scores, including the facial control sutures. This resulted in the total sample used for analysis, reflected in Table 4-13. Individuals with missing data for palatal variants were not eliminated from the analyzed sample. More than 25 samples for European males and females over the age of 70 years were present in the un-scrubbed sample, and these groups were culled so that their total sample sizes were not over 25 per group to avoid biasing the sample towards very old individuals. The age distribution is given in Figure 4-11; Figures 4-12 and 4-13 display the sample distribution by age and sex and age and ancestry. For the sample as a whole, the mean age is 50.94 years, median age is 50 years, and minimum and maximum ages are 20 and 102 years, respectively.

Due to the power analyses that informed data collection in terms of sample size, the balanced demographic composition of the sample, and the overall large size of the sample, parametric statistics were employed as long as the data reasonably meet assumptions for the particular method used. When data did not meet or come reasonably close to meeting the assumptions inherent to parametric methods, nonparametric methods were employed (e.g., scores were ordinal or non-normally distributed in a correlation analysis). Chapter 5 (Results) details the particular test used for each analysis, and Occam's razor and the data themselves dictate the analyses (i.e., a simpler test is always preferred over a more complex one). All statistical analyses were conducted in *R* version 3.1.2 (RCoreTeam, 2014). In tests of statistical significance, a result is considered to be significant if it falls below the $p = 0.05$ threshold. For correlation analyses, *p*-values are not reported since they can be affected by large sample sizes and only inform on the difference from that value from 0.

Hypothesis Testing

Data were analyzed in the order of the research questions outlined in Chapter 1: age and sutural closure, group affiliation and sutural closure, biomechanical proxies, and palatal variants. This order serves as a type of model-building in that it first determines the relationships of each type of variable to the two variables being investigated – age at death and fusion – and then uses those explanatory variables with the strongest relationship with age and/or fusion to move to the next level. The final step is to incorporate all data. Specific details inherent to the testing of each of the four main research questions are given below and in Chapter 5.

Age and Sutural Closure

Degree of palatal suture closure is expressed both categorically and continuously. Categorical data include nominal and ordinal scoring of sutural closure for full sutures and sections of sutures as well as summary scores developed from those scores. Continuous data include ratios of fusion for individual sutures and a fusion ratio summary score. The relationship between known age and degree of palatal suture closure based on categorical scoring was first visually examined to determine the appropriate statistical method to use in analyzing these data, and the ability to treat summary scores as continuous data was also investigated. Due to the largely categorical nature of the closure scores, nonparametric tests were used to compare age and closure even for the continuous scoring system as it enabled easier comparison of this system with ordinal systems. Scoring systems were also investigated via ANOVA to determine if certain scoring categories could be collapsed and if there was any need to eliminate certain variables from the 15-section/4-phase system. The main goal of testing this hypothesis was to determine which system had the strongest relationship to known age at death.

Group Affiliation and Sutural Closure

The relationship of group affiliation and sutural closure was first visually examined, and then data were checked to see if they met the assumptions for parametric comparisons of means, namely constant variance and normally distributed error. For this stage of analysis, the scoring system/combination of sutures with the highest relationship to age was employed. In cases where the data violated parametric assumptions, nonparametric tests were employed. A full model, excluding groups with non-significant differences in means/medians was also run to examine potential interactions among variables.

Biomechanical Variables

Each of the three biomechanical variables – wear, AMTL, and complexity – was compared to fusion, known age at death, and group, as well as to one other. Because of the continuous nature of the biomechanical variables, all three were compared to both the 15-section/4-phase summary score and the fusion ratio scores, as appropriate. Due to the way that complexity scores were measured and calculated, it was not possible or valid to combine complexity scores across palatal sutures. Therefore, complexity scores were analyzed in terms of fusion of separate sutures

Variable relationships were examined through Spearman's rank-order correlations due to the non-normal frequency distributions of the majority of biomechanical variables. With continuous data, regression was employed to look at the effects of variables on one another. For comparison across groups, data were checked first for constant variance. With relatively constant variance and large sample size, parametric comparison of groups means – ANOVA – was employed; in cases where the data did not reasonably meet these assumptions, nonparametric alternatives were used.

Palatal Variants

Palatal trait expression was analyzed in terms of age, group affiliation, biomechanical variables, and the relationship of palatal traits to one another. Spearman's rank-order correlations, appropriate for categorical data, were used to summarize relationships of palatal traits with other variables and each other. Frequencies of traits by sex, ancestry, and time period were compiled. While frequencies are generally informative for looking at between and among group differences in trait frequencies, these values were further tested using Pearson's *chi*-square tests to determine if differences between observed and expected frequencies were statistically significant. When at least one expected cell count was < 5 in a table Yates' continuity correction was applied. Because of the number of palatal traits analyzed, no further tests of significance were conducted at this phase of analysis, and *rho* values were employed to inform variable selection in subsequent analyses.

The Full Picture

Based on testing of the four hypotheses, models were developed using those variables shown to have a significant effect on or otherwise moderate to strong association with age or fusion – generally set at a threshold of correlation value > 0.100 or < -0.100. Details of specific testing and variables used can be found in Chapter 5. The goal of this final step of analysis was to best describe fusion in terms of all variables investigated and understand age variation across the palate.

Error and Limitations

Error in this study could potentially come from several sources, both random and systematic. Random error is most often attributed to human or observer error, and while it is always present, it is also statistically quantifiable and limited by repeated measurement and controls (Youden, 1998; Brach and Dunn, 2004). A good way to control for random error is to include tests of intra- and interobserver error. Systematic error is more difficult to control for as it relates to variation of the sample mean value in relation to the true population mean value (Brach and Dunn, 2004). This type of error can be minimized by repeatedly refining measurement techniques in order to better calibrate them with what they are measuring, but it lacks true statistical quantification (Brach and Dunn, 2004).

In this research, the potential for random error was mainly during data collection. It includes: inexact measurements in ImageJ (Rasband, 1997-2014), transposition of numbers during data collection and entry, and the incorrect association of individuals with photographs or scores. Several protocols are put in place to minimize the introduction of random error, to include standardized data collection worksheets with headers containing specimen identification numbers, double-checking of manual and transcribed data entry, a log sheet to record dates when data were collected, the photography of specimen identification number before each set of photographs as well as the retention of this identifying photograph with associated images throughout image transfer, and the relabeling of all photos to include the specimen identification number. Error from measurement in ImageJ (Rasband, 1997-2014), especially of total suture length including all oscillations, is believed to be negligible. An additional human-introduced source of error that cannot be controlled for in this study is problems with documentation in the skeletal collections, to include transposition of numbers or the association of remains with the wrong demographic information. While the current research cannot resolve these particular issues, by collecting a relatively large sample size, it is hoped that these types of error will be minimized by the amount of data points analyzed.

Systematic error in this research is largely related to human variability and biology. The variability of aging is discussed in detail in Chapter 2. The biological process of sutural fusion means that sutures that are largely obliterated are difficult to measure total length (including all oscillations). Therefore, for individuals with a large amount of obliteration, total length may approach or be equal to chord length, meaning that sutural complexity will be estimated as very low. Another issue with the measure of sutural complexity is that it only measures surface complexity. Because of their structure as three-dimensional objects sutures can vary in complexity and morphology beyond what is seen on the surface (Hotzman, 2010). Thus the suture length ratio may not give the complete or accurate picture of sutural complexity as it relates to suture structure and function. Accounting for this variability could be done with methods that include computed tomography imaging, but that is beyond the scope of the current investigation.

Summary

This chapter outlined the sampling strategy, sample, data collection methods, and data analyses employed in this research. It also addressed possible error and limitations in this specific research and research in skeletal biology. The following chapter discusses the results of the data analyses.

Table 4-1. Power analyses for sample size based on previously reported correlation (*r*) values for age and palatal suture closure.

n	*r*	Significance level (*α*)	Power (1-*β*)	Reference
105	0.27	0.05	0.8	Wheatley (1996)
30	0.49	0.05	0.8	Wheatley (1996)
23	0.55	0.05	0.8	Nawrocki (1998)

Table 4-2. Power analyses for sample sized based on desired effect size in ANOVA for group assignment and sutural closure.

n	*k*[a]	*F*[b]	Significance level (*α*)	Power (1-*β*)
394	2	0.10	0.05	0.8
323	3	0.10	0.05	0.8
64	2	0.25	0.05	0.8
53	3	0.25	0.05	0.8
26	2	0.40	0.05	0.8
22	3	0.40	0.05	0.8

[a]Number of groups.
[b]Desired effect size, larger numbers indicate larger effects.

Table 4-3. Collection summary information. This table represents all individuals examined prior to data scrubbing.

Collection	Location	Total Size	Ages (in years)	Period	Ancestry	Number of individuals examined for this research
Maxwell Documented	University of New Mexico	278	Fetal-100	Modern	European	173
William M. Bass Donated	University of Tennessee, Knoxville	~1000	Fetal-101	Modern	European, African, Asian	177
Robert J. Terry	Smithsonian National Museum of Natural History	1728	14-102	Historic	European, African	225
Hamann-Todd Osteological	Cleveland Museum of Natural History	~3100	Fetal-105	Historic	European, African	15
Chiba Documented	Chiba University School of Medicine, Japan	199	17-83	Historic	Asian	153
Jikei Documented	Jikei University School of Medicine, Japan	283 skeletons, 757 skulls	Fetal-95	Modern	Asian	114

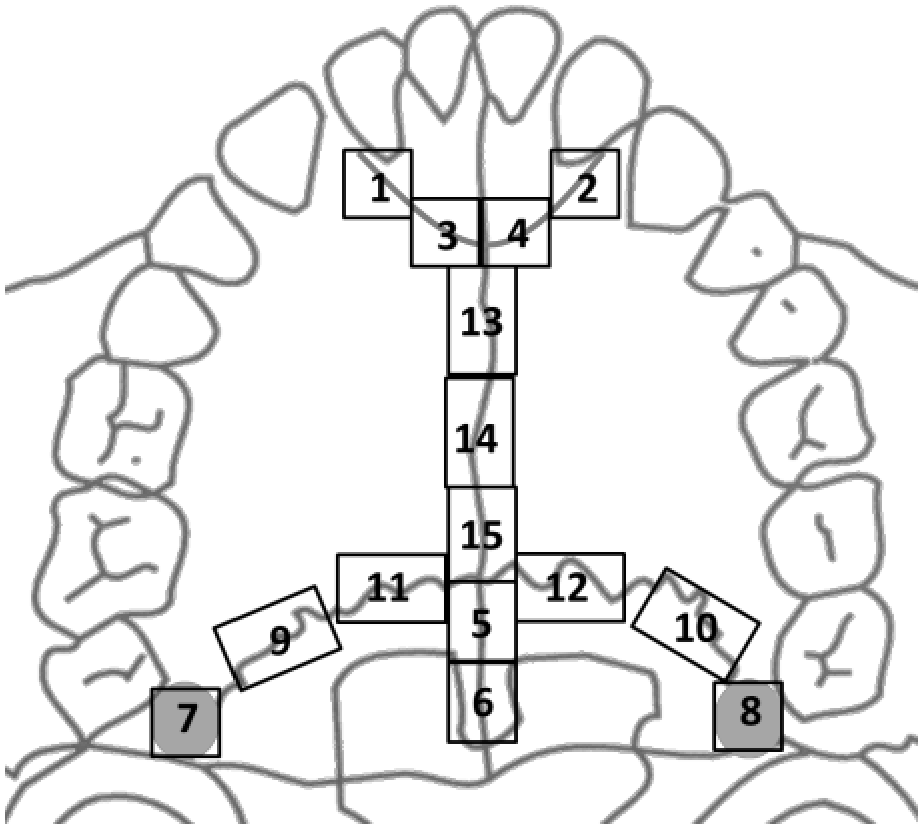


Figure 4-1. Palate divided into 15 sections. The drawing is not to scale.

Table 4-4. Numerical designators and descriptions for each of the 15 sections of the palatal sutures.

Numerical designator	Suture	Section	Side
1	Incisive	Lateral	Right
2	Incisive	Lateral	Left
3	Incisive	Medial	Right
4	Incisive	Medial	Left
5	Posterior median palatine	Anterior	Midline
6	Posterior median palatine	Posterior	Midline
7	Transverse palatine	Greater palatine foramen	Right
8	Transverse palatine	Greater palatine foramen	Left
9	Transverse palatine	Lateral	Right
10	Transverse palatine	Lateral	Left
11	Transverse palatine	Medial	Right
12	Transverse palatine	Medial	Left
13	Anterior median palatine	Anterior	Midline
14	Anterior median palatine	Mid-section	Midline
15	Anterior median palatine	Posterior	Midline

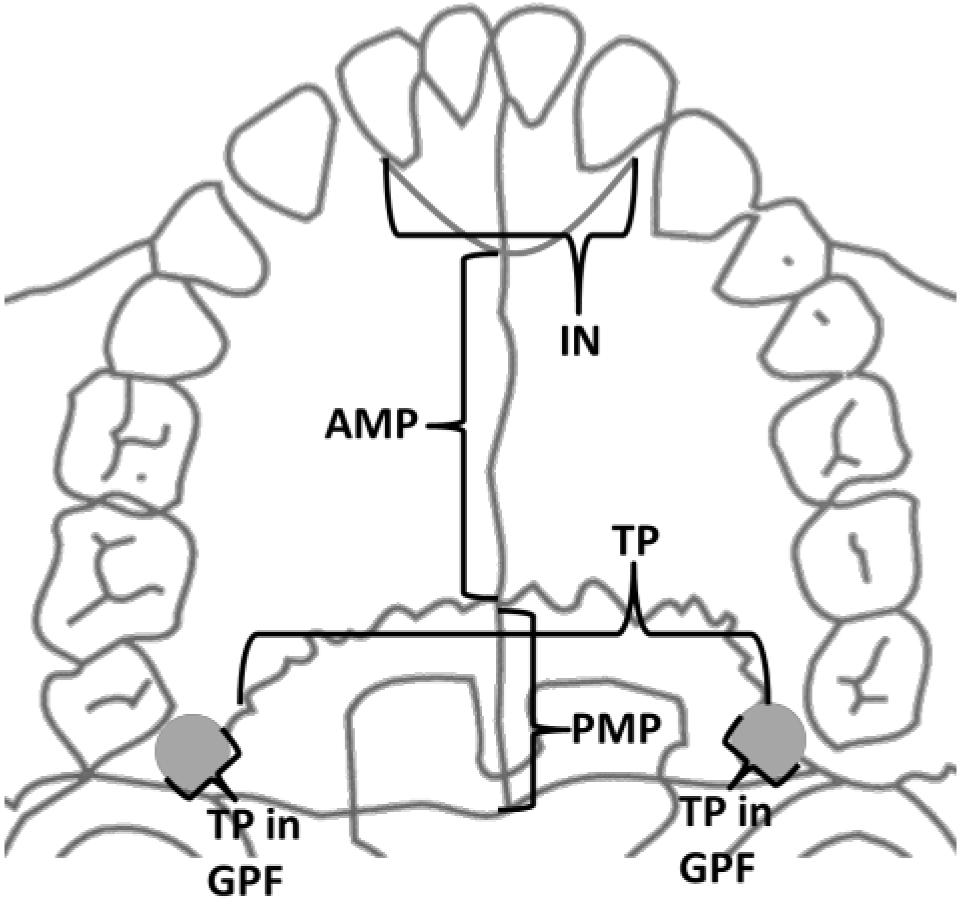


Figure 4-2. Palate scoring based on the entirety of each palatal suture. The drawing is not to scale.

Table 4-5. Palatal variant scoring. More detailed trait descriptions are available in Chapter 3.

Variant	Score 0	1	2	3	Reference
Accessory lesser palatine foramina[a]	None present	1 present	2 present	3 present[b]	Berry and Berry (1967), Hauser and De Stefano (1989)
Cristi marginalis[a]	Absent	Present	N/A	N/A	Stieda (1891)
Lateral/medial groove bridging[a]	Absent	Spurs/ridges present	Spurs/ridges present, tendency towards bridging	Complete	Hauser and De Stefano (1989); modified
Palatine torus	Absent	Small, including thin mounding in vicinity of suture	Moderate	Pronounced	Hauser and De Stefano (1989), modified
Maxillary tori[a]	Absent	Small	Moderate	Pronounced	Hauser and De Stefano (1989), modified
Maxillary exostoses[a]	Absent	Small	Moderate	Pronounced	Developed
Maxillary/palatine bone quality	Good	Moderate	Thin/Poor	N/A	Developed
Porosity	Absent	Present	N/A	N/A	Developed
Palate shape	Elliptic	Hyperbolic	Parabolic	Trapezoidal	Gill (1998), modified
Transverse palatine shape	Straight	Anterior deviation	Anterior and posterior deviation (M-shaped)	Posterior deviation	Hefner (2009)
Zygomaticomaxillary suture shape[a]	No angles; greatest lateral projection at inferior zygomatic	1 angle; greatest lateral projection near midline	2+ angles; variable position for greatest lateral projection; S-shaped/jagged	N/A	Hefner (2009)

[a]Sides scored separately.
[b]LPF scored as number present. Majority less than 3, but some scores of 4 and 5 observed.

Table 4-6. Dental inventory categories, modified from Buikstra and Ubelaker (1994).

Score	Description
1	Present, not in occlusion
2	Present, development complete, in occlusion
3	Missing, no associated alveolar bone
4	Missing, antemortem loss, alveolar bone resorbing or fully resorbed
5	Missing, postmortem loss, no alveolar resorption
6	Missing, unobservable, congenital absence, unerupted; alveolar bone intact and no resorption
7	Present, damaged

Table 4-7. Dental wear scoring for the incisors and canines, following Smith (1984) and described in Buikstra and Ubelaker (1994).

Score	Description
1	Unworn, polished, or only small wear facets; no dentin exposure
2	Point or hairline of dentin exposure
3	Line of dentin with distinct thickness
4	Moderate dentin exposure, no longer resembles a line
5	Large dentin area, enamel rim still complete
6	Large dentin area, enamel rim lost on one side or very thin enamel
7	Large dentin area, enamel rim lost on two sides or small remnants of enamel remain
8	No enamel remains, complete loss of crown, crown surface same shape as roots

Table 4-8. Dental wear scoring for the premolars, following Smith (1984) and described in Buikstra and Ubelaker (1994).

Score	Description
1	Unworn, polished, or small facets; no dentin exposure
2	Moderate cusp removal, blunting
3	Full cusp removal and/or moderate dentin patches
4	Minimum of one large dentin exposure on one cusp
5	Two large dentin areas, possible coalescence of these areas
6	Dentin areas coalesced, enamel rim still complete
7	Full dentin exposure, loss of rim on at least one side
8	Severe loss of crown height, crown surface takes on shape of roots

Table 4-9. Dental wear scoring for the molars, following Scott (1979) and described in Buikstra and Ubelaker (1994). Note: the molar is divided into four quadrants, and each quadrant is scored and then summed to produce a wear score between 4 and 40.

Score	Description
0[a]	No data available; tooth not in occlusion, unerupted, or absent antemortem or postmortem.
1	Wear facets invisible or very small
2	Wear facets large, large cusps present, surface features evident; pinprick-sized dentin exposure or dots possible.
3	Cusp(s) rounded and not clearly defined; cusp coming obliterated but not flat
4	Area and cusp(s) flat; no dentin exposure or only very small pinprick-sized dot
5	Area and cusp(s) flat; dentin exposure one-fourth of quadrant or less
6	Greater dentin exposure than 5, dentin exposure more than one-fourth of quadrant, but enamel still present; quadrant surrounded by enamel on all sides
7	Enamel on only two sides of quadrant
8	Enamel on only one side of quadrant, usually outer rim; enamel thick to medium on remaining side
9	Enamel on only one side of quadrant; enamel is very thin; sides may be worn through
10	No enamel on any part of quadrant; complete dentin exposure; wear below cervicoenamel junction and into root

[a]Not employed in this research.

Table 4-10. Landmark definitions, listed alphabetically.

Name	Description	Reference
Antero-lateral transverse palatine (altp)	The most antero-lateral point on the transverse palatine suture. This point does not include any descent into the greater palatine foramen but may vary in relative location among individuals.	Defined for this study
Incisulare (inc)	The most anterior point on the median palatine suture directly posterior to the posterior margin of the incisive foramen.	Skrzat et al. (2003: p 124)
Posterior nasal spine (pns)	The midpoint of the posterior edge of the hard palate. In cases where the posterior termination of the PMP and the pns did not correspond, the measurement was taken to the most posterior point of the suture.	Steele and Bramblett (1988)
Staurion (sr)	The intersection of the median and TP sutures.	Martin (1928)

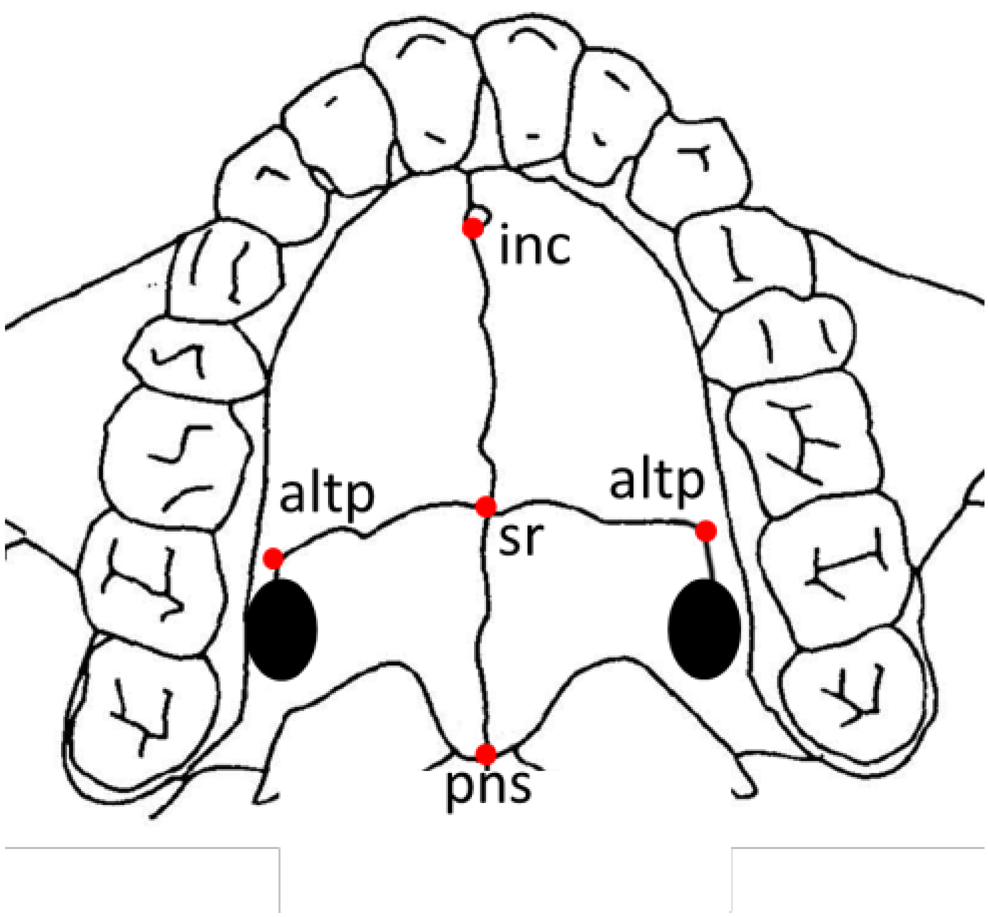


Figure 4-3. Palatal landmarks used in this study.

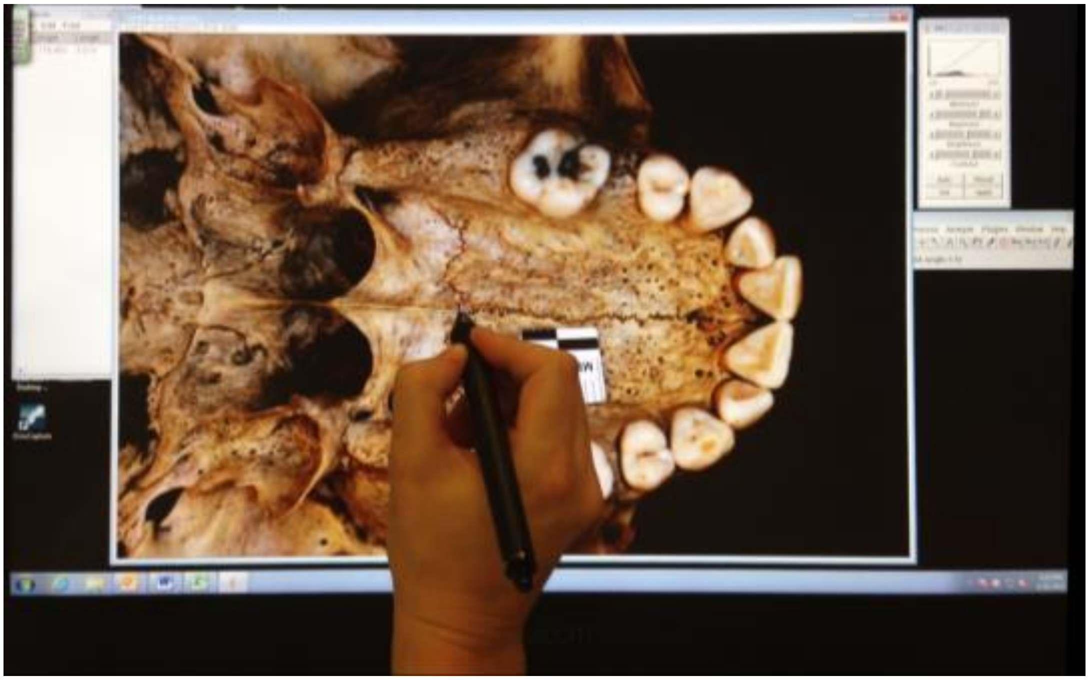


Figure 4-4. Digital measurement set-up: Wacom Tablet touchscreen monitor, stylus, and Image J. Photograph courtesy of Carrie A. Brown.

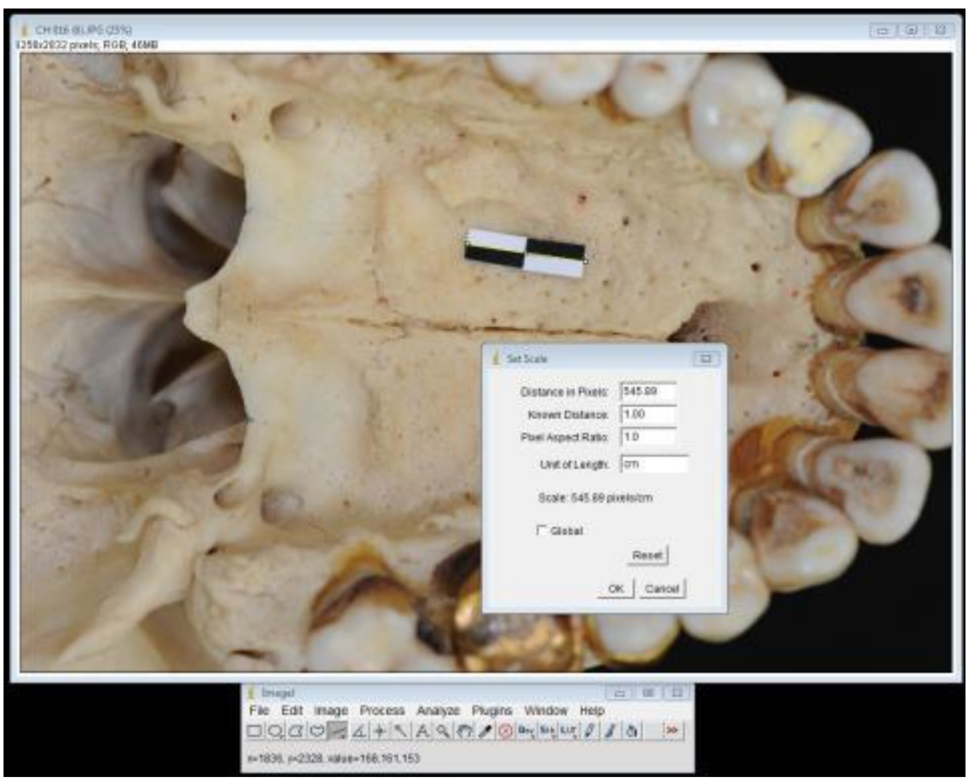


Figure 4-5. Setting the scale in ImageJ. Photograph courtesy of Carrie A. Brown.

A

B

Figure 4-6. Example of brightness and contrast adjustment in ImageJ. A) Palatal photograph before adjustment, B) palatal photograph after adjustment. Photographs courtesy of Carrie A. Brown.

Table 4-11. Measurements and their landmarks. All measurements taken in cm.

Suture	From	To
AMP	inc	sr
PMP	sr	pns
TP	R altp	L altp
TP R	sr	R altp
TP L	sr	L altp

Table 4-12. Order of measurements in ImageJ.

#	Measurement
1	AMP chord
2	PMP chord
3	R TP chord
4	L TP chord
5	AMP length
6	PMP length
7	R TP length
8	L TP length
9	AMP fusion
10	PMP fusion
11	R TP fusion
12	L TP fusion

A

B

Figure 4-7. Measurements of the AMP suture in ImageJ. A) AMP chord, B) AMP total length. Photographs courtesy of Carrie A. Brown.

A

B

Figure 4-8. Measurements of the PMP suture in ImageJ. A) PMP chord, B) PMP total length. Photographs courtesy of Carrie A. Brown.

A

B

Figure 4-9. Measurements of the TP suture, right side, in ImageJ. A) Right TP chord, B) right TP total length. Photographs courtesy of Carrie A. Brown.

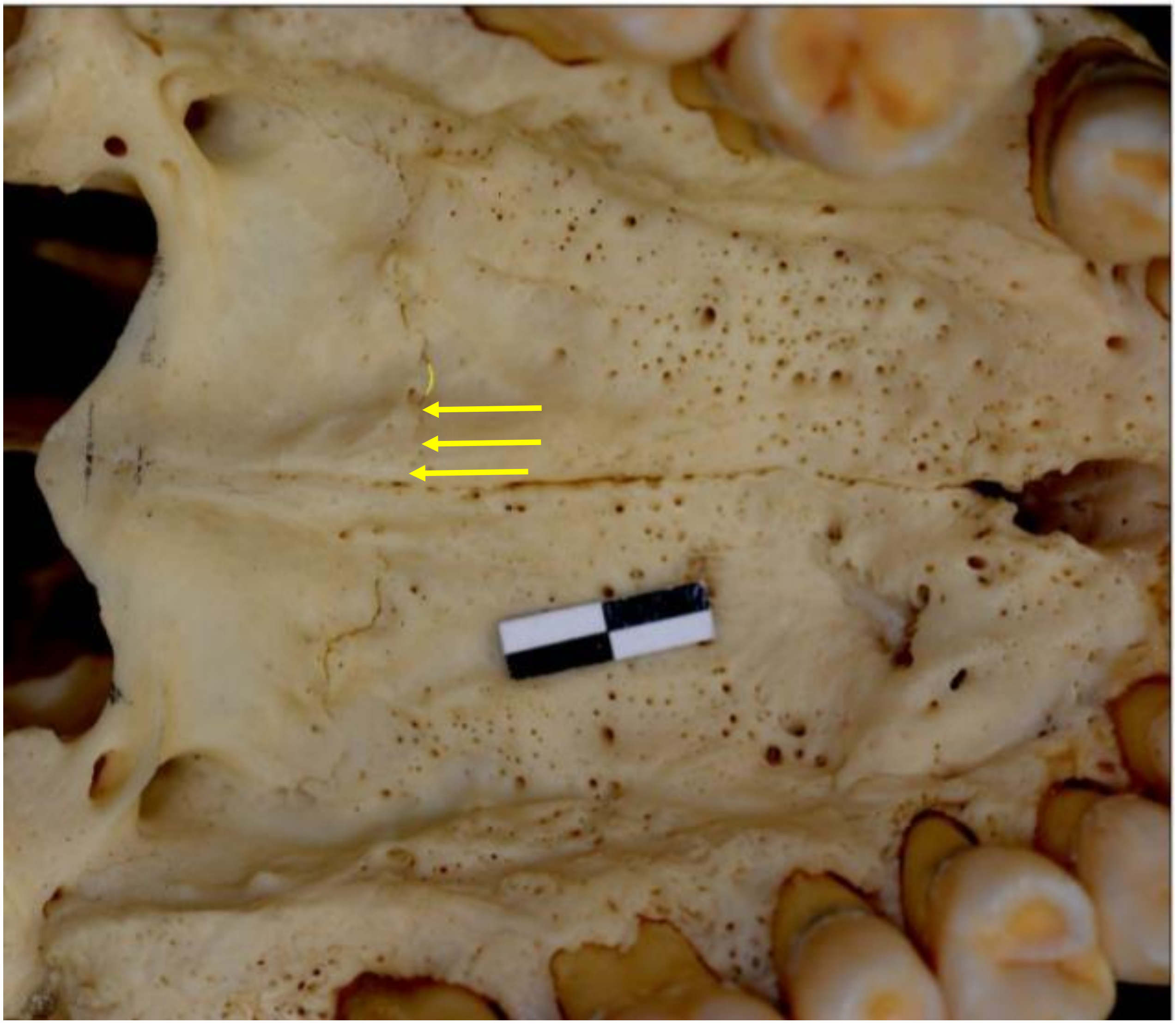


Figure 4-10. Measuring sutural fusion in ImageJ; each location of fusion is measured individually (yellow line), and total fusion per suture is calculated as the sum of all individual measurements. Yellow arrows indicate other areas of fusion to be measured. Photograph courtesy of Carrie A. Brown.

Table 4-13. Total sample analyzed for this research, broken down by demographic groups with mean and median ages per group.

Ancestral group	Sex	Age group	*n*	Mean age	Median age
African	Female	20-29	22	25.09	24.5
		30-39	20	34.75	35
		40-49	20	44.85	45
		50-59	19	54.79	55
		60-69	21	64.38	65
		70+	22	83.32	81.5
African	Male	20-29	23	24.74	25
		30-39	20	34.80	35
		40-49	22	44.91	45.5
		50-59	20	54.55	55
		60-69	22	64.36	64
		70+	19	78.32	77
Asian	Female	20-29	22	24.23	24
		30-39	22	33.91	33
		40-49	21	43.24	43
		50-59	20	53.65	53
		60-69	22	64.36	64
		70+	23	77.09	76
Asian	Male	20-29	22	24.36	24
		30-39	22	34.14	34
		40-49	24	43.58	43
		50-59	22	53.59	53
		60-69	22	64.09	65.5
		70+	22	77.82	77
European	Female	20-29	10	26.00	26
		30-39	22	35.00	35.5
		40-49	22	44.95	44.5
		50-59	20	53.55	53
		60-69	22	64.82	64.5
		70+	25	84.00	82
European	Male	20-29	19	24.47	24
		30-39	25	35.52	36
		40-49	22	45.18	46
		50-59	17	54.47	54
		60-69	19	65.21	66
		70+	25	79.44	78
TOTAL			762	50.94	50

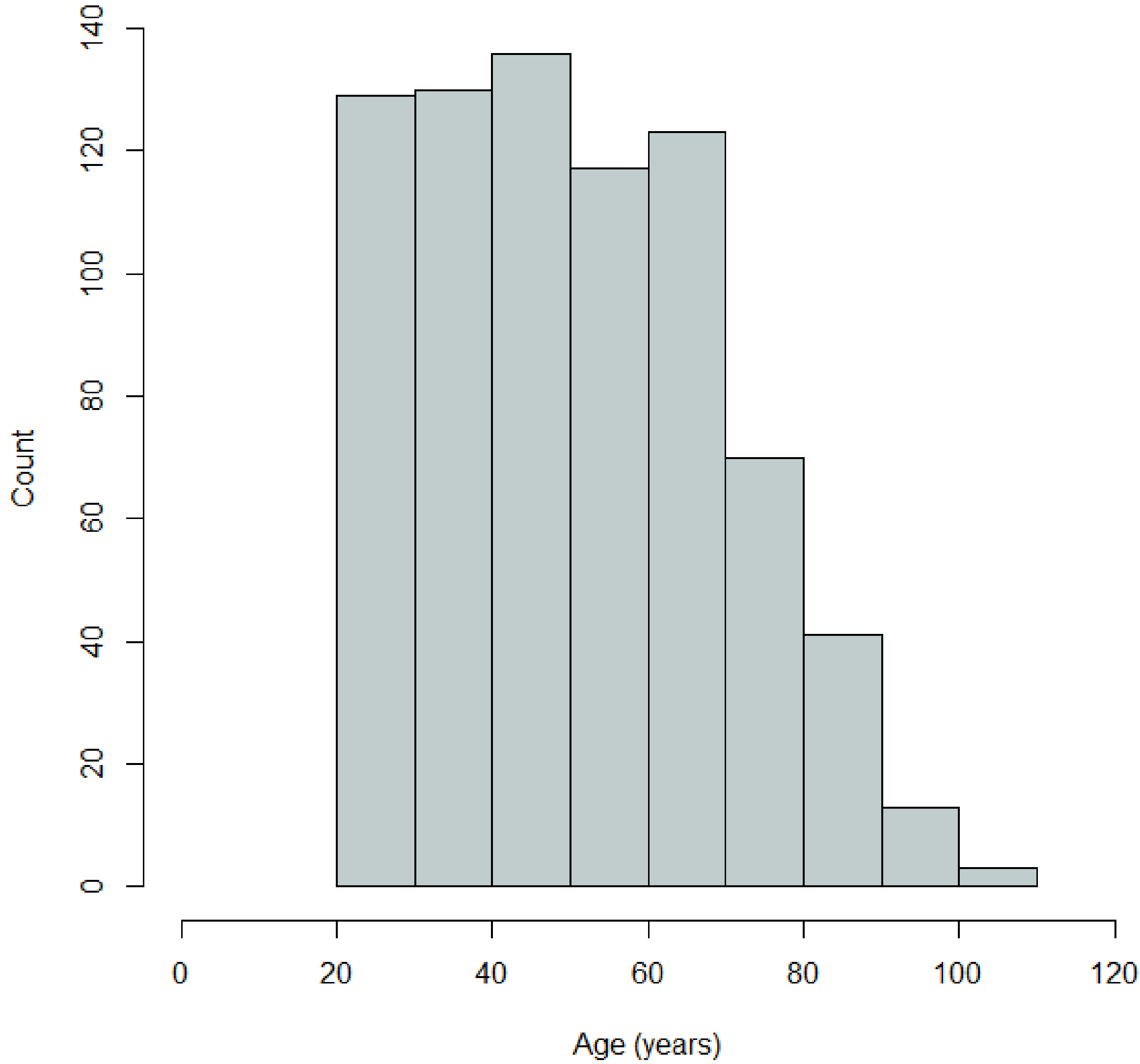


Figure 4-11. Age distribution of sample (n = 762).

