AN EXAMINATION OF THE RELATIONSHIP BETWEEN ASYMMETRICAL ANTEMORTEM TOOTH LOSS AND ASYMMETRICAL CRANIAL SUTURE CLOSURE

By

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ABSTRACT

AN EXAMINATION OF THE RELATIONSHIP BETWEEN ASYMMETRICAL ANTEMORTEM TOOTH LOSS AND ASYMMETRICAL CRANIAL SUTURE CLOSURE

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Bilateral asymmetry in cranial suture closure has the potential to hinder age at death estimation for unidentified human remains. The objective of this research was to determine whether there was a relationship between asymmetrical antemortem tooth loss and asymmetrical suture closure in a modern human sample. 101 crania from the historical Hamann-Todd Collection and the modern Bass Collection were examined. The variables degree of suture asymmetry and points of dental asymmetry (PDA) were designed to measure asymmetry in cranial suture closure at 13 sites and asymmetry in antemortem molar and premolar loss. The variables age at death, sex, ancestry, and skeletal collection of origin were also examined.

This study did not produce any evidence of a relationship between PDA and degree of suture asymmetry. Further research is needed, however, because the variable PDA may not be truly representative of asymmetry in antemortem tooth loss. The significant interaction effect between suture site and age indicates that there is a relationship between suture asymmetry and age at some sites or in some age categories, but not others. There was no evidence of sexual dimorphism in suture asymmetry. The mean degree of suture asymmetry in those of African ancestry was significantly higher than in those of European ancestry. Age and ancestry should be included in future studies. The Bass and Hamann-Todd subsamples differed significantly in terms of degree of suture asymmetry, but this may be a result of bias introduced by the differing distribution of the subsamples according to age, sex, and ancestry. Alternatively, it could be evidence of secular change.

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KEY TO SYMBOLS AND ABBREVIATIONS

Parietomastoid Site MQ

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Parietomastoid Site on Right MRQ

Squamosal Site QQ

Squamosal Site on Left QLQ

Squamosal Site on Right QRQ

Occipitomastoid Site DQ

Occipitomastoid Site on Left DLQ

Occipitomastoid Site on Right DRQ

Pterion Site PQ

Pterion Site on Left PLQ

Pterion Site on Right PRQ

Sphenofrontal Site SQ

Sphenofrontal Site on Left SLQ

Sphenofrontal Site on Right SRQ

Inferior Sphenotemporal Site IQ

Inferior Sphenotemporal Site on Left ILQ

Inferior Sphenotemporal Site on Right IRQ

Superior Sphenotemporal TQ

Superior Sphenotemporal Site on Left TLQ

Superior Sphenotemporal Site on Right TRQ

Ectocranial Midlambdoid Site LQV

Ectocranial Midlambdoid Site on Left LLQ

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Ectocranial Midcoronal Site CQV

Ectocranial Midcoronal Site on Left CLQ

Ectocranial Midcoronal Site on Right CRQ

Endocranial Midcoronal Site CZV

Endocranial Midcoronal Site on Left CLZ

Endocranial Midcoronal Site on Right CRZ

Incisive Site IP

Incisive Site on Left ILP

Incisive Site on Right IRP

Transverse Palatine Site TP

Transverse Palatine Site on Left TLP

Transverse Palatine Site on Right TRP

First Maxillary Premolar P^1

Second Maxillary Premolar P^2

First Maxillary Molar M^1

Second Maxillary Molar M^2

Third Maxillary Molar M^3

First Mandibular Premolar P_1

Second Mandibular Premolar P_2

First Mandibular Molar M_1

Second Mandibular Molar M_2

Third Mandibular Molar M_3

CHAPTER 1: INTRODUCTION

When human remains of potential forensic significance are recovered, forensic anthropologists are often tasked with constructing a biological profile based on those remains that will allow law enforcement officers to identify potential matches among missing persons' cases (Komar and Buikstra, 2008; Byers, 2011). The biological or demographic profile normally consists of sex, ancestry, stature, and age at death (Byers, 2011). Age at death is a crucial component of the biological profile (Brown, 2010).

Age at death can be estimated with relative precision and accuracy for subadult human skeletal remains using methods based on established patterns of skeletal growth and development. Around 23-25 years of age, however, many processes of skeletal growth and development cease and degenerative and other maturational changes begin (Stewart, 1979). Forensic anthropologists must utilize these changes to estimate age at death for adult individuals. Plato and colleagues (1994, p 272) note that maturational skeletal changes "…progress at a slower rate, [and] are less uniform" than the developmental changes that are used to estimate age in subadults. As a result, physical anthropologists struggle to develop and improve methods of adult age at death estimation that are both precise and accurate (Komar and Buikstra, 2008).

Physical anthropologists commonly use skeletal age indicators such as the pubic symphysis, auricular surface of the ilium, fourth sternal rib end, and the cranial sutures. Although these elements all provide reasonably accurate and precise age estimates, they are also fairly fragile and prone to postmortem degradation and destruction. The cranium, however, is relatively robust and may be the only skeletal element recovered intact (Loth and Iscan, 1994). A cranial suture closure method, then, may be the only viable option for estimating age at death in some forensic cases.

Unfortunately, some individuals display extremely unusual patterns of suture closure, such as bilaterally asymmetrical closure (Živanović, 1983; Falk et al., 1989). When suture closure methods are applied to these individuals, extremely inaccurate age at death estimates may be generated. Ultimately, understanding the causes of asymmetrical closure should allow for the refinement of suture closure age at death estimation methods. At the very least, it should facilitate the identification of individuals for whom suture closure methods are inappropriate.

Previous studies have focused primarily on two different types of factors that may influence the timing of cranial suture closure: biomechanical (Moss, 1954, 1957, 1958, 1959, 1960, 1961; Smith and Tondury, 1978) and biochemical (Opperman et al., 1993, 1995, 1996, 1997, 1998, 1999, 2000, 2006) factors. A number of studies suggest that suture closure is affected by the function of the masticatory apparatus (Kimbel and Rak, 1985; Byron et al., 2004, 2008). Asymmetrical antemortem tooth loss causes changes in dental occlusion. Dental occlusion affects the bite forces that are transmitted the cranium (Daegling, 2010). This research focuses on asymmetrical antemortem tooth loss in order to determine whether it is a causative factor in the development of asymmetrical cranial suture closure.

CHAPTER 2: BACKGROUND – CRANIAL SUTURES AS AGE INDICATORS

Estimation of Age at Death

Steadman (2009, p 1) defines forensic anthropology as "the application of anthropological and skeletal biological principles to medicolegal issues." One of the medicolegal issues that benefits from anthropological and osteological expertise is positive human identification. When attempting to identify human remains, forensic anthropologists generally begin by constructing a biological profile that includes the following characteristics: age at death, sex, ancestry, and stature (Byers, 2011). Determining or estimating these characteristics allows law enforcement officers to narrow down possible matches in missing persons reports and thus facilitates the identification of individuals (Komar and Buikstra, 2008).

Skeletal aging is a multifaceted process that is complicated by the influence of genetic and environmental factors. Age at death can be estimated with more precision and accuracy for subadult human skeletal remains than those of adults, because subadult age at death estimation methods are based on skeletal growth and development rather than skeletal maturation. As Saunders (2000, p 141) explains, "subadult age at death estimations can be considered more accurate than adult age estimations because of the telescoped time span of human growth relative to the total life span over which age variability is assessed." Unfortunately, skeletal growth and most developmental changes in humans cease around 23-25 years of age, necessitating the use of maturational changes to estimate age at death after this point (Stewart, 1979). Maturational changes proceed in a slower, more sporadic manner than skeletal changes related to growth and development (Plato et al., 1994). Consequently, physical anthropologists struggle to develop and refine methods of adult age at death estimation that are as accurate and precise as possible.

Many forensic anthropologists prefer to use age at death estimation methods based on the pubic symphysis, the auricular surface of the ilium, and the fourth sternal rib end (Garvin and Passalacqua, 2012). Although it is widely accepted that these age indicators provide reasonably accurate and precise age at death estimates, they are also all easily damaged or destroyed. Due to its robust nature, the cranium may be the only skeletal element recovered intact (Loth and Iscan, 1994). A cranial suture closure method, then, may be the only viable option for estimating age at death in some forensic cases. Consequently, it is crucial that patterns of cranial suture closure be understood in as much detail as possible in order to improve the age at death estimation methods that depend on it.

Cranial Sutures

At birth, the human skull is made up of approximately 45 separate elements (White and Folkens, 2005). During juvenile development, many of these bones fuse together. By early adulthood, most human skulls are made up of approximately 22 separate bones, not including the ear ossicles (White and Folkens, 2005). Most of these bones are connected to one another at fibrous interlocking joints known as cranial sutures (Moore et al., 2010). As adults age, the cranial bones fuse together as the fibrous sutures ossify, or transform into bone (Burns, 2007).

Many of the cranial sutures are named after the bones they unite (White and Folkens, 2005). For example, the zygomaticomaxillary suture connects the zygomatic bone to the maxilla (White and Folkens, 2005). Other sutures, however, have unique names, such as the sagittal, coronal, lambdoid, and squamosal sutures (White and Folkens, 2005). Although there are a number of different ways to categorize the sutures, this research follows Meindl and Lovejoy (1985) in their use of the terms vault and lateral-anterior sutures. The vault category (Figure 1) includes the sagittal, coronal, and lambdoid sutures. The lateral-anterior category (Figure 2) consists of the squamosal, sphenofrontal, sphenotemporal, occipitomastoid, and parietomastoid sutures. A third category included in the current study is the palatine region. The palatine sutures are discussed below and depicted in Figure 4.

Each vault suture has both an external, or ectocranial, aspect and an internal, or endocranial, aspect. The ectocranial and endocranial aspects ossify at different rates (Todd and Lyon, 1924; Meindl and Lovejoy, 1985; Key et al., 1994). Some age estimation methods based on cranial suture closure utilize ectocranial sutures alone (McKern and Stewart, 1957; Meindl and Lovejoy, 1985), some make use of endocranial closure (Acsádi and Nemeskéri, 1970; Masset, 1989), and yet others combine the use of both ectocranial and endocranial sutures (Todd and Lyon, 1924, 1925 a; Buikstra and Ubelaker, 1994; Nawrocki, 1998). The endocranial aspects of the vault sutures are depicted in Figure 3.