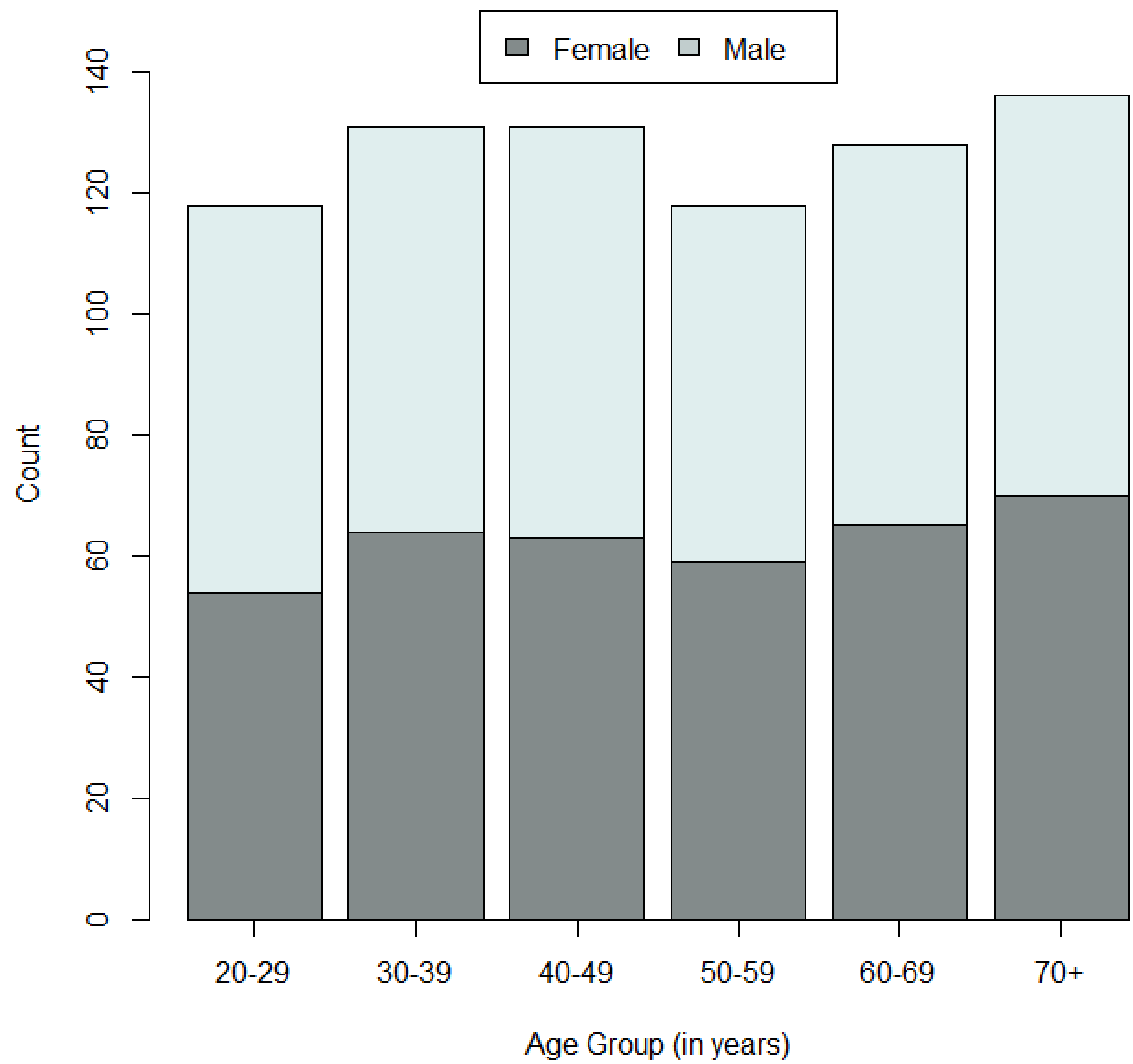


Figure 4-12. Sample distribution by age group and sex.

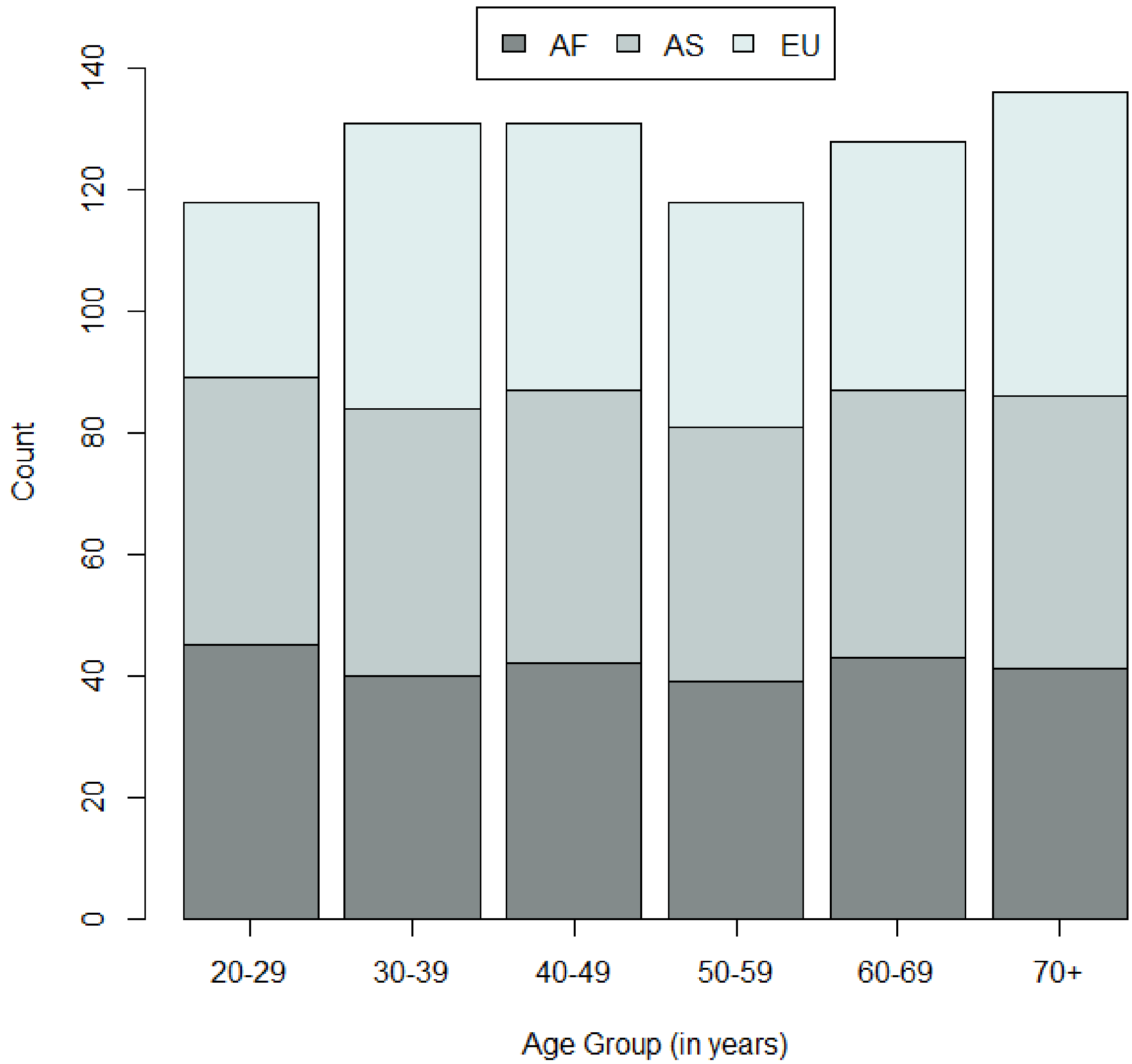


Figure 4-13. Sample distribution by age group and ancestry (AF = African, AS = Asian, EU = European).

Table 4-14. Summary of dummy variables developed from nominal variables. Original score is listed first, followed by dummy variable underneath.

Variable	Dummy variables			
Sex	Female	Male		
	0	1		
Ancestry	African	Asian	European	
	1,0	0,1	0,0	
Time period	Historic	Modern		
	0	1		
Zygomaticomaxillary suture shape	Straight (0)	1 angle (1)	2+ angles (2)	
	1,0	0,1	0,0	
TP suture shape	Straight (0)	Anterior deviation (1)	M-shaped (2)	Posterior deviation (3)
	1,0,0	0,1,0	0,0,1	0,0,0
Palatal shape	Elliptic (0)	Hyperbolic (1)	Parabolic (2)	Trapezoidal (3)
	1,0,0	0,1,0	0,0,1	0,0,0
Marginal crest	Absent	Present		
	0	1		
Dental restorations	Absent	Present		
	0	1		
Full edentulism	Absent	Present		
	0	1		
Porosity	Absent	Present		
	0	1		

CHAPTER 5
RESULTS

Palatal Suture Closure and Age

Three qualitative, categorical systems were employed in the first phase of data collection: 15-section/4-phase, full suture/4-phase, and full suture/binary. The relationships of age and closure for the qualitative, categorical scoring systems are summarized with box-and-whisker plots (Figures 5-1 through 5-14). The boxes display the median age and first and third quartiles for age per closure score for sections of sutures, individual sutures, and summary scores. In all plots a general trend of increasing age with increasing closure score is noted, though the dispersion of values per closure score is quite large. It also appears that reducing the number of categories by collapsing certain scores may be warranted (e.g., scores of 1 and 2 for the TP suture in the 15-section/4-phase system [see Figure 5-3 and below]). Distributions of summary scores show the most frequent scores are those towards the lower end of the fusion spectrum (Figure 5-15).

The box-and-whisker plot for age and summary score of the 15-section/4-phase system is quite complex and therefore also graphed as a scatterplot for comparison (Figure 5-16). When graphed as a scatterplot it can be seen that summary score approximates continuous data due to the number of possible scores available (n = 45). Figure 5-16 includes a least squares regression line (black), but the scatterplot does not show a strong or clear relationship between summary score and age. Since the data do not appear to conform to any known models that could potentially strengthen or linearize the relationship between age and suture closure summary score, the data were not transformed. A nonparametric smoother was not helpful in summarizing the data due to the approximation of continuous data (i.e., the data still behave as discrete data even with the large number of possible scores).

To compare the relationship of suture closure to age for each of the sutures or sections of sutures within the categorical systems, ANOVA tests were run. In order to do this, palatal fusion scores were treated as ordinal factors and the mean age per fusion score was compared for sections of sutures and full sutures. Homogeneity of variance for scores produced by the three categorical systems was tested using Fligner-Killeen tests (Crawley, 2013). The majority of sutural fusion scores showed constant variance, making the choice of a parametric test appropriate. Tables 5-1 through 5-3 display the results of these tests and indicate that the IN and PMP sutures differ significantly in closure score by age for the 15-section/4-phase and full suture/4-phase systems, while the PMP and right TP sutures differ significantly for the binary system. The AMP suture shows differences in score by age for only one section in the 15-section/4-phase system. In terms of summary scores for each of the systems, one-way ANOVA tests for age and each summary score, treating each possible combination of scores as a factor, indicate that there are significant differences in mean age by each level of summary score ($p < 0.001$, all three systems).

Because the boxplots appear to show some degree of overlap in fusion scores for the 4-phase systems, the potential of collapsing certain fusion scores was also investigated. Tables 5-4 through 5-6 display Tukey's honest significant difference (HSD) *post-hoc* comparisons of differences in mean age per fusion score; the binary system is presented for comparison. Most of the significant differences are found in unfused (0) versus partial (1 or 2) or complete (3) fusion categories for both iterations of the 4-phase system (Tables 5-4 and 5-5). In the 15-section/4-phase system, differences in mean age for fusion scores 1 and 2 are significant only for right and left portions of the medial IN suture. The full suture/binary system shows significant differences in mean age for scores of no fusion (0) and any amount of fusion (1) for all sutures except the IN suture (Table 5-6). Based on these results, fusion scores 1 and 2 were experimentally collapsed for the 15-section/4-phase and full suture/4-phase systems to determine if a 3-phase system was preferable to a 4-phase or binary system. This collapsing resulted in a 3-phase system with scores of: 0 – no fusion, 1 – partial fusion, and 2 – complete fusion, and new summary scores were calculated. Comparison of the new 3-phase system with known age was done alongside this same comparison for the 4-phase and binary systems.

Spearman's rank-order correlation was used to examine the relationship between age and closure since suture closure scores are ordinal-level data. Correlation values (*rho*) were computed for sections of sutures, full sutures, and summary scores for the qualitative, categorical scoring systems (Tables 5-7 through 5-11). All *rho* values have positive correlations (i.e., a larger value in age is associated with a higher sutural fusion score), although values for sections of sutures and full sutures are always less than 0.400. The lowest value is for the IN suture in the full suture/binary scoring system (*rho* = 0.052; Table 5-9), and the highest value is for the left medial portion of the IN suture in the 15-section/4-phase scoring system (*rho* = 0.368; Table 5-7). The control sutures have *rho* values lower than most values for individual sutures or sections of sutures in all systems (Table 5-10). Correlation values for the summary suture scores are generally greater than the individual sutural values, with the highest correlation between age and score in the 15-section/4-phase system (Table 5-11). However, this value is not markedly different from that of the full suture/4-phase system, nor does the inclusion of the TP suture within the GPF drastically affect the correlation between age and summary score (e.g., full suture/4-phase *rho* = 0.423 versus full suture/4-phase with GPF *rho* = 0.419; Table 5-11). When comparing the 4-phase scoring system to the collapsed 3-phase scoring system there is no remarkable difference between the two systems in terms of *rho* (Tables 5-7, 5-8, and 5-11). Of the qualitative, categorical scoring systems, the summary score from the 15-section/4-phase system has the strongest relationship between known age and sutural closure (Table 5-11).

Descriptive statistics for fusion ratios in the quantitative system are given in Table 5-12, and the relationship of fusion ratio and age is summarized with scatterplots (Figures 5-17 and 5-18). Only the AMP, PMP, and TP sutures (but not within the GPF) are available for the quantitative system, since the IN suture was largely fused in adults and could not be scored or measured and the TP suture within the GPF was not measured from photographs (see Chapter 4). While the fusion ratios are continuous, their distributions are not normal; all are skewed to the right with the majority of ratios around 0 (Figure 5-19 and Table 5-12). As can be seen in Figures 5-17 and 5-18 the data do not conform well to a linear model (indicated by the black lines), and values tend to cluster close to 0. Arcsine transformation of the fusion ratio summary score, appropriate for values between 0 and 1 and following Herring (1972) and McDonald (2014), was conducted. This transformation produced the same relationship of age and summary score (*rho* = 0.349) and did not greatly reduce residual error as compared to the untransformed fusion score data, but it did produce a better distribution of points around the least squares regression line (Figure 5-20). Because no large-scale improvement was made by arcsine transformation, these values were not used further. Log transformation, commonly used in biological data, is not possible for the fusion ratio summary scores because of multiple instances of non-fusion of AMP, PMP, and TP sutures, resulting in scores of 0.

The Spearman's rank-order correlation values for fusion ratios for the summary score and individual sutures are given in Table 5-13 along with a comparison of *rho* values for the same individual sutures and summary scores scored categorically. As compared to categorical systems, the suture fusion ratio results are similar, although suture ratio *rho* values are lower that full suture/4-phase values for all except the AMP suture. The fusion scores for the full suture/4-phase system were also compared to those of the fusion ratio system for the PMP, TP, and AMP sutures. Spearman's *rho* values indicate moderately high levels of agreement among the two systems (PMP suture *rho* = 0.790, TP suture *rho* = 0.671, AMP suture *rho* = 0.679), though these values indicate the relationship is less than perfect.

Plotting the residuals for all summary score systems indicates that the qualitative, categorical systems fare slightly better in terms of residual errors as compared to the quantitative system. Of the various qualitative systems tested, the summary score of the 15-section/4-phase system has the highest correlation with known age and the most normally distributed error. When treating summary scores as continuous variables and comparing them to age via regression analyses, all have significant relationships with age ($p < 0.001$). However, the R^2 values, which explain the amount of variation in the response variable that is accounted for by variation in the explanatory variable, indicate that the effect of age on fusion, while significant, is not fully explained by variation in age. For the 15-section/4-phase summary score, R^2 = 0.161, indicating that only 16% of the variation in fusion summary score is being accounted for by variation in age. The R^2 value for age and the fusion ratio summary score is 0.076, and the other two categorical systems fall between these two values (full suture/4-section system R^2 = 0.156, full suture/binary system R^2 = 0.111).

Group Affiliation and Sutural Closure

Sex, ancestry, and time period were visually compared to the sutural closure summary score with the highest *rho* (15-section/4-phase system; Tables 5-11 and 5-13) using box-and-whisker plots (Figures 5-21 through 5-23). These plots indicated that there appear to be differences in closure summary score for sex and ancestry, but not for time period. For sex, there are several outliers in the higher summary scores for females (see Figure 5-21). Homogeneity of variance for sex, ancestry, and time period in terms of summary score were checked with Fligner-Killeen tests (Crawley, 2013). Variance is not constant for sex (p < 0.001), is constant but approaches significance for ancestry (p = 0.086), and is constant for time period (p = 0.918). Error distributions are examined by plotting the residuals for each of the three groups. Based on Normal Q-Q plots for all three groups, error approaches a normal distribution. However, due to non-constant variance in two of the groups and several outliers for suture fusion in females, a parametric model that included all three groups and their interactions falsely identified a significant difference in sutural fusion between historic and modern individuals when no such difference exists (see Figure 5-23). Therefore, initial testing was done by group and results from parametric and non-parametric tests were compared prior to performing multiple group comparisons.

Wilcoxon rank-sum tests, the non-parametric equivalent of the Student's t-test (Crawley, 2013), indicate that there is a statistically significant difference in summary fusion score between males and females ($p < 0.001$) but not between historic and modern individuals ($p = 0.876$). A Kruskal-Wallis test of medians, the non-parametric equivalent of ANOVA, indicates that there is a significant difference in summary fusion score among ancestral groups ($p < 0.001$). These tests confirm the visual differences seen in Figures 5-21 through 5-23. Parametric tests had similar results – Student's t-tests for sex and time period produced *p*-values of < 0.001 and 0.844, respectively, and ANOVA for ancestry showed differences among groups that were significant at $p < 0.001$. Based on these results, time period was removed from subsequent group analyses.

Given the similar values in nonparametric and parametric tests and the large sample size, ANOVA was used to further investigate potential interactions between sex and ancestry in terms of suture fusion using the 15-section summary score, which approximates a continuous variable. While both sex and ancestral groups were still significantly different for suture fusion (*p*-values < 0.001), no significant interaction effect was present for sex and ancestry ($p = 0.861$). To test for the effects of sex and ancestry while controlling for age, an ANCOVA was run, and interactions among all terms were explored. These results are displayed in Table 5-14. Notably, sex, ancestry, and age display significant differences in terms of suture closure, and there is an interaction between sex and age. No other interactions are significant at the $p < 0.05$ level, though the interaction of sex, age, and ancestry is just above the *p*-value cutoff.

Biomechanical Variables

Descriptive Statistics

Inventory scores by tooth are presented in Table 5-15 to display the overall picture of the dentition in the study sample. The most frequent scores, regardless of tooth number, are 2 (present and in occlusion) and 4 (absent antemortem). Unobservable teeth (score of 6) are most common for the third molars, while postmortem tooth loss (score of 5) is most common for the incisors. Teeth that are present but not in occlusion (score of 1) along with teeth that are missing with no associated alveolar bone (score of 3) are the least common in the sample.

Descriptive statistics for dental wear scores for the maxillary teeth are presented in Table 5-16. Because of the categorical scale of dental wear scores, the median is presented along with the mean to give a picture of the distribution of wear scores per tooth. For the molars, the distributions are slightly skewed right (mean > median), indicating that higher scores are less common, while for the premolars, canines, and incisors, the distributions approach normal (mean = median). Of all tooth positions, the third molar had the lowest number of observable teeth, which corresponds with the results presented in Table 5-15. Comparison of wear scores by side per tooth number (e.g., first right molar and left first molar) was undertaken by testing if the absolute value of the differences in wear per side by tooth were statistically significantly different from 0. For all teeth, Student's *t* tests indicated that the mean of the absolute values for wear were significantly different than 0 for all teeth ($p<0.001$). When teeth were compared within class (e.g., third molar and second molar) using a Student's *t* test to examine if the difference in wear was significantly different from 0, significant differences in wear by tooth position were noted for all pairs ($p<0.001$).

Because wear differs significantly by side and tooth class, mean wear scores for all maxillary dentition, posterior dentition, and anterior dentition were calculated for each individual; descriptive statistics and wear score distributions are displayed in Table 5-17 and distributions in Figure 5-24. All mean wear scores are skewed to the right, indicating that a low level of wear is more frequent in the sample than a high level of wear. Posterior wear scores have higher means and medians than anterior wear scores, and the overall mean wear falls between wear scores for the posterior and anterior dentition. These results correspond to those displayed in Table 5-16, where the molars display higher mean and median wear scores than the anterior dentition, although the premolars are nearly identical to the canines and incisors in terms of wear.

The frequency of antemortem tooth loss (AMTL) by tooth number and in the total sample, as summarized by the AMTL Index, is presented in Table 5-18 and Figure 5-25. The first and second molars represent the highest percentages of teeth lost antemortem, and the lowest percentage of teeth lost antemortem are the canines and third molars. The mean AMTL Index is 39.55 and the median is 25.00, and its distribution in this sample is bimodal, with the most frequent scores representing individuals with no to very little tooth loss and individuals with near to complete tooth loss. Individuals with moderate tooth loss, at the center of the histogram, are less common. In the total sample, 167 individuals are fully edentulous, compared to 595 individuals with at least one tooth present (21.92% and 78.08% of the sample, respectively).

Frequency distributions for sutural complexity for each of the three measured palatal sutures (PMP, TP, and AMP) are given in Figures 5-26. Mean sutural complexity is greatest in the TP suture (1.53) and less but nearly equal in the PMP and AMP sutures (1.24 and 1.25, respectively). All three histograms show distributions that are skewed to the right. Along with the mean complexity scores, this indicates that very complex sutures in the palate are rare.

Relationship to Sutural Fusion

The relationship of mean dental wear scores and fusion, as summarized by the 15-section and fusion ratio summary scores is given in Figures 5-27 through 5-29. Each figure caption also lists the Spearman's rank-order correlation values for wear and fusion; non-parametric correlation was employed due to non-normal distributions of wear scores. For all mean wear scores, values are positive and similar between qualitative and quantitative systems, indicating that with increased wear, increased fusion is observed. The relationship of mean anterior wear and fusion is the highest of the three. Separate regression analyses were conducted for summary fusion scores and overall wear and then scores and anterior/posterior wear, since combining the wear variables violates the assumption of independence. These analyses indicate that overall mean wear has a significant effect on fusion ($p < 0.001$, $R^2 = 0.026$), while when considered separately, only anterior wear has a significant effect (Table 5-19; $R^2 = 0.104$). Regressing wear on the fusion ratio summary score, overall wear also has a significant effect on fusion ($p < 0.001$, $R^2 = 0.052$), as do both anterior and posterior wear (Table 5-20; $R^2 = 0.104$). These R^2 values indicate that when posterior and mean wear score are considered, around 10% of the variation in fusion summary score is explained by variation in dental wear.

Both summary fusion scores were then compared with the AMTL Index (Figure 5-30). The least squares regression lines and *rho* values indicate that there is a positive correlation between fusion summary score and AMTL, though the relationship for AMTL and fusion ratio summary score is less strong than AMTL and 15-section summary fusion score. Linear regression of summary scores and the AMTL Index indicates that tooth loss is a significant effect on sutural fusion regardless of fusion system ($p < 0.001$, both systems), but the R^2 values indicate that the amount of variation in fusion is being explained by only a small amount of the variation in AMTL Index (15-section summary score $R^2 = 0.136$, fusion ration summary score $R^2 = 0.041$). Comparing fusion summary scores with edentulous status – individuals with at least one tooth present versus those who were fully edentulous – shows that individuals without any dentition have higher fusion summary scores than those with at least one tooth present (Figure 5-31). Wilcoxon rank-sum tests, performed due to the non-normal distributions of both fusion and edentulism in the sample, indicated that the difference in edentulous and non-edentulous individuals in terms of fusion is significant, regardless of summary system used ($p < 0.001$).

Sutural complexity and fusion have a negative relationship for all three measured sutures (Figure 5-32). Spearman's rank-order correlation values indicate that the relationship between complexity and fusion, while negative, is moderate in strength, with PMP suture complexity having the strongest relationship to fusion ratio. Negative *rho* values indicate that with an increase in complexity there is a decrease in fusion. Linear regression of fusion ratio and suture complexity per suture shows that PMP and TP complexity have significant effects on fusion, while AMP suture complexity does not (Table 5-21). The adjusted R^2 value for regression of fusion on sutural complexity is

0.187, indicating that variation in complexity accounts for about 19% of variation in suture fusion.

Fusion of the control sutures was also compared to wear and tooth loss. It was not compared to complexity since this variable was not measured for these sutures. Fusion of the nasofrontal and zygomaticomaxillary sutures has low associations with overall mean dental wear. For the nasofrontal, the relationship is negative (*rho* = -0.040) and for the zygomaticomaxillary, the relationship is positive (left *rho* = 0.048, right *rho* = 0.068). Comparing posterior wear and fusion, *rho* values for the nasofrontal and left zygomaticomaxillary sutures are negative (*rho* = -0.067 and -0.011, respectively), and the right zygomaticomaxillary suture is positive (*rho* = 0.012). For anterior wear, all associations are positive, with a low association for the nasofrontal suture (*rho* = 0.071) and moderate associations for the left and right zygomaticomaxillary sutures (left *rho* = 0.211, right *rho* = 0.232). All associations for AMTL Index and control suture fusion are positive, with moderately strong relationships (nasofrontal *rho* = 0.184, left zygomaticomaxillary *rho* = 0.242, right zygomaticomaxillary *rho* = 0.238).

Relationship to Age

Age and mean dental wear scores display a positive correlation, based on Spearman's rank-order correlations (Figure 5-33). Older individuals show larger mean wear scores, while younger individuals have smaller wear scores. The strongest relationship of wear and age is for the mean anterior wear score. Regression of mean wear on age indicates that age is a significant effect for wear (all mean wear scores, $p < 0.001$). Coefficients of determination for mean wear are as follows: overall mean wear $R^2 = 0.056$, mean posterior wear $R^2 = 0.061$, and mean anterior wear $R^2 = 0.230$.

The regression of age on wear was not performed as this does not reflect biological reality (i.e., wear does not explain variation in age) and because the overall mean wear score includes posterior and anterior dentition.

AMTL Index and age also has a positive correlation, and the *rho* value is moderately strong (Figure 5-34). In this sample, an increase in tooth loss is associated with increased age, and vice versa. Linear regression of the AMTL Index on age showed that the age does have a significant effect on AMTL Index ($p < 0.001$, $R^2 = 0.346$).

Sutural complexity of the PMP, TP, and AMP sutures shows little to no relationship with age (Figure 5-35). The *rho* values, while extremely small, are also negative. Linear regression for complexity by suture and age indicates that age does have a significant effect on PMP and AMP suture complexity at the $p < 0.05$ level (PMP $p = 0.027$, AMP $p = 0.033$), but the R^2 values are quite low (PMP $R^2 = 0.006$, AMP $R^2 = 0.006$). The effect of age on TP suture complexity is not significant ($p = 0.516$, $R^2 = 0.001$).

Relationship to Group Affiliation

Mean wear scores by sex, ancestry, and time period are displayed in Figures 5-36 to 5-38, and descriptive statistics are in Tables 5-22 to 5-24. For all mean wear scores, females have lower wear scores than males, though there are high wear outliers for both sexes across all three scores. Europeans have lower mean wear score than Africans and Asians for overall and posterior wear, but Asians are lower than both Europeans and Africans for anterior wear. As with sex, all groups display outliers for high wear. Comparing modern and historic, historic individuals always have higher mean wear scores than modern individuals, regardless of mean wear score system.

There are a few high wear outliers in the historic group, but far less than for sex or ancestry. Due to non-constant variance, differences in mean wear scores by sex, ancestry, and time period were compared non-parametrically (Table 5-25). Significant differences are present across all groups and mean wear scores except for mean anterior wear and time period.

The AMTL Index across sex, ancestry, and time period was analyzed via ANOVA and summary statistics by group are provided in Table 5-26. While variance does exhibit significant differences for population and era, results from non-parametric tests were almost identical to ANOVA, so the parametric option with *post-hoc* tests was preferred. There are no significant differences in mean AMTL Index by sex ($p = 0.591$), but there are significant differences in mean AMTL Index by ancestry and time period ($p = 0.012$ and $p < 0.001$, respectively). Tukey's HSD *post-hoc* tests indicate that ancestral differences in mean tooth loss are significant between Europeans and Asians ($p = 0.013$) and approach significance between Europeans and Africans ($p = 0.066$), with Europeans having a higher mean AMTL Index than Africans and Asians. Modern individuals have a higher mean AMTL Index than historic individuals.

Suture complexity scores for the PMP, TP, and AMP sutures were also analyzed via ANOVA for each of the three groups. Variance was found to be significantly different prior to running ANOVA, but parametric tests were still run because of the large sample size. Descriptive statistics for suture complexity by group are given in Table 5-27. Sutural complexity displays significantly different mean values by sex and ancestry for all three sutures ($p < 0.001$) and by time period for the AMP suture ($p = 0.033$). Tukey's HSD *post-hoc* tests indicate that significant differences for PMP suture complexity exist between Asian-African ($p < 0.001$) and Asian-European ($p < 0.001$), for TP suture complexity between Asian-African ($p < 0.001$) and African-European ($p < 0.001$), and for AMP suture complexity between Asian-African ($p < 0.001$) and European-Asian ($p = 0.020$), with the African-European comparison approaching significance ($p = 0.078$).

Relationship to Each Other

The relationship of mean tooth wear scores and antemortem loss is depicted in Figure 5-39, which also includes Spearman's rank-order correlation coefficients. There is a positive correlation between AMTL Index and wear, though the relationship for overall mean wear and posterior mean wear is weak. Mean anterior wear score shows a moderate, positive relationship. Regressing AMTL on overall mean wear shows that overall mean wear score has a significant effect on AMTL ($p < 0.001$, $R^2 = 0.020$). Regressing AMTL on posterior and anterior mean wear scores shows that anterior wear has a significant effect on AMTL ($p < 0.001$) while the effect of posterior wear score approaches significance ($p = 0.071$). In this model, adjusted $R^2 = 0.183$.

As with antemortem tooth loss, dental wear was compared to sutural complexity by mean wear score for each of the three measured sutures (Figures 5-40 to 5-42). The scatterplots indicate that the relationship of wear and complexity is weak, with little to no differences in scores by complexity, regardless of the suture. Spearman's rank-order correlation coefficients, given in each figure confirm that the relationships are weak and largely negative (i.e., decreased complexity is associated with increased wear). No *rho* values exceed the absolute value of 0.200 and most are very close to 0. Regressing complexity on wear, mean wear scores have no significant effects on PMP, TP, or AMP complexity (p-values from 0.370 to 0.725).

Sutural complexity and AMTL Index scatterplots are given in Figure 5-43. Complexity and AMTL do not show a strong relationship, regardless of suture or wear score employed. Correlation values are close to 0. Regressing complexity on tooth loss with simple linear regression shows that while AMTL has a significant effect on PMP and AMP complexity (p = 0.001 and p < 0.001, respectively), R^2 values of the amount of variation of PMP and AMP complexity explained by variation in AMTL Index are quite low (R^2 = 0.014 and R^2 = 0.031, respectively). The effect of AMTL on TP complexity was not found to be significant (p = 0.787). The reverse regression – regressing AMTL on complexity – was not performed, as complexity is unlikely to explain tooth loss and the correlation values were so low.

Palatal Variants

Relationship to Sutural Fusion

The relationship of palatal traits and sutural fusion, as measured by the 15-section/4-phase summary score, was examined through Spearman's rank-order correlations (Table 5-28). The majority of traits show little to no relationship with sutural fusion, though there are slight positive correlations between maxillary and palatine bone quality (*rho* = 0.175 and 0.231, respectively). Because a higher bone quality score indicates poorer bone quality, this relationship is indicative of increased fusion being associated with a loss in bone quality. The palatine torus is also positively correlated with fusion (*rho* = 0.105), though the relationship is not strong. All other traits do not have *rho* values greater than 0.100 or less than -0.100 in regards to fusion.

The relationship of sutural shape, scored ordinally, and fusion was also investigated for the TP and zygomaticomaxillary sutures. The correlation values are low for all comparisons. For the TP suture, when compared to the fusion score from the full suture/4-phase system, *rho* = 0.038, and when compared to measured fusion, *rho* = -0.025. For the left and right zygomaticomaxillary sutures and fusion score from the full suture/4-phase systems, values are *rho* = 0.015 and 0.005, respectively.

Relationship to Age

The relationships of palatal traits to age, as measured through Spearman's rank-order correlations, are given in Table 5-29. Most traits exhibit very low values, indicating little to no relationship to age. Traits with absolute *rho* values between 0.200 and 0.300 include: left and right maxillary tori and exostoses and maxillary and palatine bone quality. Tori and exostoses show a negative correlation, indicating that as age increases, frequency and expression of tori and exostoses decreases. For bone quality, a higher score indicates bone that is of poor quality, so the positive correlation found with age indicates that as age increases, poor quality bone is more common.

Relationship to Group Affiliation

Palatal trait frequencies by group are given in Appendix B: sex – Tables B-1 to B-20; ancestry – Tables B-21 to B-40; and time period – Tables B-41 to B-60. To test to see if the palatal traits different significantly in frequency by sex, ancestry, or time period, Pearson's *chi*-square tests were employed (Table 5-30). These values show that significant differences by sex occurred for the lesser palatine foramina, palatine and maxillary tori, maxillary exostoses, palatal porosity, and zygomaticomaxillary suture shape. Males appear to display higher counts of additional lesser palatine foramina than females (Tables B-1 and B-2). Females show a tendency to exhibit more pronounced palatal tori, while for males this is the case for maxillary tori and exostoses (Tables B-9 to B-13). An absence of palatal porosity is more common in females as opposed to males (Table B-16), and for traits that could not be observed due to obliteration, there was always a higher number of males than females that were scored as unobservable (Tables B-18 to B-20). The significant differences in zygomaticomaxillary shape may be due to these higher frequencies of obliteration; however scores of 1 also appear more commonly in males than females (Tables B-19 and B-20).

In terms of ancestry, all traits display significant differences except the lesser palatine foramina. While the frequency tables are harder to interpret for this three-way comparison, they are informative in showing the presence and significance ancestral variation across palatal traits. Notably, palatal shape and TP shape show marked differences in frequencies among groups (Tables B-37 and B-38).

Results for time period are also significant, except for the lesser palatine foramina, palatine and right maxillary tori, and TP and right zygomaticomaxillary suture shapes. Modern individuals tend to have higher numbers of accessory palatine foramina and slightly increased presence of marginal crests as compared to historic individuals (Tables B-41 to B-44). Full bridging of medial and lateral grooves is markedly higher in historic individuals, and a proclivity towards bridging is also higher for historic (Tables B-45 to B-48). Presence of pronounced left maxillary tori is more common in historic individuals, but there is no such difference for the right side (Tables B-50 and B-51). Moderate expressions of maxillary exostoses are observed with higher frequencies in historic individuals, while extreme expression is more common for modern individuals (Tables B-52 and B-53). Moderately poor to poor bone quality is more frequent for historic individuals, while the presence of porosity is slightly higher in modern individuals (Tables B-54 to B-56). Hyperbolic and trapezoidal palate shapes are more common for historic individuals, while parabolic shapes are observed with higher frequency in modern (Table B-57). Finally, zygomaticomaxillary sutures with one angle are more common in modern individuals, although the difference is not statistically significant for the right side (Tables B-59 to B-60).

Relationship to Biomechanical Variables

Spearman's rank-order correlations were calculated for the three mean wear scores and each of the palatal traits (Table 5-31). These results indicate little to no relationship between wear and trait, regardless of mean wear score used or trait. Values are less than 0.100 or greater than -0.100, with the exception of palate and TP suture shapes and palatal porosity for the overall and posterior mean wear scores.

Spearman's rank-order correlation coefficients for AMTL Index and palatal traits are presented in Table 5-32. The AMTL Index shows moderate relationships with left and right maxillary tori and exostoses and maxillary and palatine bone quality. The tori and exostoses have negative *rho* values, indicating that with an increase in AMTL Index there is an associated decrease in expression of maxillary tori and exostoses. For bone quality, a positive correlation indicates that as bone quality declines there is an associated rise in tooth loss, due to the scoring of bone quality in which a higher number indicates poorer bone quality.

Sutural complexity and palatal traits have only a small association with the exception of the palatine torus (Table 5-33). The remainder of the *rho* values are generally near 0.100 or -0.100. The negative correlation between palatine torus and sutural complexity indicates that a larger torus is associated with less complex sutures, regardless of suture measured.

Relationship to Other Variants

In terms of bilateral expression, bilateral traits show no significant differences in frequency of expression and show moderate to high levels of association between left and right sides (Table 5-34). Because the variables show no significant differences in left and right expression, the left side was used for comparisons among variables (Table 5-35). The highest *rho* value is between maxillary bone and palatine bone qualities, followed by the association of maxillary tori and exostoses; both correlations are positive. For tori and exostoses this signifies that large, more pronounced exostoses are associated with large, more pronounced tori. For bone quality, the positive association between maxillae and palatines indicates that similar bone quality is found between these two areas of the hard palate (i.e., poor bone quality in one is associated with poor bone quality in the other). Other associations with *rho* > 0.100 include: lateral bridging with medial bridging, maxillary tori, and maxillary exostoses; medial bridging with maxillary tori and exostoses; and palatine tori with maxillary tori. Associations with *rho* < -0.100 include: marginal crest with palatine bone quality; palatine tori with maxillary bone quality and porosity; maxillary exostoses with maxillary and palatine bone quality; and palatine bone quality with porosity. The lesser palatine foramina show no marked association with other palatal variables.

Putting it All Together

The above results were all considered when looking at the significant factors that contribute to palatal suture fusion and age. In these considerations, summary fusion scores were used, as they provide the most complete picture of the state of palatal fusion per individual and serve to simplify analyses that already include many variables. The control sutures were not included. Dummy variables (DV) were employed for nominal variables found to have a significant effect on or relationship with fusion or age (see Chapter 4). For ancestry, DV0 is European, DV1 is African, and DV2 is Asian. Additionally, geometric means of the AMP, PMP, and TP suture chords were calculated for each individual and included in larger models for fusion and age prediction to aid in determining if size is a significant factor in fusion or age prediction or if it interacted with any significant terms.

Variables determined to have a significant effect on suture fusion include: age, sex, ancestry, mean wear, AMTL Index, edentulism, PMP and TP suture complexities, palatine torus, and maxillary and palatine bone qualities. The highest correlation for wear is between summary score and anterior mean wear, but overall wear was used in these analyses for its ability to summarize all dental wear in one variable. Additionally, because of the asymmetry of wear detected, it is most appropriate to use a summary score that encompasses all teeth present and scorable. The AMTL Index and edentulism were not included in the same equation as these two variables are not independent, and the AMTL Index was preferred as it provides a greater level of detail per individual.

The interactions of variables were also considered based on relationships and significant effects as outlined above. For fusion, variables with potential interactions include: sex and age; wear and sex/ancestry/time period; AMTL Index and ancestry/time period; PMP/TP/AMP suture complexity and sex/ancestry; AMP suture complexity and time period; AMTL Index and wear; AMTL Index and PMP/AMP suture complexity; palatine torus and sex/ancestry; bone quality and ancestry/time period; bone quality and AMTL Index; and palatine torus and complexity. Variables determined to have non-significant effects on fusion include time period and the interaction of mean wear and complexity.

Multiple regression analyses were conducted in a manual stepwise procedure by first running an analysis with all variables determined to have a significant effect on or relationship to fusion as well as potentially significant interaction effects. For the 15-section summary fusion score, this initial model included 14 variables and 34 two-way interactions. Of these, age, sex, PMP and TP suture complexity, palatine torus, and the interactions between sex and suture complexity (all three measured sutures) were significant at the $p < 0.10$ threshold. A higher threshold was used for this initial analysis because of the large number of variables compared and potential compounding effects. The adjusted R^2 for this initial model was 0.559. The same large-scale initial analysis was also conducted for fusion ratio summary score and found these significant effects ($p < 0.10$): age, sex, PMP and TP suture complexity, palatine torus, and interactions of age and sex, sex and PMP and TP suture complexities, and TP suture complexity and palatine torus. The adjusted R^2 value for the fusion ratio summary score was 0.489. The geometric mean of the chords was not found to be significant for either fusion summary score.

Additional models were then run for each of the fusion summary scores, eliminating all non-significant terms during each iteration. At this stage, effects were considered to be significant if the p-value was < 0.05. Final models for fusion are presented in Tables 5-36 and 5-37. The adjusted R^2 values for the 15-section summary score and fusion ratio summary score are 0.506 and 0.470, respectively. Collectively, these results indicate that about 50% of variation in fusion is accounted for by variation in age, sex, sutural complexity, and expression of the palatine torus.