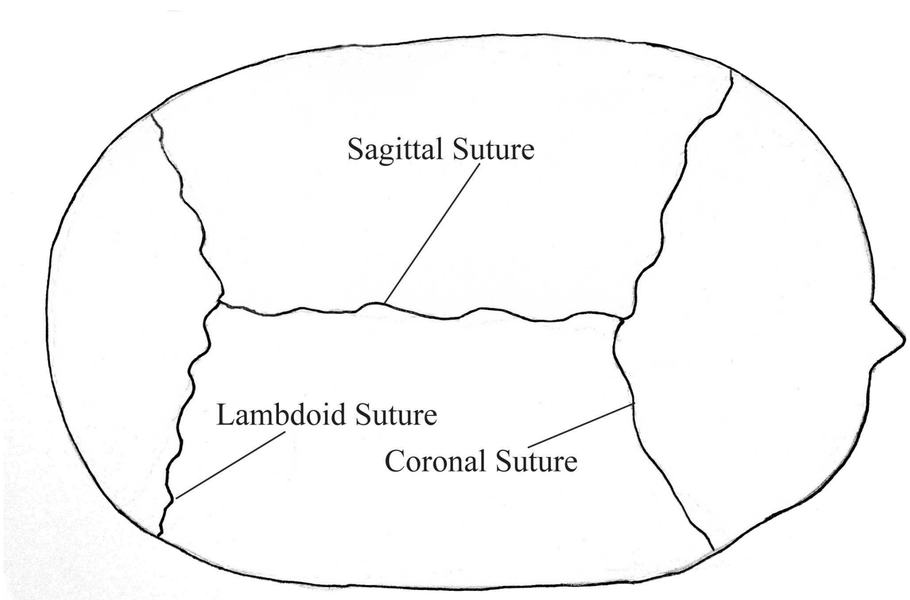

Figure 1: The Vault Sutures

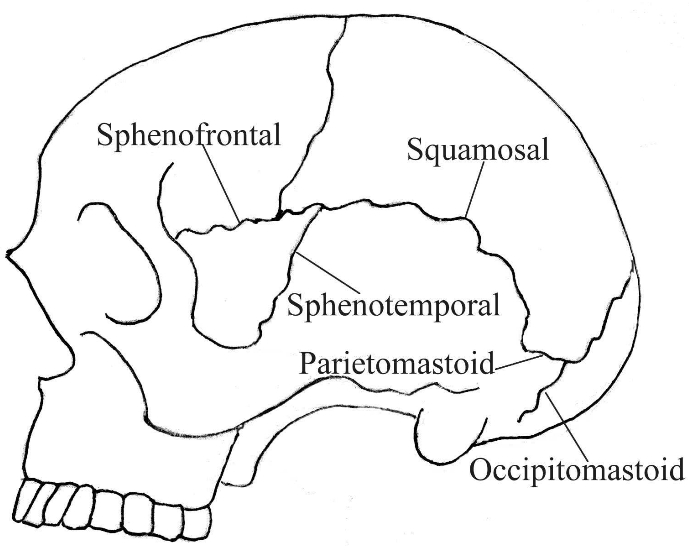

Figure 2: The Lateral-Anterior Sutures

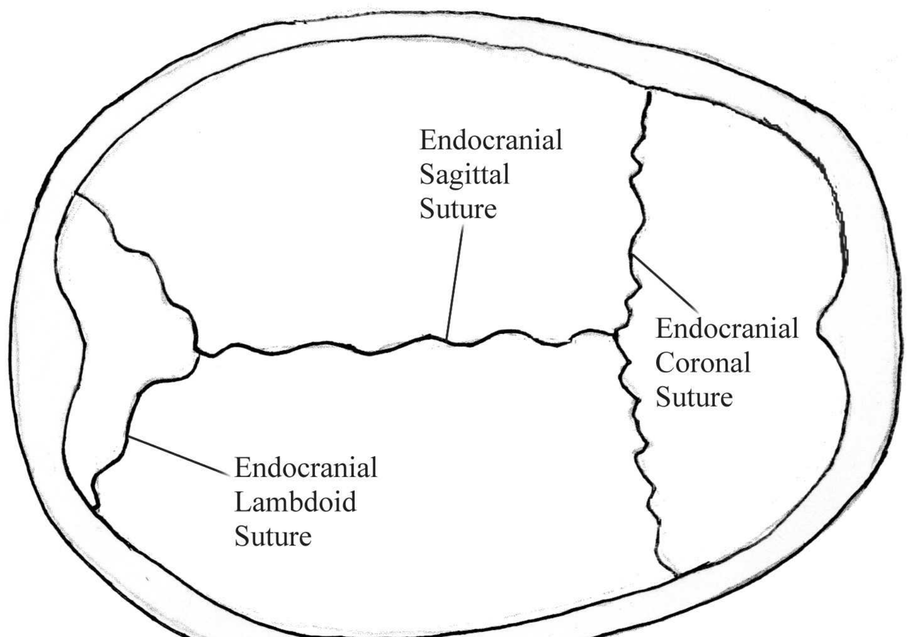

Figure 3: The Endocranial Aspects of the Vault Sutures

The terms palatine, palatal, and maxillary all refer to the sutures that hold together the bones of the upper portion of the jaw. Each maxilla develops out of two ossification centers, one for the larger posterior portion of the maxilla and the other for the smaller anterior portion known as the premaxilla. Although the two portions begin to fuse together during fetal development, the incisive suture that marks the junction of the "maxilla proper" and the premaxilla usually remains patent into early adulthood (White and Folkens, 2005). The anterior median palatine suture (Mann et al., 1991), also known as the intermaxillary suture (Bass, 2005) holds together the right and left maxillae. The posterior median palatine suture (Mann et al., 1991), also referred to as the interpalatine suture (Bass, 2005), unites the right and left palatine bones. The anterior and posterior median palatine sutures together make up the median palatine suture (Mann et al., 1991; Bass, 2005). The transverse palatine (Mann et al., 1991) or palatomaxillary (Bass, 2005) suture marks the union of the maxillae to the two palatine bones. The palatine sutures are depicted in Figure 4.

Prior to fusion, cranial sutures are described as open, patent, or unfused. The terms closure, synostosis, ossification, obliteration, and fusion are used interchangeably to describe the process by which the fibrous sutures become bone. The cranial sutures fuse according to a pattern that is not only correlated with age but also relatively consistent between individuals (Krogman and Iscan, 1986; White and Folkens, 2005; Schwartz, 2007). Physical anthropologists utilize this closure pattern to estimate an individual's age at death based on the degree of suture closure present at a number of locations on the skull (Buikstra and Ubelaker, 1994; Schwartz, 2007; Komar and Buikstra, 2008).

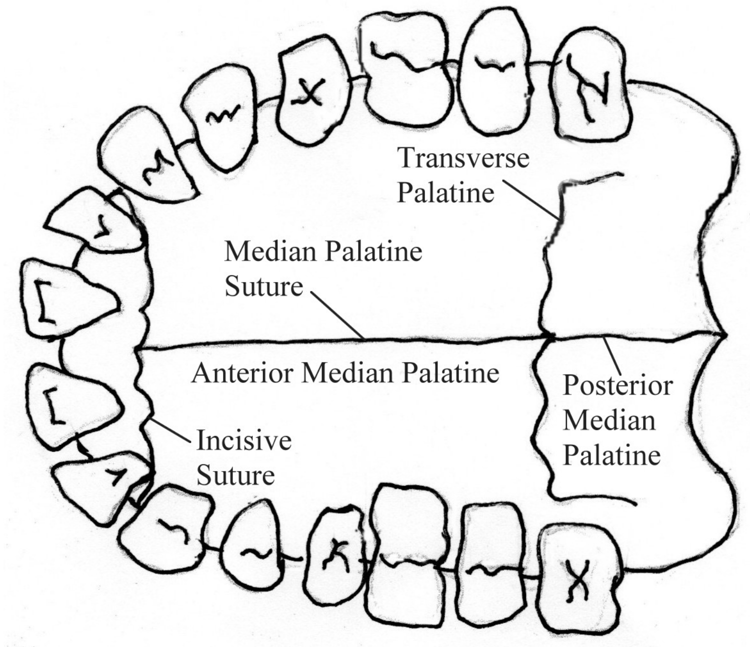

Figure 4: The Palatine Sutures

Historical Research on Cranial Sutures as Skeletal Age Indicators

As early as the sixteenth century, scholars identified a relationship between age and the progression of cranial suture closure (Vesalius, 1543). In 1866, a German scholar named Welcker proposed that skulls could be sorted into four age categories based on the state of their suture closure (Masset, 1989). By the late nineteenth century, formal studies of the age progression of cranial suture closure were being conducted (Pommerol, 1869; Dwight, 1890). These early studies were hampered by several problems. The sample sizes were very small and thus the likelihood of sampling error was high. Additionally, age at death, sex, and ancestry must be reliably documented for each individual in the study, and this was not always the case. Finally, the samples used generally consisted of males of European ancestry, making it impossible for the researchers to examine the possibility of variation between sexes and ancestral groups (Todd and Lyon, 1924).

The First Systematic Study

Todd and Lyon's (1924, 1925 a; b; c) landmark study examined endocranial and ectocranial suture closure in 514 individuals of known age, sex and ancestry from a collection at the Western Reserve University Department of Anatomy that would eventually become known as the Hamann-Todd collection (Lovejoy et al., 1985). Todd had begun assembling this collection in 1912 from cadavers provided by several major hospitals in the Cleveland, Ohio area (Lovejoy et al., 1985). The vast majority of these individuals, 307 to be exact, were white males. Unfortunately, the comparatively small number of females available (58 of European ancestry, 29 of African ancestry) meant that the authors do not claim that "the female crania in the series are of any independent value" (Todd and Lyon, 1924, p 330). Consequently, this study provided no reliable information on sexual dimorphism in the timing of cranial suture closure. Although the sample did include a sizable number of males of African ancestry (120 to be exact), Todd and Lyon (1924, p 330) still decided "we shall base our conclusions upon the male White series." As a result, this study also did not provide dependable information on variation between ancestral groups.

As soon as the data had been collected and analyzed, it was immediately clear that there was a correlation between age and degree of suture closure (Todd and Lyon, 1924). There were, however, significant differences between ectocranial and endocranial suture closure. Although the endocranial and ectocranial sutures usually began to close simultaneously in each individual, Todd and Lyon (1925 a, p 39) discovered that "ectocranial closure proceeds more slowly and shows more individual variation than endocranial closure." They conclude that the smaller amount of variation between individuals demonstrated by endocranial closure makes it a more dependable age indicator than ectocranial closure.

Todd and Lyon (1924, p 333) also found that there were “marked exceptions in certain skulls to the usual course of union”. The question of what to do with such “exceptions” has plagued anthropologists for many decades since. Todd and Lyon (1924) chose the simple method of excluding the anomalous specimens, believing them to be cases of accelerated or delayed closure due to pathological and “phylogenetic” causes. For example, any skulls with “partial or compete closure of certain sutures, notably the sagittal and masto-occipital, at an early age” were removed from consideration (Todd and Lyon, 1924, p 340). Unfortunately, this decision led to the correlation between age and suture closure appearing much stronger and more consistent than if they had retained these outliers as part of the study sample (McKern and Stewart, 1957; Masset, 1989).

Once they had determined the age range in which each suture usually closed, Todd and Lyon (1925 a) attempted to use this information to determine age at death for 30 individuals. Their average deviation was only six years, but due to the small size of the sample, the authors still conclude that suture closure methods are too inaccurate for individual forensic age determination, although they may be valuable for studying the age at death distribution of large groups of people, as in a bioarchaeological setting. Despite these discouraging conclusions, research into the utility of cranial suture closure for the purpose of adult age at death estimation in a forensic context has continued.

McKern and Stewart (1957)

The next major study of cranial suture closure as an age at death estimation method was conducted by McKern and Stewart (1957). These authors put together a report entitled "Skeletal Age Changes in Young American Males". Their subjects were 450 American soldiers who had been killed in the Korean War and subsequently repatriated by North Korea. Naturally, the sample was primarily made up of young adult males, making this study comparable to Todd and Lyon's (1924, 1925 a; b; c) in that it offered no information on the possible existence of sexual dimorphism in suture closure. Most of the crania were from individuals of European ancestry (McKern and Stewart, 1957), so this study also does not reliably address the possibility of variation in suture closure patterns between ancestral groups.

McKern and Stewart (1957) chose to study ectocranial sutures alone because the crania in their sample had not been sectioned to reveal the inner surfaces when Stewart made the observations, and he felt that this made it too challenging to observe the inner surfaces of the skull. They divided the sutures into three main categories: calvarial, facial, and basilar. The calvarial category included both the three vault sutures (Figure 1) and the lateral-anterior sutures (Figure 2). The facial category consisted of those sutures that surround the nasal aperture, as well as the zygomaticomaxillary and zygomaticotemporal sutures, and the median palatine suture (Figure 5). The basilar category consisted solely of the so-called basilar suture. However, because this joint is actually a synchondrosis (White and Folkens, 2005), the results for this particular joint will not be discussed here.

Ultimately, McKern and Stewart (1957) determined that facial and calvarial sutures were so erratic in closure times that they could provide only very wide age ranges. While they were correct in their conclusion that these areas are of little value in distinguishing among individuals in a group primarily made up of young adult males, they failed to consider that even an age estimate with a twenty or thirty year range could be of value in other circumstances. After all, an age estimate with a two-decade range is preferable to being able to say no more than that an unidentified individual is an adult.

Acsádi and Nemeskéri (1970)

Acsádi and Nemeskéri (1970) approached the issue of age at death estimation in the midst of growing frustration with cranial suture methods. Although it is unclear what their reasons were, Acsádi and Nemeskéri (1970) chose to base their study on observations of the three vault sutures (Figure 1, Figure 4) alone. They examined both endocranial and ectocranial closure in 285 crania from cadavers housed at the Institute of Forensic Medicine of Semmelweis University School of Medicine in Budapest (Acsádi and Nemeskéri, 1970). The authors note that they eliminated "pathological cases" from the sample but failed to define what constituted a "pathological case" (Acsádi and Nemeskéri, 1970, p 116). Again, this may result in the elimination of outliers and the appearance of a stronger relationship between suture closure and age at death than really exists.