Variables determined to be significantly related to age include: fusion, dental wear, AMTL Index, PMP and AMP suture complexity, maxillary tori and exostoses, and maxillary and palatine bone quality. For fusion, summary scores are employed, and overall mean wear score is used for ease of comparison. Variables with potential interactions include fusion and sex/ancestry; wear and sex/ancestry/time period; AMTL Index and ancestry/time period; PMP, TP, and AMP suture complexity and sex/ancestry; AMP suture complexity and time period; wear and AMTL Index; AMTL Index and PMP and AMP suture complexity; maxillary tori/exostoses and sex/ancestry/time period; bone quality and ancestry/time period; and AMTL Index and maxillary tori and exostoses/bone quality. TP suture complexity does not have a significant relationship with age.

As with fusion, multiple regression analyses were conducted in a manual stepwise procedure. The first model was run using the 15-section summary score and included 17 variables and 57 two-way interactions. Of these, significant terms ($p < 0.010$) include: summary fusion score, left and right maxillary tori, and palatine bone quality, and interactions between fusion score and sex; fusion score and ancestry DV1; wear and ancestry; AMTL Index and ancestry DV 1; AMTL Index and time period; PMP suture complexity and ancestry; left and right maxillary tori and ancestry; palatine bone quality and ancestry; maxillary bone quality and time period; and AMTL Index and right maxillary torus and left maxillary exostoses. The adjusted R^2 value for this model was 0.481. The same large-scale analysis was also run using the fusion ratio summary score. Significant effects included: fusion ratio summary score, left and right maxillary tori, and palatine bone quality, and interactions between fusion ratio summary score and sex; fusion ratio summary score and ancestry DV1; wear and ancestry; wear and time period; AMTL Index and ancestry DV1; AMTL Index and time period; PMP suture complexity and ancestry DV1; AMTL Index and wear; left and right maxillary tori and ancestry; palatine bone quality and ancestry; maxillary bone quality and time period; and AMTL Index and right maxillary torus and left maxillary exostoses. These results are nearly identical to the 15-section fusion summary score, with the exception of the addition of the wear and time period interaction. The adjusted R^2 model for the fusion ratio summary score was 0.456.

Models were re-run, removing non-significant terms ($p < 0.05$) until the simplest model was found. For 15-section summary fusion score, the model remains quite complex with many interactions (Table 5-38). All interaction coefficients are significant, but the main effects of ancestry and left maxillary exostoses on their own are not significant. The adjusted R^2 for the final model is 0.445. Using the fusion ratio summary score, the model remains complex with many interactions (Table 5-39), and the adjusted R^2 value for this model is 0.422. These results indicate that just less than 50% of the variation in age is accounted for by variation in fusion, sex, ancestry, AMTL Index, and expression of maxillary tori and exostoses.

Predicting age using the models in Tables 5-38 and 5-39 is complex due to the number of variables shown to have a significant effect. In order to facilitate prediction, the model was further simplified to include eliminating bilateral traits and interaction terms. At this stage, only the left side was employed since no difference was previously found between sides in bilateral traits. The 15-section summary score was employed instead of the fusion ratio summary score due to its higher individual correlation with age and the ease in scoring the sutures visually rather than metrically. Non-significant results are included in this model as they are known to affect other variables in the model. Results of the simpler, no-interaction model are in Table 5-40; the adjusted R^2 value for this model is 0.412. Comparing the R^2 values for the more complex model with interactions and the simpler model without interactions, it can be seen that they are not drastically different. A point estimate for age can thus be derived by entering information for summary fusion score, sex, ancestry, AMTL Index, and left maxillary torus expression and multiplying by the coefficients given in Table 5-40. The standard error of the estimate is 14.6; doubling this number and adding to/subtracting from the age point estimate gives an approximately 95% prediction interval for age (Nawrocki, 1998).

Because palatal size could be affecting certain palatal variables, such as complexity or fusion, the geometric means of the chords were taken and compared to fusion and age as with the other variables.

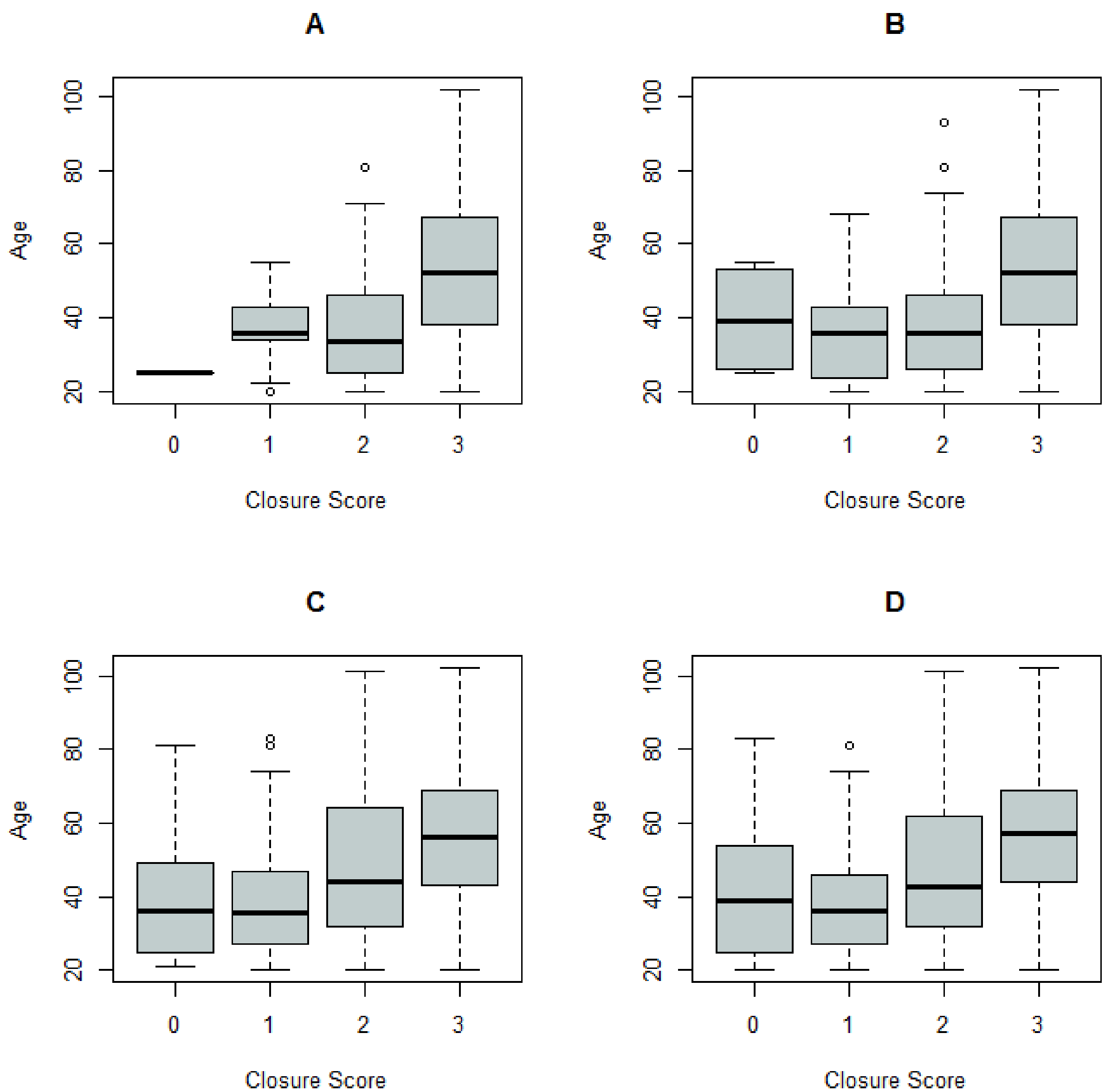


Figure 5-1. Box-and-whisker plots of age per closure score for sections of the IN suture, 15-section/4-phase system. A) Right lateral IN suture, B) left lateral IN suture, C) right medial IN suture, D) left medial IN suture.

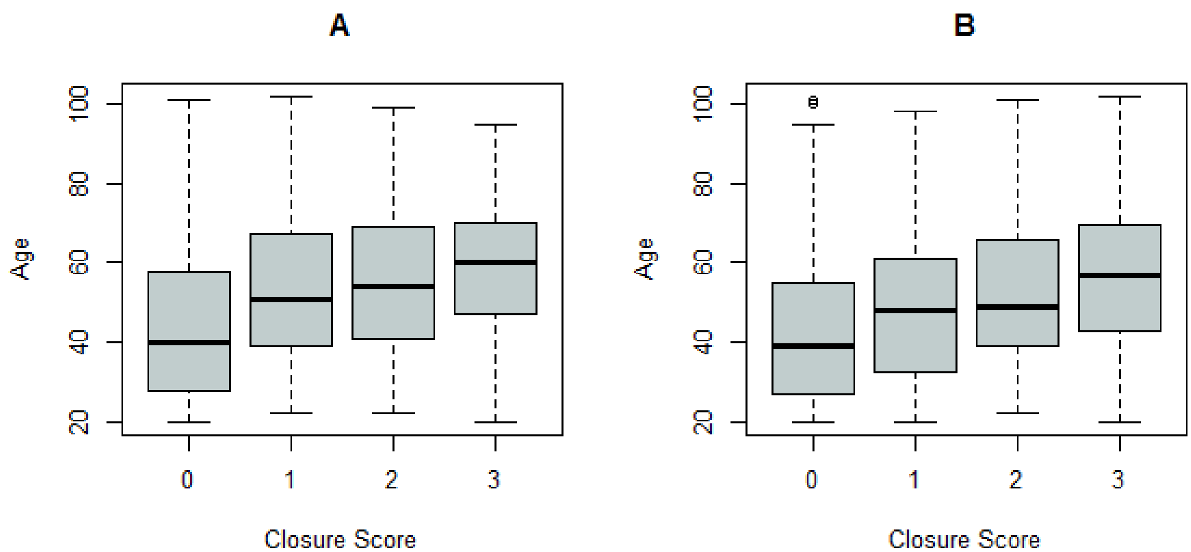


Figure 5-2. Box-and-whisker plots of age per closure score for sections of the PMP suture, 15-section/4-phase system. A) Anterior PMP suture, B) posterior PMP suture.

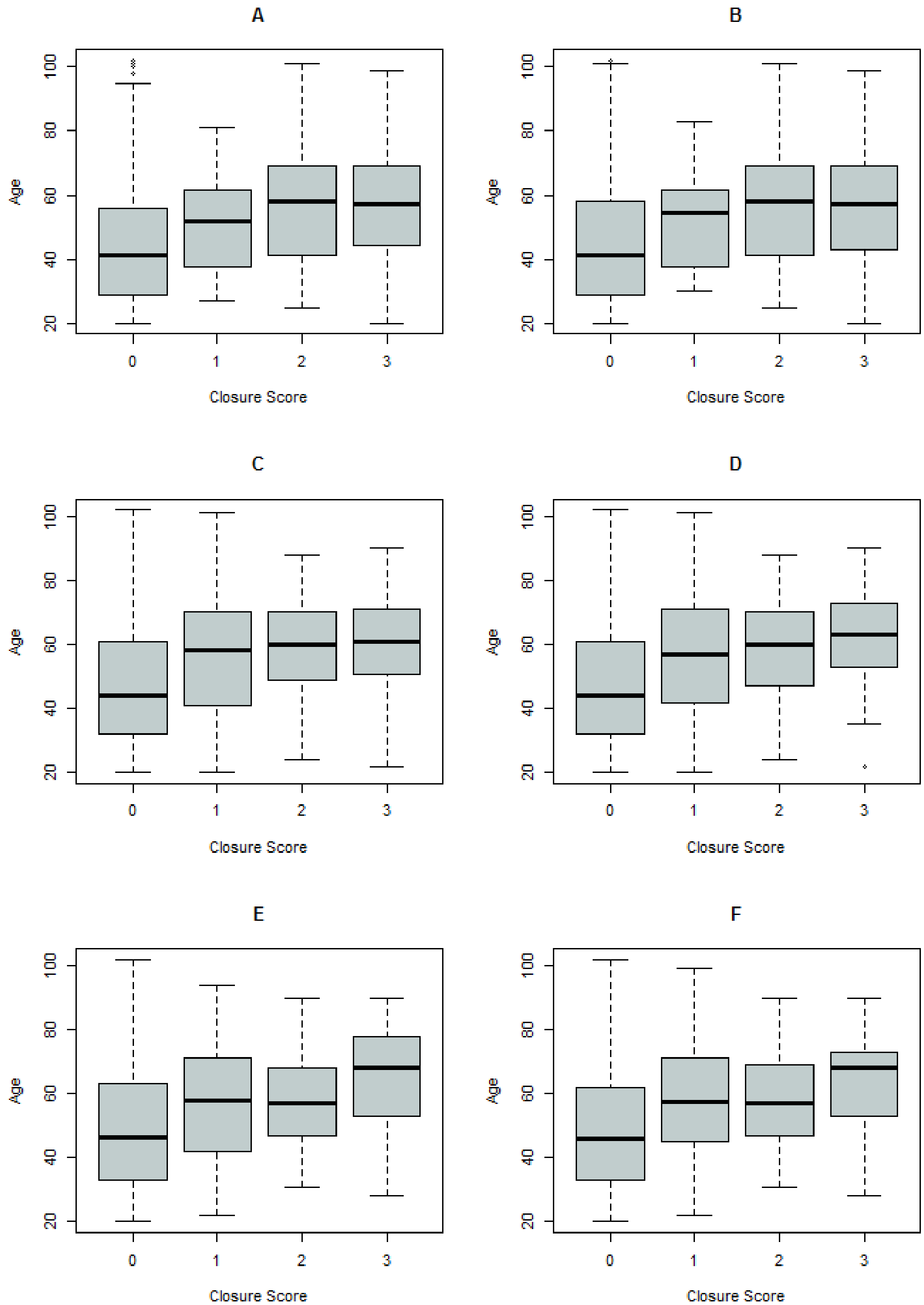


Figure 5-3. Box-and-whisker plots of age per closure score for sections of the TP suture, 15-section/4-phase system. A) Right TP suture in GPF, B) left TP suture in GPF, C) right lateral TP suture, D) left lateral TP suture, E) right medial TP suture, F) left medial TP suture.

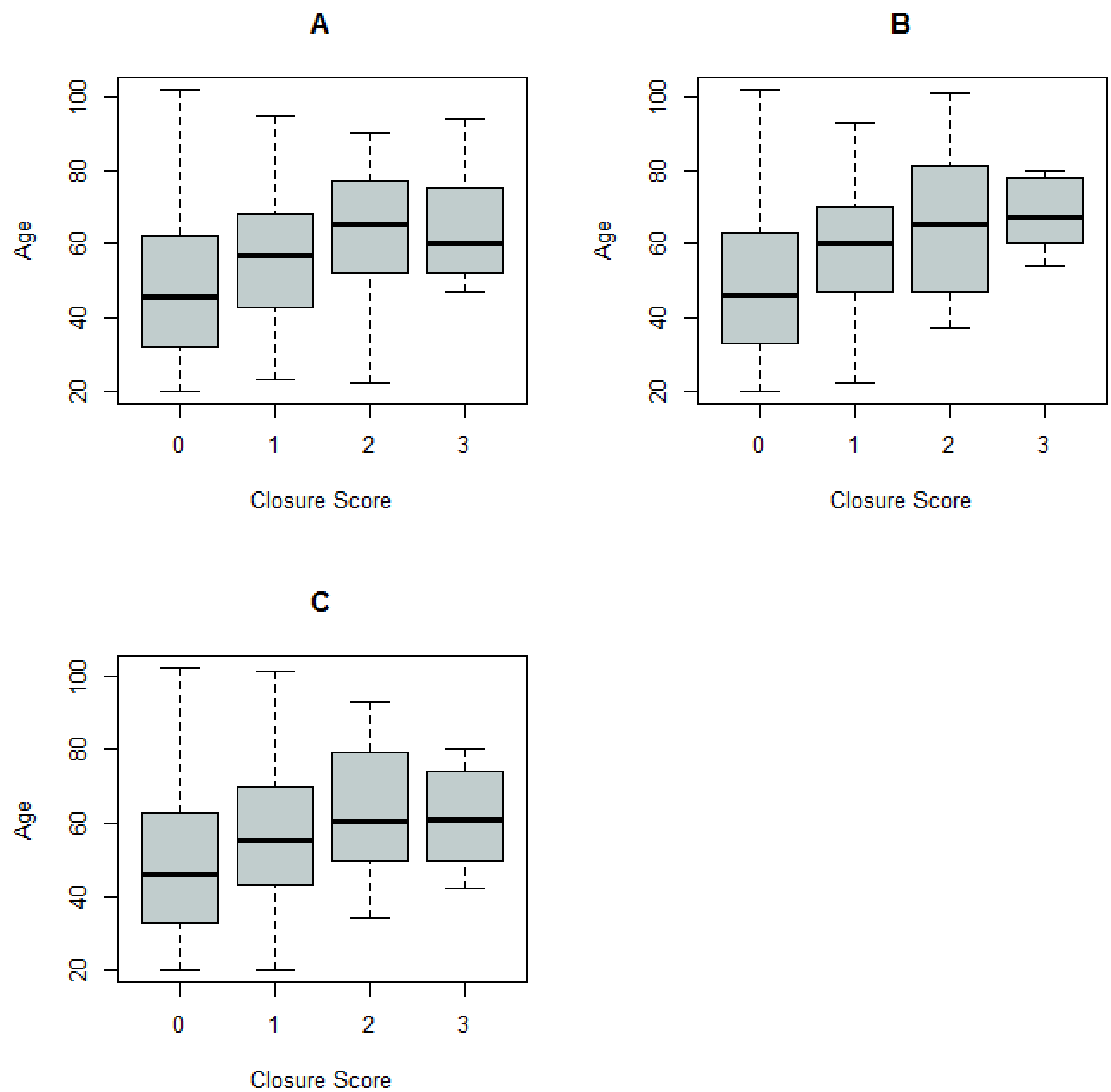


Figure 5-4. Box-and-whisker plots of age per closure score for sections of the AMP suture, 15-section/4-phase system. A) Anterior AMP suture, B) mid-AMP suture, C) posterior AMP suture.

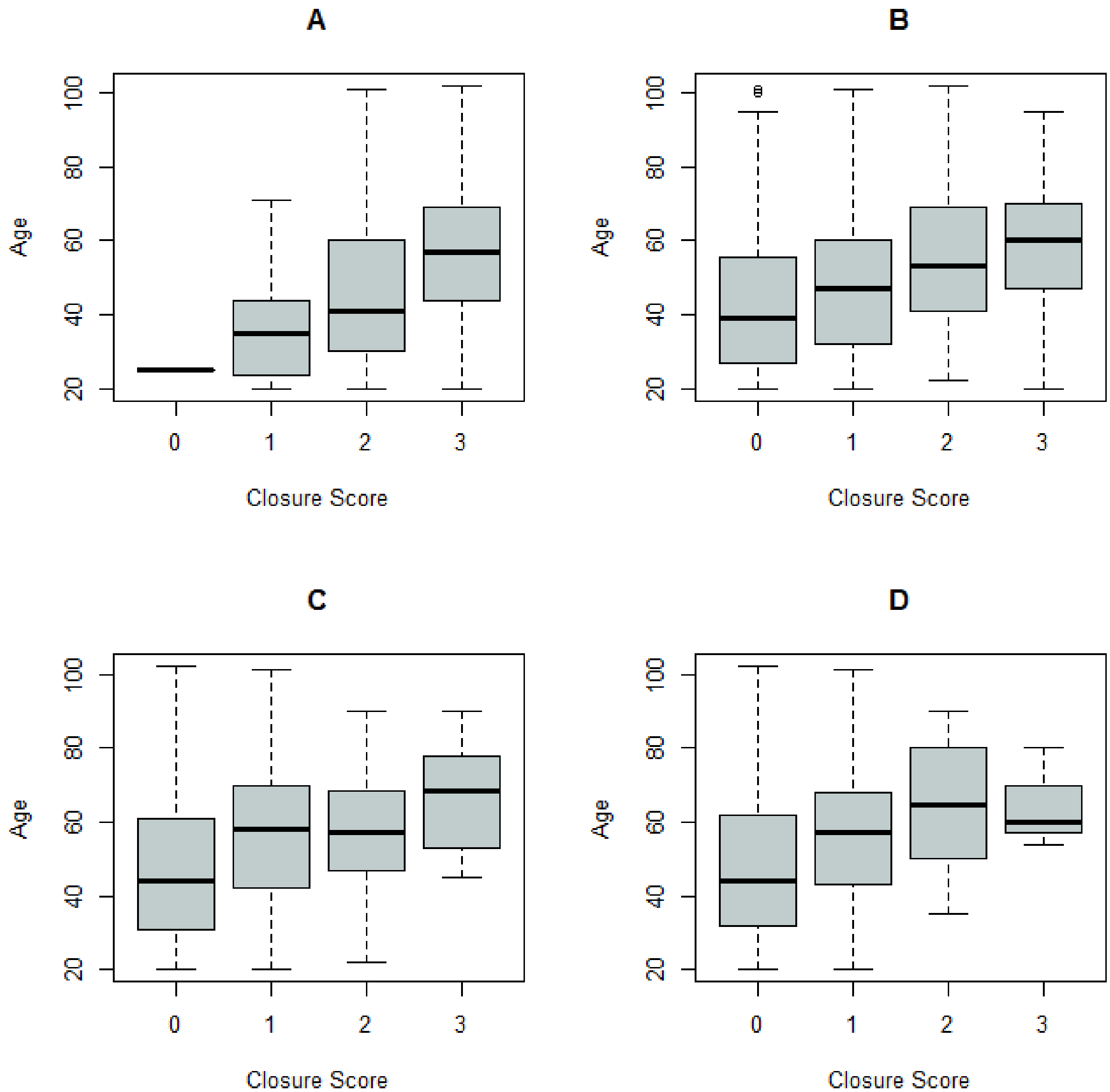


Figure 5-5. Box-and-whisker plots of age per closure score for the full suture/4-phase system. A) IN suture, B) PMP suture, C) TP suture, D) AMP suture.

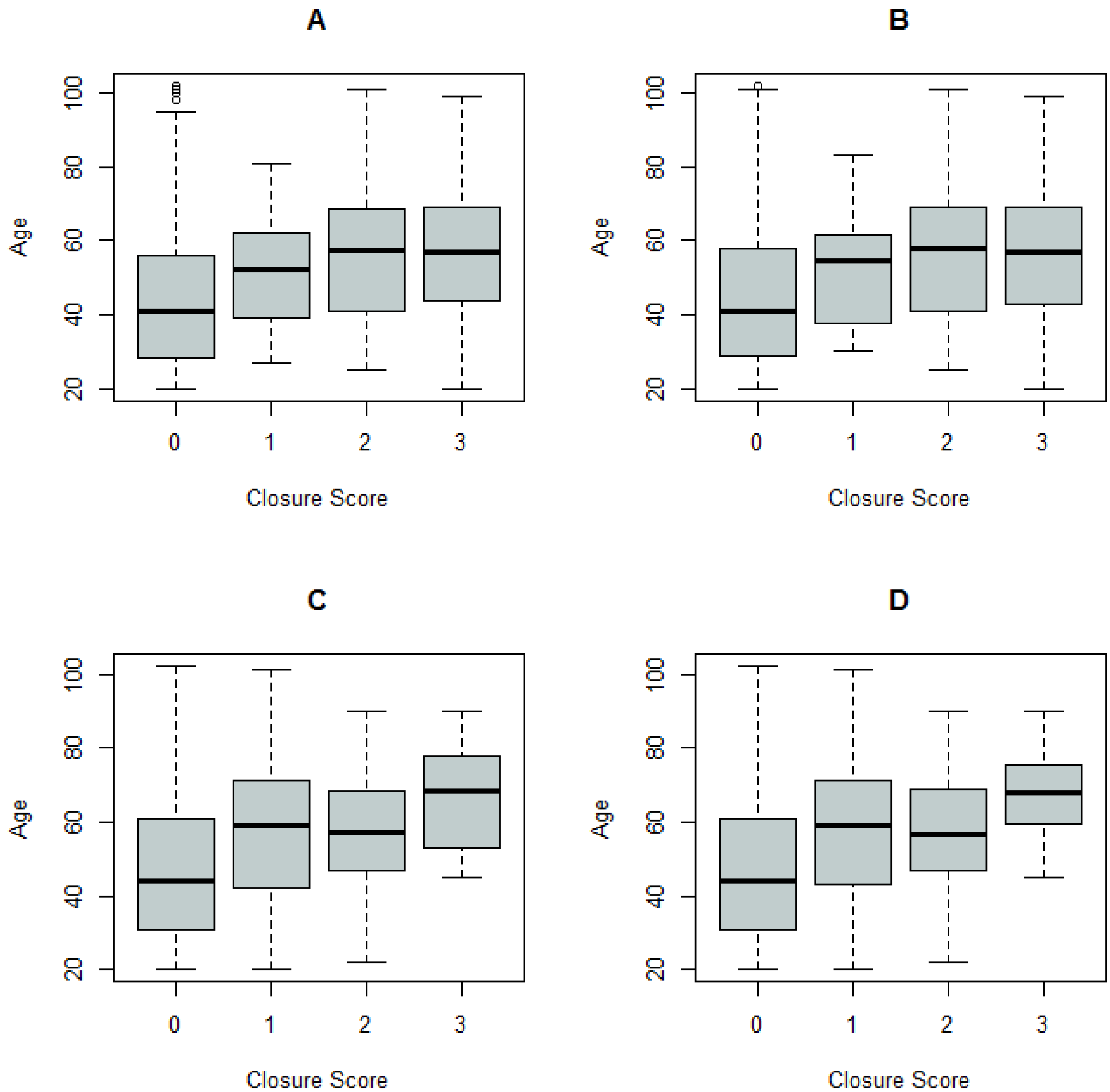


Figure 5-6. Comparison of the box-and-whisker plots of age per closure score for the right and left sides of the TP suture within and outside the GPF, full suture/4-phase system. A) Right TP suture in GPF, B) left TP suture in GPF, C) right TP suture, D) left TP suture.

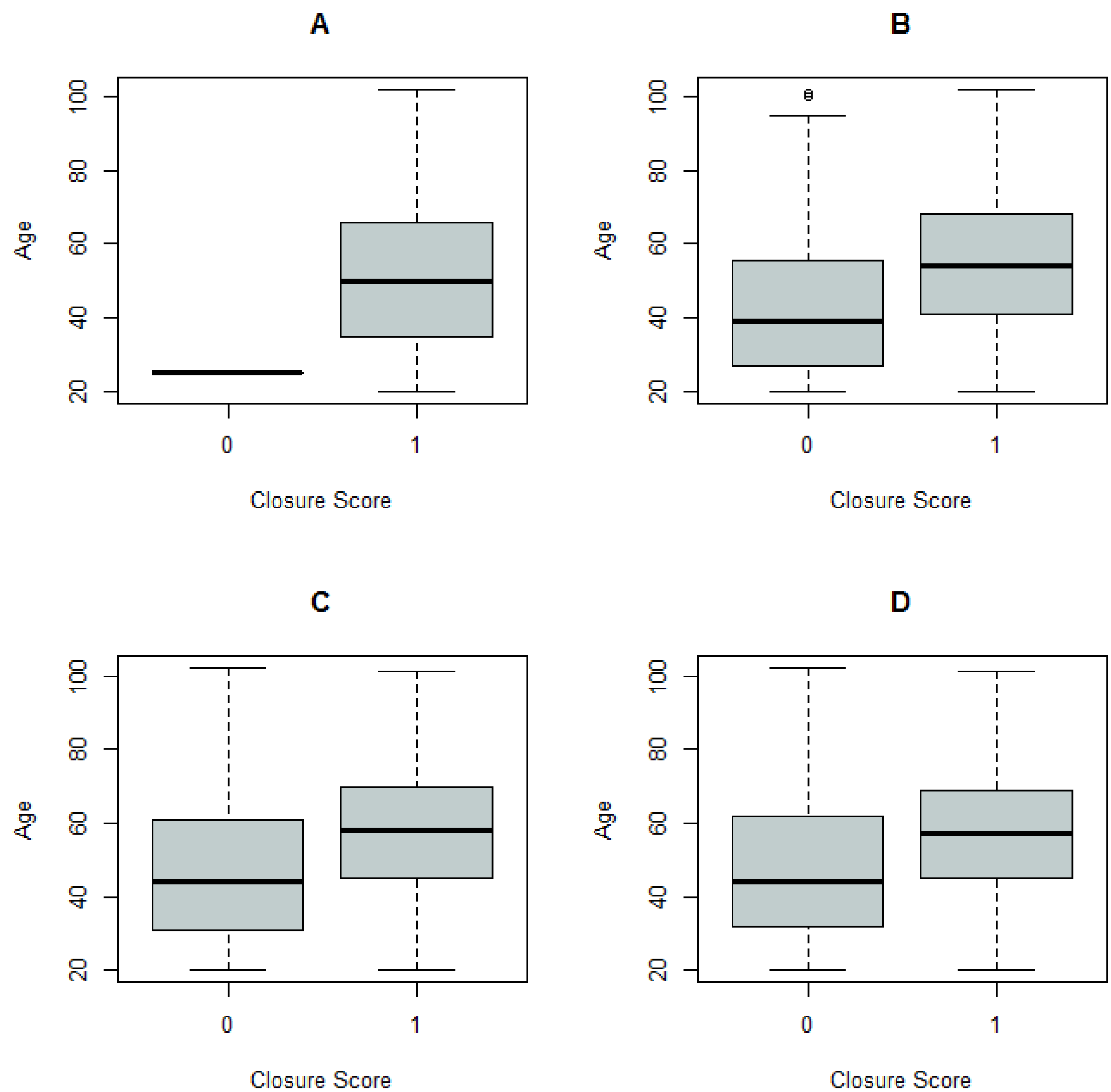


Figure 5-7. Box-and-whisker plots of age per closure score for the full suture/binary system. A) IN suture, B) PMP suture, C) TP suture, D) AMP suture.

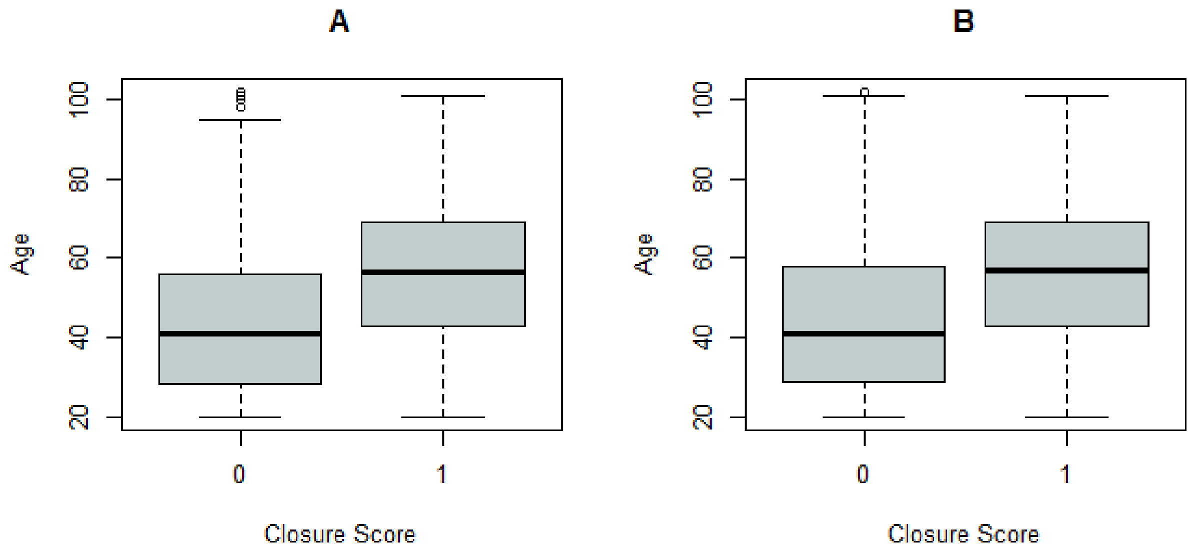


Figure 5-8. Comparison of the box-and-whisker plots of age per closure score for the right and left sides of the TP suture within and outside the GPF, full suture/binary system. A) Right TP suture in GPF, B) left TP suture in GPF, C) right TP suture, D) left TP suture.

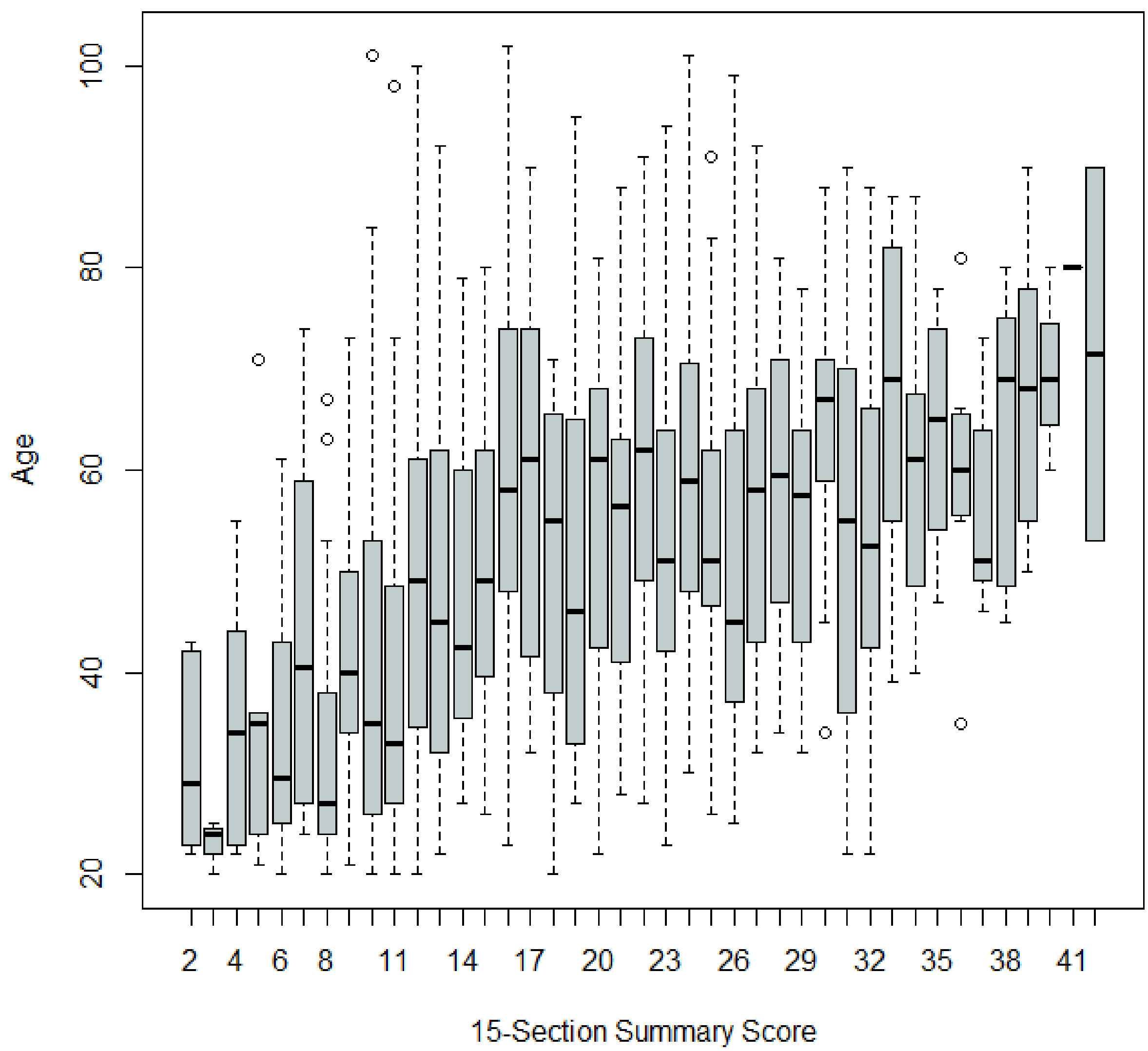


Figure 5-9. Box-and-whisker plot of age per summary score for the 15-section/4-phase system. Compare to Figure 5-16, which displays the same data as a scatterplot.

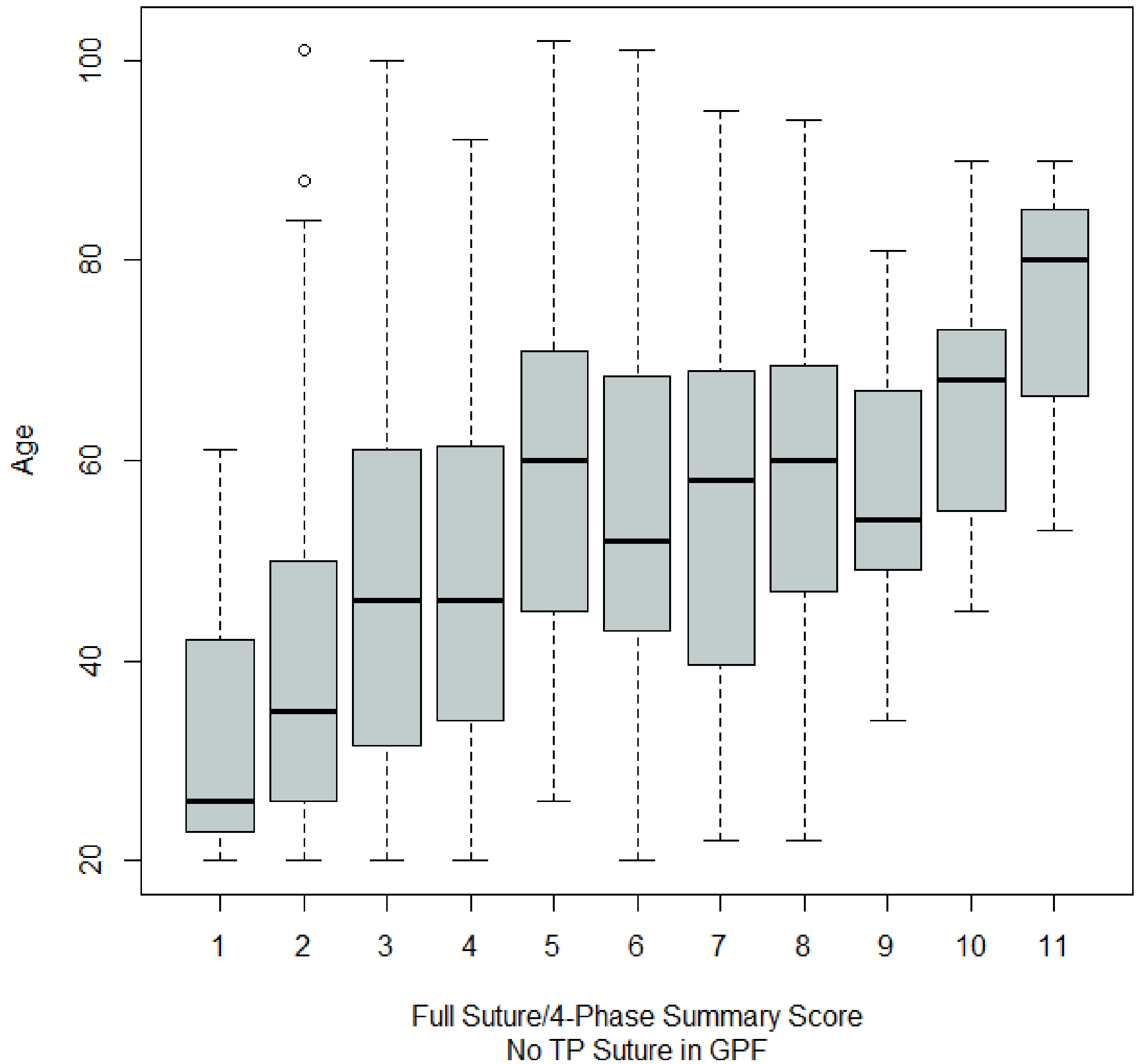


Figure 5-10. Box-and-whisker plot of age per summary score for the full suture/4-phase system not including the TP suture within the GPF.