Although the ancestral composition of the sample was not explicitly described, it is reasonable to assume that most of the individuals were of Eastern European ancestry, and that therefore the study would provide no information on ancestral variation in suture closure. The sample was composed of both males and females. The authors state that they looked for significant sex differences in the timing of both ectocranial and endocranial suture closure but did not find any such differences (Acsádi and Nemeskéri, 1970).

After scoring suture closure at 16 sites on each skull, Acsádi and Nemskeri (1970) next calculated mean closure scores for each suture by adding the score for each site along the length of a single suture, then dividing that sum by the number of sites which comprised the suture. They provided a key that associated each mean closure score with an estimate of age at death (Acsádi and Nemeskéri, 1970). Unlike Todd and Lyon (1925 a), Acsádi and Nemeskéri (1970) found that endocranial suture closure generally began earlier in life than ectocranial closure. Although they examined both types of closure, Acsádi and Nemeskéri (1970) chose to utilize only endocranial suture closure in their age estimation method. They did not state their reasons for this decision, but it is consistent with Todd and Lyon's (1924) conclusion that ectocranial closure is too erratic to serve as a useful age indicator.

Meindl and Lovejoy (1985)

Meindl and Lovejoy (1985) designed what is probably the most commonly used cranial suture age at death estimation method today (Garvin and Passalacqua, 2012). They analyzed ectocranial suture closure in 236 crania of known age from the Hamann-Todd skeletal collection. Meindl and Lovejoy (1985) were particularly interested in developing age at death estimation methods for older adults. At least one earlier study suggested that ectocranial suture closure begins later in life than endocranial closure (Acsádi and Nemeskéri, 1970). Consequently, Meindl and Lovejoy (1985) reasoned that ectocranial suture closure would be a more useful age indicator in older individuals than endocranial suture closure.

Meindl and Lovejoy (1985) noticed that two facial suture sites demonstrated frequent bilateral asymmetry in the individuals in their sample, and excluded those sites from consideration. In the interest of including only those suture sites that were most valuable in the estimation of age, they also eliminated sites that exhibited high levels of inter-observer error, that did not exhibit closure during mid- to late-adulthood, and that were unlikely to survive archaeologically. In this fashion, Meindl and Lovejoy (1985) whittled their list of suture sites down to 10. Next, they divided the 10 remaining suture sites into two systems: the vault system (Figure 1), and the lateral-anterior system (Figure 2).

Meindl and Lovejoy's (1985) method, similar to that of Acsádi and Nemeskéri (1970), involved summing the scores for a set of sites. In the Meindl and Lovejoy (1985) method, however, the scores are summed for each system (lateral-anterior or vault) rather than for each suture as in the Acsádi and Nemeskéri (1970) method. The composite scores are then listed with corresponding mean ages and standard deviations in a table which the authors provide (Meindl and Lovejoy, 1985).

While the lateral-anterior system turned out to be more accurate, Meindl and Lovejoy (1985)considered the vault system more likely to survive archaeologically, and suggested that the vault system should only be used if parts of the lateral-anterior system were missing or damaged. Unfortunately, even the lateral-anterior system showed only a moderate correlation with age at death. Meindl and Lovejoy (1985) advocated their multifactorial method, in which cranial suture closure is used in combination with several other skeletal age indicators to produce an overall estimate of age at death. While combining multiple age indicators can certainly improve age estimation (Nawrocki, 2010), it is only possible if all of the relevant skeletal elements are present and in relatively good condition, which is certainly not always the case.

Palatine Sutures

Mann (1987) was the first physical anthropologist to present a method of adult age at death estimation based solely on the palatine sutures (Figure 5). In 1991, a revised version of this technique was presented in the *Journal of Forensic Sciences* (Mann et al., 1991). The authors noticed that suture obliteration occurred at earlier ages in males than in females in their sample (Mann et al., 1991). Although they found that their method was rather imprecise, resulting in large ranges of estimated age at death, Mann and colleagues (1991, p 781) point out that much like the vault and lateral-anterior sutures, the palatine sutures are still "valuable in…sorting commingled remains, and estimating skeletal age when only the maxilla is present."

Beauthier and colleagues (2010) examined palatine sutures in a sample of 139 modern individuals of Western European ancestry. They found that the correlation between age at death and palatine suture closure was relatively poor. However, they did point out that palatine suture closure "starts later and progresses more slowly" than other cranial sutures, making palatine sutures more useful in the age estimation of elderly subjects (Beauthier et al., 2010, p 157). When other age markers have ceased to change, palatine sutures may continue to fuse, providing the observer with a usable skeletal age indicator even in elderly subjects.

Nawrocki (1998)

Just over a decade after Mann (1987) introduced his age at death estimation based solely on palatine sutures, Nawrocki (1998) presented the first cranial suture age at death estimation technique to incorporate endocranial, ectocranial, and palatine sutures into a single method. This study is also significant in that it is one of the first studies of cranial suture closure to utilize sophisticated statistical techniques (Nawrocki, 1998). As Nawrocki (1998, p 277) points out, “analysis of variance techniques are clearly underutilized” despite the fact that they have the potential to identify and isolate the variation caused by confounding variables such as sex and ancestry. Nawrocki (1998) was also the first to make use of stepwise selection procedures to select those suture sites that have the closest correlation with age at death. He found that his method achieved a similar level of accuracy to popular aging methods based on postcranial indicators such as the pubic symphysis and the sternal end of the fourth rib (Nawrocki, 1998). Zambrano (2005) later tested the Nawrocki (1998) method on a different sample and confirmed that its accuracy is comparable to other methods.

Scoring Cranial Suture Closure

Meindl and Lovejoy’s (1985) study is especially significant because they introduced a new and improved scoring method. The earliest studies of suture closure were flawed by inconsistent measurement of the degree of suture closure in individuals. For example, Dwight (1890, p 389) defined the terms “closed” and “partly closed” as “more or less bony union between the bones, though the general course of the suture may be perfectly distinct.” The term “obliterated,” meanwhile, “meant that the union is so complete that the suture has disappeared” (Dwight, 1890, p 389). Yet he also confessed that at times, he used the words “closed” and “obliterated” interchangeably. There was a need for a clear and consistent rating or scoring system for suture closure. Broca (1875) had, in fact, introduced such a scoring system in 1875, but it was not immediately adopted by American authors, perhaps because it was presented in an article written in French.

According to Broca’s (1875) suture scoring system (Table 1), sutures ranged from a score of 4 (open) to 0 (completely fused). A decade later, F.C. Ribbe reversed Broca’s (1875) system so that 0 referred to an open suture and 4 signified a completely closed suture (Masset, 1989). Frédéric (1906) adopted this reversed form of Broca's (1875) scoring system. In Frédéric's (1906, p 377) scheme (Table 2), a score of 0 signified that the suture was "not closed", 1 referred to "less than half closed," 2 signified "half closed," 3 meant the suture was "more than half closed," and 4 meant it was "completely closed."

Although it is fairly easy to differentiate between sutures that are completely closed and those that have no closure whatsoever, it is much more difficult to discriminate between a suture that is exactly half-closed, and one that is slightly more or less than half-closed. Consequently, when Todd and Lyon (1924, 1925 a; b; c) published their four part series examining the relationship between cranial suture closure and age at death, they included slightly more specific descriptions of each stage of Frédéric's (1906) scoring system. In Todd and Lyon's (1924, p 331) modified version (Table 3), although 0 and 4 still indicated an absence of closure and complete closure respectively, the scores 1, 2, and 3 were described as "amount of union…one-quarter," "…one-half," and "…three-quarters" respectively.

Score	Description
4	"Suture free [open]"
3	"Less than half" fused
2	"Half" fused
1	"More than half is fused"
0	"Complete fusion"

All descriptions are translations from Broca (1875, p Planche VI).
Table 1: Broca's (1875) Cranial Suture Closure Scoring Scale

Score	Description
0	“Not fused”
1	“Less than half fused”
2	“Half fused”
3	“More than half fused”
4	“Completely fused”

All descriptions are translations from Frédéric (1906, p 377).
Table 2: Frédéric’s (1906) Cranial Suture Closure Scoring Scale

Score	Description
0	“No union”
1	“Amount of union…one-quarter”
2	“Amount of union…one-half”
3	“Amount of union…three-quarters”
4	“Complete closure”

All descriptions are from Todd and Lyon (1924, p 331).
Table 3: Todd and Lyon’s (1924) Cranial Suture Closure Scoring Scale

Although Todd and Lyon’s (1924) descriptions are slightly more specific than Frédéric’s (1906), the system is still quite subjective and difficult to apply, particularly because the authors failed to outline instructions for how to score a suture with a degree of closure that fell midway between two stages. For example, it is unclear whether a suture with approximately 40% closure should be assigned a score of 1 for “one-quarter [closure]” or 2 for “one-half [closure]” (Todd and Lyon, 1924, p 331).

To score the sutures in their study, Acsádi and Nemeskéri (1970, p 115) adopted what they referred to as “Martin’s” scoring scale. In fact, Martin (1958) drew on Frédéric’s (1906, 1910) work to write the chapter on cranial sutures in his *Lehrbuch der Anthropologie* (Masset, 1989). Presumably Martin (1958) also adopted Frédéric’s (1906) modified form of Broca’s (1875) scoring scale. Acsádi and Nemeskéri (1970, p 115) described the stages of suture closure as “suture open = 0, incipient closure = 1, closure in progress = 2, advanced closure = 3, closed suture = 4” (Table 4). Unfortunately, these descriptions are even less detailed than the ones provided by Todd and Lyon (1924), making this system once again very subjective and difficult to put into practice.

Score	Description
0	“Suture open”
1	“Incipient closure”
2	“Closure in progress”
3	“Advanced closure”
4	“Closed suture”

All descriptions are from Acsádi and Nemeskéri (1970, p 115).
Table 4: Acsádi and Nemeskéri’s (1970) Cranial Suture Closure Scoring Scale

Meindl and Lovejoy (1985) resolved many of the issues described above when they modified the scoring scheme used by Todd and Lyon (1924, 1925 a; b; c). They provide very specific instructions for applying every aspect of the scoring procedure. For example, they offer detailed descriptions of each stage of closure (Table 5). Stage 0 is described as “open; there is no evidence of any ectocranial closure at the site” (Meindl and Lovejoy, 1985, p 58). In stage 1, there is “minimal to moderate closure, i.e., from a single bony bridge across the suture to about 50% synostosis at the site” (Meindl and Lovejoy, 1985, p 58). Meindl and Lovejoy (1985, p 58) explain that in stage 2 “there is a marked degree of closure but some portion of the site is still not completely fused”. Finally, stage 3 is defined by “complete obliteration” (Meindl and Lovejoy, 1985, p 58). Furthermore, they specify, “small (1 cm) lengths of a suture or specific sites were selected for inspection. A score was recorded for that site—other activity close to the site was disregarded” (Meindl and Lovejoy, 1985, p 58). These detailed instructions make the scoring system much easier to use with confidence.

Score	Description
0	“Open”
1	“Minimal closure…from a single bony bridge across the suture to about 50% synostosis at the site”
2	“Significant closure: there is a marked degree of closure but some portion of the site is still not completely fused”
3	“Complete obliteration”

All descriptions are from Meindl and Lovejoy (1985, p 58).
Table 5: Meindl and Lovejoy’s (1985) Cranial Suture Closure Scoring Scale

Meindl and Lovejoy’s (1985) scoring system is also an improvement on earlier schemes because it demonstrates low intra-observer and inter-observer error. By reducing the scale to four stages instead of five, “only one significant judgment need ever be made by the observer, that of choosing between scores of 1 or 2 for a site with substantial activity” (Meindl and Lovejoy, 1985, p 58). They assert that in their experience, it was rarely difficult to make that judgment, and in fact when they tested the system for repeatability, the resultant intra-observer and inter-observer error rates were quite low (Meindl and Lovejoy, 1985).