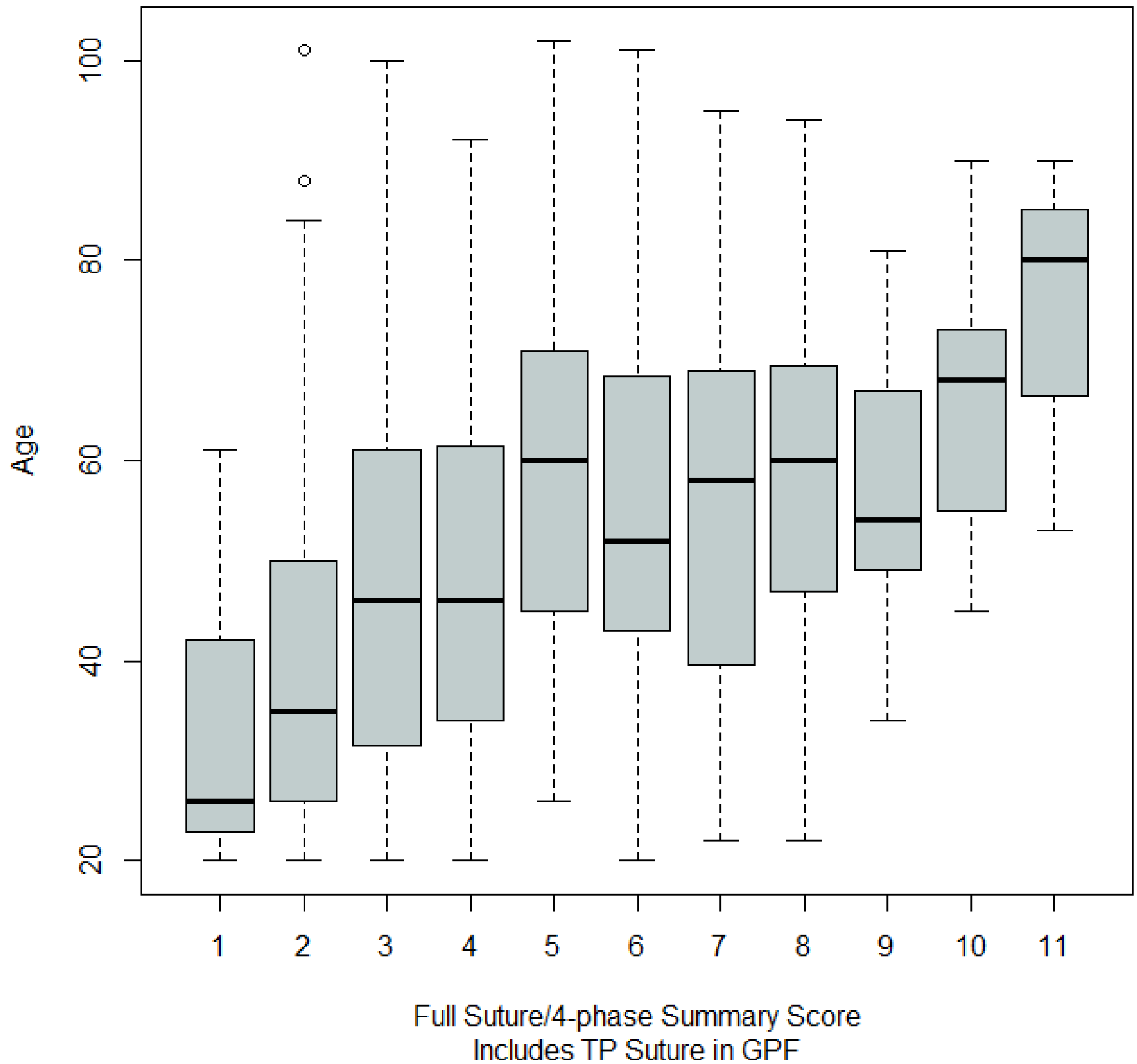


Figure 5-11. Box-and-whisker plot of age per summary score for the full suture/4-phase system including the TP suture within the GPF.

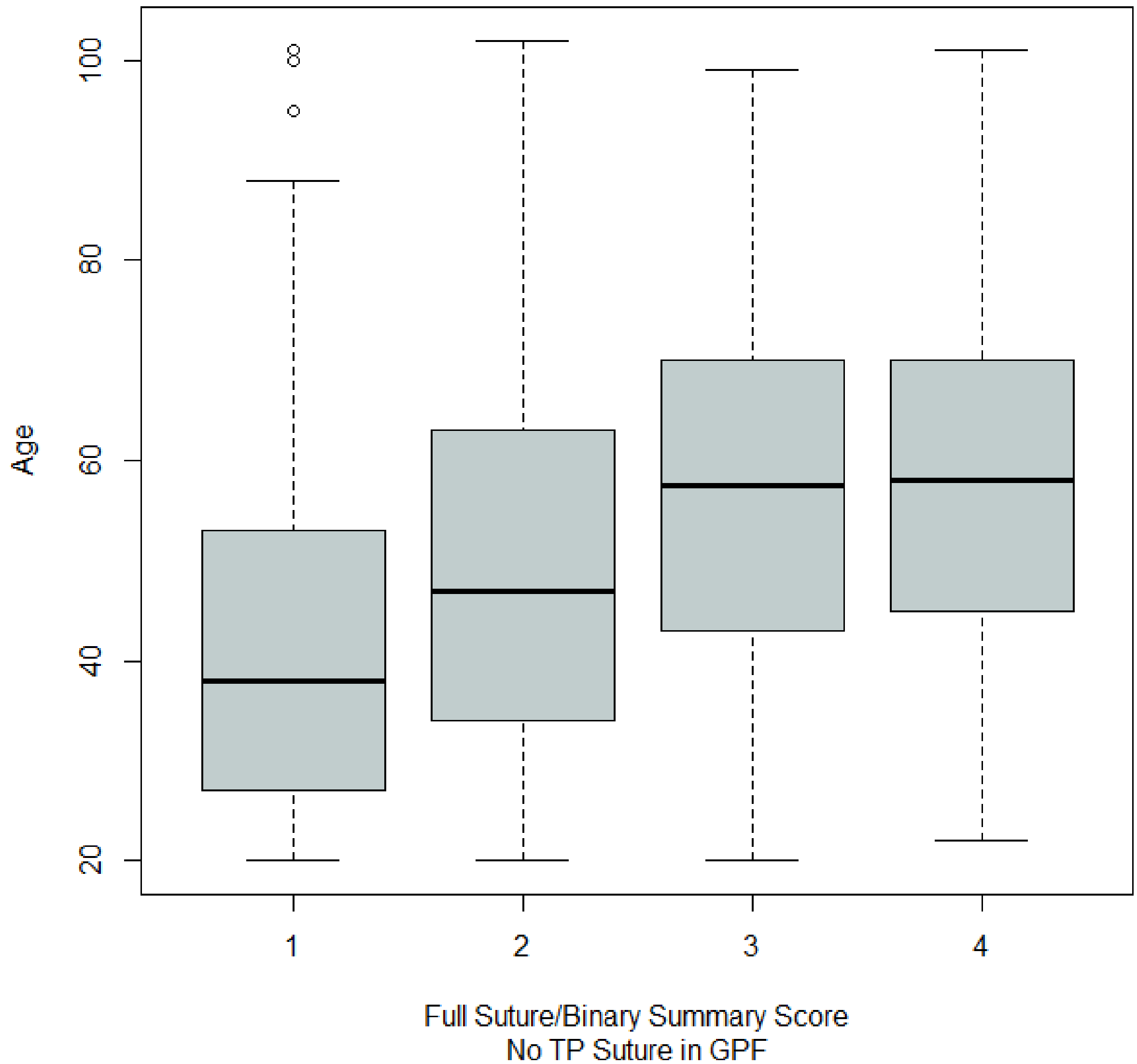


Figure 5-12. Box-and-whisker plot of age per summary score for the full suture/binary system not including the TP suture within the GPF.

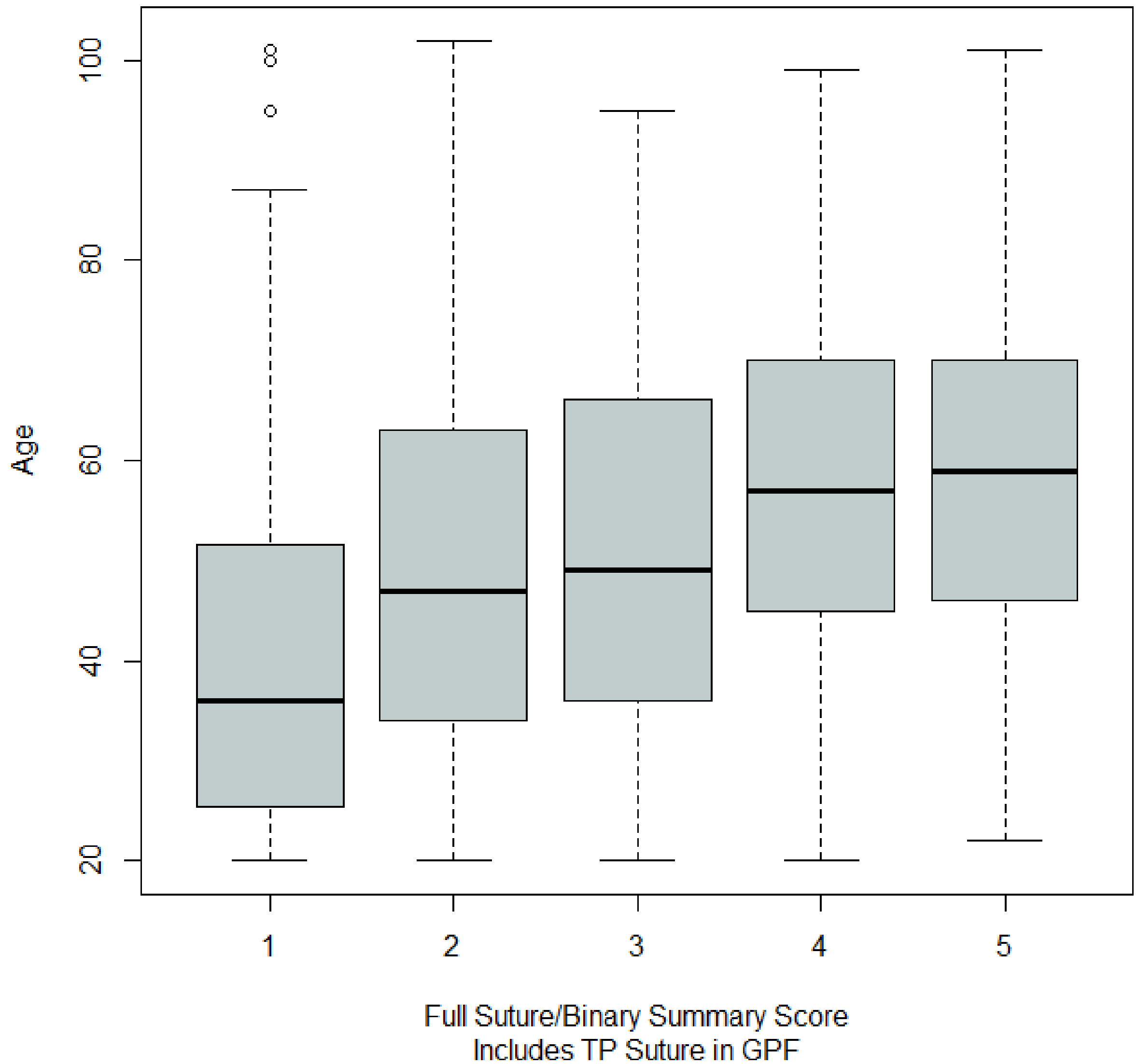


Figure 5-13. Box-and-whisker plot of age per summary score for the full suture/binary system including the TP suture within the GPF.

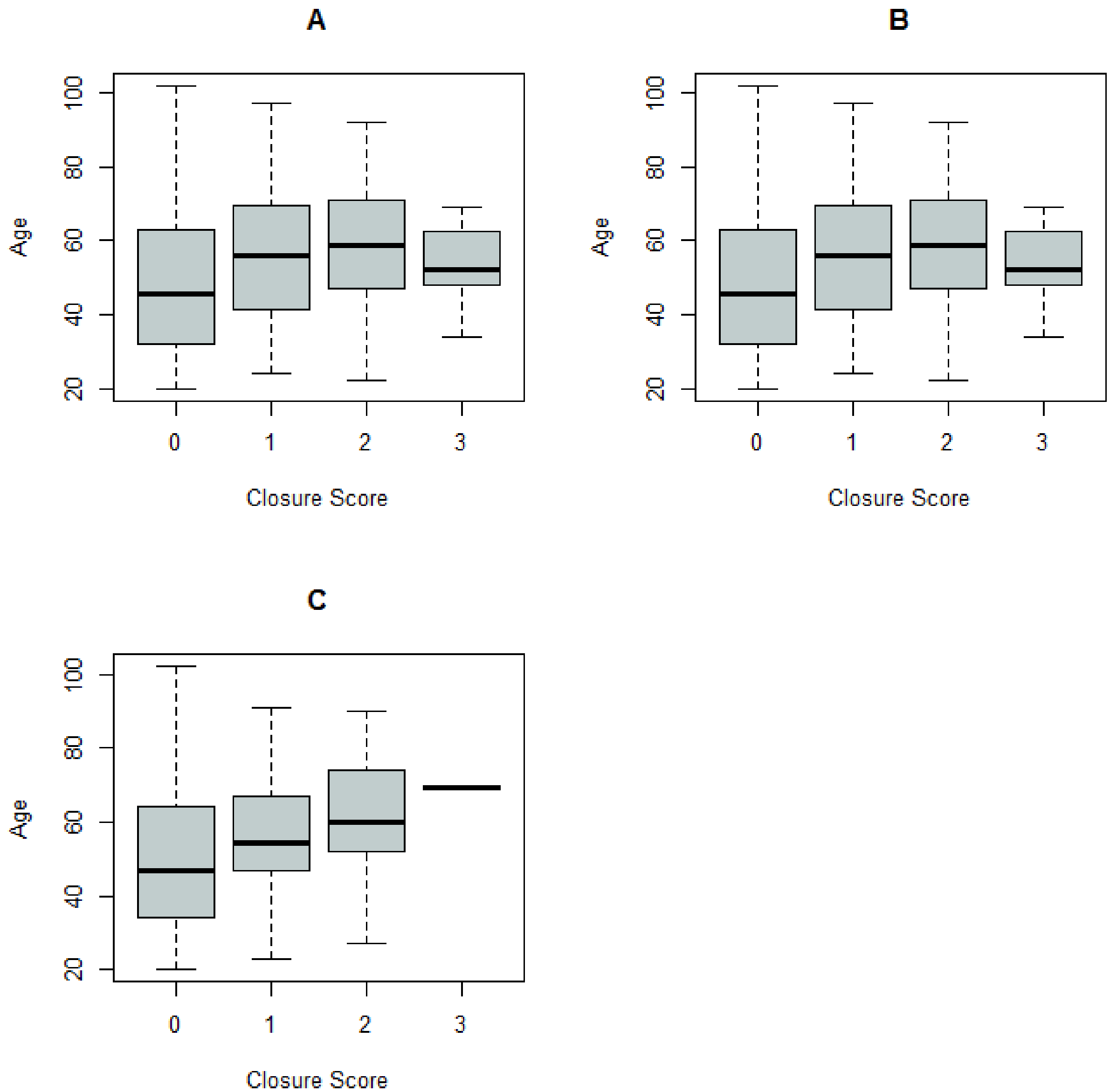


Figure 5-14. Box-and-whisker plots of age per closure score for the control sutures, full suture/4-phase system. A) Right zygomaticomaxillary suture, B) left zygomaticomaxillary suture, C) nasofrontal suture.

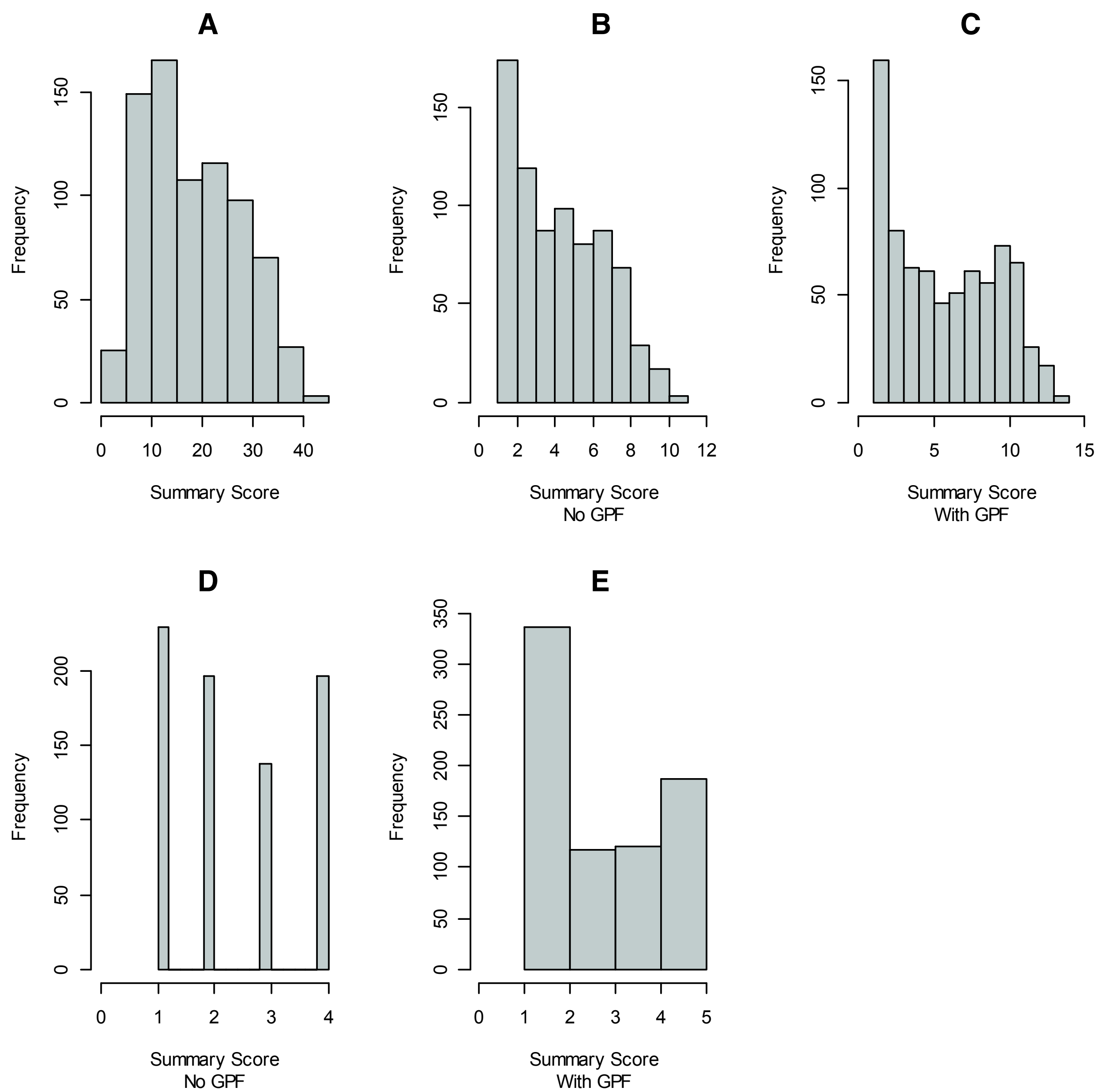


Figure 5-15. Distributions of summary scores, all categorical systems. A) 15-section/4-phase system, B) full suture/4-phase system, no TP suture in GPF, C) full suture/4-phase system, including TP suture in GPF, D) binary/4-phase system, no TP suture in GPF, E) binary/4-phase system, including TP suture in GPF.

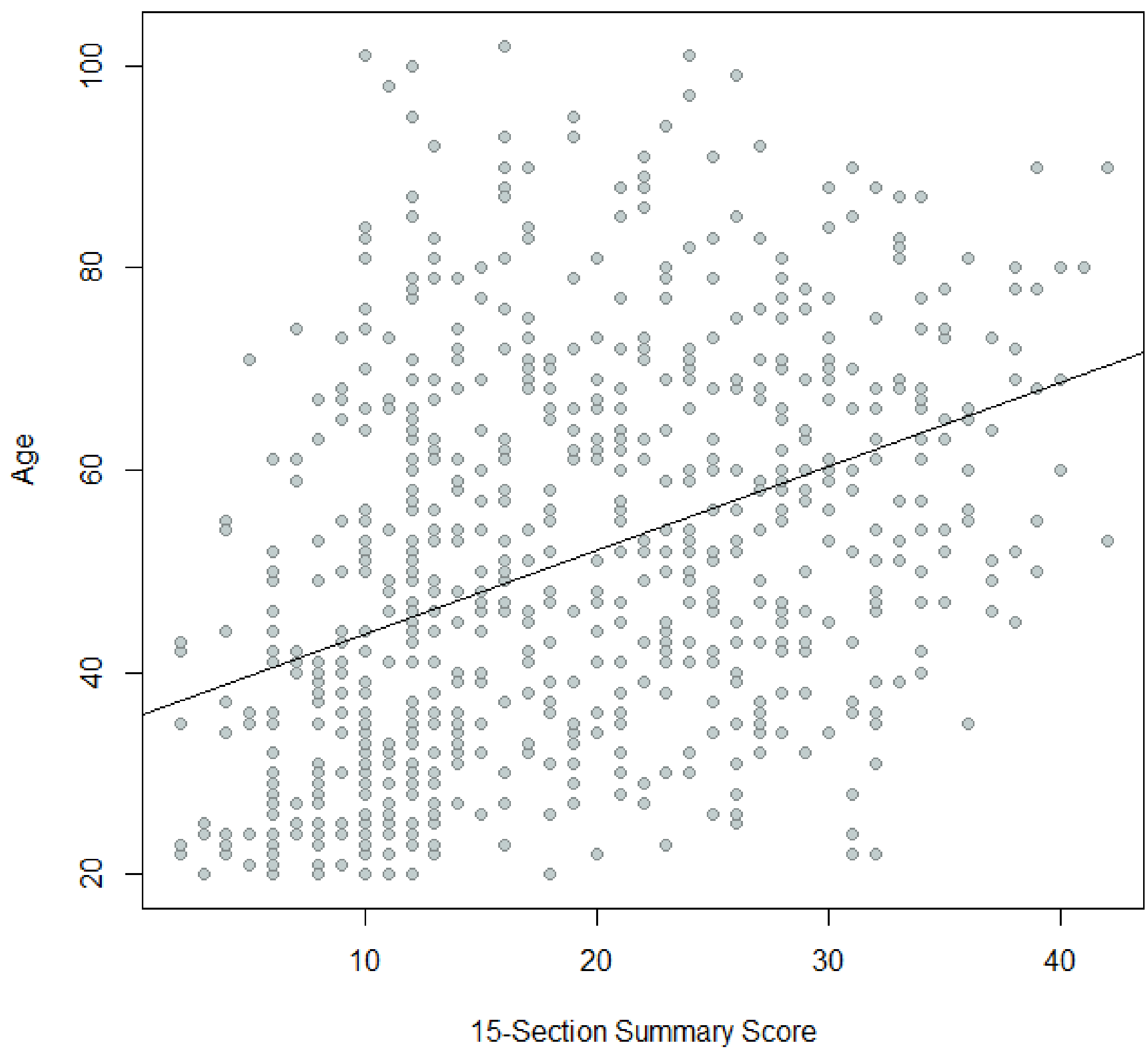


Figure 5-16. Scatterplot for age and summary score in the 15-section/4-phase system. The black line indicates the least squares regression line.

Table 5-1. Results from ANOVA for suture section scores and age in the15-section/4-phase system.

Variable	Df	Sum of Squares	Mean Square	F value	Probability
IN.lat.R.1	3	21451	7150	24.085	<0.001[a]
IN.lat.L.1	3	1433	478	1.609	0.186
IN.med.R.1	3	15499	5166	17.403	<0.001[a]
IN.med.L.1	3	2981	994	3.347	0.019[a]
PMP.ant.1	3	11385	3795	12.783	<0.001[a]
PMP.post.1	3	1048	349	1.177	0.318
TP.GPF.R.1	3	1825	608	2.049	0.106
TP.GPF.L.1	3	465	155	0.522	0.667
TP.lat.R.1	3	1292	431	1.450	0.227
TP.lat.L.1	3	291	97	0.326	0.806
TP.med.R.1	3	1062	354	1.192	0.312
TP.med.L.1	3	368	123	0.413	0.743
AMP.ant.1	3	2564	855	2.879	0.035[a]
AMP.mid.1	3	1148	383	1.289	0.277
AMP.post.1	3	253	84	0.284	0.837
Residuals	719	212561	297		

[a]Difference is significant at the $p < 0.05$ level.

Table 5-2. Results from ANOVA for full suture scores and age in the full suture/4-phase system.

Variable	Df	Sum of Squares	Mean Square	F value	Probability
IN.C	3	34768	11589	38.607	<0.001[a]
PMP.C	3	13402	4467	14.881	0.001[a]
TP.GPF.R.C	3	1686	562	1.872	0.133
TP.GPF.L.C	3	636	212	0.706	0.548
TP.R.C	3	1221	407	1.356	0.255
TP.L.C	3	234	78	0.260	0.854
TP.C	3	322	161	0.537	0.585
AMP.C	3	1817	606	2.018	0.110
Residuals	738	221538	300		

[a]Difference is significant at the $p < 0.05$ level.

Table 5-3. Results from ANOVA for full suture scores and age in the full suture/binary system.

Variable	Df	Sum of Squares	Mean Square	F value	Probability
IN.B	1	674	674	2.106	0.147
PMP.B	1	23216	23216	72.578	<0.001[a]
TP.GPF.R.B	1	6890	6890	21.539	<0.001[a]
TP.GPF.L.B	1	38	38	0.119	0.731
TP.R.B	1	2563	2563	8.012	0.005[a]
TP.L.B	1	258	258	0.807	0.369
TP.B	1	281	281	0.877	0.349
AMP.B	1	840	840	2.626	0.105
Residuals	753	240865	320		

[a]Difference is significant at the $p < 0.05$ level.

Table 5-4. Differences in mean age by closure score for the 15-section/4-phase system.

			Comparison					
Suture	Section	Side	0-1	0-2	0-3	1-2	1-3	2-3
IN	Lateral	Right	0.916	0.902	0.421	0.999	0.000[a]	0.000[a]
IN	Lateral	Left	0.989	1.000	0.463	0.934	0.000[a]	0.000[a]
IN	Medial	Right	1.000	0.030[a]	0.000[a]	0.001[a]	0.000[a]	0.000[a]
IN	Medial	Left	0.688	0.305	0.000[a]	0.000[a]	0.000[a]	0.000[a]
PMP	Anterior	Midline	0.000[a]	0.000[a]	0.000[a]	0.480	0.035[a]	0.447
PMP	Posterior	Midline	0.102	0.000[a]	0.000[a]	0.687	0.002[a]	0.031[a]
TP	GPF	Right	0.349	0.000[a]	0.000[a]	0.713	0.482	0.981
TP	GPF	Left	0.096	0.001[a]	0.000[a]	0.914	0.905	0.999
TP	Lateral	Right	0.000[a]	0.000[a]	0.000[a]	0.698	0.686	0.983
TP	Lateral	Left	0.000[a]	0.000[a]	0.000[a]	0.901	0.505	0.792
TP	Medial	Right	0.001[a]	0.001[a]	0.016[a]	0.917	0.459	0.699
TP	Medial	Left	0.000[a]	0.001[a]	0.025[a]	0.999	0.686	0.746
AMP	Anterior	Midline	0.000[a]	0.000[a]	0.007[a]	0.111	0.336	0.970
AMP	Mid	Midline	0.000[a]	0.000[a]	0.062	0.204	0.627	0.995
AMP	Posterior	Midline	0.000[a]	0.000[a]	0.218	0.240	0.935	0.993

[a]Difference is significant at the $p < 0.05$ level.

Table 5-5. Differences in mean age by closure score for the full suture/4-phase system.

	Comparison					
Suture	0-1	0-2	0-3	1-2	1-3	2-3
IN	0.931	0.661	0.286	0.003[a]	0.000[a]	0.000[a]
PMP	0.081	0.000[a]	0.000[a]	0.001[a]	0.000[a]	0.185
TP in GPF, right	0.222	0.000[a]	0.000[a]	0.828	0.585	0.968
TP in GPF, left	0.098	0.001[a]	0.000[a]	0.915	0.909	0.999
TP, right	0.000[a]	0.000[a]	0.003[a]	1.000	0.353	0.391
TP, left	0.000[a]	0.000[a]	0.001[a]	1.000	0.306	0.358
TP	0.000[a]	0.000[a]	0.003[a]	0.990	0.301	0.399
AMP	0.000[a]	0.000[a]	0.375	0.040[a]	0.845	1.000

[a]Difference is significant at the $p < 0.05$ level.

Table 5-6. Differences in mean age by closure score for the full suture/binary system.

	Comparison
Suture	0-1
IN	0.173
PMP	0.000[a]
TP in GPF, right	0.000[a]
TP in GPF, left	0.000[a]
TP, right	0.000[a]
TP, left	0.000[a]
TP	0.000[a]
AMP	0.000[a]

[a]Difference is significant at the $p < 0.05$ level.

Table 5-7. Spearman's rank-order correlations for age and individual sutural closure in the 15-section/4-phase and 3-phase scoring systems.

Suture	Section	Side	*rho* (4-phase)	*rho* (3-phase)
IN	Lateral	Right	0.285	0.286
IN	Lateral	Left	0.272	0.271
IN	Medial	Right	0.358	0.344
IN	Medial	Left	0.368	0.345
PMP	Anterior	Midline	0.335	0.332
PMP	Posterior	Midline	0.340	0.337
TP	GPF	Right	0.318	0.317
TP	GPF	Left	0.292	0.293
TP	Lateral	Right	0.294	0.290
TP	Lateral	Left	0.296	0.294
TP	Medial	Right	0.220	0.218
TP	Medial	Left	0.228	0.228
AMP	Anterior	Midline	0.260	0.252
AMP	Mid-section	Midline	0.249	0.246
AMP	Posterior	Midline	0.244	0.239

Table 5-8. Spearman's rank-order correlations for age and individual sutural closure in the full suture/4-phase and 3-phase scoring systems.

Suture	*rho* (4-phase)	*rho* (3-phase)
IN	0.362	0.345
PMP	0.352	0.325
TP in GPF, right	0.316	0.316
TP in GPF, left	0.291	0.291
TP, right	0.292	0.295
TP, left	0.295	0.298
TP	0.290	0.298
AMP	0.269	0.259

Table 5-9. Spearman's rank-order correlations for age and individual sutural closure in the full suture/binary scoring system.

Suture	*rho*
IN	0.052
PMP	0.302
TP in GPF, right	0.321
TP in GPF, left	0.303
TP, right	0.291
TP, left	0.294
TP	0.287
AMP	0.259

Table 5-10. Spearman's rank-order correlations for age and individual sutural closure in the control sutures.

Suture	*rho*
Nasofrontal	0.141
Zygomaticomaxillary, right	0.227
Zygomaticomaxillary, left	0.225

Table 5-11. Spearman's rank-order correlations for age and summary score in all qualitative, categorical systems.

System	*rho*
15-section/4-phase	0.438
15-section/3-phase	0.436
Full suture/4-phase	0.423
Full suture/3-phase	0.404
Full suture/4-phase with GPF	0.419
Full suture/3-phase with GPF	0.412
Full suture/binary	0.352
Full suture/binary with GPF	0.369

Table 5-12. Descriptive statistics for fusion ratios of the measured palatal sutures.

Suture	Mean	St Dev	Median	Minimum	Maximum
PMP	0.296	0.304	0.173	0.000	1.132[a]
TP	0.067	0.124	0.000	0.00	0.799
AMP	0.070	0.129	0.000	0.000	0.771
Summary	0.105	0.127	0.053	0.00	0.700

[a]This maximum represents slight error introduced from estimating *staurion* due to obliteration.

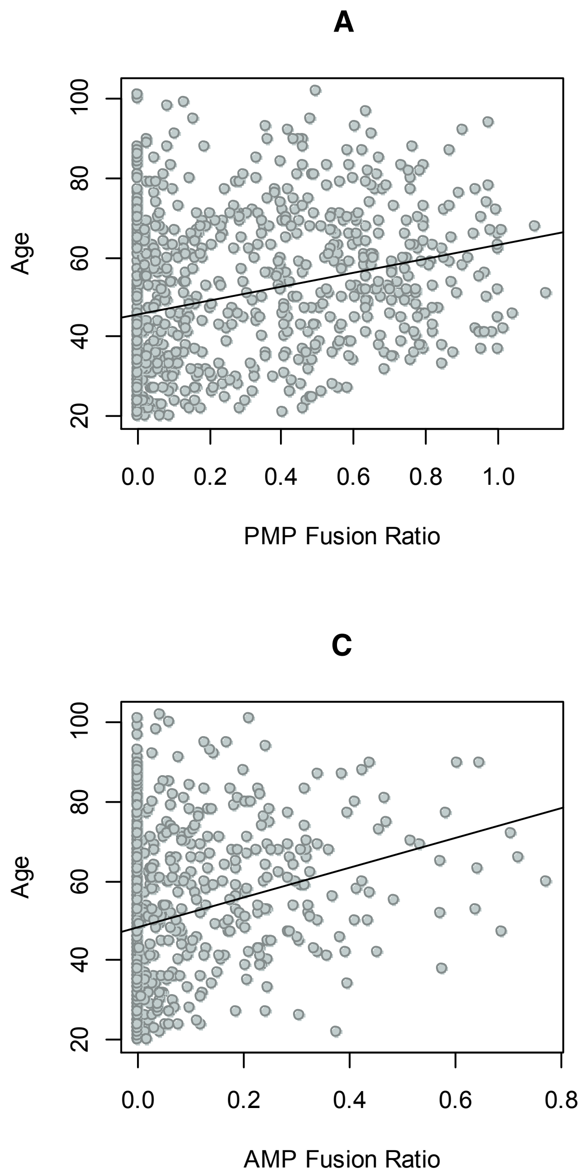


Figure 5-17. Scatterplots of age and fusion ratio for each of the measured palatal sutures (PMP, TP, and AMP). The black line in each plot indicates the least squares regression line. A) PMP suture, B) TP suture, C) AMP suture.

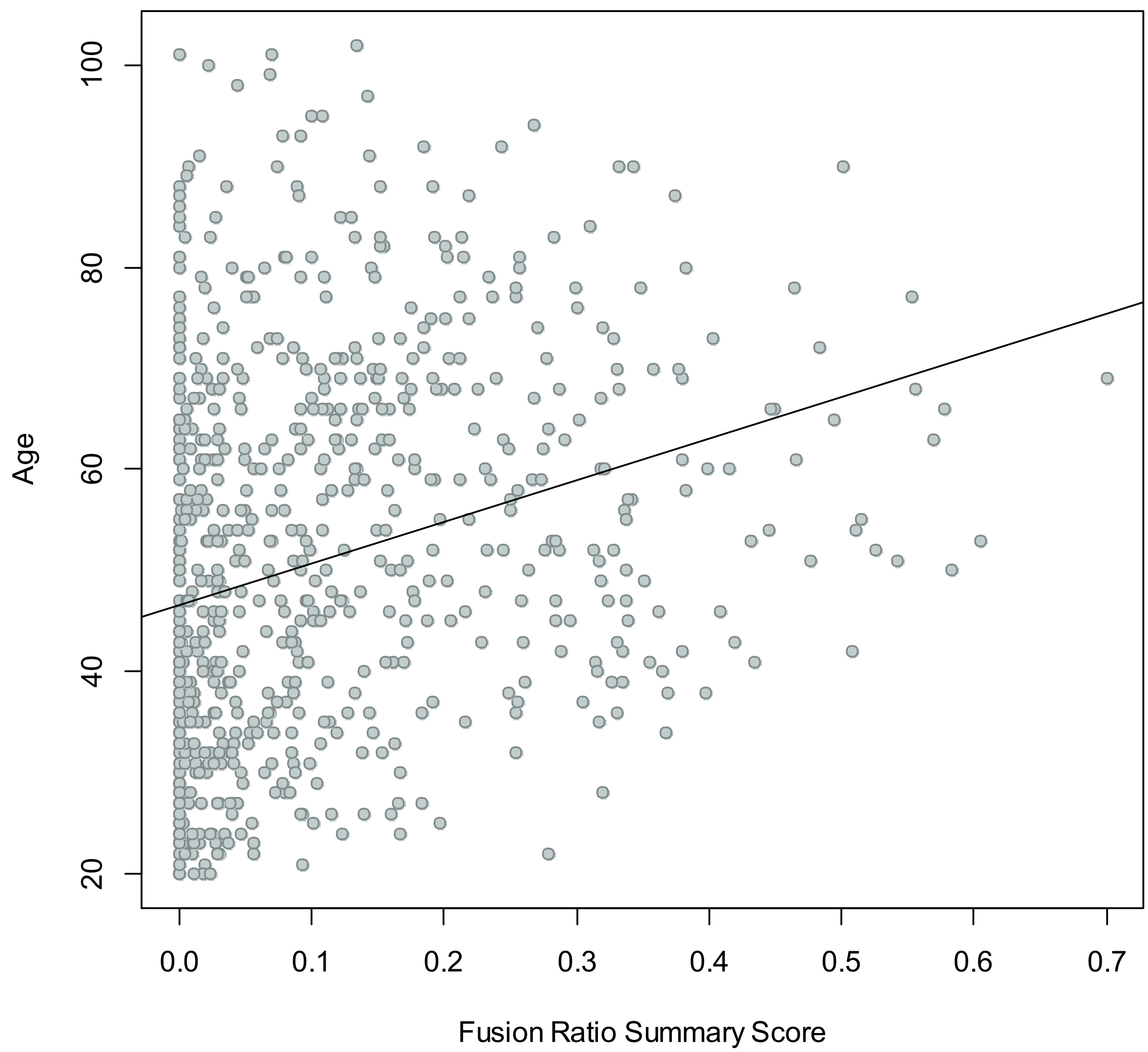


Figure 5-18. Scatterplot of age and fusion ratio summary score (AMP + PMP + TP). The black line indicates the least squares regression line.

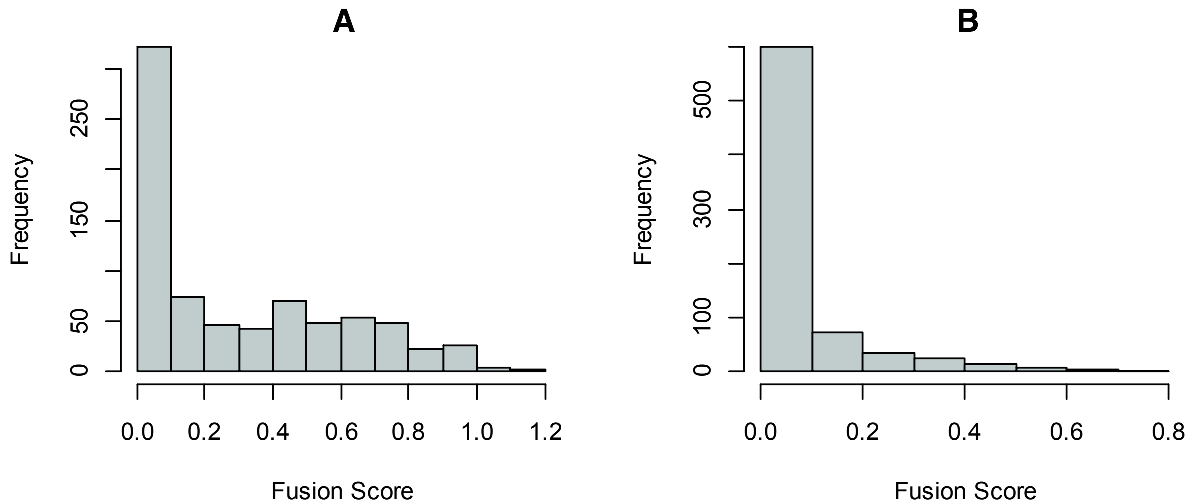


Figure 5-19. Distributions of fusion ratio scores. A) PMP suture fusion, B) TP suture fusion, C) AMP suture fusion, D) fusion ratio summary score.