CHAPTER 3: BACKGROUND – ANOMALOUS CRANIAL SUTURE CLOSURE

Although the existence of a general relationship between cranial suture closure and age at death is well established, there is a good deal of skepticism among physical anthropologists regarding the accuracy of cranial suture-based age at death estimation methods. Studies have shown that not only is there a wide range of natural variation in the timing of suture closure (Todd and Lyon, 1924, 1925 a; b; c; McKern and Stewart, 1957; Powers, 1962), but some individuals display extremely anomalous suture closure in the form of precocious or premature cranial synostosis (Bennett, 1967; Krogman and Iscan, 1986; Reichs, 1989), a complete absence of closure late in life known as "lapsed union" (Todd and Lyon, 1924; Powers, 1962), asymmetrical closure (Živanović, 1983; Falk et al., 1989), and closure in an unusual order (Key et al., 1994).

When cranial suture based age at death estimation methods are applied to individuals with anomalous suture closure, extremely inaccurate age estimates may be produced (Živanović, 1983; Reichs, 1989; Key et al., 1994). If the age at death estimate for a set of remains that is provided to law enforcement in a biological profile is inaccurate, the matching missing person file may be overlooked. The individual could remain unidentified for some time and in fact may never be identified at all. Clearly, it is crucial that forensic anthropologists have some way of determining whether an individual's cranial sutures are anomalous enough to effect an age at death estimate that incorporates those features. If it could be established that this was the case for a particular set of remains, the anthropologist can be prepared to enlarge the range of estimated age at death and inform law enforcement that they should put more stock in the other aspects of the biological profile when searching for matching missing person reports. Finally, if law enforcement cannot locate a missing person report with a biological profile that matches the age at death estimate produced based on the individual with anomalous cranial suture closure, they can successively expand their search to include ever wider age estimates until a match, if it exists, is found.

Asymmetrical Cranial Suture Closure

While precocious cranial synostosis, or closure prior to the age of seven (Krogman and Iscan, 1986) is one form of anomalous suture closure that has been the focus of great interest due to its clinical significance, very little attention has been paid to other forms of anomalous closure. Bilaterally asymmetric closure has been particularly neglected. Many of the landmark works on cranial suture closure make sweeping generalizations about the rarity or insignificance of suture asymmetry in their samples, while providing dubious (if any) quantitative support for their statements (Todd and Lyon, 1924; McKern and Stewart, 1957; Acsádi and Nemeskéri, 1970). For example, while Acsádi and Nemeskéri (1970, p 116) report that "asymmetrically ossified crania were subjected to special examination" they conclude that the suture closure of these specimens "showed no substantial departure from the normal." Although they do not report the frequency of individuals with asymmetrical cranial suture closure in their sample, Acsádi and Nemeskéri (1970) still imply that when it did occur, asymmetry is essentially cancelled out by the otherwise normal pattern of suture closure in the individual, and therefore has a negligible effect on the estimation of the individual's age. Yet they provide no quantitative or even anecdotal support for this conclusion.

McKern and Stewart (1957) simply did not have enough time to consistently observe and score both sides of bilateral sutures. Although they report that they made a note whenever "asymmetrical closure was deemed significant," they do not define exactly what qualified as “significant” asymmetry, and they also do not relate how often such “significant” asymmetry was noted (McKern and Stewart, 1957, p 26). They justify the decision to ignore asymmetry by referring to a study by William Montague Cobb that was still in manuscript form at the time. According to McKern and Stewart (1957, p 26), Cobb found that “the percentage of suture closure within any one age group for the coronal and lambdoid sutures is practically the same for each side.” It is unclear if Cobb ever included this information in any of his published works. Even if this statement is true for the coronal and lambdoid sutures in Cobb’s sample, it does not automatically mean that there is very little asymmetry in closure of other sutures and in other samples.

Likewise, Masset (1989, p 88) reports that in his experiments with Ferraz de Macedo’s Portuguese skeletal collection, collected in the late nineteenth century, “whether one uses only one side of the skull or whether the average between the symmetrical segments is preferred, the correlation with age is somewhat the same.” He does not, however, clarify exactly how much similarity is involved in the phrase “somewhat the same” (1989, p 88). Masset (1989) also does not appear to have directly compared the right and left sides, but instead compared each side to the average of both sides. Todd and Lyon (1925 a, p 26) report that “we find no essential difference in closure pattern” between right and left sides, but again they fail to provide any information to support that statement. They even go so far as to state that “the discussion [of asymmetry] would have served only to prolong the paper without adding to its value” (Todd and Lyon, 1925 a, p 26).

While the consideration of asymmetrical cranial suture closure may have been devoid of value to Todd and Lyon (1924, p 326), whose stated purpose was “to present the facts concerning suture closure and its relation to the racial form and individual contour of the braincase," it has the potential to be extremely significant to the forensic anthropologist interested in the identification of the individual. After all, it is not uncommon to recover skeletal remains of forensic significance that are extremely fragmentary. If only one half of the skull is recovered, asymmetrical suture closure could lead to an erroneous age estimate (Živanović, 1983).

Asymmetrical suture closure also has the potential to hinder the separation of commingled remains (Reichs, 1989). Both forensic anthropologists and bioarchaeologists often find themselves in situations where they need to determine whether a jumble of skeletal elements represents a single individual or multiple individuals. If a rough estimate of age can be obtained using the cranial sutures, cranial and postcranial elements from the same individual can be matched. However, if the sutures on the right side of a cranium provide a different age estimate than those on the left side, as in cases of asymmetrical suture closure, it may not be possible to determine whether a given cranium represents the same individual as a given postcranial element.

Nawrocki (1998, p 283) examined the effect of asymmetry on the success of his equations by "substituting the opposite side for bilateral landmarks," and found that asymmetry "has no major effect on the errors." While this may be the case with most individuals who demonstrate only mild asymmetry, it is unlikely to hold true for those individuals with extreme bilateral asymmetry. Before one can assume that bilateral asymmetry in suture closure does not significantly affect age at death estimation, it must first be established that extreme bilateral asymmetry in suture closure does not occur frequently enough in modern populations to be of concern to the forensic anthropologist.

Although the researchers referenced above suggest that bilateral asymmetry in suture closure is not frequent enough to be important to the forensic anthropologist, other studies suggest that asymmetry occurs fairly often in modern samples. Key and colleagues (1994) noted extremely asymmetrical suture closure in both male and female crania from the Spitalfields collection in London, England. Meindl and Lovejoy (1985) found frequent bilateral asymmetry in two facial sutures. When Živanović (1983) conducted a study of modern East African Bantu and European skulls, he found that not only was the pattern of suture closure almost never perfectly symmetric, but in seven individuals, the coronal suture was completely fused on one side, but completely open on the other. In sum, Živanović (1983, p 431) concludes that asymmetry in suture closure is "rather common in recent skulls."

Finally, Falk and colleagues (1989) studied endocranial suture closure in 330 rhesus macaques and found that two sutures, the masto-occipital and rostral squamosal sutures, closed significantly earlier on the right side of the skull than on the left. While these results do not necessarily apply to humans, in combination with the results of the studies described above, they do suggest that it would be wise to further examine the frequency and degree of asymmetrical suture closure in modern humans.

Causes and Functions of Cranial Suture Closure

Although Živanović's (1983) study was groundbreaking in that it was the first study to focus exclusively on the frequency of asymmetrical cranial suture closure in a modern human sample, he did not examine the possible causes of such asymmetrical closure. The first step towards understanding why sutures sometimes close asymmetrically is the comprehension of the causes and functions of normal cranial suture closure. As Key and colleagues (1994, p 206) put it, “this understanding is surely required if we are ever going to be able to use cranial suture closure as an accurate ageing technique”.

There are two main positions regarding the causative factors behind cranial suture closure. Proponents of the first position emphasize the role of tensile forces in suture closure. Supporters of the second position point to biochemical signals that determine the patency of cranial sutures. Opperman and colleagues (1993, p 313) propose that “biochemical [rather than biomechanical] factors governing the position and patency of the suture originate in the dura mater”. The dura mater is the thick, tough, external layer of the membranous protective coverings of the brain known as cranial meninges. The dura mater adheres to the endocranial surface of the cranial vault and base (Moore et al., 2010) but does not extend to the facial area. Certainly studies by Opperman in conjunction with various colleagues seem to support the importance of biochemical signals from the dura in the regulation of cranial suture closure (Opperman et al., 1993, 1995, 1996, 1997, 1998, 1999, 2000). However, as Opperman (2000) herself recognizes, “facial sutures, which appear very similar to cranial vault sutures in both morphology and function, do not have contact with an underlying dura mater”. Clearly, the patency of facial sutures is not likely to be affected by biochemical signals from the dura mater. This suggests that the fusion of cranial sutures is not solely associated with biochemical signals.

Although Kroman and Thomspon (2007) do not explicitly advocate the biochemical explanation of cranial suture closure, they do adopt a similar position. Kroman and Thomspon (2007, p 327) found that in a random sample of individuals from the Bass Collection, cranial suture closure was more strongly correlated with "somatic dysfunction" than with age at death. Kroman and Thomspon (2007, p 327) conclude that the fusion of the cranial sutures should therefore be viewed as a result of pathological conditions rather than as a "degenerative consequence of aging." This explanation has more in common with the biochemical explanation described above than the biomechanical one described below, in that it places an emphasis on internal biological factors rather than physical forces. However, the study is problematic because at least one of the conditions that Kroman and Thomspon (2007) deemed evidence of somatic dysfunction, sacroiliac fusion, is itself a degenerative change that becomes more common with increasing age (Waldron and Rogers, 1990; Dar et al., 2005). It is also unclear how a postcranial condition such as sacroiliac fusion could impact the timing of cranial suture closure, and it is unknown whether Kroman and Thomspon (2007) constructed their sample or selected statistical tests in order to properly control for additional sources of variation such as sex and ancestry. Finally, Kroman and Thomspon (2007, p 327) also report that cranial suture closure was highly correlated with "identified strain pattern in the cranium," which is more consistent with the biomechanical or functional model of cranial suture closure.

The Biomechanical or Functional Model

Extensive work by Moss (1954, 1957, 1959, 1960, 1961) provides a strong foundation for the biomechanical model of cranial suture closure. Moss' experiments with cranial sutures in rats led him to the conclusion that tensile forces, determined by the development of the cranial base, affect the timing of suture closure. Glucksmann (1942, p 238) reports that experiments with chicken embryos supported the conclusion that "tension stresses promote bone formation in osteogenic tissue in vitro and determine the pattern of osseous architecture". Moss (1958, 1960) found that this statement holds true for the posterior interfrontal suture, also known as the frontal suture, in the young postnatal rat. This suture, which overlies the falx ceribri (a portion of the cranial meninges), is the only suture in the rat calvarium, or skullcap, that normally fuses after birth (Moss, 1960). Moss (1960, p 457) found that sectioning the falx cerebri resulted in the inhibition of frontal suture closure, which "supports a mechanistic hypothesis concerning the role of the cranial dura in the initation of normal sutural synostosis in the rat".

Smith and McKeown (1974, p 559) likewise found that "isolation of the coronal sutural area from its normal functional connections results in…sutural fusion…related to…mechanical factors associated with changes in fibre orientation". There is a good deal of evidence, then, in support of the mechanical explanation of suture closure. Indeed, this explanation seems to have been accepted by a portion of the medical community as well. According to Moore and colleagues (2010, p 841), editors of a clinical anatomy textbook, the "prevailing hypothesis" is that "abnormal development of the cranial base creates exaggerated forces on the dura mater (outer covering membrane of the brain) that disrupt normal cranial sutural development", an explanation that clearly places more emphasis on biomechanics that biochemistry.

Further support for the functional model of suture closure comes from recent biomechanical studies. Byron and colleagues (2004) found that increased temporalis muscle mass in skeletally mature mice was associated with increased sagittal suture complexity. A later study demonstrated that increased temporalis muscle mass was also associated with changes in temporal bone size and squamosal suture morphology (Byron et al., 2008). Although neither study addressed whether masticatory muscle mass affected suture patency, they did serve to support the notion that the morphology of cranial sutures can be affected in some fashion by changes in the muscles of mastication.