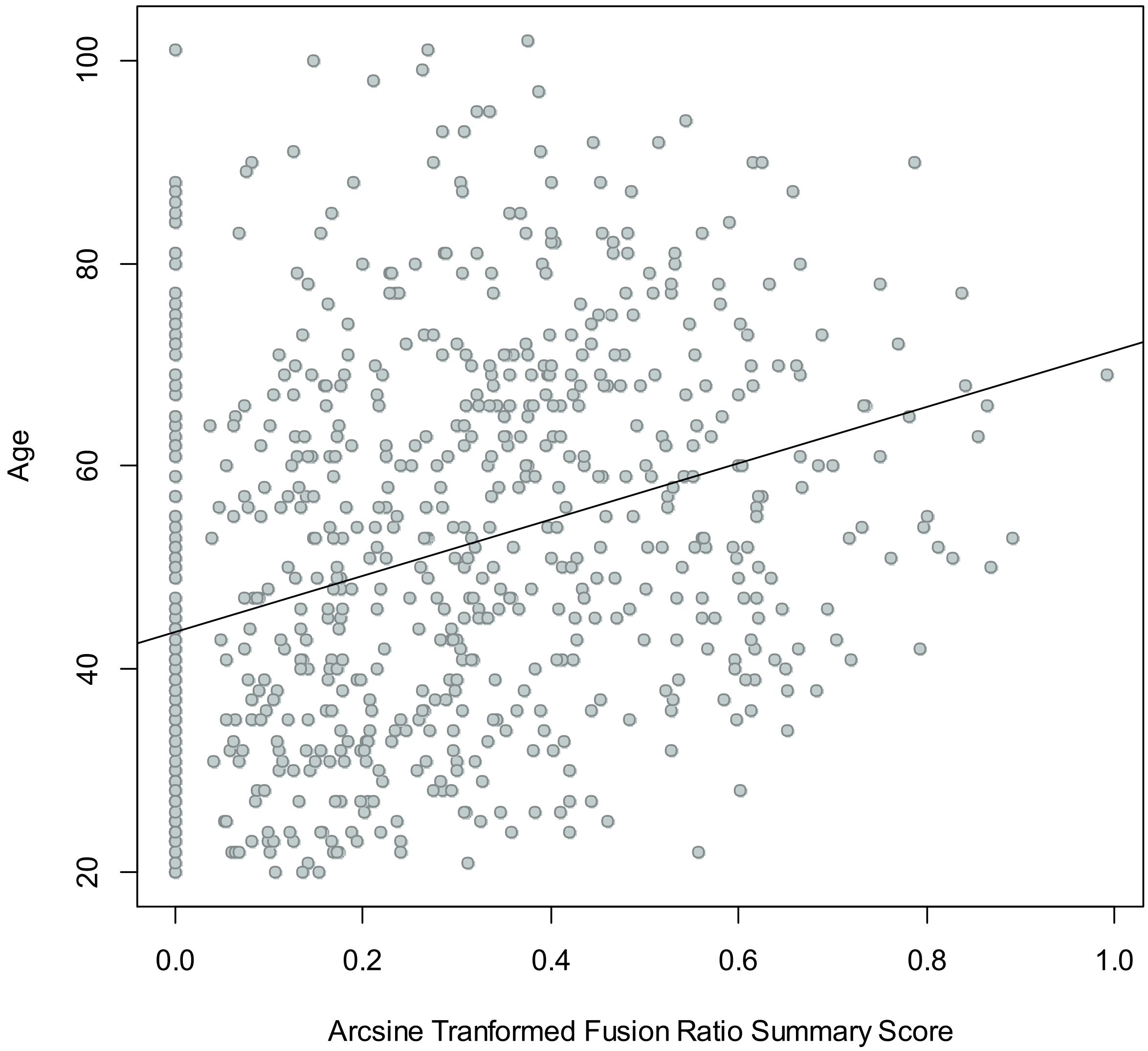


Figure 5-20. Scatterplot of age and arcsine transformed fusion ratio summary score. The black line indicates the least squares regression line. Compare to Figure 5-18 with untransformed data.

Table 5-13. Spearman's rank-order correlations for age and sutural fusion in full suture categorical and continuous systems.

Designator	*rho* Full suture/4-phase	Full suture/binary	Suture ratio
PMP suture	0.352	0.302	0.315
TP suture	0.290	0.287	0.224
AMP suture	0.269	0.259	0.280
Summed	0.423	0.352	0.349

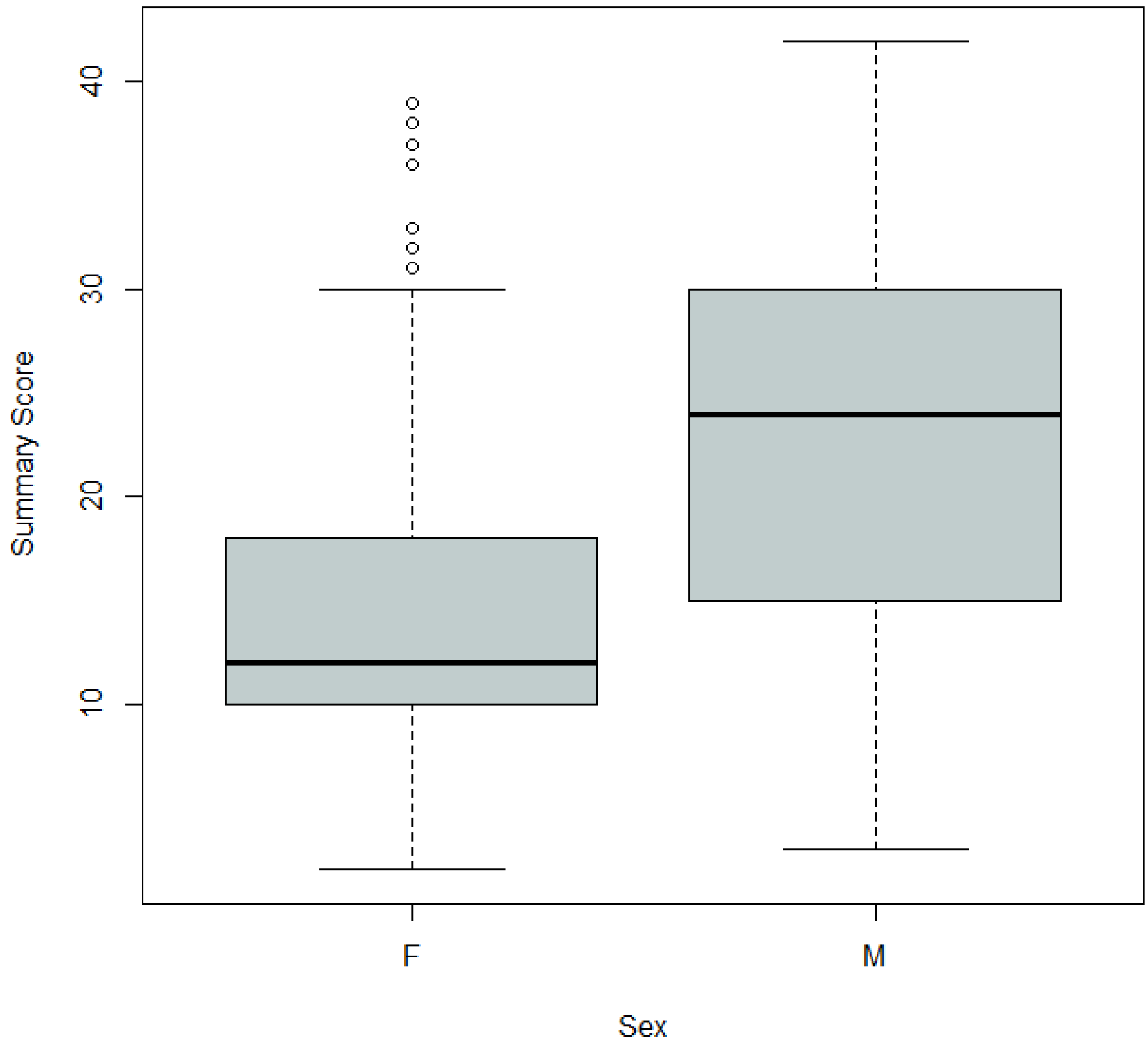


Figure 5-21. Summary score by sex (F = female, M = male). Note female outliers at the top of the plot but overall lower female summary scores as compared to males.

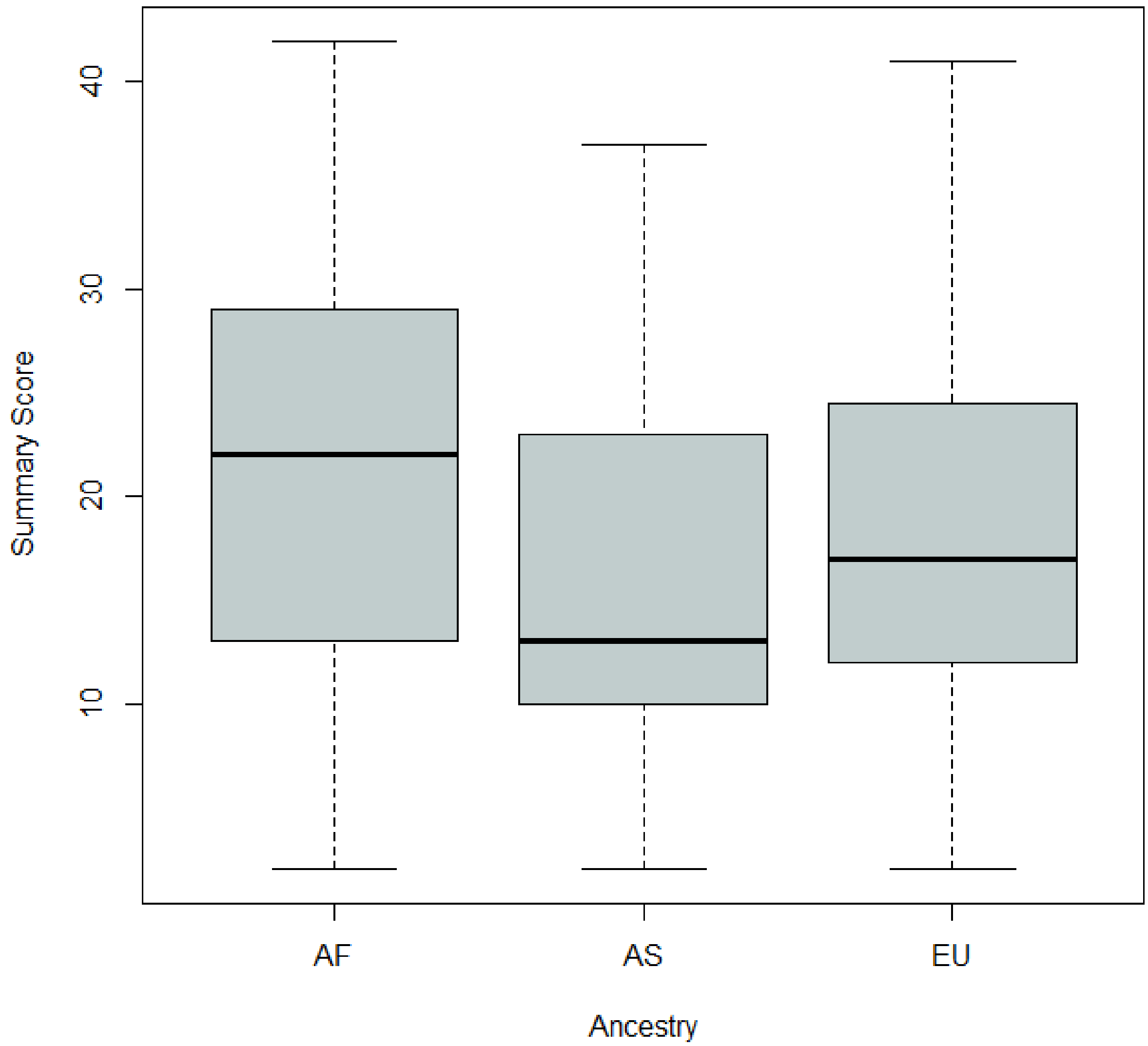


Figure 5-22. Summary score by ancestry (AF = African, AS = Asian, EU = European).

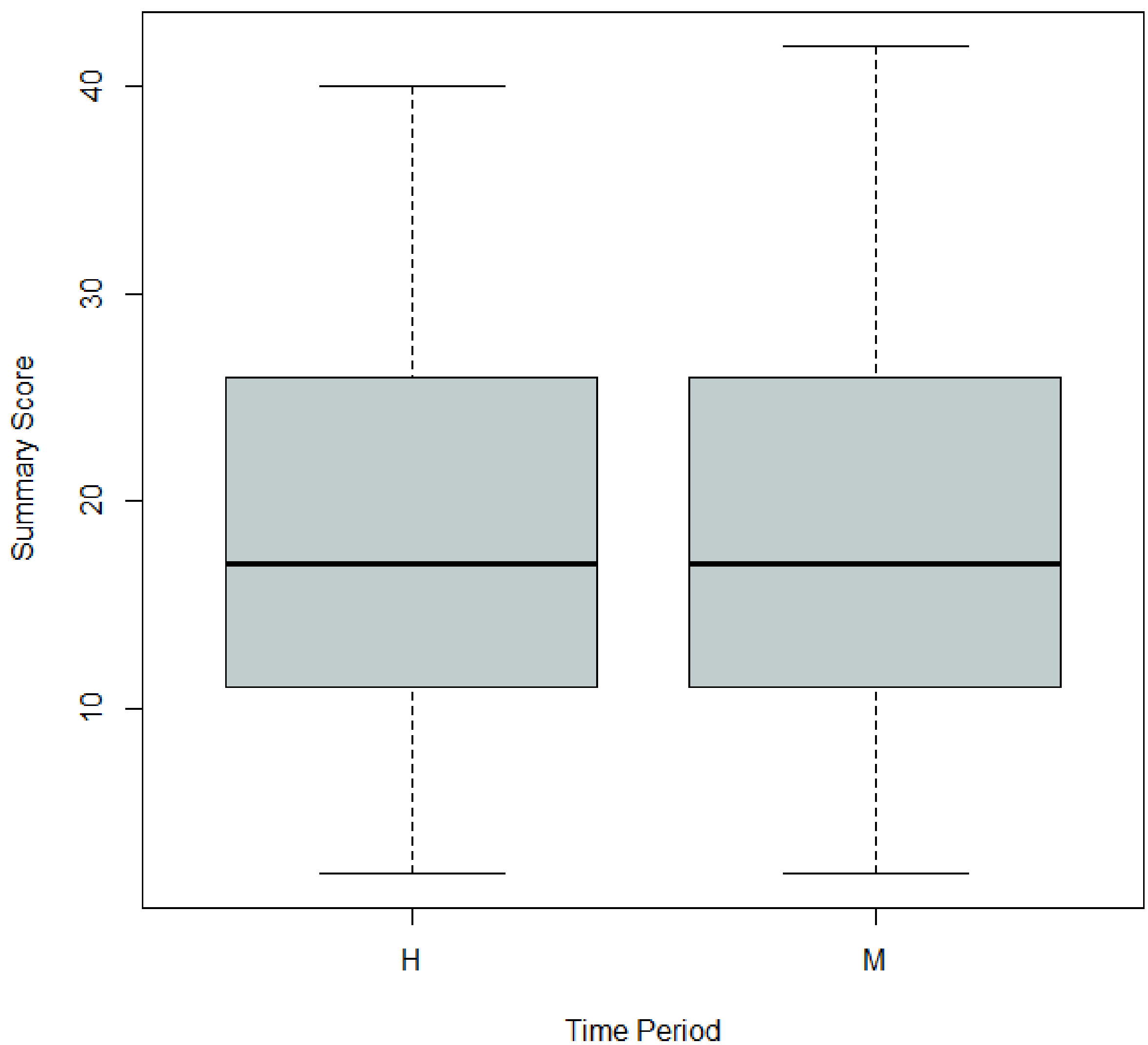


Figure 5-23. Summary score by time period (H = historic, M = modern).

Table 5-14. Results from ANCOVA for 15-section/4-phase summary score and age, sex, and ancestry.

Variable	Df	Sum of Squares	Mean Square	F value	Probability
Sex	1	12793	12793	280.28	<0.001[a]
Ancestry	2	4646	2323	50.89	<0.001[a]
Age	1	11271	11271	246.94	<0.001[a]
Sex:Ancestry	2	47	23	0.51	0.601
Sex:Age	1	691	691	15.14	<0.001[a]
Ancestry:Age	2	163	82	1.79	0.168
Sex:Ancestry:Age	2	269	135	2.95	0.053
Residuals	750	34231	46		

[a]Difference is significant at the $p < 0.05$ level.

Table 5-15. Inventory scores by tooth.

Tooth	Score 1	2	3	4	5	6	7	All
RM3	40	158	22	208	30	288	16	762
RM2	0	340	10	345	25	15	27	762
RM1	0	324	4	380	20	2	32	762
RP4	0	365	2	302	64	2	27	762
RP3	0	356	1	288	80	2	35	762
RC	3	369	1	213	103	1	72	762
RI2	0	277	1	259	135	5	85	762
RI1	0	261	3	280	128	2	88	762
LI1	0	264	1	284	122	1	90	762
LI2	0	276	1	266	128	6	84	762
LC	3	351	3	228	94	0	83	762
LP3	1	356	2	298	65	0	40	762
LP4	1	327	2	327	70	4	31	762
LM1	0	327	1	381	9	2	42	762
LM2	1	326	14	357	25	12	27	762
LM3	33	165	26	213	31	275	19	762

Table 5-16. Descriptive statistics for dental wear scores by tooth.

Tooth	*n* (observable)[a]	*n* (unobservable)[b]	Median	Mean	St Dev	Min	Max
RM3	156	606	5	6.615	4.167	4	28
RM2	321	441	7	7.960	3.727	4	24
RM1	290	472	9	9.586	4.498	4	27
RP4	347	415	2	1.859	1.051	1	7
RP3	344	418	2	2.038	1.208	1	8
RC	360	402	2	2.381	1.200	1	6
RI2	266	496	2	2.030	1.159	1	7
RI1	246	516	3	2.614	1.136	1	7
LI1	250	512	3	2.624	1.173	1	7
LI2	263	499	2	1.989	1.096	1	6
LC	339	423	2	2.425	1.258	1	8
LP3	343	419	2	2.009	1.186	1	8
LP4	314	448	2	1.834	1.041	1	7
LM1	305	457	9	9.875	4.646	4	30
LM2	302	460	7	8.106	4.054	4	34
LM3	163	599	5	7.190	5.835	4	40

[a]The presence of minor crown damage and restorations resulted in sample sizes for wear score per tooth that are less than the sample sizes for teeth present (recorded as a score of 2 in Table 5-15).
[b]Wear not recorded due absence or damage of tooth.

Table 5-17. Descriptive statistics for mean wear scores.

Teeth	*n* (observable)	*n* (unobservable)	Median	Mean	St Dev	Min	Max
All	554	208	3.79	4.60	2.69	1.00	18.33
Posterior	534	228	4.78	5.65	3.44	1.00	23.50
Anterior	468	294	2.08	2.42	1.12	1.00	8.00

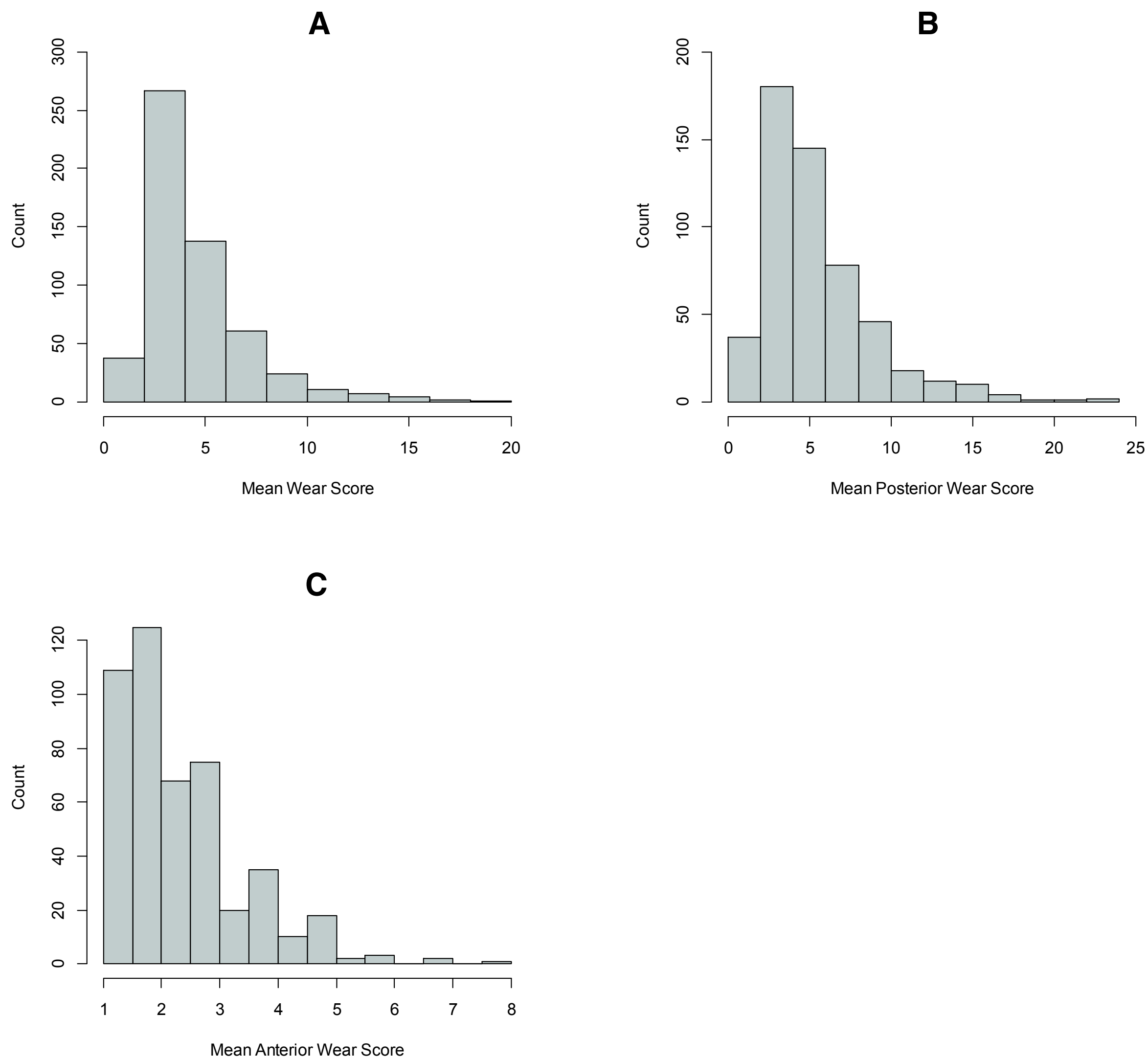


Figure 5-24. Distributions of mean wear scores. A) Mean wear score, all maxillary teeth, B) mean posterior wear score, C) mean anterior wear score.

Table 5-18. Count and percentage of antemortem tooth loss by tooth number.

Tooth	Count	All	% AMTL
RM3	208	762	27.30
RM2	345	762	45.28
RM1	380	762	49.87
RP4	302	762	39.63
RP3	288	762	37.80
RC	213	762	27.95
RI2	259	762	33.99
RI1	280	762	36.75
LI1	284	762	37.27
LI2	266	762	34.91
LC	228	762	29.92
LP3	298	762	39.11
LP4	327	762	42.91
LM1	381	762	50.00
LM2	357	762	46.85
LM3	213	762	27.95

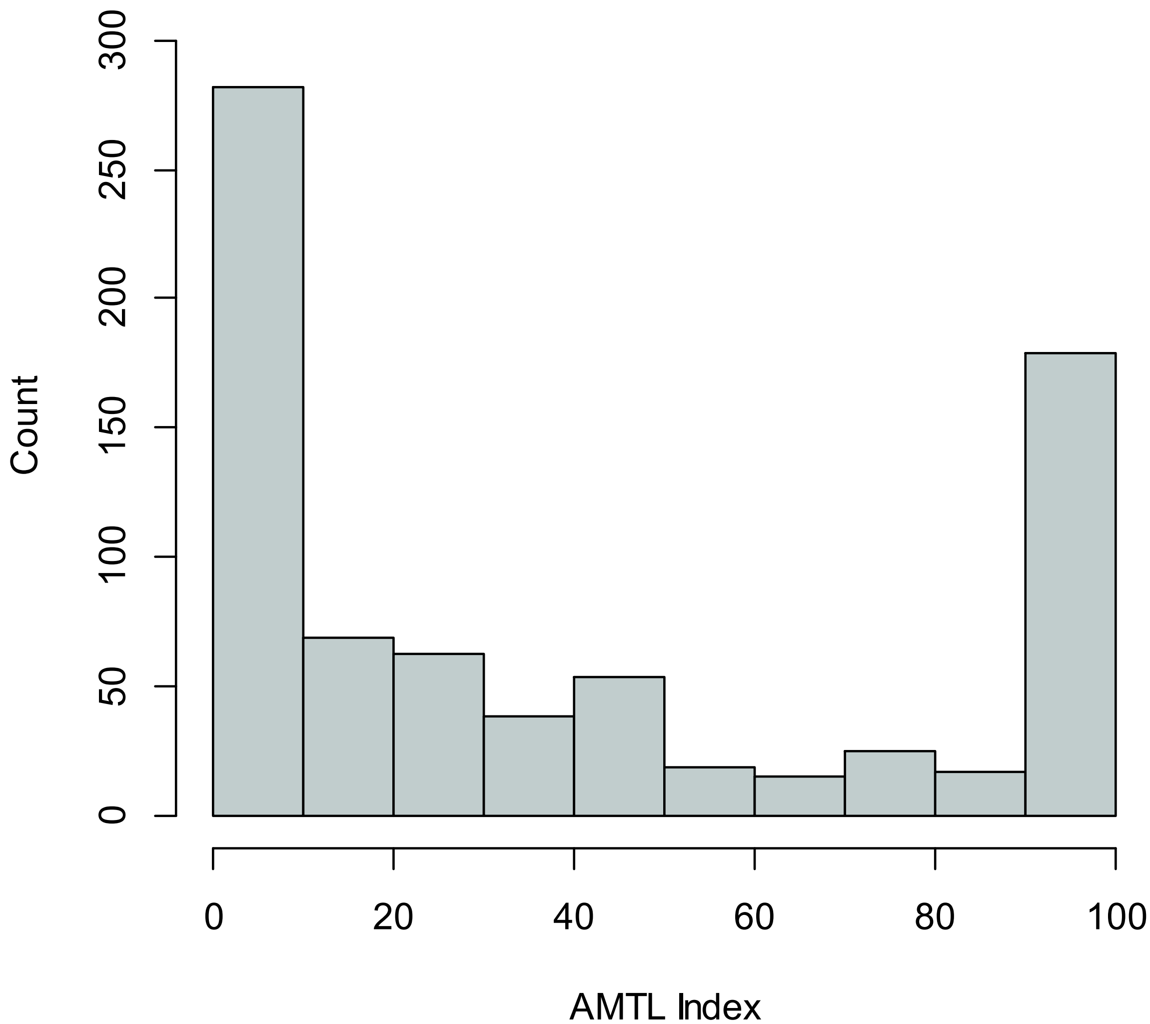


Figure 5-25. Frequency distribution of AMTL index in the total sample. Note that the distribution is bimodal.

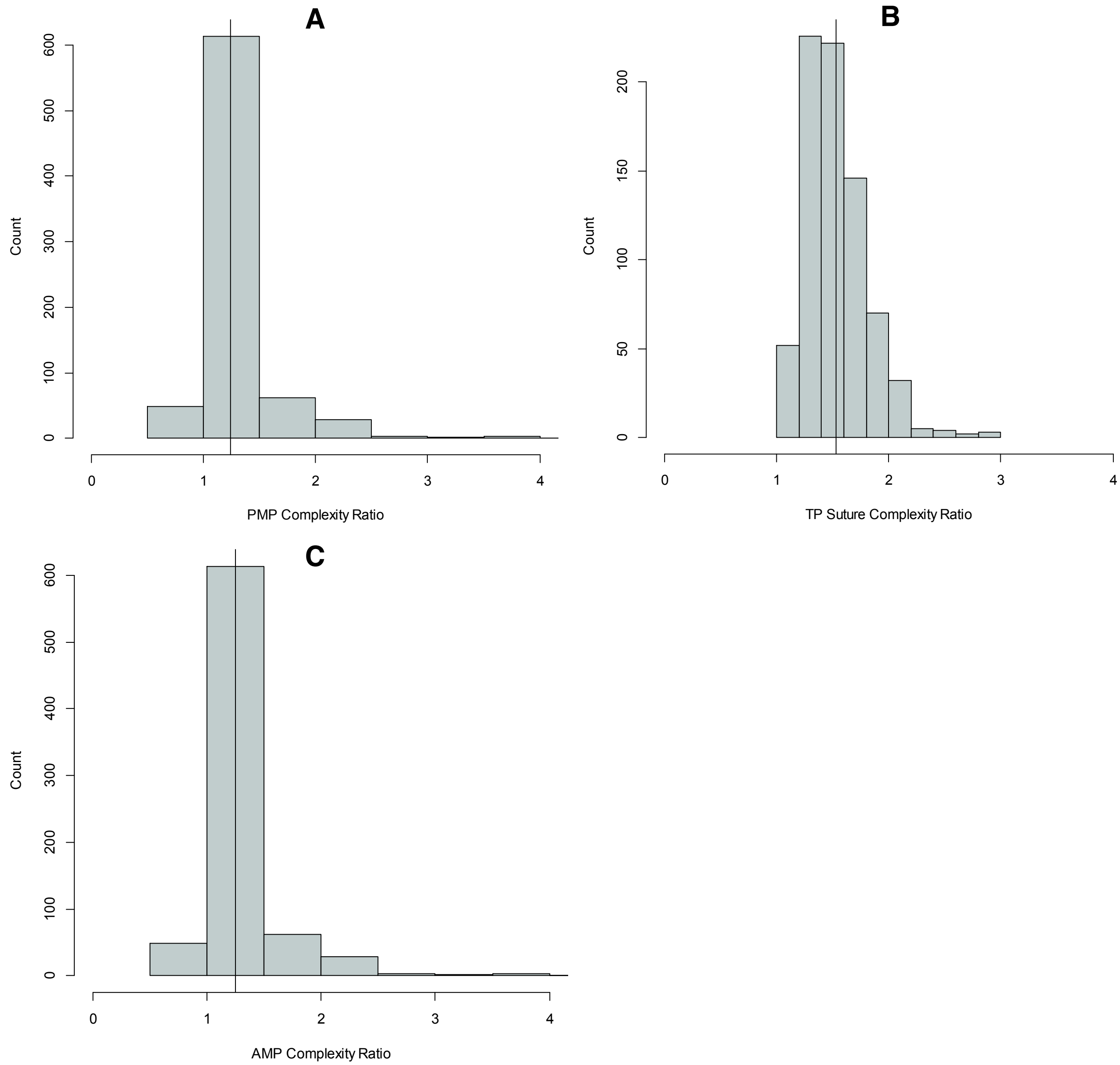


Figure 5-26. Frequency distributions of suture complexity ratios in the total sample. A) PMP suture complexity, B) TP suture complexity, C) AMP suture complexity.

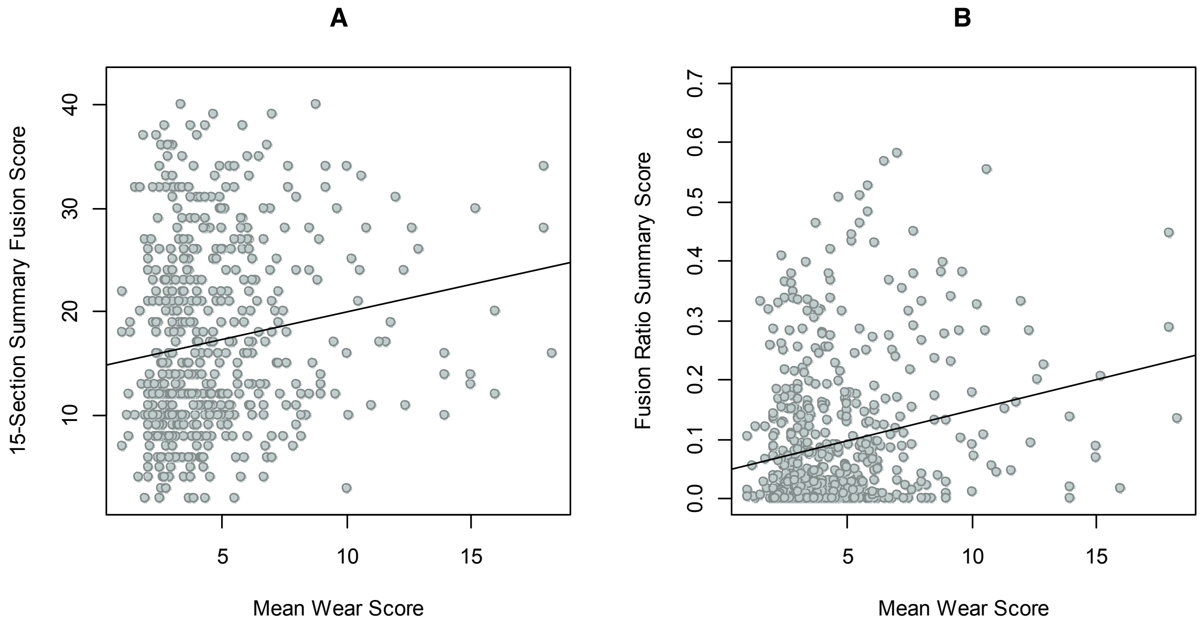


Figure 5-27. Scatterpots of fusion summary and mean wear scores. The black line in each plot indicates the least squares regression line. A) 15-section summary and mean wear scores, *rho* = 0.192; B) fusion ratio summary and mean wear scores, *rho* = 0.227.

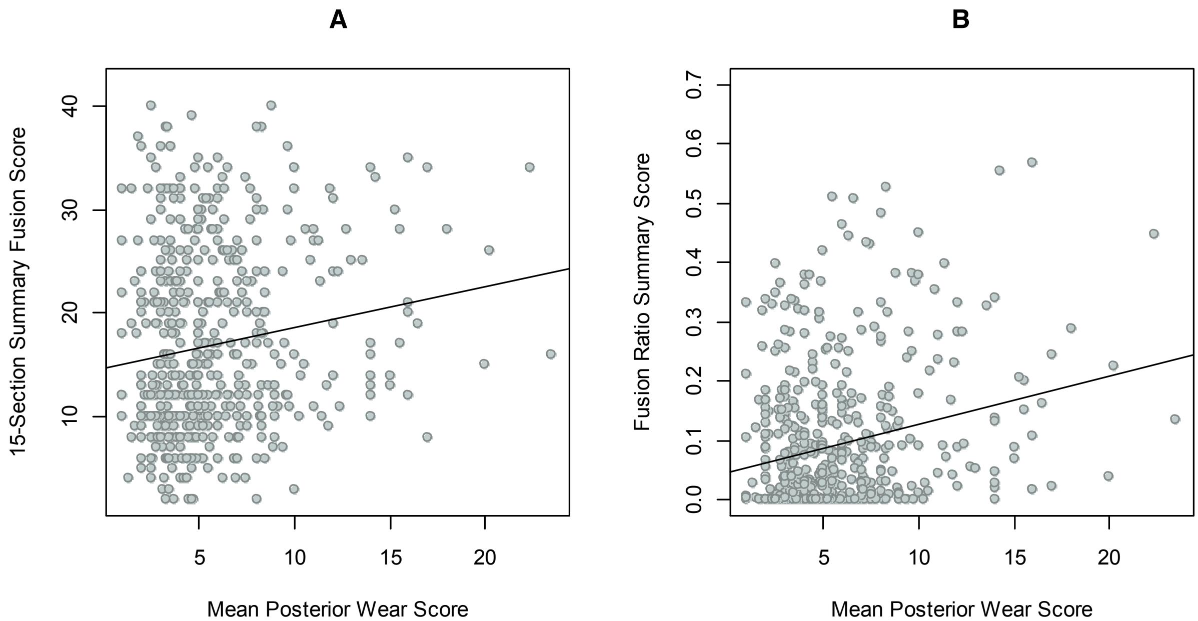


Figure 5-28. Scatterpots of fusion summary and mean posterior wear scores. The black line in each plot indicates the least squares regression line. A) 15-section summary and mean posterior wear scores, *rho* = 0.141; B) fusion ratio summary and mean posterior wear scores, *rho* = 0.201.

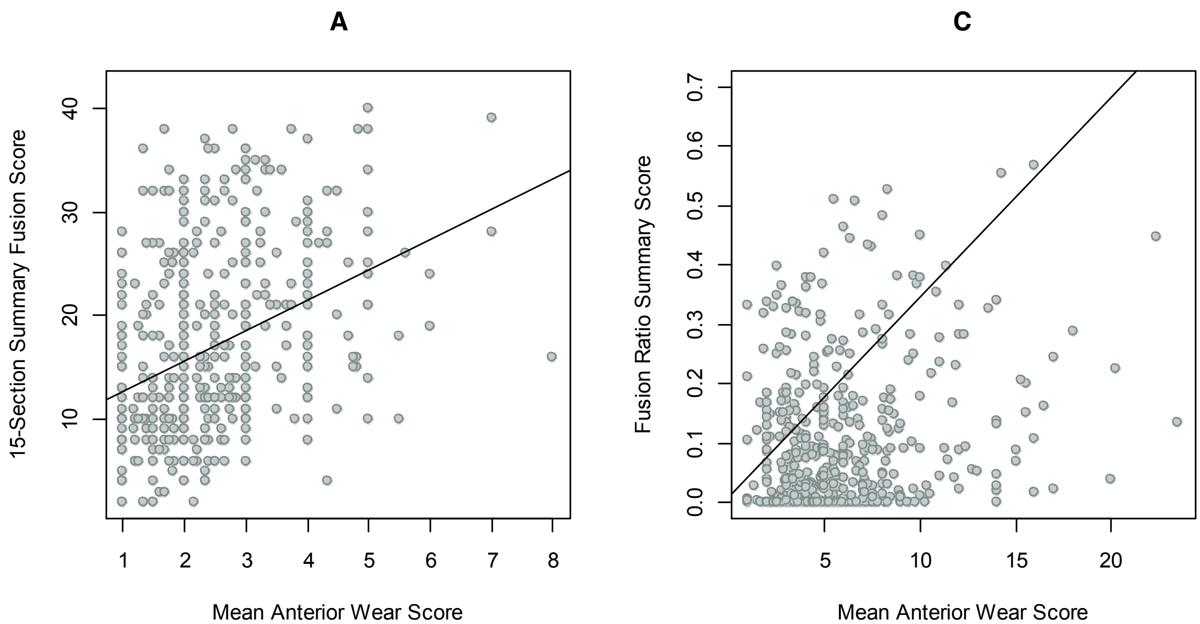


Figure 5-29. Scatterpots of fusion summary and mean anterior wear scores. The black line in each plot indicates the least squares regression line. A) 15-section summary and mean anterior wear scores, *rho* = 0.389; B) fusion ratio summary and mean anterior wear scores, *rho* = 0.318.

Table 5-19. Regression results for 15-section summary fusion score and mean anterior and posterior wear scores.

Variable	Estimate	Std Error	t value	Probability
Intercept	9.5890	0.9851	9.734	<0.001[a]
Mean posterior wear	0.1029	0.1295	0.794	0.427
Mean anterior wear	2.6871	0.3835	7.006	<0.001[a]

[a]Difference is significant at the $p < 0.05$ level.

Table 5-20. Regression results for fusion ratio summary score and mean wear scores.

Variable	Estimate	Std Error	t value	Probability
Intercept	2.719e-05	1.329e-02	0.002	0.998
Mean posterior wear	5.953e-03	1.747e-03	3.407	0.001[a]
Mean anterior wear	2.358e-02	5.174e-03	4.557	<0.001[a]

[a]Difference is significant at the $p < 0.05$ level.

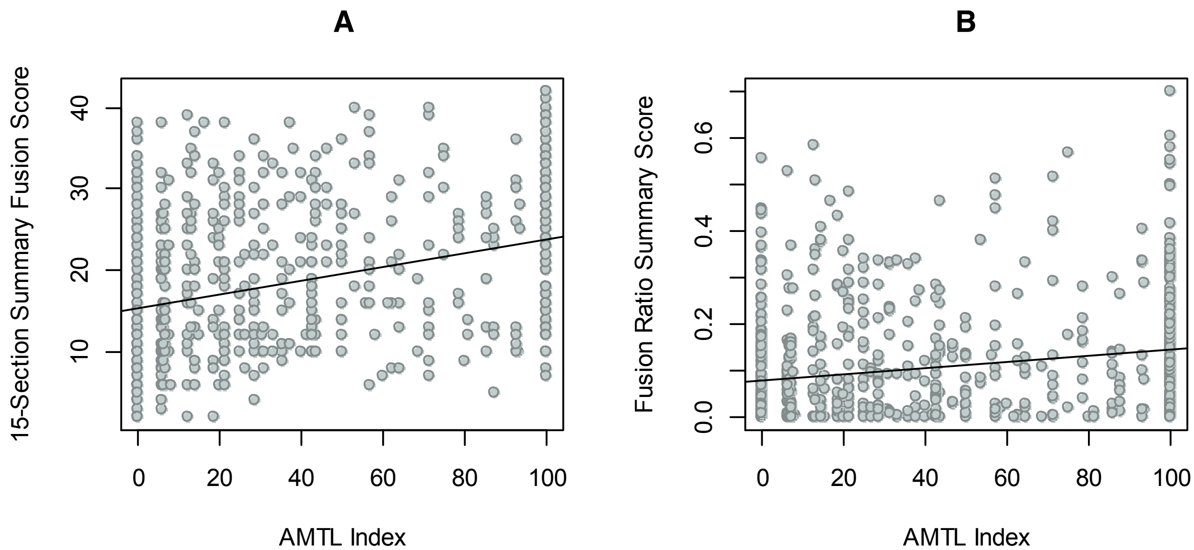


Figure 5-30. Scatterplots of summary fusion scores and AMTL Index. The black lines indicate the least squares regression lines. A) 15-section/4-phase summary fusion score and AMTL index, *rho* = 0.397; B) fusion ratio summary score and AMTL Index, *rho* = 0.260.

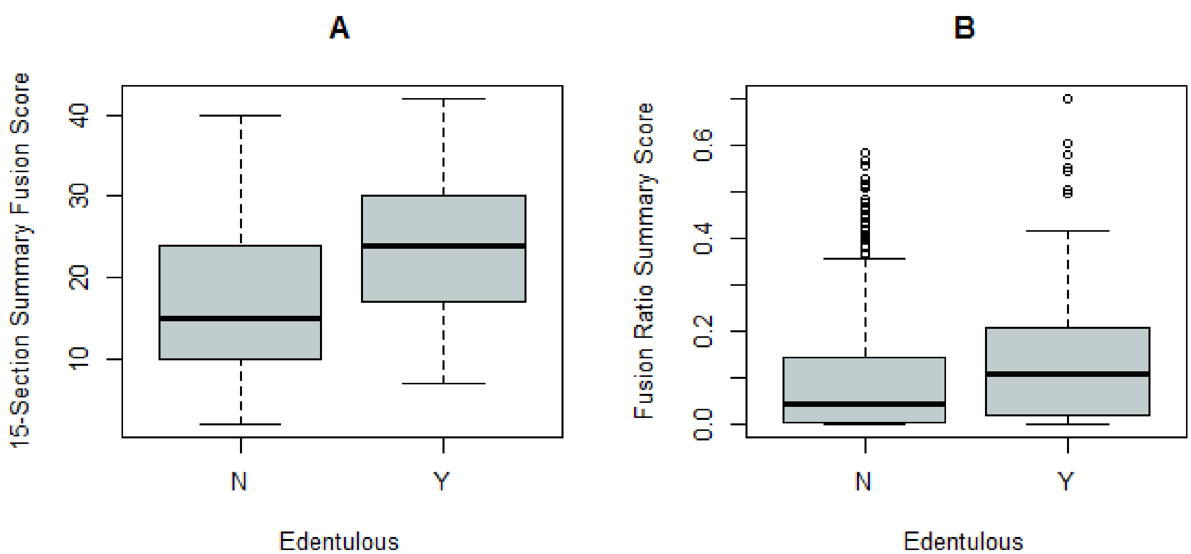


Figure 5-31. Box-and-whisker plots of suture fusion by edentulous status (N=at least one tooth present, Y=completely edentulous). A) Summary fusion score and edentulism, B) fusion ratio summary score and edentulism.

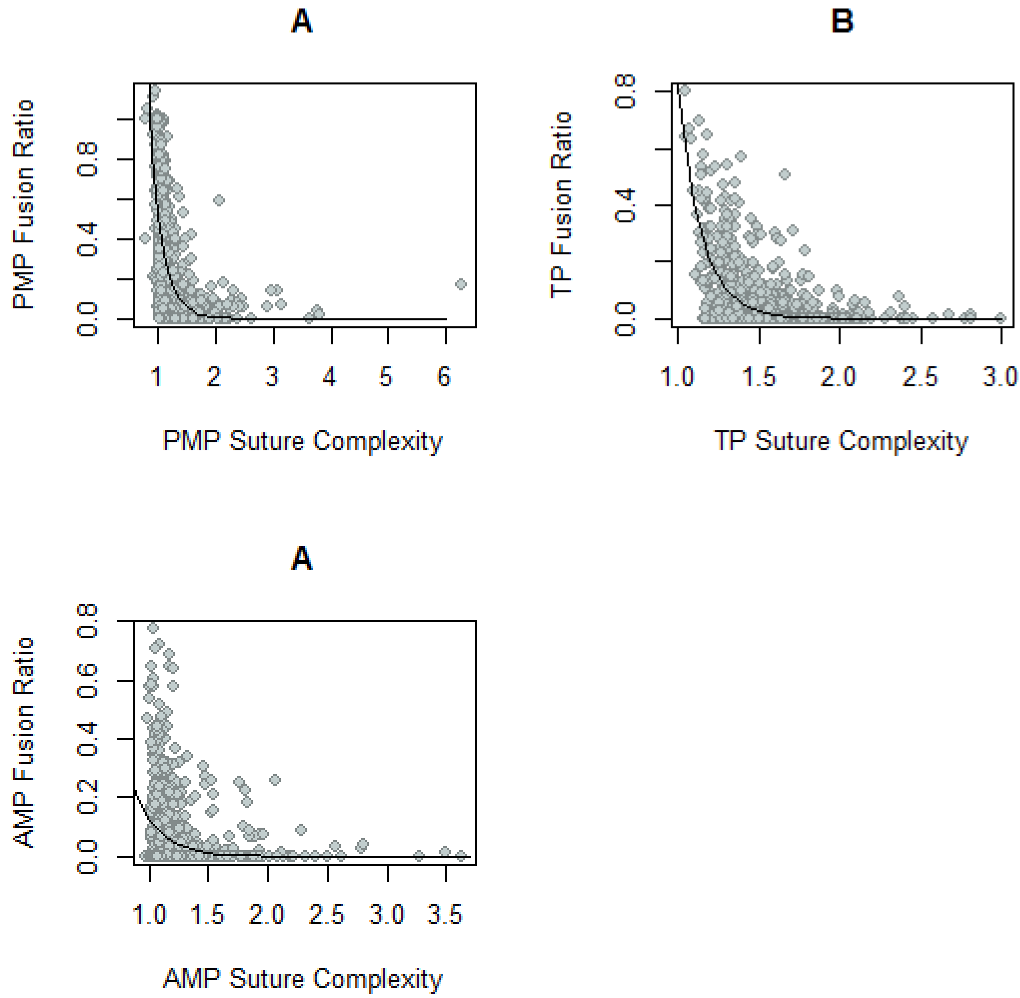


Figure 5-32. Scatterplots of individual suture fusion ratios and suture complexity. The black line in each plot indicates the fitted exponential decay curve. A) PMP fusion ratio and suture complexity, *rho* = -0.591; B) TP fusion ratio and suture complexity, *rho* = -0.391; C) AMP fusion ratio and suture complexity, *rho* = -0.206.

Table 5-21. Regression results for fusion ratio summary score and suture complexity.

Variable	Estimate	Std Error	t value	Probability
Intercept	0.421	0.025	16.613	<0.001
PMP complexity	-0.059	0.012	-4.802	<0.001
TP complexity	-0.144	0.017	-8.560	<0.001
AMP complexity	-0.018	0.017	-1.054	0.292

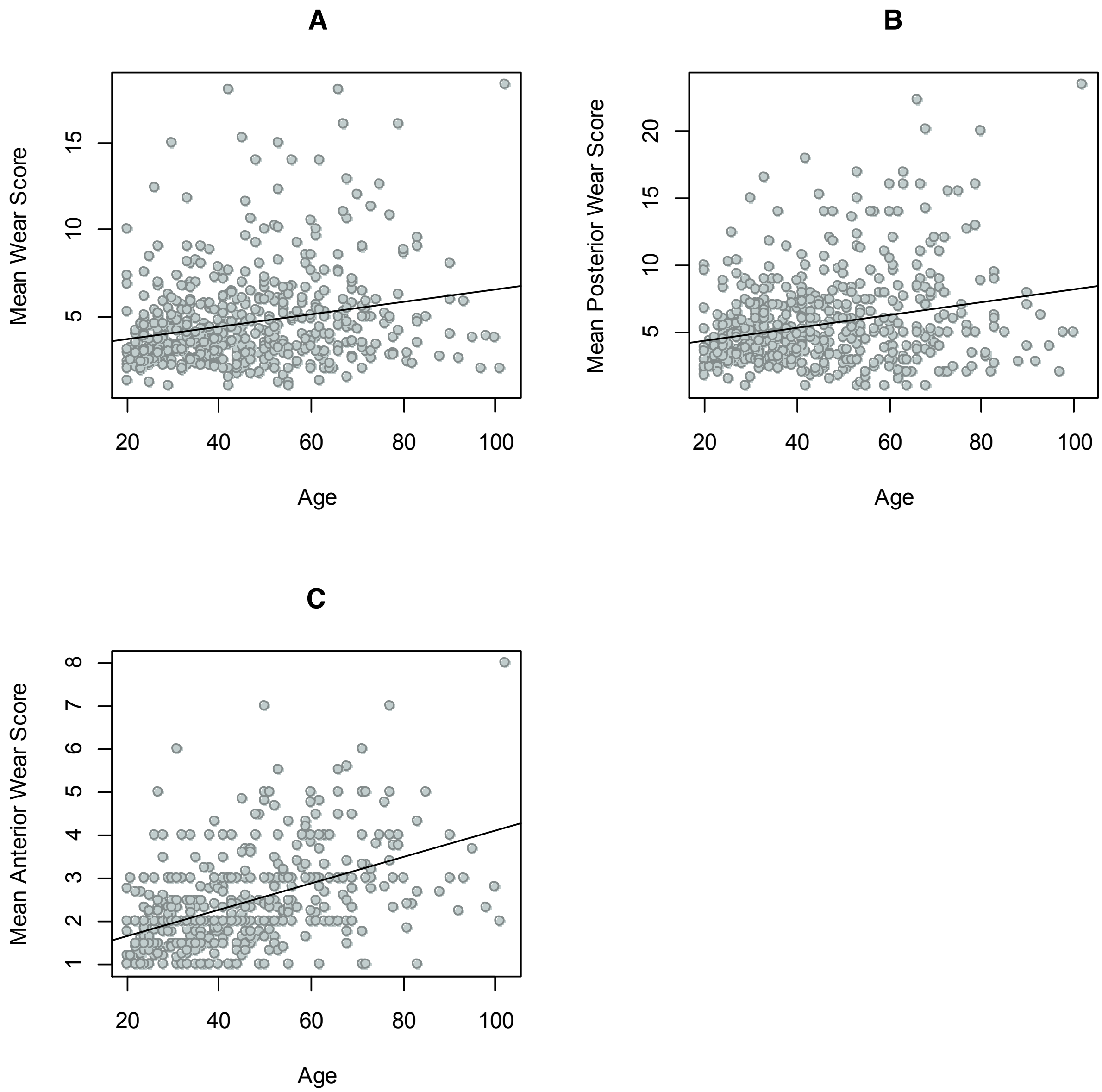


Figure 5-33. Scatterplots of age and mean wear scores. The black line in each plot indicates the least squares regression line. A) Age and mean wear score, *rho*=0.240; B) age and mean posterior wear score, *rho* = 0.209; C) age and mean anterior wear score, *rho* = 0.501.

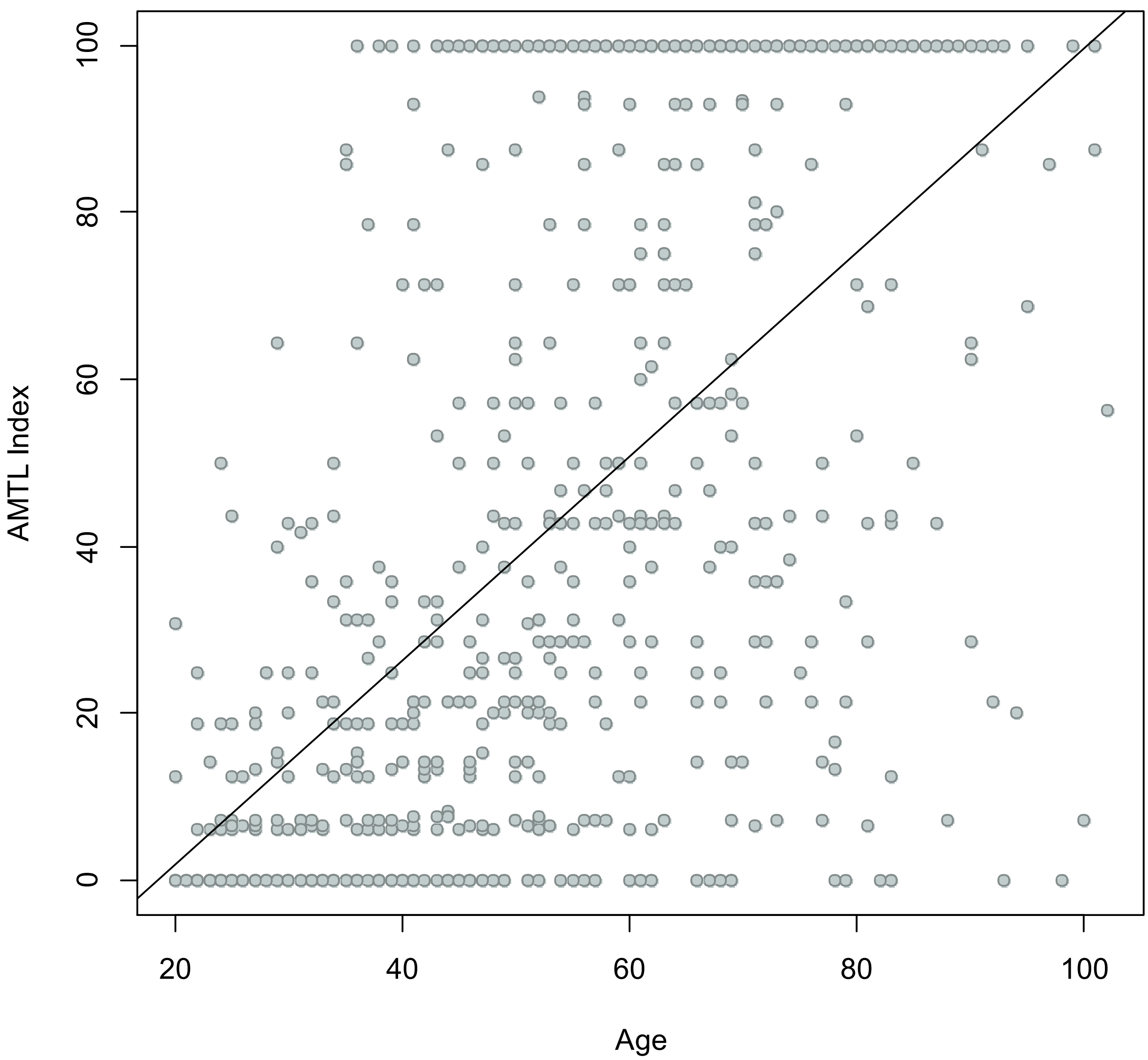


Figure 5-34. Scatterplot of AMTL index and age. The black line indicates the least squares regression line; *rho* = 0.631.

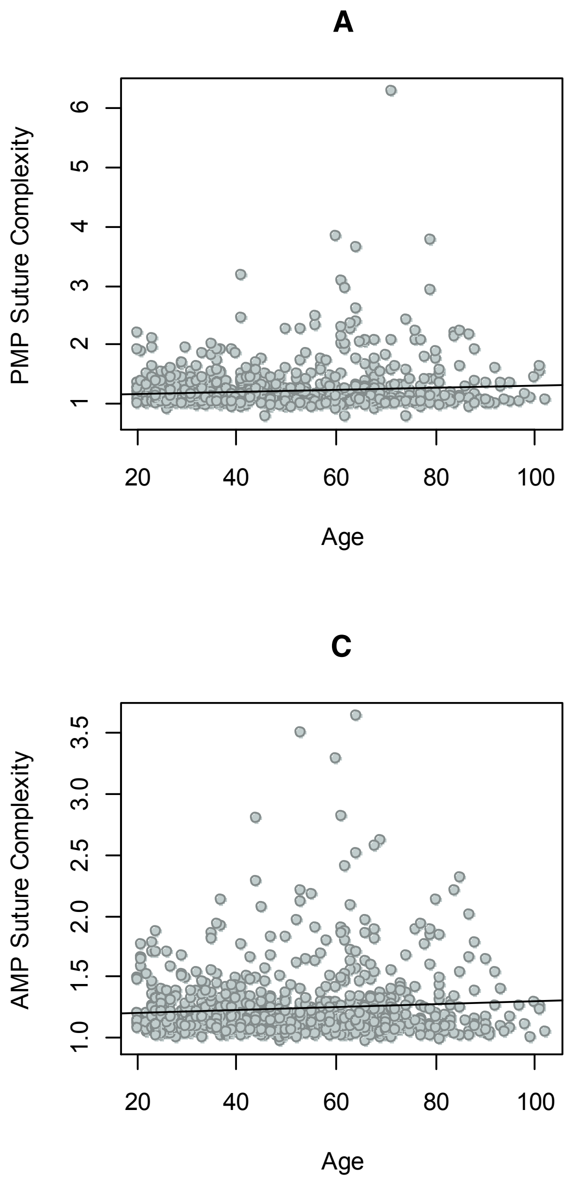


Figure 5-35. Scatterplots of individual suture complexity and age. The black lines indicate the least squares regression lines. A) PMP suture complexity and age, *rho* = -0.075; B) TP suture complexity and age, *rho* = -0.044; C) AMP suture complexity and age, *rho* = -0.017.

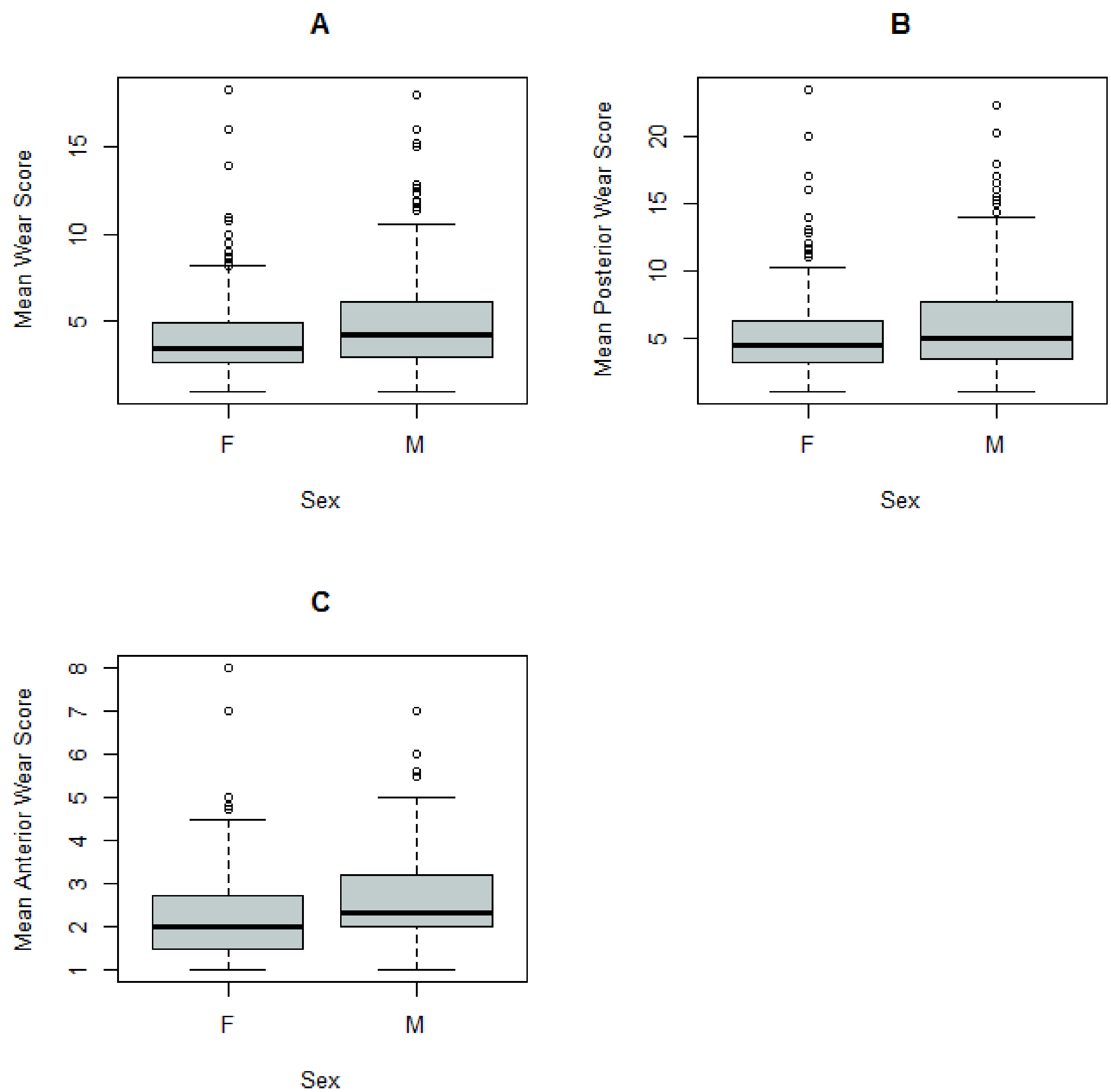


Figure 5-36. Box-and-whisker plots of mean wear scores by sex (F = female, M = male). A) Overall mean wear score, B) mean posterior wear score, C) mean anterior wear score.

Table 5-22. Descriptive statistics for sex and mean wear score.

	Females				Males			
Teeth	Mean	St Dev	Min	Max	Mean	St Dev	Min	Max
All	4.11	2.36	1.00	18.33	5.08	2.89	1.00	18.00
Posterior	5.13	3.12	1.00	23.50	6.14	3.65	1.00	22.33
Anterior	2.19	1.02	1.00	8.00	2.65	1.17	1.00	7.00

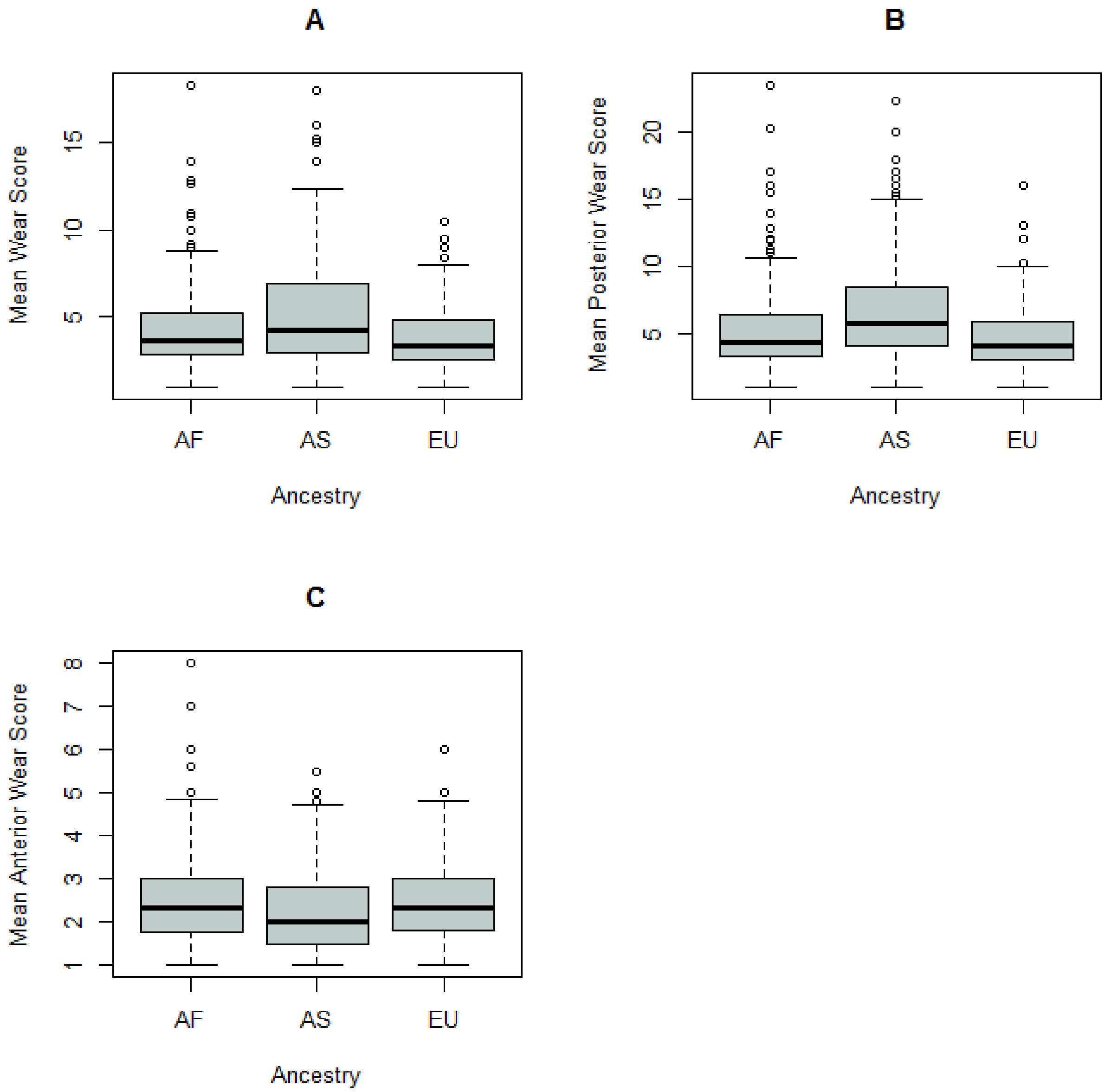


Figure 5-37. Box-and-whisker plots of mean wear scores by ancestry (AF = African, AS = Asian, EU = European). A) Overall mean wear score, B) mean posterior wear score, C) mean anterior wear score.

Table 5-23. Descriptive statistics for ancestry and mean wear score.

Teeth	African Mean	St Dev	Min	Max	Asian Mean	St Dev	Min	Max	European Mean	St Dev	Min	Max
All	4.38	2.36	1.00	18.33	5.42	3.34	1.00	18.00	3.84	1.70	1.00	10.50
Posterior	5.35	3.37	1.00	23.50	6.71	3.85	1.00	22.33	4.65	2.46	1.00	16.00
Anterior	2.56	1.25	1.00	8.00	2.22	1.05	1.00	5.50	2.50	1.01	1.00	6.00

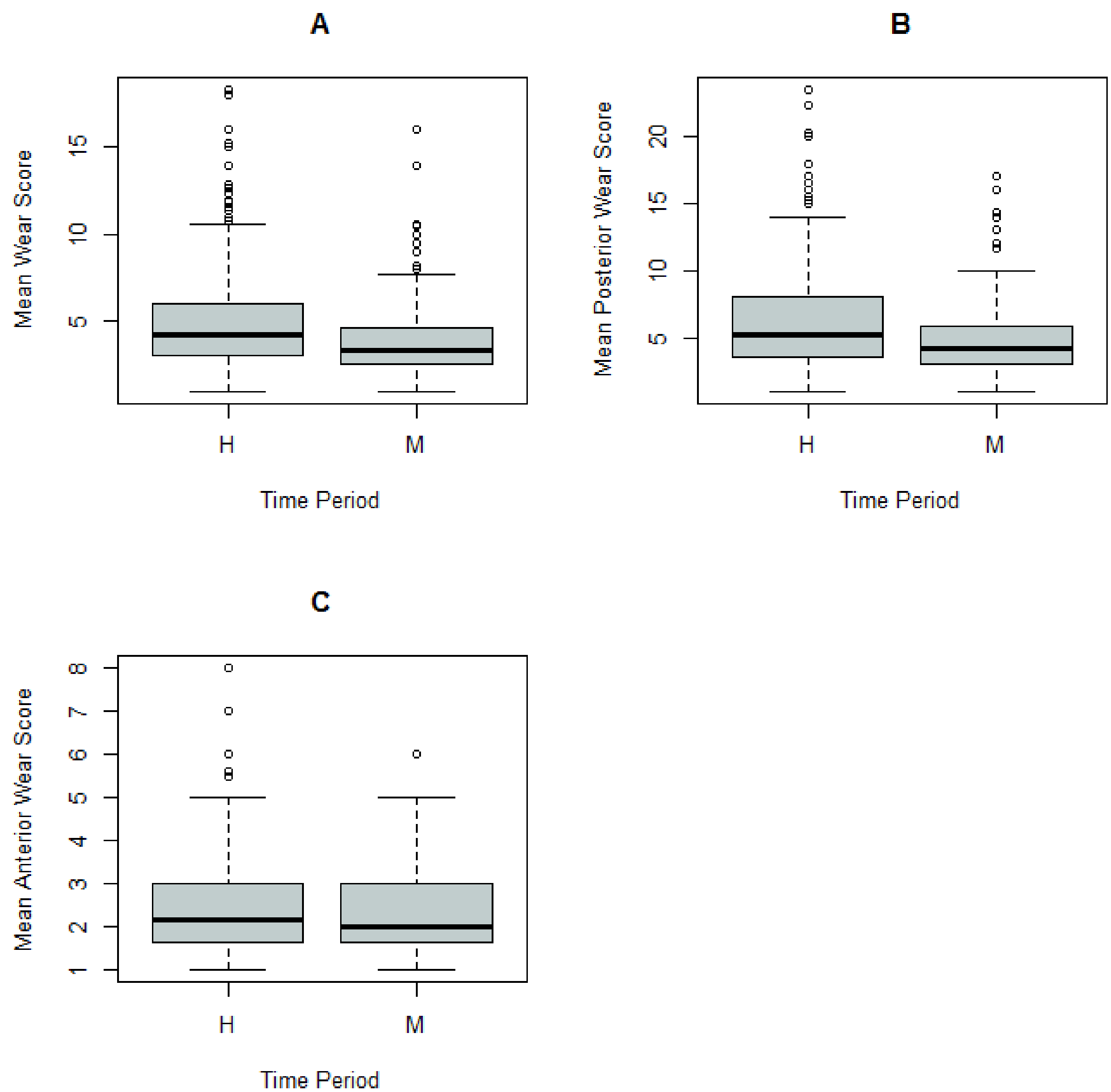


Figure 5-38. Box-and-whisker plots of mean wear scores by time period (H = historic, M = modern). A) Overall mean wear score, B) mean posterior wear score, C) mean anterior wear score.

Table 5-24. Descriptive statistics for time period and mean wear score.

	Historic				Modern			
Teeth	Mean	St Dev	Min	Max	Mean	St Dev	Min	Max
All	5.13	2.99	1.00	18.33	3.92	2.06	1.00	16.00
Posterior	6.27	3.76	1.00	23.50	4.82	2.73	1.00	17.00
Anterior	2.47	1.20	1.00	8.00	2.36	1.02	1.00	6.00

Table 5-25. Group differences in mean wear score.

Teeth	*p*-value Sex[a]	Ancestry[b]	Time Period[a]
All	<0.001[c]	<0.001[c]	<0.001[c]
Posterior	<0.001[c]	<0.001[c]	<0.001[c]
Anterior	<0.001[c]	0.004[c]	0.490

[a]Wilcoxon signed-rank test
[b]Kruskal-Wallis test
[c]Difference is significant at the $p < 0.05$ level.

Table 5-26. Descriptive statistics for AMTL Index by group.

Group	Median	Mean	St Dev	Minimum	Maximum
Female	26.67	40.32	39.49	0	100
Male	21.43	38.81	39.61	0	100
African	25.84	37.69	36.26	0	100
Asian	18.75	35.76	39.48	0	100
European	34.52	45.45	42.14	0	100
Historic	18.75	31.71	35.31	0	100
Modern	36.61	47.27	41.92	0	100

Table 5-27. Descriptive statistics for suture complexity by group.

Suture	Group	Median	Mean	St Dev	Minimum	Maximum
PMP	Female	1.210	1.377	0.506	0.784	6.282
	Male	1.065	1.104	0.140	0.795	2.198
	African	1.092	1.181	0.284	0.795	3.821
	Asian	1.132	1.333	0.548	0.784	6.282
	European	1.120	1.194	0.245	0.950	3.088
	Historic	1.106	1.217	0.338	0.784	3.821
	Modern	1.115	1.258	0.440	0.795	6.282
TP	Female	1.543	1.589	0.293	1.128	2.994
	Male	1.419	1.479	0.248	1.044	2.814
	African	1.393	1.447	0.250	1.044	2.994
	Asian	1.562	1.393	0.291	1.073	2.807
	European	1.517	1.517	0.266	1.095	2.814
	Historic	1.460	1.508	0.266	1.044	2.994
	Modern	1.503	1.559	0.285	1.095	2.814
AMP	Female	1.211	1.319	0.356	0.973	3.635
	Male	1.127	1.183	0.187	0.983	2.614
	African	1.114	1.192	0.246	0.973	3.279
	Asian	1.210	1.311	0.348	0.983	3.635
	European	1.163	1.244	0.253	1.013	2.794
	Historic	1.143	1.222	0.253	0.973	3.279
	Modern	1.172	1.278	0.322	0.992	3.635

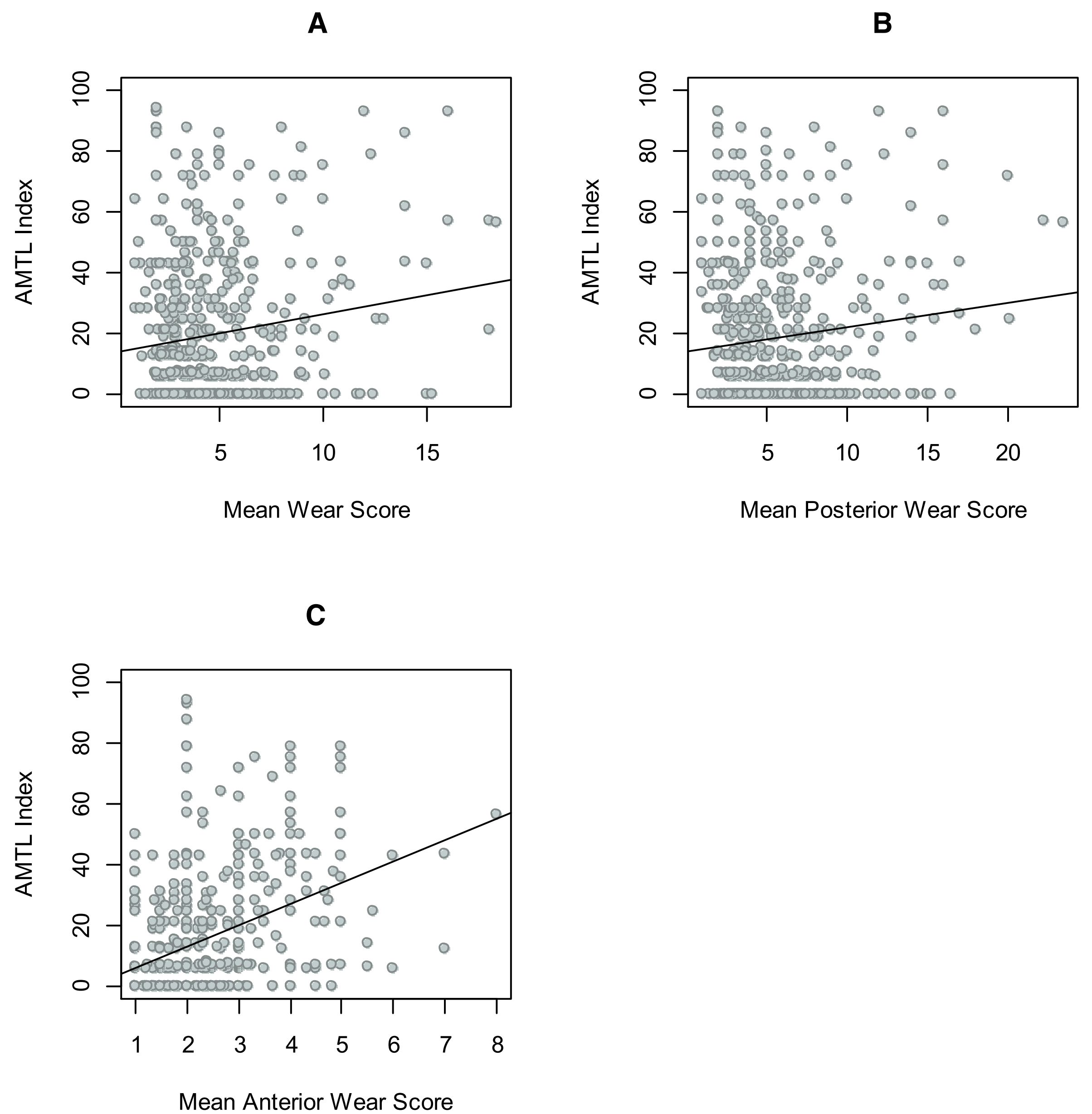


Figure 5-39. Scatterplots of AMTL Index and mean molar wear. The black line indicates the least squares regression line. A) AMTL Index and mean wear score, *rho* = 0.058; B) AMTL Index and mean posterior wear score, *rho* = 0.015; C) AMTL Index and mean anterior wear score, *rho* = 0.401.