Suture Closure and the Masticatory Apparatus

Mastication, "the first stage of digestion" is defined as "the physical breaking up of food and mixing with saliva in the mouth" (Thomas, 1997, p 1166). The masticatory apparatus or system refers to "a functional unit, which consists of the dentition, the periodontium, the jaws, the temperomandibular joints, the muscles involved in moving the mandible, the lip-cheek-tongue system, the salivary system, and the neuromuscular and nutritive (vascular) mechanisms" (Kraus et al., 1969, p 203). The four muscles primarily responsible for moving the mandible are collectively known as the muscles of mastication. They all attach to the mandible and to various parts of the skull (Moore et al., 2010).

An anthropological study conducted by Kimbel and Rak (1985, p 31) related "different sutural patterns to functional changes in the masticatory apparatus". Specifically, Kimbel and Rak (1985, p 31) found that unlike in the great apes and *A. afarensis*, "the common juvenile hominoid edge-to-edge asterionic articulation is maintained in adult *A. africanus*, *A. robustus*, female *A. boisei*, and most *Homo* crania". Kimbel and Rak (1985) suggest that the simple edge-to-edge asterionic sutural pattern is related to hypertrophy of the anterior fibers of the temoporalis muscle in *A. africanus*, *A. robustus*, and *A. boisei* and to craniofacial paedomorphosis in *Homo*. Essentially, in humans, the juvenile temporalis muscle configuration, in which the posterior muscle fibers fail to reach the asterionic region, is retained into adulthood. Because the posterior temporalis fibers do not reach asterion, they do not affect the suture pattern in that region. In *A. africanus*, *A. robustus*, and female *A. boisei*, the posterior temporalis muscle fibers do reach the asterionic region, but hypertrophy of the anterior temporalis muscle fibers results in less well-developed posterior temporalis fibers, and again results in the temporalis muscle having no affect on the suture pattern in this region (Kimbel and Rak, 1985). In sum, this study demonstrates that hypertrophy of one of the muscles of mastication has a direct relationship with suture pattern in at least one region of the human skull.

Within the area of evolutionary anthropology, there is a heavy emphasis on the relationships between the various components of the masticatory apparatus: the dentition, the bones that make up the jaw, the muscles of mastication, and the skull (Daegling, 2010). Although the primary goal of evolutionary mastication research is to reach a better understanding of diet and subsistence strategies in the context of recent human evolution, it is also applicable to the study of cranial suture closure. These studies have shown that "more mechanically challenging foods require greater force to be processed, greater biting forces require higher muscular forces…" and a skull subjected to higher muscular forces will require "...either structural reinforcement or reorganization in order to accommodate masticatory stress" (Daegling, 2010, p 505). Essentially, bite forces are transmitted from the masticatory apparatus into the cranium. Additionally, bite forces are determined in part by the nature of the food being subjected to mastication. It is reasonable to assume that changes in dental occlusion due to asymmetric antemortem tooth loss could also result in changes in bite forces, and thus changes to the skull.

Falk and colleagues (1989) examined the endocasts of 330 rhesus macaques and found that the masto-occipital and rostral squamosal sutures closed significantly earlier on the right than they did on the left. The authors suggest that these types of bilateral asymmetries in suture closure in both human and non-human primates may be related to minor brain/skull asymmetries known as cranial petalias (Falk et al., 1989). However, the fact that both of these sutures are situated in such close proximity to the attachment sites of the muscles of mastication suggests that the high frequency of asymmetrical suture closure may be related to changes in the forces transmitted to the skull via the masticatory apparatus.

In summary, a review of the literature on cranial suture closure and the biomechanics of mastication brings to light several key points. First, cranial suture closure is essential to the estimation of age at death in some forensic cases. Second, although very little investigation has been conducted into the frequency of asymmetry in human cranial suture closure, it certainly has the potential to affect the estimation of age at death and hinder positive identification. Third, the timing of cranial suture closure is likely dependent at least in part on tensile forces. Finally, bite forces are transmitted from the dentition, through the masticatory apparatus, to the skull, affecting skull morphology, including patterns of cranial suture closure. The nature of the food items undergoing mastication affects bite forces, so it is likely that changes in dental occlusion due to asymmetrical antemortem tooth loss will also change bite forces, the masticatory apparatus, and thus the cranial sutures, in an asymmetrical manner.

Research Questions and Hypotheses

Research Questions

This study is intended to answer the following research questions:

1. How frequent and extreme is asymmetrical cranial suture closure in modern Americans?
2. Is there a relationship between degree of asymmetry in cranial suture closure and age at death?

3. Does the degree of asymmetry in cranial suture closure vary between males and females?
4. Does the degree of asymmetry in cranial suture closure vary between ancestral groups?
5. Is there a relationship between asymmetrical antemortem tooth loss and asymmetrical cranial suture closure in modern humans?
6. Does the relationship between asymmetrical antemortem tooth loss and asymmetrical cranial suture closure vary according to suture site?

<u>Research Hypotheses</u>

Hypothesis 1:

Null Hypothesis: Asymmetrical cranial suture closure will not be frequent or extreme enough in a sample of modern Americans to hinder estimation of age at death.

Alternative Hypothesis: Asymmetrical cranial suture closure will be frequent and extreme enough in a sample of modern Americans to hinder estimation of age at death.

Hypothesis 2:

Null Hypothesis: There will be no relationship between age at death and degree of suture asymmetry.

Alternative Hypothesis: There will be a positive correlation between age at death and degree of suture asymmetry.

Hypothesis 3:

Null Hypothesis: Degree of suture asymmetry will differ significantly between males and females.

Alternative Hypothesis: Degree of suture asymmetry will not differ significantly between males and females.

Hypothesis 4:

Null Hypothesis: Degree of suture asymmetry will differ significantly between subjects of European ancestry and those of African ancestry.

Alternative Hypothesis: Degree of suture asymmetry will not differ significantly between subjects of European ancestry and those of African ancestry.

Hypothesis 5:

Null Hypothesis: There will be no relationship between asymmetrical antemortem molar and premolar loss and asymmetrical cranial suture closure.

Alternative Hypothesis: It is predicted that there will be a positive correlation between asymmetrical antemortem molar and premolar loss and asymmetrical cranial suture closure.

Hypothesis 6:

Null Hypothesis: The relationship between asymmetrical antemortem molar and premolar loss and asymmetrical cranial suture closure will be the same at all suture sites examined.

Alternative Hypothesis: The relationship between asymmetrical antemortem molar and premolar loss and asymmetrical cranial suture closure will vary according to suture site.

CHAPTER 4: MATERIALS AND METHODS

Materials

This research utilized human remains from both the WM Bass Donated Skeletal Collection and the Hamann-Todd Human Osteological Collection. The final study sample consisted of 101 crania of documented age at death, sex, and ancestry. Table 6 demonstrates the distribution of these characteristics within the overall sample. Table 7 depicts the distribution for the portion of the sample drawn from the Bass Collection, while Table 8 corresponds to the portion of the sample drawn from the Hamann-Todd Collection.

N = 101		**Ancestry**			
		European		**African**	
		Sex		**Sex**	
		Male	**Female**	**Male**	**Female**
Age at Death Category	20-24 years	2	1	2	2
	25-29 years	2	3	2	2
	30-34 years	2	2	2	2
	35-39 years	2	2	2	2
	40-44 years	2	2	2	2
	45-49 years	2	2	2	2
	50-54 years	2	2	2	2
	55-59 years	1	2	2	2
	60-64 years	2	2	2	2
	65-69 years	1	2	2	2
	70-74 years	2	2	2	2
	75-79 years	2	2	2	2
	80-84 years	2	2	1	2
	Total	**24**	**26**	**25**	**26**

Table 6: Total Sample Distribution by Age at Death, Sex, and Ancestry

n = 55		Ancestry			
		European		African	
		Sex		Sex	
		Male	Female	Male	Female
Age at Death Category	20-24 years	0	0	0	0
	25-29 years	1	1	0	0
	30-34 years	2	0	0	0
	35-39 years	2	1	1	0
	40-44 years	2	2	0	0
	45-49 years	2	2	2	0
	50-54 years	2	2	1	1
	55-59 years	1	2	2	1
	60-64 years	2	2	2	0
	65-69 years	1	2	1	1
	70-74 years	2	2	2	0
	75-79 years	2	2	0	0
	80-84 years	2	2	0	0
	Total	**21**	**20**	**11**	**3**

Table 7: Bass Collection Subsample Distribution by Age at Death, Sex, and Ancestry

The sample was constructed so as to include two individuals from each ancestry/sex category for each half decade, starting with the early twenties (20-24 years of age) and continuing through the early eighties (80-84 years of age), similar to the procedure outlined by Nawrocki (1998). As he explains, “large, well-balanced samples with substantial numbers of individuals of both sex and ancestry groups in each decade are needed to facilitate strong a priori hypotheses testing” (Nawrocki, 2010, p 96).

Following the procedure outlined above would have resulted in a total sample size of 104 individuals. Unfortunately, due to a shortage of elderly individuals, one 85-year-old female of African ancestry was included in the “early eighties” category for the purposes of this study. A one-year age difference is not anticipated to have a significant effect on the results. The author was also unable to find more than one female of European ancestry in the “early twenties” age category. However, data was collected on a 25-year-old female of European ancestry. That individual was placed in the "late twenties" (25-29 years of age) age category.

In addition, although the Cleveland Museum of Natural History has records that document the age, sex, and race of each skeleton as stated on the individual's death certificate, there is some question regarding the accuracy of the stated age at death for some individuals in the Hamann-Todd Collection (Lovejoy et al., 1985). In fact, one specimen had to be eliminated from this study because of the wide gap between the stated age and the skeletal age. The absence of records such as a birth certificate made it impossible to verify this individual's actual age at death (Jellema, 2012). Thus, only individuals for whom the documented age at death closely approximated the skeletal age were included in this study. The issues described above resulted in a slightly uneven sample distribution.

The WM Bass Donated Skeletal Collection is composed of nearly 1,000 individuals collected between 1981 and the present. Birth years range from 1892 to 2011 with the majority of individuals having been born after 1940. The collection is housed at the University of Tennessee, Knoxville in Knoxville, Tennessee. All skeletal remains were either donated by the individual prior to death, or donated by the deceased individual's family or the Medical Examiner. Most of the individuals in the collection have documented age, sex, and ancestry (University of Tennessee Knoxville Forensic Anthropology Center).

Although data was originally collected on nearly 100 individuals from the Bass Collection, quite a few had to be eliminated because they were completely edentulous and therefore offered no information on asymmetry in antemortem tooth loss. Several individuals who had retained all of their permanent teeth were included, although there were not many of these in this collection. Ultimately, 55 individuals from the WM Bass Donated Skeletal Collection were included in the study sample, including 21 males of European ancestry, 20 females of European ancestry, 11 males of African ancestry, and 3 females of African ancestry.

n = 46		Ancestry			
		European		African	
		Sex		Sex	
		Male	Female	Male	Female
Age at Death Category	20-24 years	2	1	2	2
	25-29 years	1	2	2	2
	30-34 years	0	2	2	2
	35-39 years	0	1	1	2
	40-44 years	0	0	2	2
	45-49 years	0	0	0	2
	50-54 years	0	0	1	1
	55-59 years	0	0	0	1
	60-64 years	0	0	0	2
	65-69 years	0	0	1	1
	70-74 years	0	0	0	2
	75-79 years	0	0	2	2
	80-84 years	0	0	1	2
	Total	**3**	**6**	**14**	**23**

Table 8: Hamann-Todd Collection Subsample Distribution by Age at Death, Sex, and Ancestry

The Hamann-Todd Human Osteological Collection is housed at the Cleveland Museum of Natural History. The collection is comprised of over 3,000 skeletons from cadavers collected between 1912 and 1938 by the Western Reserve University Department of Anatomy. The cadavers originally came from several major hospitals in the Cleveland, Ohio area. Age, sex, and race are documented for most individuals in the collection (Lovejoy et al., 1985). Completely edentulous individuals were once again excluded although individuals with full sets of permanent dentition were retained in the final study sample. 46 crania from the Hamann-Todd

Collection were included in the final study sample, including 3 males of European ancestry, 6 females of European ancestry, 14 males of African ancestry, and 23 females of African ancestry.

Additional Information Collected: Age at Death, Sex, Ancestry

In addition to the information on suture closure and tooth loss, the following variables were collected for each individual: age at death, sex, and ancestry. Because it is well established that the timing of cranial suture closure is correlated with age (Todd and Lyon, 1924; Meindl and Lovejoy, 1985; Nawrocki, 1998), it was important that the documented age at death was recorded for each individual, allowing this variable to be statistically controlled for and isolated from other sources of variation. Furthermore, some studies have shown a relationship between sex and cranial suture closure (Masset, 1989; Mann et al., 1991; Key et al., 1994; Nawrocki, 1998; Zambrano, 2005; Beauthier et al., 2010) as well as ancestry and cranial suture closure (Živanović, 1983; Key et al., 1994; Sahni et al., 2005). In at least one case, apart from the effect (or lack thereof) of sex and ancestry on suture closure when these variables were examined separately, the interaction of sex and ancestry did affect suture closure (Nawrocki, 1998). The inclusion of sex, ancestry, and age at death in the statistical analysis enables the identification and isolation of any effect these variables might have on the asymmetry of suture closure.

Age at death, sex, and ancestry for each individual were drawn from the databases associated with the skeletal collection of origin. The database for the Bass Collection was emailed to the author prior to data collection (Steadman, 2012). The database for the Hamann-Todd Collection is available on the collection's website (The Cleveland Museum of Natural History, 2013).

Although the documentation establishing the known information for the individuals in both skeletal collections describes ancestral origin in terms of race, there is some controversy within the field of physical anthropology regarding the validity of race as a biological category. Rather than entering into that discussion here, the terms "African ancestry" and "European ancestry" will be used in place of the terms "black" and "white" respectively. It is hoped that these terms will place emphasis on biological affinity rather than cultural affinity. It is also important to note that although these terms may be shortened to "African" and "European" for the sake of convenience, they are still references to ancestral origin rather than nationality. The vast majority of the individuals in the sample are American by nationality.

Methods

Scoring Cranial Suture Closure

For each individual, suture closure was examined at 13 bilateral sites. The sites were chosen based on their inclusion in at least one of the two most commonly used suture closure based age estimation methods: the Meindl and Lovejoy (1985) method and the Nawrocki (1998) method. Data was collected on both the right and the left sides in order to compare the two and thus measure asymmetry. Consequently, 26 closure scores (13 right and 13 left) were collected for each individual, except where damage it impossible to assign a score. This study used the scoring scale developed by Meindl and Lovejoy (1985) and depicted in Table 5 on page 20. According to this scale, each one centimeter suture site is given a score of 0 ("open"), 1 ("minimal closure"), 2 ("significant closure"), or 3 ("complete obliteration") (Meindl and Lovejoy, 1985, p 58). The Meindl and Lovejoy (1985) scale was selected for use in this study due its ease of applicability and low rates of inter-observer and intra-observer error. A photograph of each stage of suture closure is provided in Buikstra and Ubelaker (1994).

Nawrocki (1998) provides additional guidance for applying the Meindl and Lovejoy (1985) scoring scale. He notes that some "endocranial sutures in the final stages of closure commonly leave behind very tiny pinpoint openings along the former suture line" (Nawrocki, 1998, p 279). Nawrocki (1998) instructs the observer to assign the site a score of "2" rather than "3" if more than two or three of such pinpoint openings remain. Nawrocki (1998) also notes that some suture sites are made up of the junction of three separate sutures. In this case, "those portions of all three legs that fall in a circle one centimeter in diameter centered at the juncture point" should be utilized to assign a score to the site (Nawrocki, 1998, p 279). Both of Nawrocki's (1998) recommendations were adopted in this study where applicable.

Seven of the thirteen bilateral suture sites are located in the lateral-anterior region (Figure 5). The following lateral-anterior suture sites were scored in each individual: parietomastoid, squamosal, occipitomastoid, midcoronal, pterion, sphenofrontal, inferior sphenotemporal, and superior sphenotemporal. All lateral-anterior sites were viewed and scored ectocranially. The following two sites in the vault region were viewed both ectocranially (Figure 6) and endocranially (Figure 7), resulting in a total of four vault suture sites: ectocranial midlambdoid, endocranial midlambdoid, ectocranial midcoronal, and endocranial midcoronal. The abbreviations used in the illustrations are defined in the Key to Symbols and Abbreviations. Some of these abbreviations are drawn from Nawrocki (1998) while others were constructed for use in the current study.

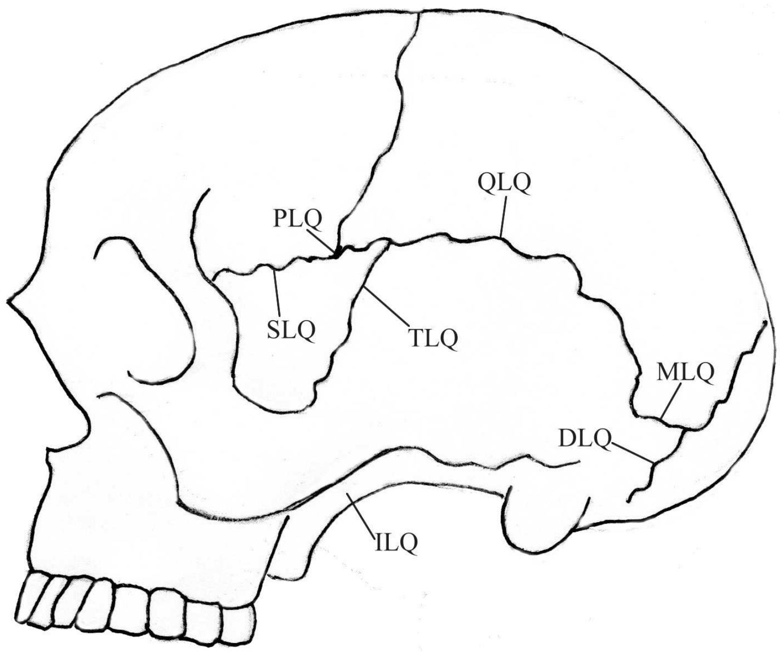

Figure 5: The Lateral-Anterior Suture Sites

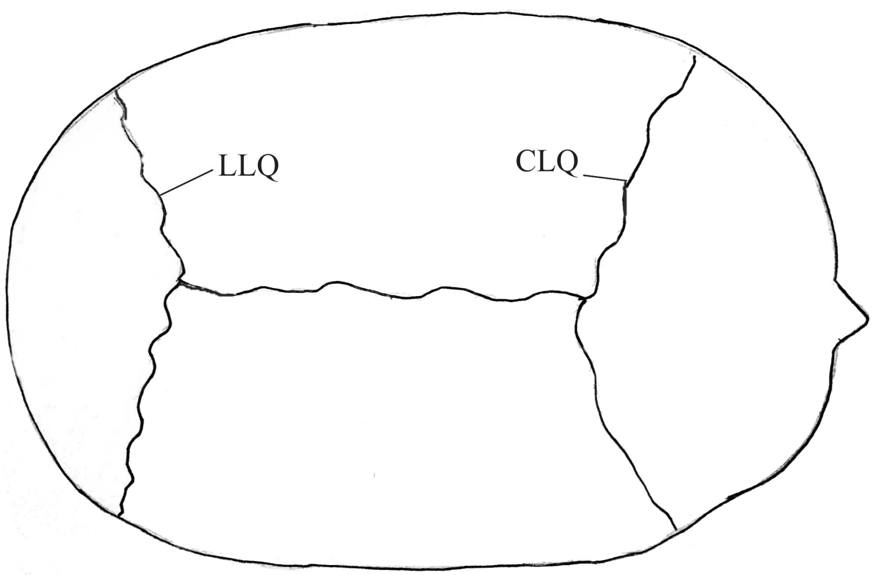

Figure 6: The Ectocranial Vault Suture Sites

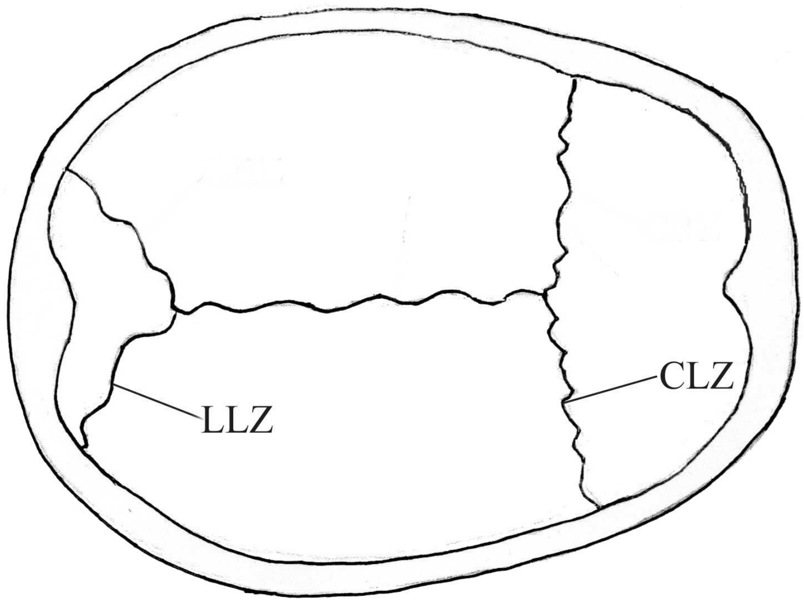

Figure 7: The Endocranial Vault Suture Sites

Finally, two palatine sutures were examined: the incisive suture and the transverse palatine suture (Figure 4). Both palatine sutures were divided into right and left portions at the median palatine suture. Rather than one centimeter sections, each palatine suture portion was examined along its entire extent from the median palatine suture to the alveolar process where the teeth insert, similar to the instructions provided in Nawrocki (1998). This resulted in a total of two bilateral palatine suture sites per individual (Figure 8).

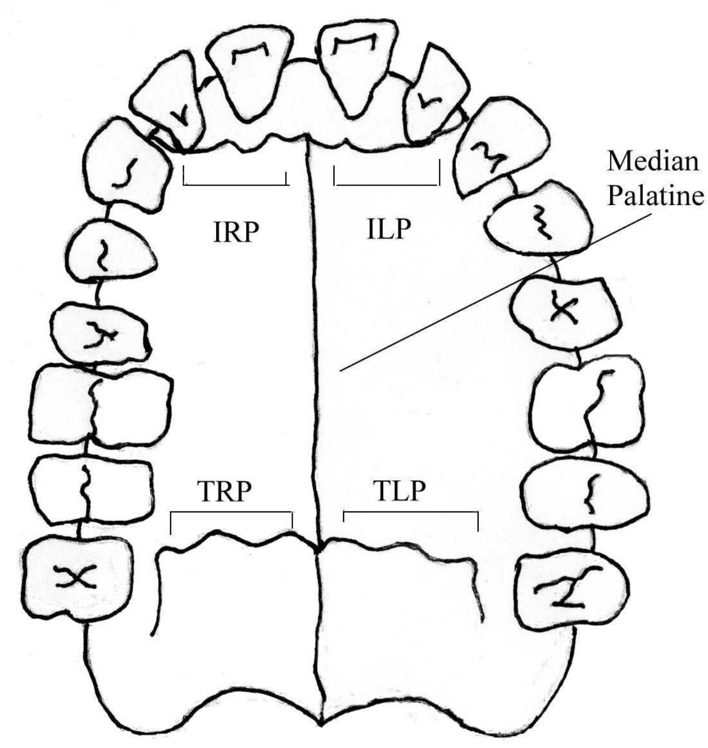

Figure 8: The Palatine Suture Sites

For the sake of consistency, when in doubt, the author assigned the lower of two potential scores. For example, if it seemed that a case could be made for a particular site to be scored as either a 1 or a 2, the author scored it as a 1. If damage made it difficult to determine the appropriate score, the site was assigned no score at all. This was most common at the palatine sites and the squamosal site (Tables 9-10). All of the Hamann-Todd specimens were sagittally sectioned and unfortunately, in some cases, the sectioning resulted in damage to the hard palate that obscured portions of the palatine sutures, making it impossible to assign a score to those suture sites. A similar situation occurred with the Bass Collection regarding the squamosal suture site. Many of the crania in the Bass Collection were transversely sectioned. Occasionally the sectioning resulted in damage to the temporal bone that obscured the state of closure of the squamosal suture site.