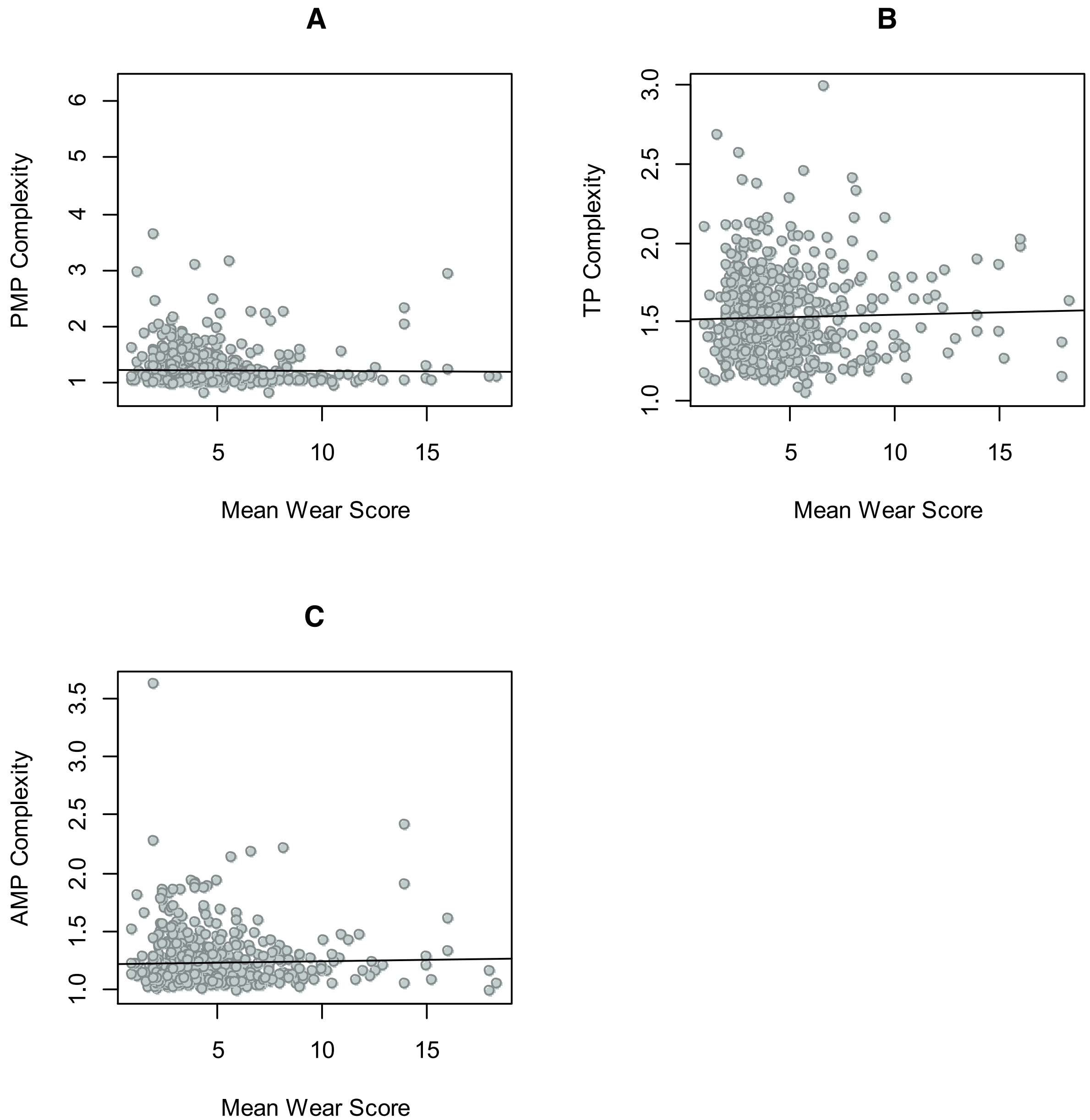


Figure 5-40. Scatterplots of suture complexity and mean wear score. The black line indicates the least squares regression line. A) PMP complexity and mean wear score, *rho* = -0.144; B) TP complexity and mean wear score, *rho* = 0.017; C) AMP complexity and mean wear score, *rho* = 0.038.

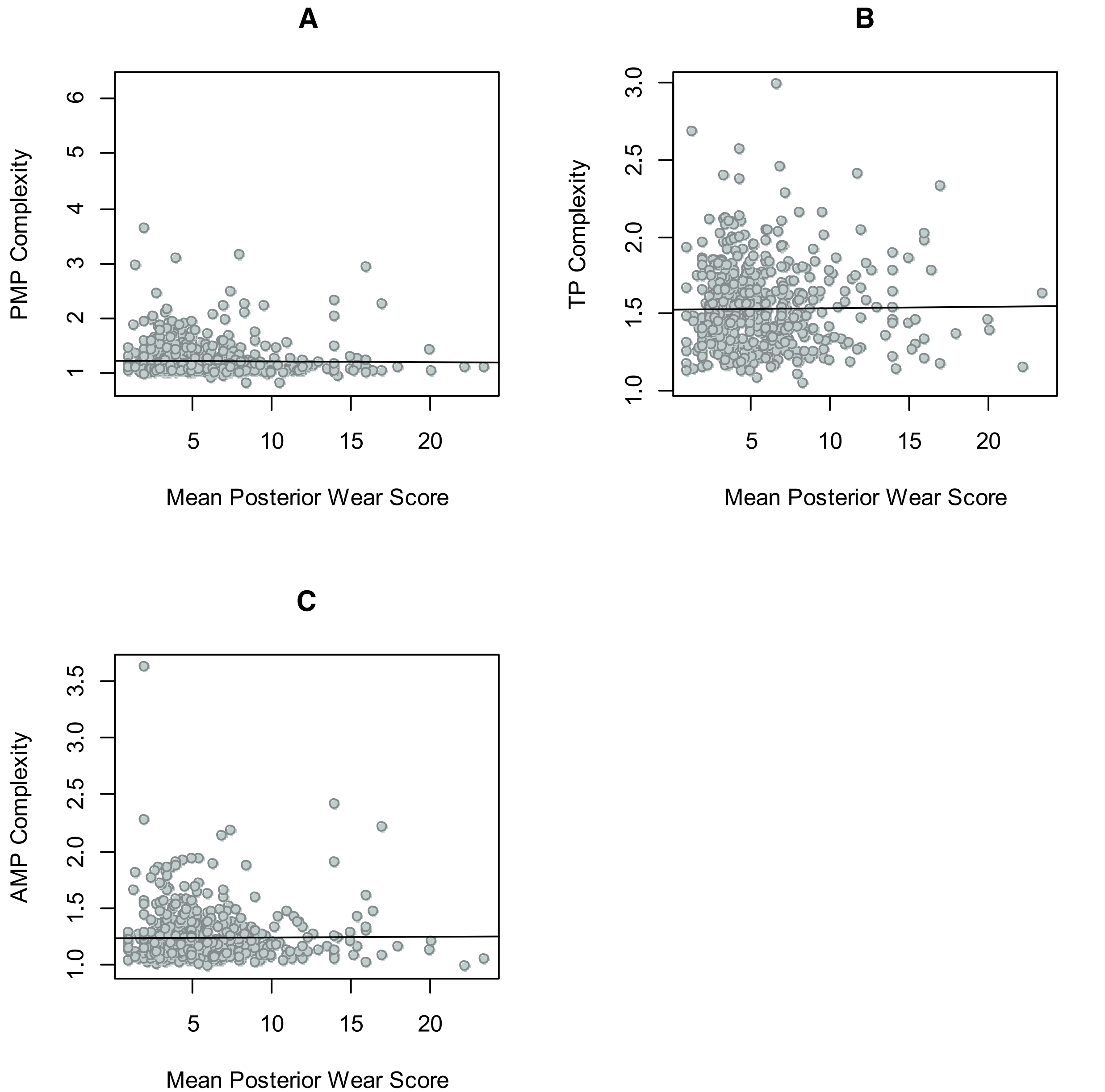


Figure 5-41. Scatterplots of suture complexity and mean posterior wear score. The black line indicates the least squares regression line. A) PMP complexity and mean posterior wear score, *rho* = -0.113; B) TP complexity and mean posterior wear score, *rho* = 0.012; C) AMP complexity and mean posterior wear score, *rho* = 0.060.

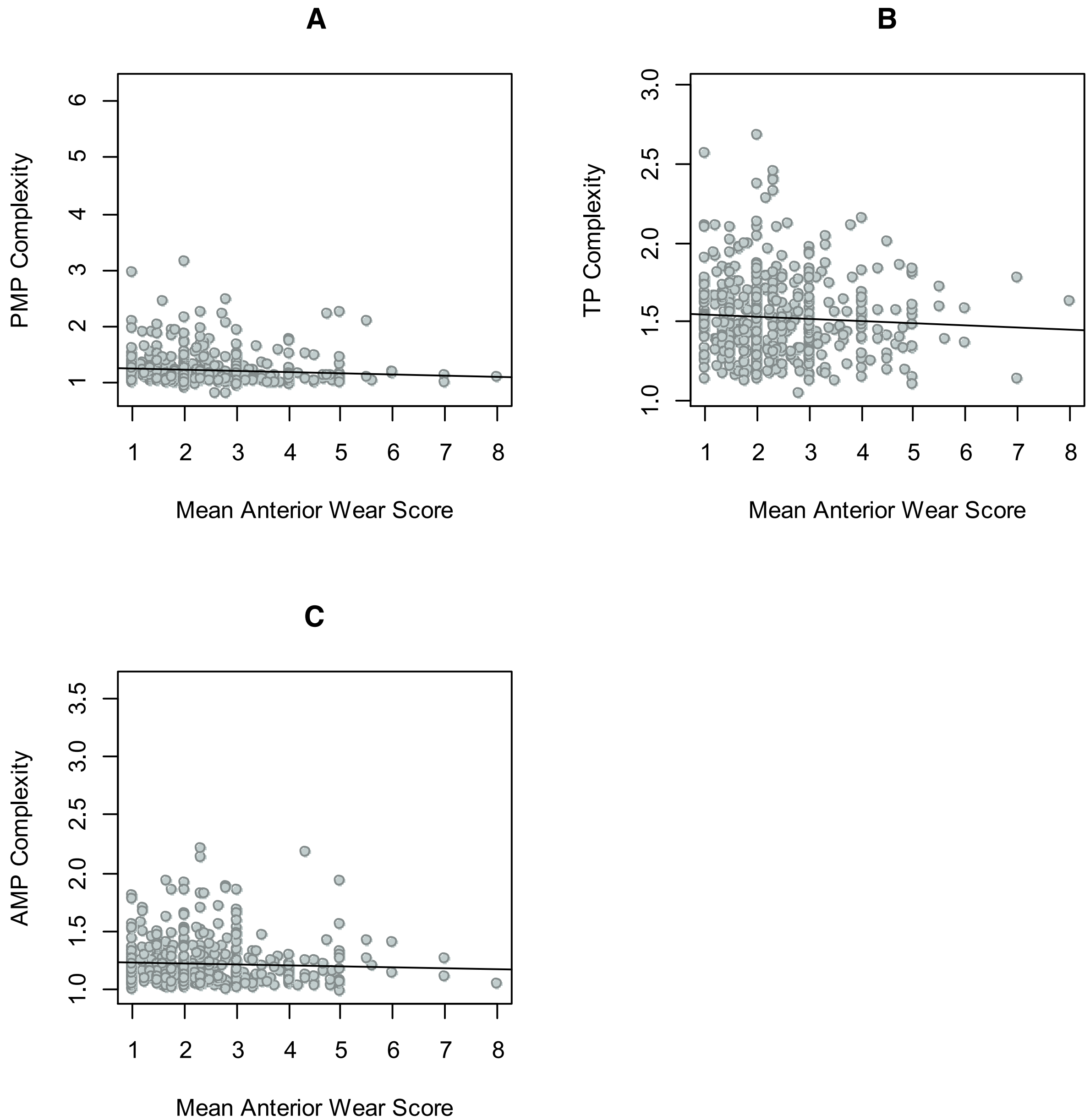


Figure 5-42. Scatterplots of suture complexity and mean anterior wear score. The black line indicates the least squares regression line. A) PMP complexity and mean anterior wear score, *rho* = -0.198; B) TP complexity and mean anterior wear score, *rho* = 0.068; C) AMP complexity and mean anterior wear score, *rho* = -0.093.

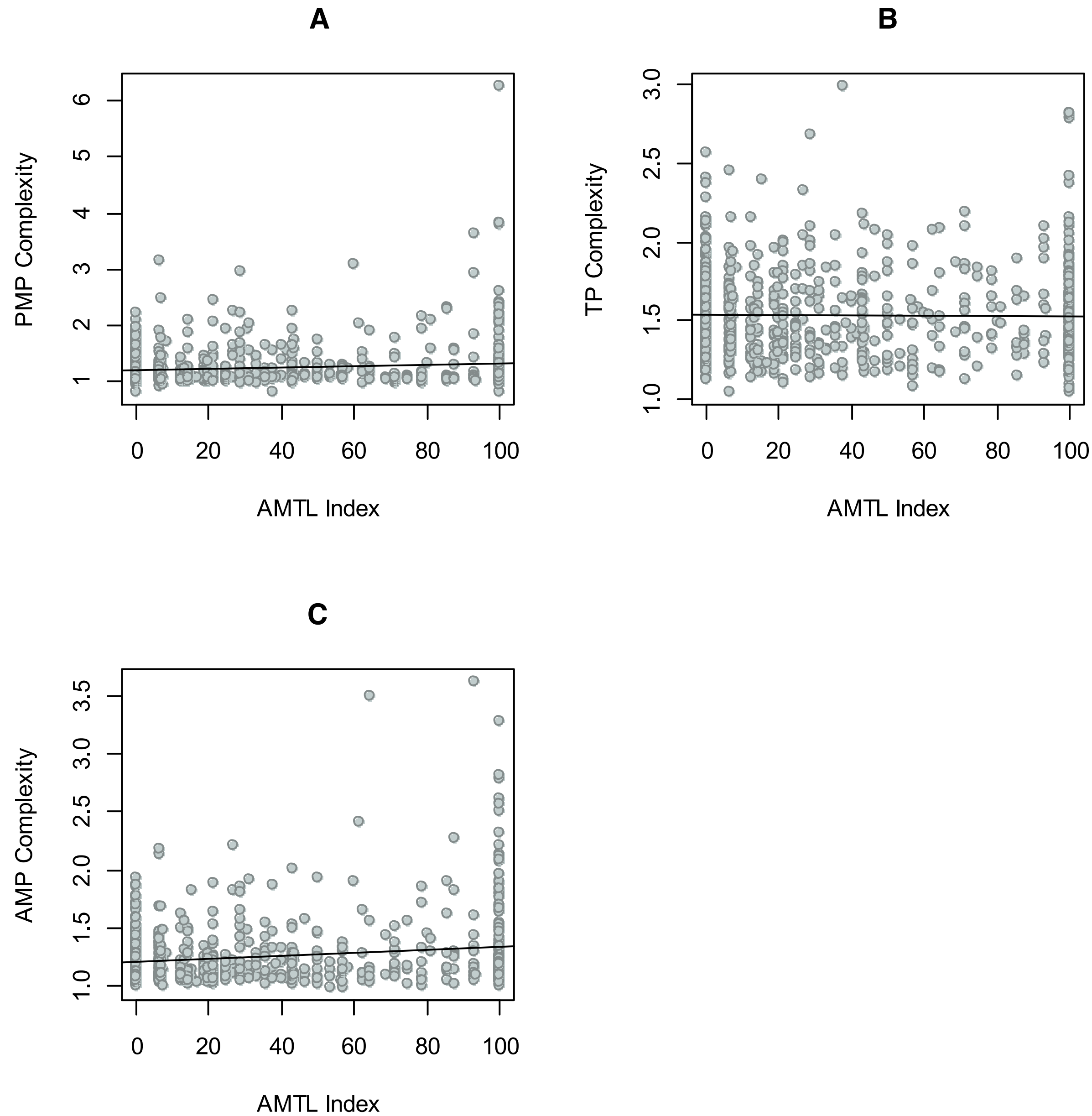


Figure 5-43. Scatterplots of suture complexity and AMTL Index. The black line indicates the least squares regression line. A) PMP complexity and AMTL Index, *rho* = -0.030; B) TP complexity and AMTL Index, *rho* = -0.044; C) AMP complexity and AMTL Index, *rho* = 0.064.

Table 5-28. Relationship of fusion and palatal traits, employing the 15-section/4-phase summary score.

Trait	*rho*
Left accessory lesser palatine foramina	0.029
Right accessory lesser palatine foramina	<0.001
Left marginal crest	0.013
Right marginal crest	0.037
Left lateral groove bridging	0.038
Right lateral groove bridging	0.054
Left medial groove bridging	-0.015
Right medial groove bridging	-0.042
Palatine torus	0.105
Left maxillary torus	0.056
Right maxillary torus	0.036
Left maxillary exostoses	-0.011
Right maxillary exostoses	0.011
Maxillary bone quality	0.175
Palatine bone quality	0.231
Palatal porosity	-0.025
Palate shape	0.029
Transverse palatine suture shape	0.061
Left zygomaticomaxillary suture shape	0.081
Right zygomaticomaxillary suture shape	0.084

Table 5-29. Relationship of age and palatal traits.

Trait	*rho*
Left accessory lesser palatine foramina	-0.023
Right accessory lesser palatine foramina	-0.054
Left marginal crest	-0.059
Right marginal crest	-0.047
Left lateral groove bridging	-0.040
Right lateral groove bridging	-0.034
Left medial groove bridging	-0.092
Right medial groove bridging	-0.115
Palatine torus	0.050
Left maxillary torus	-0.232
Right maxillary torus	-0.211
Left maxillary exostoses	-0.205
Right maxillary exostoses	-0.200
Maxillary bone quality	0.228
Palatine bone quality	0.265
Palatal porosity	-0.007
Palate shape	-0.077
Transverse palatine suture shape	-0.006
Left zygomaticomaxillary suture shape	0.029
Right zygomaticomaxillary suture shape	0.021

Table 5-30. Results from Pearson's chi-square tests of palatal trait frequency for sex, ancestry, and time period.

Trait	Sex X^2	df	*p*-value	Ancestry X^2	df	*p*-value	Time Period X^2	df	*p*-value
Left accessory lesser palatine foramina	11.322	5	0.045[a]	16.891	10	0.077	6.989	5	0.221
Right accessory lesser palatine foramina	23.133	5	<0.001[a]	5.739	10	0.837	2.992	5	0.701
Left marginal crest	2.891	1	0.089	14.695	2	<0.001[a]	9.680	1	0.002[a]
Right marginal crest	3.134	1	0.077	11.828	2	0.003[a]	5.335	1	0.021[a]
Left lateral groove bridging	5.056	3	0.168	98.459	6	<0.001[a]	40.509	3	<0.001[a]
Right lateral groove bridging	7.190	3	0.066	82.871	6	<0.001[a]	23.969	3	<0.001[a]
Left medial groove bridging	2.303	3	0.512	31.561	6	<0.001[a]	18.449	3	<0.001[a]
Right medial groove bridging	3.562	3	0.313	37.686	6	<0.001[a]	8.373	3	0.039[a]
Palatine torus	22.406	3	<0.001[a]	26.201	6	<0.001[a]	1.387	3	0.709
Left maxillary torus	12.405	3	0.006[a]	72.245	6	<0.001[a]	14.678	3	0.002[a]
Right maxillary torus	21.367	3	<0.001[a]	32.806	6	<0.001[a]	0.073	3	0.995
Left maxillary exostoses	17.434	3	0.001[a]	28.212	6	<0.001[a]	20.017	3	<0.001[a]
Right maxillary exostoses	20.796	3	<0.001[a]	31.537	6	<0.001[a]	16.177	3	0.001[a]
Maxillary bone quality	2.940	2	0.230	35.134	4	<0.001[a]	17.343	2	<0.001[a]
Palatine bone quality	2.220	2	0.330	83.098	4	<0.001[a]	65.575	2	<0.001[a]
Palatal porosity	25.341	1	<0.001[a]	73.696	2	<0.001[a]	3.938	1	0.047[a]
Palate shape	3.498	3	0.321	241.152	6	<0.001[a]	28.525	3	<0.001[a]
Transverse palatine suture shape[b]	1.831	3	0.608	125.401	6	<0.001[b]	1.651	3	0.648
Left zygomaticomaxillary suture shape[b]	10.188	2	0.006	49.272	4	<0.001[a]	7.220	2	0.027[a]
Right zygomaticomaxillary suture shape[b]	11.012	2	0.004	40.871	4	<0.001[a]	5.277	2	0.071

[a]Significant at $p < 0.05$

[b]Did not include unobservable/obliterated values

Table 5-31. Spearman's rank-order correlations of mean wear and palatal variants.

Trait	*rho* All	Posterior	Anterior
Left accessory lesser palatine foramina	0.012	0.004	0.023
Right accessory lesser palatine foramina	-0.067	-0.079	-0.008
Left marginal crest	-0.014	-0.003	0.010
Right marginal crest	-0.040	-0.041	0.020
Left lateral groove bridging	0.011	-0.021	-0.022
Right lateral groove bridging	-0.031	-0.059	-0.043
Left medial groove bridging	-0.005	-0.017	-0.013
Right medial groove bridging	0.004	-0.015	-0.011
Palatine torus	0.002	-0.009	0.057
Left maxillary torus	-0.013	-0.067	-0.012
Right maxillary torus	0.009	-0.009	-0.050
Left maxillary exostoses	-0.011	-0.025	-0.036
Right maxillary exostoses	0.067	0.061	-0.016
Maxillary bone quality	0.069	0.049	0.092
Palatine bone quality	0.093	0.085	0.058
Palatal porosity	0.147	0.153	0.010
Palate shape	-0.105	-0.100	-0.054
Transverse palatine suture shape[a]	-0.103	-0.117	-0.008
Left zygomaticomaxillary suture shape[a]	-0.034	-0.072	0.011
Right zygomaticomaxillary suture shape[a]	-0.038	-0.072	0.009

[a]Did not include unobservable/obliterated values

Table 5-32. Spearman's rank-order correlations of AMTL Index and palatal variants.

Trait	*rho*
Left accessory lesser palatine foramina	-0.029
Right accessory lesser palatine foramina	-0.052
Left marginal crest	-0.061
Right marginal crest	-0.051
Left lateral groove bridging	-0.064
Right lateral groove bridging	-0.061
Left medial groove bridging	-0.092
Right medial groove bridging	-0.137
Palatine torus	-0.064
Left maxillary torus	-0.292
Right maxillary torus	-0.324
Left maxillary exostoses	-0.341
Right maxillary exostoses	-0.331
Maxillary bone quality	0.314
Palatine bone quality	0.315
Palatal porosity	0.031
Palate shape	-0.123
Transverse palatine suture shape	-0.008
Left zygomaticomaxillary suture shape	0.003
Right zygomaticomaxillary suture shape	-0.020

Table 5-33. Spearman's rank-order correlations of suture complexity and palatal variants.

Trait	*rho* PMP Complexity	TP Complexity	AMP Complexity
Left accessory lesser palatine foramina	-0.067	-0.020	-0.017
Right accessory lesser palatine foramina	-0.076	0.009	0.030
Left marginal crest	-0.129	0.019	-0.051
Right marginal crest	-0.124	0.038	-0.036
Left lateral groove bridging	-0.025	-0.077	-0.081
Right lateral groove bridging	-0.009	-0.087	-0.068
Left medial groove bridging	0.027	0.009	-0.012
Right medial groove bridging	0.029	0.004	-0.039
Palatine torus	-0.201	-0.179	-0.264
Left maxillary torus	-0.086	-0.113	-0.132
Right maxillary torus	-0.110	-0.054	-0.094
Left maxillary exostoses	-0.040	-0.055	-0.071
Right maxillary exostoses	-0.089	-0.026	-0.085
Maxillary bone quality	0.059	-0.001	0.095
Palatine bone quality	0.033	-0.100	0.072
Palatal porosity	-0.103	0.083	0.054
Palate shape	-0.095	-0.081	-0.089
Transverse palatine suture shape	0.052	0.006	-0.087
Left zygomaticomaxillary suture shape	-0.083	-0.022	-0.083
Right zygomaticomaxillary suture shape	-0.058	-0.028	-0.048

Table 5-34. Results from Pearson's chi-square tests of bilateral palatal traits and Spearman's rank-order correlations for right and left sides per trait.

Trait	X^2	df	*p*-value	*rho*
Accessory lesser palatine foramina	1.940	5	0.857	0.340
Marginal crest	0.043	1	0.836	0.880
Lateral groove bridging	6.632	3	0.085	0.724
Medial groove bridging	0.327	3	0.955	0.585
Maxillary torus	4.122	3	0.249	0.692
Maxillary exostoses	0.231	3	0.972	0.833
Zygomaticomaxillary suture shape	0.707	3	0.872	0.855

Table 5-35. Spearman's rank-order correlations of palatal traits as compared to each other.

Trait	LPF[a]	Crista[a]	Lat bridge[a]	Med bridge[a]	Pal torus	Max torus[a]	Max exo[a]	Max bone	Pal bone	Porosity	Pal shape	TP shape	ZM shape[a]
LPF	-												
Crista	0.065	-											
Lat bridge	0.023	0.033	-										
Med bridge	0.009	0.013	0.191	-									
Pal torus	-0.021	-0.001	0.092	0.049	-								
Max torus	0.011	-0.008	0.171	0.129	0.139	-							
Max exo	-0.005	-0.006	0.106	0.134	0.087	0.417	-						
Max bone	-0.085	-0.095	0.024	-0.016	-0.133	-0.061	-0.151	-					
Pal bone	-0.058	-0.156	0.040	0.025	-0.069	-0.037	-0.124	0.636	-				
Porosity	0.045	0.060	0.022	0.038	-0.135	-0.040	0.017	-0.047	-0.109	-			
Pal shape	-0.025	0.005	-0.055	-0.058	0.043	0.089	0.077	0.015	-0.033	-0.091	-		
TP shape	0.036	-0.014	-0.023	-0.047	0.013	0.047	-0.006	0.007	-0.006	-0.080	0.029	-	
ZM shape	-0.046	0.009	-0.031	0.010	0.050	0.085	-0.020	0.025	0.032	0.027	-0.018	0.047	-

[a]Left side used in comparison.

Table 5-36. Results from multiple regression analyses for 15-section fusion summary score.

Variable	Estimate	Std Error	t value	Probability
Intercept	39.113	3.207	12.195	<0.001[a]
Age	0.227	0.018	12.617	<0.001[a]
Sex	-18.669	3.801	-4.911	<0.001[a]
PMP suture complexity	-7.178	2.481	-2.893	0.004[a]
TP suture complexity	-13.405	1.389	-9.650	<0.001[a]
Age:Sex	-0.062	0.025	-2.504	0.013[a]
Sex:PMP suture complexity	5.757	2.578	2.233	0.026[a]
Sex:TP suture complexity	5.549	1.834	3.026	0.003[a]

[a]Difference is significant at the $p < 0.05$ level.

Table 5-37. Results from multiple regression analyses for fusion ratio summary score.

Variable	Estimate	Std Error	t value	Probability
Intercept	0.544	0.052	10.390	<0.001[a]
Age	0.002	0.000	9.240	<0.001[a]
Sex	-0.517	0.055	-9.434	<0.001[a]
PMP suture complexity	-0.234	0.036	-6.524	<0.001[a]
TP suture complexity	-0.166	0.025	-6.637	<0.001[a]
Palatine torus	0.077	0.032	2.390	0.017[a]
Age:Sex	-0.001	0.000	-3.442	0.001[a]
Sex:PMP suture complexity	0.206	0.037	5.559	<0.001[a]
Sex:TP suture complexity	0.165	0.026	6.235	<0.001[a]
TP suture complexity:Palatine torus	-0.051	0.021	-2.431	0.015[a]

[a]Difference is significant at the $p < 0.05$ level.

Table 5-38. Results from multiple regression analyses for age using the 15-section summary fusion score.

Variable	Estimate	Std Error	t value	Probability
Intercept	25.841	2.225	11.614	<0.001[a]
15-section summary fusion score	0.829	0.091	9.080	<0.001[a]
Sex	7.068	1.207	5.858	<0.001[a]
AF (ancestry DV1)	-2.690	3.173	-0.848	0.397
AMTL Index	0.179	0.021	8.689	<0.001[a]
Left maxillary torus	-10.533	2.137	-4.930	<0.001[a]
AS (ancestry DV2)	2.022	1.673	1.208	0.227
Right maxillary torus	10.870	2.257	4.817	<0.001[a]
Left maxillary exostoses	-0.954	1.201	-0.794	0.427
Summary fusion:DV1	-0.341	0.131	-2.593	0.010[a]
DV1:AMTL Index	0.155	0.034	4.621	<0.001[a]
DV1:Left maxillary torus	12.396	2.523	4.914	<0.001[a]
DV2:Left maxillary torus	8.605	2.790	3.085	0.002[a]
DV1:Right maxillary torus	-11.407	2.482	-4.595	<0.001[a]
DV2:Right maxillary torus	-10.869	2.661	-4.084	<0.001[a]
AMTL Index:R maxillary torus	-0.047	0.022	-2.080	0.038[a]
AMTL Index:L maxillary exostoses	0.067	0.030	2.256	0.024[a]

[a]Difference is significant at the $p < 0.05$ level.

Table 5-39. Results from multiple regression analyses for age using the fusion ratio summary score.

Variable	Estimate	Std Error	t value	Probability
Intercept	36.579	1.842	19.857	<0.001[a]
Fusion ratio summary score	36.492	6.458	5.651	<0.001[a]
Sex	3.356	1.461	2.297	0.022[a]
AF (ancestry DV1)	-4.511	2.540	-1.776	0.076
AMTL Index	0.231	0.019	11.888	<0.001[a]
Left maxillary torus	-11.127	2.179	-5.106	<0.001[a]
AS (ancestry DV2)	-0.515	1.703	-0.302	0.763
Right maxillary torus	11.922	2.298	5.187	<0.001[a]
Left maxillary exostoses	-1.051	1.225	-0.857	0.392
Fusion ratio summary score:Sex	28.363	12.189	2.327	0.020[a]
Fusion ratio summary score:DV1	-19.118	8.807	-2.171	0.030[a]
DV1:AMTL Index	0.127	0.033	3.852	<0.001[a]
DV1:Left maxillary torus	12.888	2.575	5.006	<0.001[a]
DV2:Left maxillary torus	9.285	2.846	3.263	0.001[a]
DV1:Right maxillary torus	-12.056	2.525	-4.774	<0.001[a]
DV2:Right maxillary torus	-11.348	2.716	-4.179	<0.001[a]
AMTL Index:R maxillary torus	-0.055	0.023	-2.380	0.018[a]
AMTL Index:L maxillary exostoses	0.074	0.031	2.435	0.015[a]

[a]Difference is significant at the $p < 0.05$ level.

Table 5-40. Results from multiple regression analyses for age using the 15-section summary fusion score and no interactions.

Variable	Estimate	Std Error	t value	Probability
Intercept	27.268	1.909	14.281	<0.001[a]
15-section summary fusion score	0.713	0.076	9.434	<0.001[a]
Sex	7.085	1.232	5.752	<0.001[a]
AF (ancestry DV1)	-2.674	1.386	-1.930	0.054
AS (ancestry DV2)	0.425	1.304	0.326	0.744
AMTL Index	0.213	0.016	13.601	<0.001[a]
Left maxillary torus	-1.282	0.741	-1.729	0.084

[a]Difference is significant at the $p < 0.05$ level.

CHAPTER 6
DISCUSSION

Research Question 1

The expectation of some degree of association between maxillary suture fusion and age was met. There are positive correlations between known age and fusion scores for all sections of sutures, full sutures, and summary scores, though the strength of the relationship varies based on what locations are analyzed and how. Overall, the correlation of known age and closure, regardless of system employed, is never more than 0.500. Summary scores show higher correlations with age than single sutures or sections of sutures, but there do not appear to be any appreciable differences in correlation values for age and closure when comparing sections of sutures versus full sutures or 4-phase, 3-phase, and binary systems. Because of this, a system akin to Nawrocki (1998) or Wheatley (1996) is preferred due to the inclusion of all palatal sutures, as opposed to examining all sutures but basing the age estimate on the last suture to display any amount of obliteration (Mann et al., 1991). Galera et al. (1998) also found that the use of a summary score produced lower bias values for age estimation from the Terry Collection.

The full suture/binary system, designed for this study to be as close as possible to the description of palatal suture aging provided by Mann et al. (1991) while also attempting to provide some degree of objectivity to the scoring of the sutures, has generally lower correlations per suture and overall than the other qualitative scoring systems. This attempt at standardization was not effective at devising a system to clarify or improve the revised scoring method procedure, likely due to an oversimplification of the variation seen in palatal suture fusion. Because scores of no fusion are fairly common in this sample and have been noted in other studies (e.g., Kokich, 1976; Wang et al., 2006; Beauthier et al., 2010) failure to account for subtleties in fusion across sutures may produce lower correlation values for fusion and age. Thus, again the recommendation is made that a system with multiple phases that encompasses all sutures of the palate is preferred to a fused/non-fused categorical system. An additional recommendation by Mann et al. (1991) is to incorporate other traits of the palate; discussion of these additional traits can be found in sections below.

Comparing the quantitative system, which employs measured values from three full-length sutures, correlation values are similar to the qualitative full suture/4-phase binary systems for all three sutures and similar in summary score to the binary system. Both the quantitative and binary system summary score correlation values are lower than summary scores for 4-phase systems, whether full suture or suture sections are employed. The quantitative system may suffer from the inability to include the IN suture. This suture is the first to fuse, fuses nearly completely in most individuals, and shows the highest correlation values for age in the 15-section and full suture/4-phase systems. Therefore, the inability to quantitatively capture the IN suture likely affects the overall relationship of the quantitative summary score to age.

Scoring the sutures as sections does create a marginally higher correlation between known age and suture closure when an overall summary score is then employed. However, condensing categories into a no fusion-some fusion-complete fusion scoring system does not improve the correlation between known age and suture closure. In fact, the simplest system – scoring fusion as present or absent – produces the lowest correlation value between age and closure. The reduction of the number of categories for scoring may aid in decreasing interobserver error but it does not markedly improve the relationship between known age at death and suture closure.

Concerning developmental asymmetry, there are no large-scale differences in correlation values of suture fusion and age for left and right sides. Where significance was tested for sides, such as with the TP suture, no significant differences between left and right sides are observed. Either side is therefore appropriate for use in age estimation, but here it is recommended that if a choice must be made then the right side be used for the TP suture due to a slightly higher correlation with known age at death. Methods that combine left and right sides, such as component methods, have been previously recommended (McCormick and Kenyhercz, 2015), and this recommendation is further supported in this research, where the summary score that includes both sides has the highest correlation with age.

The correlation values for the control sutures are lower than those for the palatal sutures. Of the three scored, the nasofrontal suture has not only the lowest *rho* for the control sutures, but also of all sutures examined. Right and left zygomaticomaxillary sutural fusion is nearly identical, indicating symmetry in sides. The difference between values for the nasofrontal and zygomaticomaxillary sutures is also interesting in terms of functional considerations because the nasofrontal suture is likely subjected to less force from mastication than the zygomaticomaxillary sutures or the palatal sutures (Rogers, 1984; Wroe et al., 2007). The relationship of biomechanical variables and fusion is discussed further below.

What is clear is that the palatal sutures alone do not demonstrate correlation values that indicate a large amount of variation in age can be accounted for by variation in suture closure, though they do perform better in terms of age than the other facial sutures tested. In order to be a powerful tool for age estimation, the relationship between indicator (biological age) and chronological age must be fairly strong and age progressive changes should be easily classified, unidirectional, and occur at similar times across populations (Milner and Boldsen, 2012a). This is not the case when considering palatal sutures in isolation, though as others have found, the fusion of palatal sutures alone does relate to age and may be useful for general categorization of individuals into broad age categories (Wheatley, 1996; Ginter, 2005; Sakaue and Adachi, 2007; Beauthier et al., 2010; Apostolidou et al., 2011; Siegel and Passalacqua, 2012). Based on the lack of a clear linear relationship between fusion and age and the fact that many of the age ranges per fusion score show overlap, it is not possible to categorize certain combinations of closure into phases. Together the results indicate that other variables are influencing palatal suture closure.

Research Question 2

While there were several outliers in the female group, overall females have much lower average summary fusion scores than males. This indicates that males undergo fusion earlier than females, consistent with previous studies (Ashley-Montagu, 1938; Mann et al., 1991; Nawrocki, 1998). Because of this difference in fusion, sex must be considered as a meaningful contributor to variation in palatal suture closure. It is difficult to tie these differences to sexual dimorphism, as overall palate size was not one of the variables considered in this research. However, more likely than differences in size is an underlying difference between the sexes in aging and the progression of palatal fusion, which may relate to genetics or differing environmental conditions. If fusion were a solely maturational process, it would be expected that females would undergo fusion earlier than males, as is the case in overall skeletal growth and development. Thus this difference in the sexes points not only to intrinsic and extrinsic differences in males and females concerning suture obliteration, but it also suggests that fusion differs from maturation.

Significant differences in summary fusion scores were also observed for ancestral groups. Of the three ancestral groups examined here, Asian individuals have the lowest mean suture scores, African individuals have the highest, and European individuals fall between these two groups. This differs from the results of Mann et al. (1991) and Meindl and Lovejoy (1985), who found no differences between European and African Americans, but it is consistent with Galera et al. (1998) and Nawrocki (1998), who did find differences. Galera et al. (1998) found a higher correlation with age and fusion for African American individuals from the Terry Collection, and Nawrocki (1998) found that palatine sutures played more of a role in equations for individuals of African ancestry than those of European. Neither study tested palatal suture closure in individuals of Asian ancestry nor commented on the amount of fusion as greater in one group over another. Because the Mann et al. (1991) method does not provide for differences among ancestral groups, this likely explains the poor performance for Japanese individuals observed by Sakaue and Adachi (2007), especially considering this group had lower average fusion scores than both African and European groups. The differences in fusion scores among the ancestral groups point to possible differences in underlying genetic make-up and/or environmental factors. These differences are often why regionally-specific age estimation methods are recommended, though large and diverse samples can alleviate the need for these types of modifications (Brooks and Suchey, 1990; Konigsberg et al., 2008).

For the palatal sutures both time periods exhibit nearly identical average fusion scores and distributions of fusion scores. The results of this study agree with Zambrano (2005), who found no significant secular trends in vault suture closure between historic and modern individuals. However, they are contrary to the finding that fusion occurs more slowly in modern individuals (Nawrocki, 1998). A decrease in fusion for modern individuals could be related to improved nutrition and decreased dental disease (i.e., loss of teeth correlated with more fusion). However, there is no systematic trend observed in this sample for decreased fusion in modern over historic individuals, therefore inferences about improved nutrition and decreased dental disease cannot be made.

An absence of secular trends in palatal suture fusion is an important finding because it means that the method as presented here can be used for both modern and historic individuals; time period does not need to be taken into account when considering age estimation from the palate. It also suggests that secular trends seen in earlier maturation and epiphyseal fusion in modern individuals are not carried over into the palate (Langley-Shirley and Jantz, 2010). It is also important to consider that palatal suture fusion, with the exception of the IN suture, occurs largely in adulthood, at a time period when skeletal maturation has completed in the rest of the skeleton. Thus, as with the results from sex, no difference in time period may further suggest that fusion is not tied to maturation and instead represents a separate process, related in part to age.

When considering ancestry and temporality together, it is seen that differences in fusion are significant for ancestry but not for time period. Because differences are seen ancestrally but not temporally, this suggests variation in fusion is due at least in part to genetics, rather than environment. This is because individuals of different ancestral backgrounds but within the same temporally-delimited skeletal collection are not likely subjected to a large amount of variation in environment (Sparks and Jantz, 2002). The absence of temporal differences thus further strengthens the difference as being attributed to intrinsic factors rather than plasticity to environmental factors.

Research Question 3

Dental Wear

The relationship of mean wear scores and fusion scores is positive, indicating that for an increase in wear score there is also an increase in fusion score. The reverse is also true – for low fusion scores individuals exhibit low wear scores. The hypothesis that low wear, indicative of decreased bite force, would be related to increased fusion is not supported by these data. Interestingly, the highest correlation values for fusion and wear are actually found with mean anterior wear and fusion scores. Based on the contact surfaces of the anterior dentition, it is unexpected that the highest relationship between wear and fusion would be for the anterior teeth since the posterior teeth contribute more to overall occlusal loading based on their larger contact surfaces. The presence of a relationship between anterior wear and fusion does suggest that anterior wear may be driving posterior palatine suture fusion, if the palate can reasonably be modeled as a plate, where stress and strain to the anterior portion causes the most force in the posterior aspect. While it could be suggested that a positive relationship between fusion and wear may be explaining fusion as a means to strengthen a palate that is subjected to higher loading (Herring, 1972), the distribution of wear scores is also an important consideration. Wear scores in the entire sample are low, even for molars with large occlusal surfaces, so this variable may not be accurately portraying bite force in the maxilla, regardless of the relationship found with fusion.

Wear differs by age and demographic group. Age and dental wear show a positive association, which is not surprising considering dental wear has long been employed for age estimation, albeit with varying rates of success (Buikstra and Ubelaker, 1994; Mays, 2014). The presence of lower female wear as compared to males is not as clear, though this may be explained by sexual dimorphism and an overall smaller masticatory complex in females as compared to males. With larger muscles, males have greater overall bite force and thus are more likely to have greater wear. Ancestral differences are even less clear, especially since they differ based on which mean wear score is employed. As with sex, higher wear may be attributed to overall palatal size, since Europeans generally have smaller palates and could also have smaller mean wear. However, ancestral differences in wear could also be attributed to diet, and without knowing the food consumed by different groups it is not possible to determine if this is the case. In this sample, historic individuals always have higher wear than modern individuals. This result supports the idea that modern individuals are eating foods that are less tough and gritty (Wescott and Jantz, 2005; Skorpinski, 2014).