		MQ	QQ	DQ	PQ	SQ	IQ	TQ
N	Valid	101	91	100	99	100	101	98
	Missing	0	10	1	2	1	0	3

Table 9: Frequency of Missing Suture Site Data at the Lateral-Anterior Sites

		LQV	LZV	CQV	CZV	IP	TP
N	Valid	100	98	101	101	100	92
	Missing	1	3	0	0	1	9

Table 10: Frequency of Missing Suture Site Data at Vault and Palatine Sites

Measuring Asymmetry in Cranial Suture Closure

Asymmetry in cranial suture closure is represented by the variable "Degree of Suture Asymmetry" (Table 11). To obtain this variable, for each suture site in each individual, the score for the right side was subtracted from the score for the left side, resulting in a single number for each bilateral suture site that represented the degree of asymmetry in suture closure at that site. The absolute value of that number was designated the degree of suture asymmetry. Thus a 0 indicates the absence of asymmetry at a particular site, a 1 indicates mild asymmetry in suture closure, a 2 represents moderate asymmetry, and a 3 indicates extreme asymmetry. Degree of suture asymmetry was calculated for each of the 13 suture sites, resulting in 13 data points per individual.

Degree of Suture Asymmetry	Description
0	No asymmetry in suture closure present at the site (suture closure is symmetrical at the site)
1	Mild asymmetry in suture closure present at the site
2	Moderate asymmetry in suture closure present at the site
3	Extreme asymmetry in suture closure present at the site

Table 11: Measuring Asymmetry in Cranial Suture Closure

Table 12 depicts the calculation of degree of suture asymmetry for individuals HTH 0781 and HTH 0333 at the ectocranial midcoronal suture site. Individual HTH 0781 received a score of 0 on the left, indicating that the suture was completely open at the ectocranial midcoronal site. The same individual received a score of 1 on the right, indicating that the suture was partially closed. The right side was subtracted from the left, resulting in a value of -1. The absolute value of -1 is 1. Thus, the degree of suture asymmetry present at the ectocranial midcoronal suture site in individual HTH 0781 is 1. The same procedure was followed for individual HTH 0333. In this case, subtracting the right from the left produced a value of 1. The absolute value of 1 is 1. Once again, the degree of suture asymmetry at the ectocranial midcoronal site is thus 1.

Skeleton #	Closure Score on Left	Closure Score on Right	Left – Right =	Degree of Suture Asymmetry
HTH 0781	0	1	0 – 1 = -1	|-1| = 1
HTH 0333	2	1	2 – 1 = 1	| 1| = 1

Table 12: Examples of the Calculation of Degree of Suture Asymmetry at the Ectocranial Midcoronal Suture Site.

Antemortem Tooth Loss

Data on antemortem tooth loss was collected using Attachment 14a "Dental Inventory Visual Recording Form: Permanent Dentition" provided in Buikstra and Ubelaker's (1994) *Standards for Data Collection from Human Skeletal Remains*. Each tooth was recorded as lost antemortem, not lost antemortem, or indeterminate. Although this information was originally collected for all teeth, ultimately only the posterior teeth (molars and premolars) were utilized in the study due to their preeminent role in the chewing process (Hillson, 1996).

While "canines are primarily piercing teeth" and incisors are "cutting teeth," molars are responsible for grinding food (Kraus et al., 1969, p 1). Premolars have a dual function, being involved in both piercing and grinding. It is expected that asymmetrical antemortem loss of the grinding teeth will have a greater effect on the asymmetry of suture closure because the lateral movements involved in grinding are already naturally asymmetric, in that these movements involve the right and left muscles of mastication functioning in opposition to one another (Kraus et al., 1969). Antemortem loss on one side alone would therefore compromise this system of opposition and affect the transmission of force to the cranium. The biomechanical model of cranial suture closure discussed earlier suggests that differential bilateral forces will result in bilateral variation in suture closure. Consequently, this study incorporates only those teeth involved in grinding actions, namely the molars and premolars.

Measuring Asymmetry in Antemortem Tooth Loss

This research incorporates a large number of predictor variables including age at death category, sex, ancestry, and asymmetry in antemortem tooth loss. Each skeleton produced 10 values that represented asymmetry in antemortem tooth loss. In order to simplify the analysis and interpretation of the data, those 10 values were converted into a single value for each mouth that was designated points of dental asymmetry (PDA). As depicted in Table 13, each tooth received a score of 0, indicating the absence of asymmetry in antemortem loss, or 1 indicating the presence of asymmetry in antemortem loss. Each score of one was considered a single point of dental asymmetry. The points of dental asymmetry were then totaled for each individual, resulting in a single value for each mouth that represents the total points of dental asymmetry present in that individual.

Score	Description
0	Absence of asymmetry in antemortem loss: both right and left teeth were present, both right and left teeth were lost postmortem, or both right and left teeth were lost antemortem
1	Presence of asymmetry in antemortem loss: right was lost antemortem and left was not, or left was lost antemortem and right was not

Table 13: Measuring Asymmetry in Antemortem Tooth Loss.

Figure 9 depicts the maxilla and mandible of the individual labeled HTH 0461. In this individual, the maxillary second molar was lost antemortem on the right but not on the left, producing a single point of dental asymmetry. The same is true of the maxillary third molar, producing a second point of dental asymmetry. The mandibular second premolar was lost antemortem on the right but not the left, producing a third point of dental asymmetry. All other teeth are symmetric in regard to antemortem loss. For example, the second maxillary premolar was lost antemortem on both the right and the left, producing 0 points of dental asymmetry.

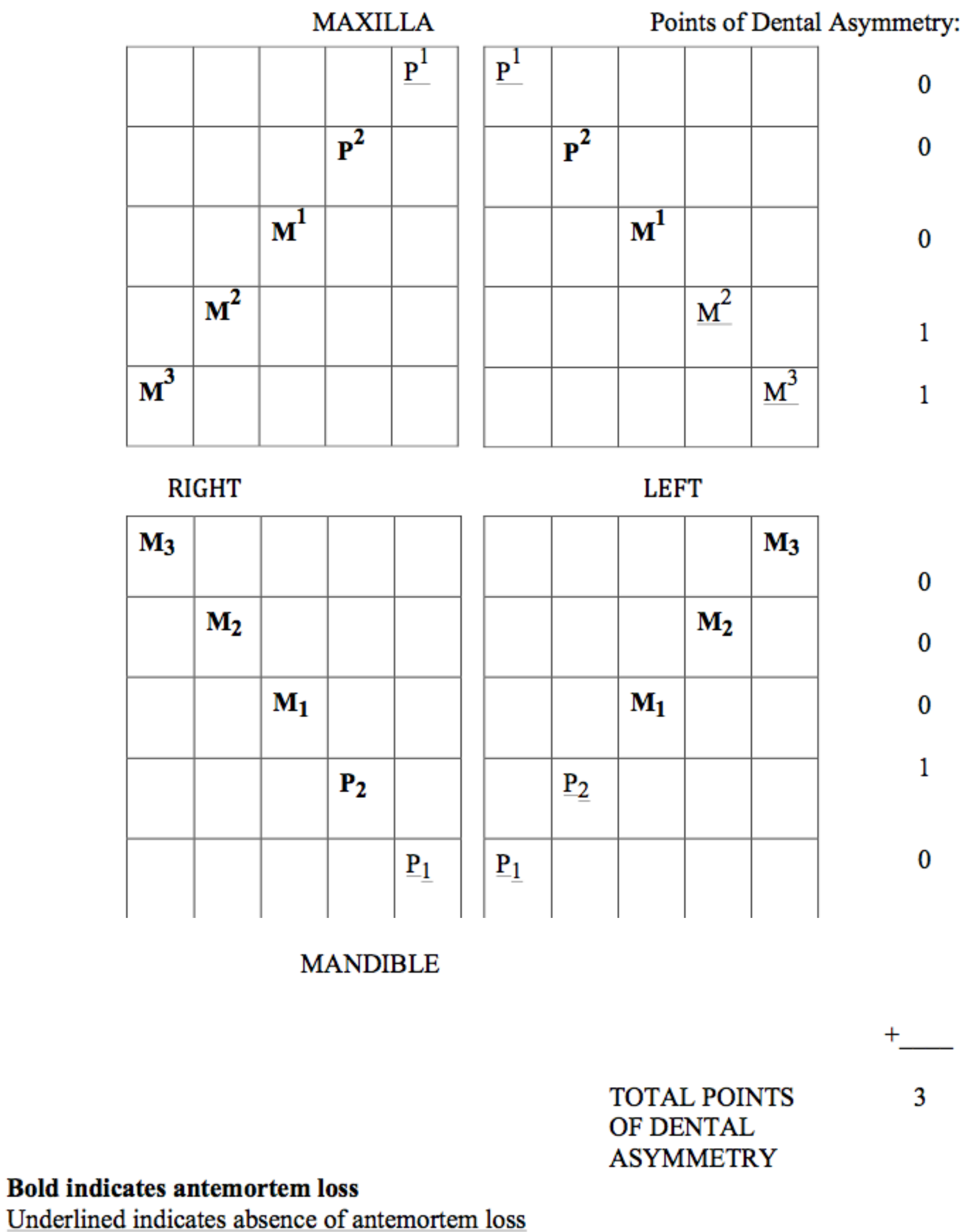

Figure 9: HTH 0461 Calculation of Points of Dental Asymmetry

When all the points of dental asymmetry for this individual are summed, it results in a value of 3, which represents the total points of dental asymmetry for the individual. Thus, 10 teeth are reduced to a single value that represents asymmetry in antemortem tooth loss in the individual HTH 0461. Points of Dental Asymmetry, or PDA, had the potential to range from 0 to 10. In reality, no individuals demonstrated more than 8 points of dental asymmetry.

Statistical Methods

All statistical analyses were carried out using IBM SPSS Statistics Version 21 (IBM Corporation, 2012). This study employed a mixed model Analysis of Variance (ANOVA) design to examine the data. The goal of an ANOVA procedure is to examine the influence of one or more independent variables on the dependent variable. It does so through "determining whether mean differences exist on the dependent variable" (Lomax and Hahs-Vaughn, 2012, p 292). When comparing the means of just two independent samples, a pair-wise independent t-test can be used effectively. However, when more than two means are being compared, multiple independent t-tests would have to be conducted, which would greatly increase the likelihood of a Type I error. A Type I error refers to incorrectly rejecting a true null hypothesis, potentially causing the researcher to assert the presence of between-group differences where there are none (Klepinger and Giles, 1998). ANOVA is an omnibus test: a single powerful test that compares the means of more than two groups without greatly increasing the probability of a Type I error (Lomax and Hahs-Vaughn, 2012).

This study involves comparing the dependent variable between sexes, ancestral groups, and age at death groups to determine whether these factors have any influence on the asymmetry of suture closure. Because more than two groups are being compared, an ANOVA procedure was selected in order to avoid the greater likelihood of a Type I error that would occur if multiple standard independent t-tests were used. However, it was necessary to select a mixed model ANOVA because this study violates one of the assumptions of the standard ANOVA, specifically the assumption of independence.

The assumption of independence refers to the assumption that "observations are independent of one another (both within and across samples)" (Lomax and Hahs-Vaughn, 2012, p 309). Violation of the assumption of independence results in the increased likelihood of making either a Type I or a Type II error (Lomax and Hahs-Vaughn, 2012). A Type II error occurs when one fails to detect significant differences that are actually present (Field, 2009). Violation of the independence assumption may also "affect the standard error of the sample means and thus influence any inferences made about those means" (Lomax and Hahs-Vaughn, 2012, p 309). The current study violates the assumption of independence in that multiple suture sites were observed for each subject. It is likely that all of the suture site observations within a single individual are interrelated, and therefore not completely independent of one another. To account for this violation of the independence assumption, this study required the use of an ANOVA model that incorporates repeated-measures data.