Antemortem Tooth Loss

Calculating the AMTL Index was a means of quantifying one of the variables given by Mann et al. (1991) to be considered in conjunction with fusion of the palatal sutures. The recording of complete edentulism versus at least one tooth present was also employed for this purpose. The AMTL Index displays a positive association with fusion, so that an increase in AMTL Index means an increase in fusion score. This result does correspond to the expected outcome, in which individuals with decreased dentition and decreased occlusal loading also display decreased bite force and increased fusion (Engström et al., 1986). Wheatley (1996) also found that partial to complete tooth loss was associated with earlier fusion of the sutures. The decrease in fusion could be related to a narrowing of the sutures from a decrease in tension, causing sutural margins to approach and enabling bony bridging. These results are further confirmed when comparing completely edentulous individuals to individuals with at least one tooth, and finding that there is a significant difference in fusion scores between the two groups.

AMTL Index differs by age, ancestry, and time period, but not between the sexes. For age, increased age is associated with increased tooth loss, which can be related to greater loss over time due to use or disease. Mays (2014) also found AMTL, as measured by the height of the posterior mandibular corpus, to be associated with age. Europeans have higher rates of tooth loss than Africans or Asians, though why this difference is present is not clear. Between modern and historic individuals, modern individuals have higher mean AMTL than historic. Given modern dental practices, this result is somewhat surprising since teeth can often be restored rather than fully removed. Dental wear and AMTL Index show a positive relationship, with the strongest correlation between tooth loss and anterior wear. In terms of indicating occlusal loading, these two variables do agree with one another: an increase in wear is related to an increase in tooth loss, and vice versa, though again the highest correlation is with the anterior teeth, which is unexpected.

Sutural Complexity

Sutures in the palate are not complex, with the most complexity displayed in the TP suture. The complexity values for the AMP and PMP are nearly identical, which is logical because these sutures represent anterior and posterior portions of the same midpalatal suture. Simple sutures are indicative of a largely tensile loading environment (Rafferty and Herring, 1999; Herring and Ochareon, 2005). Since palatal sutures tend to resist large-scale fusion, the tensile environment may explain observed fusion patterns.

The relationship of fusion and complexity is negative, indicating that increased sutural complexity is associated with decreased fusion. This means that sutures that are close to straight are more likely to fuse than sutures of a more sinuous nature. As with AMTL, a straight suture may have a proclivity towards bridging if the margins approach one another.

Sutural complexity shows little to no relationship with age, indicating that in terms of adulthood, complexity does not increase with age in the palatal sutures (Zollikofer and Weissmann, 2011). This is also related to the completion of growth and development of the palate and facial skeleton in adulthood, regardless of smaller scale changes in size and shape that may occur during the adult years (Albert et al., 2007). If growth is complete, then it may not be possible for sutures to continue to adapt to changing stresses, and the adult form of sutures may in fact be static (Herring, 1972; Zollikofer and Weissmann, 2011).

Males have less complex sutures than females. When considered alongside differences in fusion for the sexes, decreased complexity in males corresponds to higher fusion ratios in this group. This suggests that less complex sutures are more likely to fuse than more complex sutures. Asian individuals have higher mean sutural complexities for the PMP and AMP sutures, while for the TP suture Europeans have the highest mean sutural complexity. These results are interesting in light of traditionally employed methods of ancestry determination – sutural complexity indicating Asian and a jagged/M-shaped TP suture indicating European (Rhine, 1990; Gill, 1998; Hefner, 2009). For the AMP suture, complexity is slightly higher in modern individuals as compared to historic. There is no relationship between time period and complexity for the PMP and TP sutures. These relationships or lack thereof do not seem to relate to fusion as there are no significant differences in fusion between modern and historic individuals.

Biomechanics and Fusion

One of the most striking observations to be made from the three variables examined as biomechanical proxies is that sutural complexity of the PMP, TP, and AMP sutures appears to show very little association with wear or AMTL Index, but it clearly influences fusion. When considered alongside sex and ancestry the pattern becomes even clearer. In groups with simpler sutures, such as males and Africans, average fusion summary scores are higher than groups with more complex sutures, such as females and Asians. This indicates that a more complex suture is less likely to fuse than a simpler suture, though the exact mechanism is not clearly elucidated by this study. Sutural complexity does not exhibit a clear secular trend, which also is logical given the similarity in summary fusion scores between historic and modern individuals.

While complexity may not speak to dietary or health differences in individuals, as it is not related to wear or AMTL Index, it does appear to offer some predictive value in terms of fusion. Hotzman (2004) also found that mid-palatal suture complexity was poorly correlated with food toughness, and she suggested that complexity might be related more to age; this relationship is not supported by the data in this study. The weak relationships between wear and complexity and AMTL Index and complexity suggest that sutures are already adapted morphologically to their loading environments and sutural complexity is likely not related to forces sustained throughout an individual's lifetime. This again supports a lack of plasticity in sutural morphology in adulthood, as all individuals in this study were over the age of 20 years.

Control suture fusion could not be compared to complexity since complexity was not measured for these sutures, but it was compared to both wear and AMTL Index. Wear and fusion show very low relationships for all mean wear scores and all control sutures except for anterior wear and zygomaticomaxillary sutures. The weak relationship for fusion of the nasofrontal and wear is consistent with lower loading in this region of the facial skeleton, with higher loading in the zygomatic region of the maxilla (Rogers, 1984; Wroe et al., 2007). However, fusion for the nasofrontal and zygomaticomaxillary sutures is positively associated with AMTL Index, and the correlation values are nearly identical. While these values indicate a moderate positive relationship between control suture fusion and tooth loss (i.e., higher fusion related to more tooth loss), the similarity of nasofrontal and zygomaticomaxillary suture values indicates that there is not in fact a clear difference in these regions if AMTL does indeed indicate differences in occlusal loading.

Research Question 4

The large number of additional palatal traits scored complicates analyses of relationships. What is immediately clear when examining correlation values across all traits, age, groups, and biomechanical variables is that very few traits show strong associations with fusion, age, biomechanical variables, or each other. Concerning frequencies by sex, ancestry, and time period, about half of the traits show significant differences in frequency among sex or time period, while the majority of traits have significantly different frequencies for ancestry.

Very few palatal traits show any amount of association with fusion, with the exception of bone quality and, to a small extent, the palatine torus. The relationship of fusion to bone quality – more fusion seen with decreased bone quality – does support the subjective assessments included in the Mann et al. (1991) method. It is also consistent with fusion occurring alongside bone degradation as a means of strengthening the palate (Herring, 1972). However, the relationship of fusion and bone quality, while moderate when considered in isolation, is not significant when considered with multiple other traits. The slight relationship of fusion and palatal tori is likely related to the fact that these protrusions are located directly on a suture. Therefore a slight positive association indicates that when mounding is present, more fusion is also observed, perhaps due to the proximity of the sutural margins in these instances. The same relationship does not hold for maxillary tori or exostoses, suggesting that not only are these traits not related to fusion, but also that either fusion or these growths are not correlated with biomechanical processes in the palate.

It was thought that overall suture shape might affect sutural fusion since shape alters the general morphology of the suture. Comparisons of fusion and ordinally scored suture shape for the TP and zygomaticomaxillary sutures indicate that the relationship of shape and fusion, whether fusion was scored ordinally or measured, is very weak (close to 0). While complexity is related to fusion for the TP suture, the ordinal score of the shape of the TP and fusion is not. This suggests that while these shapes may be helpful in classifying observed variation for ancestry or other group differences, they are not informative in summarizing shape as it relates to actual complexity and do not influence the presence or absence of fusion along these given sutures.

As with fusion, most traits show very little relationship to age, with the exception of the maxillary tori and exostoses and bone quality. The negative relationship of tori and exostoses with age is also related to the positive correlation of tooth loss and age. As teeth are lost, alveolar bone starts to resorb due to the lack of occlusal loading. Based on the relationships of age, AMTL, and tori/exostoses, resorption does seem to affect torus and exostosis expression on the alveolar bone of the maxilla in that there is reduced expression of internal and external bony growth. Additionally, there is a small negative relationship with age and medial palatine groove bridging. Like maxillary tori and exostoses, this suggests a decrease in expression with increased age; the same negative relationship is also seen between medial bridging and the AMTL Index. Together, the results of age, fusion, AMTL Index, and maxillary torus/exostosis expression indicate that decreased masticatory loading from tooth loss results in observable osseous changes in the palate. This is in agreement with Mann et al. (1987) and Bass (2005), who describe smoother and less rugose palates with advanced age.

Bone quality also shows the same relationship with age as it does with fusion – with increased age poorer bone quality is more common – providing further support for a relationship of fusion, age, and overall bone quality as mentioned in Mann et al. (1991). Porosity, as measured here (present or absent), shows no association with age. This could indicate that older individuals are not displaying increased porosity as might be expected with bone density loss, or it is indicative that this variable poorly captures bone quality. There is a need to better quantify bone density as maxillary bone in particular shows high degrees of porosity and pitting even for healthy, dense bone in young individuals.

Females show greater degrees of expression of palatal tori, while for maxillary tori and exostoses males have greater degrees of expression. For the palatine tori this is in agreement with previous research (Miller and Roth, 1940; Woo, 1950; Eversole, 2011). The results for maxillary tori and exostoses are less clear since fusion is negatively correlated with these traits. Since males have higher rates of fusion, it would be expected that they would have reduced expression in terms of maxillary bony growth, while in fact the opposite is observed in this sample. However, the AMTL Index does not differ significantly between males and females, so it is possible that the difference in maxillary exostoses and tori is actually related to differences among the sexes versus a solely biomechanical explanation.

Additional differences by sex include higher counts of lesser palatine foramina for males, consistent with what is reported in Hauser and De Stefano (1989); increased porosity for males; and a larger occurrence of traits that could not be scored due to obliteration for males. A zygomaticomaxillary shape of only one angle is more common for males than females but this could be biased by the higher number of males scored as obliterated. It is not clear what biological significance these differences signify, and all other traits do not differ in frequency between the sexes, which is likely why they have not been used in sex determination (Hauser and De Stefano, 1989).

Since nonmetric traits are often used to aid in ancestry assessment, it is not surprising that nearly all palatal traits show significant differences in frequencies by ancestry. This indicates that palatal traits are useful for assessing population affiliation, though, as Hefner (2009) pointed out, trait expression varies across all groups; it is just the frequencies that are significantly different. Caution should still be exercised when examining a trait in isolation. Notably, palatal shape and TP suture shape follow expected ancestral trait expressions (Rhine, 1990; Gill, 1998; Hefner, 2009; Maier, 2013). The lesser palatine foramina are the only palatal traits scored that do not show significant differences in frequency by ancestry.

Significant differences in frequencies of palatal traits do exist between modern and historic individuals, to include these traits: marginal crest, lateral and medial bridging, left maxillary tori and exostoses (but not right), bone quality, porosity, palate shape, and left zygomaticomaxillary shape. The difference in significance for bilateral traits – left is significant while right is not – is not clear. For the lateral and medial bridging, historic individuals show greater expression of these traits. When considered alongside AMTL and bone quality, which are higher for modern individuals, there again appears to be a relationship among bony palatal growth, bone quality, and tooth loss, though modern individuals more frequently display the presence of a marginal crest. The same trend is not observed for tori and exostoses. With palate shape differences, the make-up of the historic group should be considered since the majority of African individuals are historic and they were less frequently encountered in modern collections. Thus the difference in palate shape can again be interpreted as a difference in ancestry, versus a secular trend.

The majority of palatal traits and the three biomechanical variables show low to no association. Wear has a negative association with palate and TP suture shapes and a positive association with porosity in both the overall and posterior mean wear scoring systems. This indicates that the posterior dentition, with larger occlusal surfaces, may be slightly affecting porosity of the palate. This relationship seems tenuous, however, when it is known that porosity is most often visible on the anterior portion of the maxilla. The anterior mean wear score and palatal porosity have no association, indicating that in the overall mean wear score it is the posterior dentition that is causing an association to be seen in the overall mean wear score. Biologically, it is not clear what effect wear alone could have on palate and TP suture shapes but with significant differences in overall and posterior mean wear scores by ancestry, it is more likely that the differences seen here are again related to sample composition in terms of ancestry.

The AMTL Index was already discussed above in terms of its relationship to bite force and palatal variants (i.e., more tooth loss associated with poor bone quality and decreased alveolar bone growth). When considered alongside wear in terms of palatal variants, it is seen that AMTL may be a better indicator of bite force as wear has little to no relationship to bone quality or maxillary bony growth. In fact, the *rho* values for AMTL Index when compared to maxillary tori and exostoses and maxillary and palatine bone quality are the highest for any palatal traits among wear, AMTL Index, and sutural complexity.

Palatal traits and complexity generally have weak associations with the exception of the palatine torus. This trait is negatively associated to complexity, and with more complexity, there is a tendency to have no or weak expression of the torus. As compared to fusion, this is the opposite effect. With fusion, there is a positive association with palatine torus expression. Thus the presence of a palatal torus indicates that fusion may be slightly more common, while complexity will be less common. This agrees with more fusion seen in less complex sutures for this sample.

Palatal traits show bilateral expression that is not significantly different between left and right sides. This indicates that these traits are not developmentally asymmetrical and either side may be scored with similar results. For ease of comparison the left side was used when comparing all palatal traits so as not to introduce correlations between left and right sides of the same traits. Not surprisingly, similar traits show higher relationships than dissimilar traits (e.g., palatine and maxillary bone quality, maxillary tori and exostoses). This result is not unexpected due to the location of these traits on the palate and the fact that the palate, regardless of being composed of multiple bony elements, is an integrated unit. Additional positive associations of traits indicative of osseous growth indicate that tori, exostoses, and bridging are found more commonly in the same individual. Negative associations are largely present among variables of bony growth and bone quality, indicating that when bone quality is poor, expression of tori, exostoses, and bridging is reduced. Along with age and fusion, these results further suggest that increased age and fusion are associated with decreased bony growth in the palate. Without a longitudinal study it is not possible to tell if these traits were initially present and resorbed due to age or reduced bite force or if these traits were never present. Their association with age, fusion, and each other would appear to suggest the latter, though their relationship to ancestry should not be overlooked.

The Final Step

The results and above discussion demonstrate that it is not enough to simply look at palatal fusion in terms of age. There are a wide array of factors that contribute to fusion of the sutures and prediction of age using palatal morphology, which necessitates a multi-faceted approach. While nearly all morphological variables were examined in this study, there are more than likely factors that cannot be observed macroscopically, including genetic factors, that contribute to palatal variation in terms of age, group affiliation, biomechanics, and palatal variants. The addition of a variable to estimate size – geometric mean of the measured chords per individual – was not shown to significantly impact fusion or age prediction.

Fusion, whether scored ordinally or measured by suture, is most influenced by age, sex, sutural complexity, palatine torus expression, and interactions of these variables. While other factors individually contribute to palatal fusion, they are not significant effects when considered alongside all factors. With significant terms and interactions, variation in fusion as measured by qualitative and quantitative summary scores is described by approximately 50% of the variation in explanatory variables. These two models leave another 50% of fusion to be explained, indicating that while they have significant effects on palatal suture fusion, part of the picture is still missing.

For age, there are far more variables that contribute to variation in age prediction, though the coefficient of determination is very close to that of fusion – approximately 50% of the variation in age prediction is accounted for by variation in the explanatory variables. Comparing the equations produced for age to those produced by Nawrocki (1998) that also included information on sex and ancestry, it is seen that standard errors range from 7.0 to 11.0 years, as compared to 14.6 years in this study when using the 15-section summary fusion score. The overall equation using the sum of all sutures provided by Nawrocki (1998) and found to be the best for predicting age regardless of sex or ancestry by Zambrano (2005) has a standard error of 12.9 years. The higher standard error for the solely palatal suture equations indicates that combining the palatal sutures with other cranial sutures is warranted.

CHAPTER 7
CONCLUSIONS

This research has shown that of the various ways of scoring suture fusion, the most effective is the inclusion of multiple sections in a four-phase ordinal scoring system. Measurement of the sutures is less effective at capturing variation in suture fusion. Differences in fusion exist for the sexes and three ancestral groups examined; no secular differences were noted.

Of the biomechanical traits analyzed in relation to fusion, sutural complexity shows the best relationship to fusion. More complex sutures are less likely to fuse than simple sutures. Wear was not shown to be a good indicator of bite force in terms of fusion; the AMTL Index is preferred. The relationships of the biomechanical proxy variables indicate that complexity is not strongly associated with either wear or AMTL Index, but that the latter are associated with one another. Palatal variants showed little relationship to fusion.

In terms of age, the most significant effects on age based on this sample included fusion, sex, ancestry, AMTL Index, maxillary tori/exostoses, and interactions of these variables. The resultant equation to generate an age estimate from these variables does so with approximately 15 years of error on either side of the point estimate, which results in a very large and inaccurate age estimate. For a more accurate age estimate, the interval would need to include two standard errors ($\pm$ 30 years), which is clearly lacking in precision. However, the presence of fusion as one of the significant effects on age and age as one of the significant on fusion does support the relationship of these two variables, though it is weaker than hoped for use as an age predictor.

While the palatal sutures do not appear to perform with enough accuracy or precision on their own, they may contribute to multiple indicator methods. With limited age estimation methods for the adult skull, it would be beneficial to combine palatal sutures with other cranial sutures, and dental observations such as tooth loss and dental wear. This more comprehensive view of age estimation from the skull is helpful when considering that the cranium and mandible are highly recognizable and thus encountered frequently by the biological anthropologist. A consideration of method usage is also important, since differences do exist between age estimation in the forensic realm versus age estimation for a sample of multiple individuals that can be seriated prior to producing age estimates.

While this research examined variability in age based on traits of the palate and attempted to account for variation in terms of sex, ancestral/geographic origin, temporality, mechanical loading patterns, and developmental asymmetry, it did not investigate health, nutritional, socioeconomic status or individual rates of senescence. To provide an even more comprehensive view of aging and fusion in the palate, it would be helpful to fully investigate all variables. There are certain limitations, namely the availability of these data in reference collections, but more invasive analyses, such as isotopes, might further elucidate dietary differences. Additionally, a “full-body” approach in which pathological conditions and antemortem trauma for the entire skeleton were noted could serve to contribute to the attribution of fusion to age or other effects.

Further research should also consider examining internal features of the palatal sutures to capture more fine-scale detail. Fusion generally occurs first internally, and then progresses outwards, so there is some level of detail being missed with a uniquely macroscopic, external view. This could be accomplished with micro-computed tomography scanning. An additional consideration would be to test bone density in different regions of the palate to examine how bone density quantitatively relates to age, fusion, wear, complexity, and tooth loss.

Finally, no age estimation technique is complete without an examination of interobserver error. While the palatal sutures and the palate as a whole are not optimal for age prediction, it is still important to see how different people score the various features of the palate. If the method produces both large age intervals and suffers from poor replicability, it cannot be recommended for age estimation.

APPENDIX A
DATA COLLECTION WORKSHEET

Specimen/Case # ______________________ ❑ In-person ❑ Photograph

Collected by ____________________ Date________________

Obliteration			
Suture		Side	Score
	1-cm sections		
Incisive (IN)			
1	IN lateral	R	
2	IN lateral	L	
3	IN medial	R	
4	IN medial	L	
Posterior median palatine (PMP)			
5	PMP anterior	M	
6	PMP posterior	M	
Transverse palatine (TP)			
7	TP in GPF	R	
8	TP in GPF	L	
9	TP lateral	R	
10	TP lateral	L	
11	TP medial	R	
12	TP medial	L	
Anterior median palatine (AMP)			
13	AMP anterior	M	
14	AMP mid	M	
15	AMP posterior	M	
	Complete		
1	IN	M	
2	PMP	M	
3	TP in GPF	R	
	TP in GPF	L	
4	TP	R	
	TP	L	
5	AMP	M	
	Control		
1	Nasofrontal	M	
2	Zyg-max	R	
	Zyg-max	L	

Score	Description
0	No obliteration
1	1-49% obliteration
2	50-99% obliteration
3	100 % obliteration

Notes:

Character states			
Suture		Side	Score
1	TP*	M	
2	Zyg-max	R	
	Zyg-max	L**	

*if obliterated do not score
**if asymmetrical, L preferred

Torus ❑ Mounding ❑

Notes:

Transverse Palatine (TPS)

Score	Description
0	Crosses palate perpendicular to med. palatine suture, no significant anterior or posterior deviations (straight)
1	Crosses palate perpendicular to med. palatine suture, with significant anterior deviation (bulging) present
2	Crosses palate, deviates anteriorly and posteriorly (M-shaped)
3	Crosses palate perpendicular to med palatine suture, posterior deviation (bulging) present

Zyg-max (ZS)

Score	Description (ignore infraorbital suture)
0	No angles, greatest lateral projection at inferior margin of malar
1	1 angle, greatest lateral projection near midline of malar
2	2+ angles, variable position for greatest lateral projection

See also figures from Hefner (2009)

Additional observations:
Max bone quality ❑good ❑mod. ❑thin
Pal bone quality ❑good ❑mod. ❑thin
Porosity? ________________

Spurs ❑P-L max ❑P-L pal ❑TP
❑lat max ❑lat pal ❑other

AM trauma ❑

Peri trauma ❑

Other:

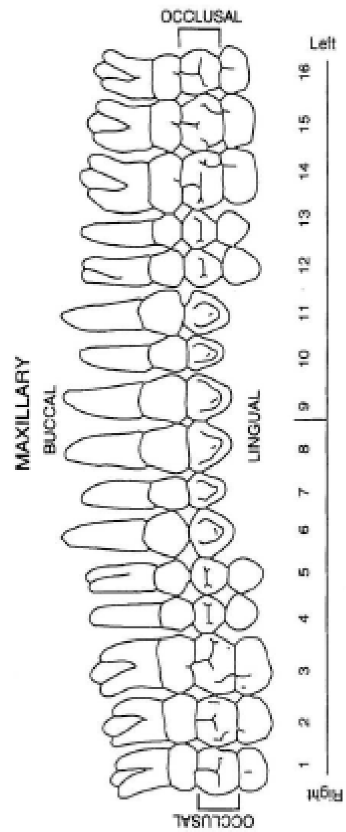
Figure A-1. Data collection worksheet page 1.

Specimen/Case # ______________________ ❑ In-person ❑ Photograph

Collected by ______________________ Date______________________

Dental Inventory & Wear			
Tooth	**Presence**	**Wear**	**Total**
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			

Note additional observations here:



Presence

Score	Description
1	Present, not in occlusion
2	Present, in occlusion, development complete
3	Missing, no associated alveolar bone
4	Missing, AMTL (resorbed/resorbing)
5	Missing, Postmortem TL (no resorption)
6	Missing, congenital absence/unobservable
7	Present, damaged (no measurement possible, other observations possible)

Wear

See Smith and Scott scoring worksheets (from *Standards*)

Photographs

❑ Cranium, inferior view
❑ Cranium, anterior view
❑ Palate, occlusal
❑ NF
❑ ZM

Digitized (ImageJ) (for ea. suture)

❑ Chord
❑ Total length
❑ % obliteration

Notes:

Figure A-2. Data collection worksheet page 2.

APPENDIX B
PALATAL TRAIT FREQUENCIES BY GROUP

Table B-1. Left accessory lesser palatine foramina frequencies by sex.

	0		1		2		3		4		5	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Female	7	46.7	191	55.4	127	43.1	45	47.9	4	40.0	1	100.0
Male	8	53.3	154	44.6	168	56.9	51	53.1	6	60.0	0	0.0
Total	15		345		295		96		10		1	

Table B-2. Right accessory lesser palatine foramina frequencies by sex.

	0		1		2		3		4		5	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Female	15	78.9	189	53.2	138	48.1	28	32.6	4	28.6	1	100.0
Male	4	21.1	166	46.8	149	51.9	58	67.4	10	71.4	0	0.0
Total	19		355		287		86		14		1	

Table B-3. Left marginal crest frequencies by sex.

	0		1	
	n	%	*n*	%
Female	178	52.8	197	46.4
Male	159	47.2	228	53.6
Total	337		425	

Table B-4. Right marginal crest frequencies by sex.

	0		1	
	n	%	*n*	%
Female	176	53.0	199	46.3
Male	156	47.0	231	53.7
Total	332		430	

Table B-5. Left lateral groove bridging frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	128	52.7	187	46.1	50	56.2	10	41.7
Male	115	47.3	219	53.9	39	43.8	14	58.3
Total	243		406		89		24	

Table B-6. Right lateral groove bridging frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	129	50.8	199	46.5	39	63.9	8	42.1
Male	125	49.2	229	53.5	22	36.1	11	57.9
Total	254		428		61		19	

Table B-7. Left medial groove bridging frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	34	58.6	168	49.0	159	47.9	14	48.3
Male	24	41.4	175	51.0	173	52.1	15	51.7
Total	58		343		332		29	

Table B-8. Right medial groove bridging frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	37	59.7	166	47.6	160	49.5	12	
Male	25	40.3	183	52.4	163	50.5	16	
Total	62		349		323		28	

Table B-9. Palatine torus frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	121	53.5	193	43.2	55	67.1	6	85.7
Male	105	46.5	254	56.8	27	32.9	1	14.3
Total	226		447		82		7	

Table B-10. Left maxillary torus frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	221	55.0	111	42.9	31	39.7	12	52.2
Male	181	45.0	148	57.1	47	60.3	11	47.8
Total	402		259		78		23	

Table B-11. Right maxillary torus frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	211	56.3	120	43.8	42	43.8	2	11.8
Male	164	43.7	154	56.2	54	56.3	15	88.2
Total	375		274		96		17	

Table B-12. Left maxillary exostoses frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	275	52.3	88	48.1	11	24.4	1	12.5
Male	251	47.7	95	51.9	34	75.6	7	87.5
Total	526		183		45		8	

Table B-13. Right maxillary exostoses frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	279	53.9	82	43.6	13	27.7	1	11.1
Male	239	46.1	106	56.4	34	72.3	8	88.9
Total	518		188		47		9	

Table B-14. Maxillary bone quality by sex.

	0		1		2	
	n	%	*n*	%	*n*	%
Female	247	48.2	74	47.4	54	57.4
Male	265	51.8	82	52.6	40	42.6
Total	512		156		94	

Table B-15. Palatine bone quality by sex.

	0		1		2	
	n	%	*n*	%	*n*	%
Female	115	46.0	97	48.5	163	52.2
Male	135	54.0	103	51.5	149	47.8
Total	250		200		312	

Table B-16. Palatal porosity by sex.

	0		1	
	n	%	*n*	%
Female	164	61.9	211	42.5
Male	101	38.1	286	57.5
Total	265		497	

Table B-17. Palate shape frequencies by sex.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Female	113	51.8	68	47.2	189	49.3	5	29.4
Male	105	48.2	76	52.8	194	50.7	12	70.6
Total	218		144		383		17	

Table B-18. Transverse palatine suture shape frequencies by sex.

	0		1		2		3		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%
Female	98	50.3	104	51.0	136	53.8	26	60.5	11	16.4
Male	97	49.7	100	49.0	117	46.2	17	39.5	56	83.6
Total	195		204		253		43		67	

[a]Suture unobservable due to obliteration.

Table B-19. Left zygomaticomaxillary shape frequencies by sex.

	0		1		2		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%
Female	266	54.6	36	37.1	68	49.3	5	12.5
Male	221	45.4	61	62.9	70	50.7	35	87.5
Total	487		97		138		40	

[a]Suture unobservable due to obliteration.

Table B-20. Right zygomaticomaxillary shape frequencies by sex.

	0		1		2		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%
Female	262	53.9	31	34.8	77	52.0	5	12.8
Male	224	46.1	58	65.2	71	48.0	34	87.2
Total	486		89		148		39	

[a]Suture unobservable due to obliteration.

Table B-21. Left accessory lesser palatine foramina frequencies by ancestry.

	0		1		2		3		4		5	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
African	5	33.3	121	35.1	102	34.6	20	20.8	2	20.0	0	0.0
Asian	4	26.7	116	33.6	108	36.6	31	32.3	5	50.0	0	0.0
European	6	40.0	108	31.3	85	28.8	45	46.9	3	30.0	1	100.0
Total	15		345		295		96		10		1	

Table B-22. Right accessory lesser palatine foramina frequencies by ancestry.

	0		1		2		3		4		5	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
African	9	47.4	117	33.0	95	33.1	24	27.9	4	28.6	1	100.0
Asian	5	26.3	118	33.2	103	35.9	33	38.4	5	35.7	0	0.0
European	5	26.3	120	33.8	89	31.0	29	33.7	5	35.7	0	0.0
Total	19		355		287		86		14		1	

Table B-23. Left marginal crest frequencies by ancestry.

	0		1	
	n	%	*n*	%
African	128	38.0	122	28.7
Asian	123	36.5	141	33.2
European	86	25.5	162	38.1
Total	337		425	

Table B-24. Right marginal crest frequencies by ancestry.

	0		1	
	n	%	*n*	%
African	120	36.1	130	30.2
Asian	126	38.0	138	32.1
European	86	25.9	162	37.7
Total	332		430	

Table B-25. Left lateral groove bridging frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	66	27.2	121	29.8	44	49.4	19	79.2
Asian	52	21.4	171	42.1	36	40.4	5	20.8
European	125	51.4	114	28.1	9	10.1	0	0.0
Total	243		406		89		24	

Table B-26. Right lateral groove bridging frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	70	27.6	129	30.1	36	59.0	15	78.9
Asian	61	24.0	184	43.0	17	27.9	2	10.5
European	123	48.4	115	26.9	8	13.1	2	10.5
Total	254		428		61		19	

Table B-27. Left medial groove bridging frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	19	32.8	114	33.2	100	30.1	17	58.6
Asian	21	36.2	93	27.1	144	43.4	6	20.7
European	18	31.0	136	39.7	88	26.5	6	20.7
Total	58		343		332		29	

Table B-28. Right medial groove bridging frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	20	32.3	120	34.4	92	28.5	18	64.3
Asian	24	38.7	92	26.4	142	44.0	6	21.4
European	18	29.0	137	39.2	89	27.5	4	14.3
Total	62		349		323		28	

Table B-29. Palatine torus frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	67	29.6	135	30.2	43	52.4	5	71.4
Asian	76	33.6	172	38.5	16	19.5	0	0.0
European	83	36.7	140	31.3	23	28.0	2	28.6
Total	226		447		82		7	

Table B-30. Left maxillary torus frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	87	21.6	100	38.6	45	57.7	18	78.3
Asian	166	41.3	77	29.7	20	25.6	1	4.3
European	149	37.1	82	31.7	13	16.7	4	17.4
Total	402		259		78		23	

Table B-31. Right maxillary torus frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	105	28.0	87	31.8	44	45.8	14	82.3
Asian	131	34.9	103	37.6	29	30.2	1	5.9
European	139	37.1	84	30.6	23	24.0	2	11.8
Total	375		274		96		17	

Table B-32. Left maxillary exostoses frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	158	30.0	64	35.0	24	53.3	4	50.0
Asian	171	32.5	80	43.7	12	26.7	1	12.5
European	197	37.5	39	21.3	9	20.0	3	37.5
Total	526		183		45		8	

Table B-33. Right maxillary exostoses frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	153	29.5	75	39.9	18	38.3	4	44.4
Asian	165	31.9	79	42.0	19	40.4	1	11.1
European	200	38.6	34	18.1	10	21.3	4	44.4
Total	518		188		47		9	

Table B-34. Maxillary bone quality by ancestry.

	0		1		2	
	n	%	*n*	%	*n*	%
African	136	26.6	66	42.3	48	51.1
Asian	186	36.3	57	36.5	21	22.3
European	190	37.1	33	21.2	25	26.6
Total	512		156		94	

Table B-35. Palatine bone quality by ancestry.

	0		1		2	
	n	%	*n*	%	*n*	%
African	47	18.8	69	34.5	134	42.9
Asian	77	30.8	98	49.0	89	28.5
European	126	50.4	33	16.5	89	28.5
Total	250		200		312	

Table B-36. Palatal porosity by ancestry.

	0		1	
	n	%	*n*	%
African	129	48.7	121	24.3
Asian	42	15.8	222	44.7
European	94	35.5	154	31.0
Total	265		497	

Table B-37. Palate shape frequencies by ancestry.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
African	34	15.6	93	64.6	119	31.1	4	23.5
Asian	154	70.6	14	9.7	86	22.5	10	58.8
European	30	13.8	37	25.7	178	46.5	3	17.6
Total	218		144		383		17	

Table B-38. Transverse palatine suture shape frequencies by ancestry.

	0		1		2		3		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%
African	27	13.8	76	37.3	105	41.5	8	18.6	34	50.7
Asian	121	62.1	58	28.4	41	16.2	28	65.1	16	23.9
European	47	24.1	70	34.3	107	42.3	7	16.3	17	25.4
Total	195		204		253		43		67	

[a]Suture unobservable due to obliteration.

Table B-39. Left zygomaticomaxillary shape frequencies by ancestry.

	0		1		2		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%
African	145	29.8	19	19.6	64	46.4	22	55.0
Asian	186	38.2	20	20.6	46	33.3	12	30.0
European	156	32.0	58	59.8	28	20.3	6	15.0
Total	487		97		138		40	

[a]Suture unobservable due to obliteration.

Table B-40. Right zygomaticomaxillary shape frequencies by ancestry.

	0		1		2		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%
African	139	28.6	19	21.3	72	48.6	20	51.3
Asian	185	38.1	22	24.7	45	30.4	12	30.8
European	162	33.3	48	53.9	31	20.9	7	17.9
Total	486		89		148		39	

[a]Suture unobservable due to obliteration.

Table B-41. Left accessory lesser palatine foramina frequencies by time period.

	0		1		2		3		4		5	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Historic	5	33.3	167	48.4	160	54.2	42	43.8	4	40.0	0	0.0
Modern	10	66.7	178	51.6	135	45.8	54	56.2	6	60.0	1	100.0
Total	15		345		295		96		10		1	

Table B-42. Right accessory lesser palatine foramina frequencies by time period.

	0		1		2		3		4		5	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Historic	10	52.6	178	50.1	138	48.1	46	53.5	5	35.7	1	100.0
Modern	9	47.4	177	49.9	149	51.9	40	46.5	9	64.3	0	0.0
Total	19		355		287		86		14		1	

Table B-43. Left marginal crest frequencies by time period.

	0		1	
	n	%	*n*	%
Historic	189	56.1	189	44.5
Modern	148	43.9	236	55.5
Total	337		425	

Table B-44. Right marginal crest frequencies by time period.

	0		1	
	n	%	*n*	%
Historic	181	54.5	197	45.8
Modern	151	45.5	233	54.2
Total	332		430	

Table B-45. Left lateral groove bridging frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	89	36.6	207	51.0	64	71.9	18	75.0
Modern	154	63.4	199	49.0	25	28.1	6	25.0
Total	243		406		89		24	

Table B-46. Right lateral groove bridging frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	106	41.7	214	50.0	46	75.4	12	63.2
Modern	148	58.3	214	50.0	15	24.6	7	36.8
Total	254		428		61		19	

Table B-47. Left medial groove bridging frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	28	48.3	146	42.6	182	54.8	22	75.9
Modern	30	51.7	197	57.4	150	45.2	7	24.1
Total	58		343		332		29	

Table B-48. Right medial groove bridging frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	31	50.0	159	45.6	168	52.0	20	71.4
Modern	31	50.0	190	54.4	155	48.0	8	28.6
Total	62		349		323		28	

Table B-49. Palatine torus frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	105	46.5	227	50.8	42	51.2	4	57.1
Modern	121	53.5	220	49.2	40	48.8	3	42.9
Total	226		447		82		7	

Table B-50. Left maxillary torus frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	183	45.5	128	49.4	50	64.1	17	73.9
Modern	219	54.5	131	50.6	28	35.9	6	26.1
Total	402		259		78		23	

Table B-51. Right maxillary torus frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	187	49.9	135	49.3	48	50.0	8	47.1
Modern	188	50.1	139	50.7	48	50.0	9	52.9
Total	375		274		96		17	

Table B-52. Left maxillary exostoses frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	242	46.0	102	55.7	33	73.3	1	12.5
Modern	284	54.0	81	44.3	12	26.7	7	87.5
Total	526		183		45		8	

Table B-53. Right maxillary exostoses frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	241	46.5	104	55.3	32	68.1	1	11.1
Modern	277	53.5	84	44.7	15	31.9	8	88.9
Total	518		188		47		9	

Table B-54. Maxillary bone quality by time period.

	0		1		2	
	n	%	*n*	%	*n*	%
Historic	227	44.3	94	60.3	57	60.6
Modern	285	55.7	62	39.7	37	39.4
Total	512		156		94	

Table B-55. Palatine bone quality by time period.

	0		1		2	
	n	%	*n*	%	*n*	%
Historic	76	30.4	136	68.0	166	53.2
Modern	174	69.6	64	32.0	146	46.8
Total	250		200		312	

Table B-56. Palatal porosity by time period.

	0		1	
	n	%	*n*	%
Historic	145	54.7	233	46.9
Modern	120	45.3	264	53.1
Total	265		497	

Table B-57. Palate shape frequencies by time period.

	0		1		2		3	
	n	%	*n*	%	*n*	%	*n*	%
Historic	110	50.5	98	68.1	161	42.0	9	52.9
Modern	108	49.5	46	31.9	222	58.0	8	47.1
Total	218		144		383		17	

Table B-58. Transverse palatine suture shape frequencies by time period.

	0		1		2		3		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%
Historic	91	46.7	97	47.5	128	50.6	24	55.8	38	56.7
Modern	104	53.3	107	52.5	125	49.4	19	44.2	29	43.3
Total	195		204		253		43		67	

[a]Suture unobservable due to obliteration.

Table B-59. Left zygomaticomaxillary shape frequencies by time period.

	0		1		2		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%
Historic	243	49.9	36	37.1	75	54.3	24	60.0
Modern	244	50.1	61	62.9	63	45.7	16	40.0
Total	487		97		138		40	

[a]Suture unobservable due to obliteration.

Table B-60. Right zygomaticomaxillary shape frequencies by time period.

	0		1		2		Unobs/ OBL[a]	
	n	%	*n*	%	*n*	%	*n*	%
Historic	238	49.0	35	39.3	81	54.7	24	61.5
Modern	248	51.0	54	60.7	67	45.4	15	38.5
Total	486		89		148		39	

[a]Suture unobservable due to obliteration.

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BIOGRAPHICAL SKETCH

Carrie Brown is originally from Wycombe, Pennsylvania. She attended Lawrence University in Appleton, Wisconsin from 2000 to 2004, where she earned a Bachelor of Arts degree in anthropology and French and graduated *cum laude* in course and *magna cum laude* in independent study in June 2004. Her undergraduate research focused on understanding community building through the use of public space in urban environments in London, England and Nantes, France. From Wisconsin, Carrie moved to France to teach elementary school English for two years.

Carrie attended California State University, Chico (CSU-C) from 2006 to 2009, earning a Master of Arts in anthropology with distinction in May 2009. In 2008, she was awarded a student research fellowship with the Joint POW/MIA Accounting Command Central Identification Laboratory (JPAC-CIL) on Hickam Air Force Base, Hawaii. During this fellowship she was a member of the inaugural Forensic Science Academy and completed a large-scale research project that investigated the uncertainty associated with age estimation at the JPAC-CIL. This research formed the basis for her master's thesis, which was awarded the 2009-2010 CSU-C School of Graduate, International, and Interdisciplinary Studies Outstanding Master's Thesis Award.

Following graduation from Chico State, Carrie was awarded a postgraduate research fellowship at the JPAC-CIL and in fall of 2009 was hired as a forensic anthropologist. In August 2011 Carrie began her doctoral coursework at the University of Florida while continuing to work at the JPAC-CIL during winter and summer breaks. During her time at the University of Florida she was first a Graduate Analyst and then the Senior Graduate Analyst in the C. A. Pound Human Identification Laboratory, taught undergraduate courses in forensic anthropology and human osteology, and served as the Vice President of the Florida Anthropology Student Association. After advancing to candidacy in April 2013, she relocated to the new JPAC-CIL laboratory on Offutt Air Force Base, Nebraska, where she has worked since May 2013; the JPAC-CIL was renamed the Department of Defense POW/MIA Accounting Agency Laboratory in January 2015. Carrie is also an adjunct instructor in the graduate program in forensic sciences at Nebraska Wesleyan University, Lincoln, Nebraska. She received her Ph.D. from the University of Florida in the spring of 2016.