Repeated-measures refers to a study design in which the dependent variable is measured more than once on the same subject "under changing experimental or observational conditions" (West et al., 2007, p 2). In this study, the changing observational conditions are the different suture sites. A pure repeated-measures ANOVA model involves only one or more repeated-measures variables, which are a type of within-subject factor (Field, 2009). This study includes not only a repeated-measures variable (suture site), but also several between-subjects fixed factors (sex and ancestry) and two continuous covariates (points of dental asymmetry and age-at-death category). Although age-at-death category can be considered either a between-subjects fixed factor or a continuous covariate, it was designated a continuous covariate in this study because the large number of age categories included (13) made pairwise comparisons between age groups ill-advised (Klepinger and Giles, 1998; Lomax and Hahs-Vaughn, 2012). A mixed design ANOVA allows for the incorporation of all of the above variables (Figure 10) in a single model (Field, 2009).

Although utilizing a mixed model ANOVA in place of a standard ANOVA removes the necessity of satisfying the assumption of independence, it does introduce an additional assumption. The mixed model ANOVA design is based on the assumption of sphericity instead of the assumption of independence. "Sphericity refers to the equality of variances of the differences between treatment levels" and the violation of this assumption results in a loss of statistical power (Field, 2009, p 459). In the current study, Mauchly's test for sphericity was conducted to check for sphericity. All ANOVAs, including the mixed model ANOVA, are based on the assumption of homogeneity of variance. Homogeneity of variance refers to the assumption that "the variance of one variable is stable (i.e. relatively similar) at all levels of another variable" (Field, 2009, p 787). Levene's Test for Homogeneity of Error Variances was conducted to check for homogeneity of variance.

Yet another assumption involved in the use of ANOVA is the assumption of normality. The assumption of normality refers to the assumption that the data are distributed in a particular fashion, with the majority of scores occurring around the center of the distribution, and the frequency of scores decreasing further away from the center (Field, 2009). Although some researchers suggest that regular bivariate normality is sufficient for the use of a mixed model ANOVA procedure (Field, 2009), others claim that repeated measures ANOVA procedures assume an even more stringent form of normality known as multivariate normality (Nimon, 2012). Multivariate normality means that "each variable in a set is normally distributed around fixed values on all other variables in the set" (Nimon, 2012, p 3). Regardless, when the assumption of normality is violated, it can once again result in the increased likelihood of a Type I or Type II error (Field, 2009).

Unfortunately, IBM SPSS Statistics Version 21 (IBM Corporation, 2012) does not incorporate any way to test for multivariate normality (Field, 2009). Instead, the histograms (Figures 21-33) in the Appendix were examined to check for visual evidence of skew and kurtosis. Skew is "a measure of the symmetry of a frequency distribution" (Field, 2009, p 794). Kurtosis "measures the degree to which scores cluster in the tails of a frequency distribution" (Field, 2009, p 788). The results of the visual examination of the histograms are reported in Chapter 5.

Finally, ANOVA assumes that the dependent variable is measured on at least an interval level (Field, 2009; Nimon, 2012). In this study, the dependent variable is degree of suture asymmetry and it is measured on an interval level. Interval data refers to ordinal data for which "equal intervals on the scale represent equal differences in the property being measured" (Field, 2009, p 9). In this case, for example, the difference between a score of 0 (no asymmetry) and a score of 1 (mild asymmetry) is the same as the difference between a score of 2 (moderate asymmetry) and a score of 3 (extreme asymmetry). Therefore, use of ANOVA is justified in this study.

In sum, the data in this study were analyzed using a two-way mixed model ANOVA that incorporated two between-subjects factors, two continuous covariates, and a dependent repeated measures variable (Figure 10). All relevant assumptions were examined using appropriate tests. The results are reported in Chapter 5.

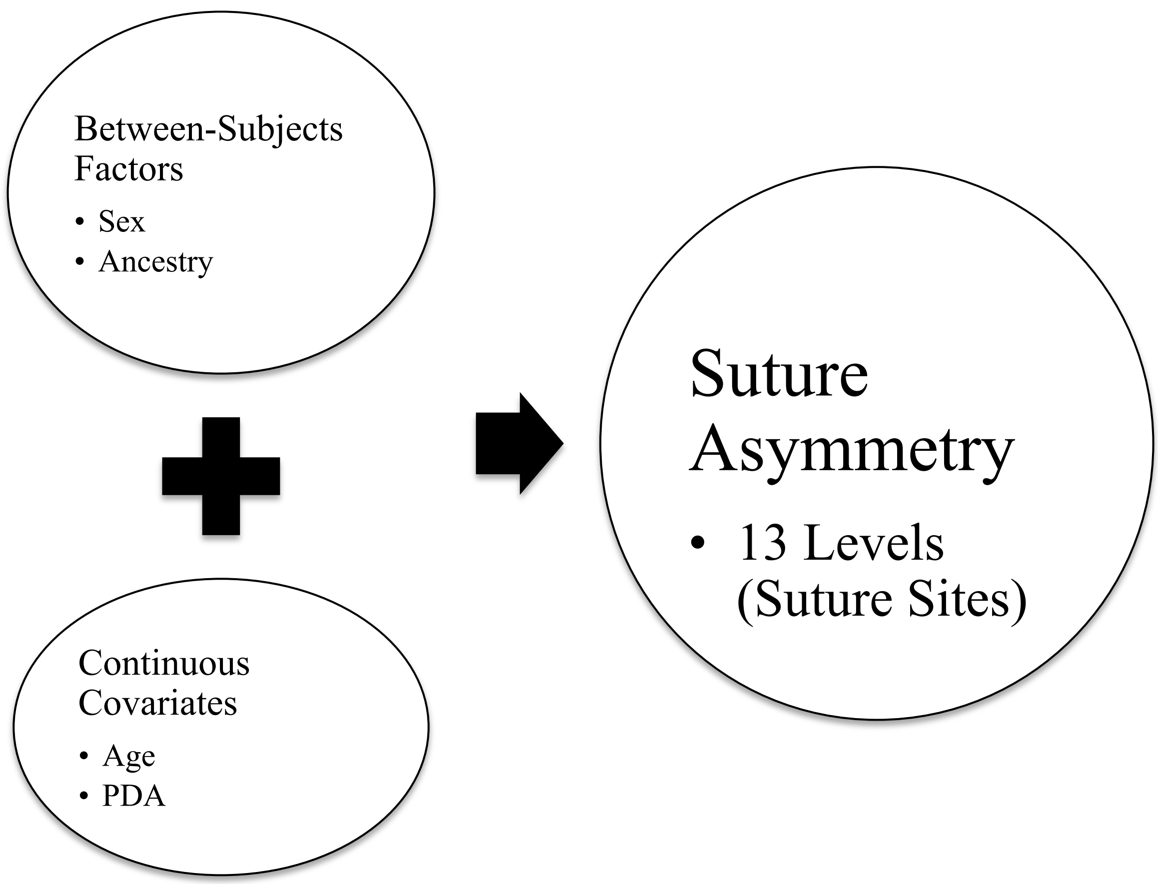

Figure 10: Variables Included in Mixed Model ANOVA I

CHAPTER 5: RESULTS

Frequency of Asymmetry in Cranial Suture Closure

Extreme suture asymmetry was present in at least one subject at the following five suture sites: parietomastoid, occipitomastoid, sphenofrontal, superior sphenotemporal, and endocranial midlambdoid. In no cases was extreme asymmetry present at the same site in more than two subjects. In no cases was moderate asymmetry present at the same site in more than four subjects. The following four sites never displayed more than mild asymmetry: pterion, ectocranial midlambdoid, and transverse palatine. Mild asymmetry was present at all suture sites in at least 12 individuals.

The most frequently symmetrical suture site was the incisive site. 85.1% of individuals with observable incisive sutures demonstrated no asymmetry in suture closure. The percentage of individuals with no asymmetry at all other sites ranged between 62.4% and 77.2%. The frequency tables (Tables 25-37) and histograms (Figures 18-30) in the Appendix demonstrate these results. The differences in frequencies between suture sites were not statistically significant. Therefore, no interpretation of the variation between sites will be attempted here.

Mixed Model ANOVA I Results

Assumptions

Mauchly's test (Table 14) indicated that the conditions for sphericity were met, $\chi^2(77) = 95.17$. Therefore, sphericity was assumed in the following analysis. Levene's test of equality of error variances (Table 15) showed that for the degree of asymmetry in cranial suture closure, the variances were equal at all sites, $p > .05$, except the occipitomastoid site, $F\ (3, 74) = 3.64$, $p < .05$. Although large violations of the assumption of homogeneity of variance can increase the likelihood of a Type I error, ANOVA is robust to violations of this assumption when the group sizes are approximately equal (Nimon, 2012). In this study, the sample was carefully constructed to have an even distribution across age at death, sex, and ancestry, resulting in very similar group sizes. Consequently, the data were not transformed to stabilize variance. Even if there was an increased likelihood of inappropriately rejecting the null hypothesis, as it turned out nearly all the predictor variables and interactions demonstrated statistically insignificant effects, so the null hypotheses were not rejected regardless.

Within Subjects Effects	Mauchly's W	Approximate Chi-Square	df	Sig.
Suture_site	.246	95.172	77	.080

Table 14: Mixed Model ANOVA I Mauchly's Test of Sphericity

Suture Site	**F**	**df1**	**df2**	**Sig.**
Parietomastoid	.963	3	74	.415
Squamosal	1.594	3	74	.198
Occipitomastoid	3.642	3	74	.016
Pterion	1.568	3	74	.204
Sphenofrontal	1.698	3	74	.175
Inferior Sphenotemporal	1.866	3	74	.143
Superior Sphenotemporal	.974	3	74	.410
Ectocranial Midlambdoid	1.173	3	74	.326
Endocranial Midlambdoid	.084	3	74	.968
Ectocranial Midcoronal	.019	3	74	.996
Endocranial Midcoronal	.130	3	74	.942
Incisive	2.508	3	74	.065
Transverse Palatine	1.805	3	74	.154

Table 15: Mixed Model ANOVA I Levene's Test of Equality of Error Variances

As mentioned in Chapter 4, the statistical software utilized in this study does not include any way to test for multivariate normality. Instead, the histograms in the Appendix (Figures 18-30) were examined visually for evidence of skew or kurtosis. The histograms clearly demonstrate that the data in this study are highly positively skewed. A positively skewed distribution is one in which “the frequent scores are clustered at the lower end” (Field, 2009, p 19). In this case, the vast majority of individuals demonstrated no asymmetry at each site, so that the scores are clustered at the lower end of the scale of degree of suture asymmetry. The data in this study clearly do not follow a normal distribution. Although transforming the data to correct for a non-normal distribution is an option, many researchers maintain that transforming data creates more problems than it solves (Games and Lucas, 1966; Glass et al., 1972; Games, 1984). For example, Glass and colleagues (1972, p 241) report that “the payoff of normalizing transformations in terms of more valid probability statements is low, and they are seldom considered to be worth the effort.”

Another way to deal with data that are not normally distributed is to use a non-parametric test, because non-parametric tests incorporate fewer assumptions. However, non-parametric tests “have been developed for only a fairly limited range of situations” and there is no non-parametric equivalent to a mixed model ANOVA (Field, 2009, p 163). There are, however, robust methods that can be used in place of the mixed model ANOVA procedure used here (Field, 2009; Wilcox, 2012). Robust methods are tests that are accurate even when their assumptions are violated (Field, 2009). Although IBM SPSS Statistics does not currently incorporate any robust methods, there is a free, downloadable statistical software package called “R” available online that is dedicated solely to robust methods (Anon). Unfortunately, due to time constraints, the use of R was not feasible in the current study. However, the advanced statistical methods available through R have the potential to be of great utility in future research into the subject of asymmetrical cranial suture closure.

Fortunately, several examinations of the performance of ANOVA under non-normal conditions have shown that when group sizes are equal or nearly equal, violation of the normality assumption has little effect on either the Type I error rate (Lunney, 1970) or the power of the test to detect significant differences between groups (Donaldson, 1968). In the current study, the sample was carefully constructed to have equal group sizes. Consequently no transformations or non-parametric tests were deemed necessary in this study, and the results should still be fairly accurate despite the use of mixed model ANOVA in place of robust methods.

<u>Tests of Between-Subjects Effects</u>

All effects are reported as significant at $p < .05$. The covariate age was not significantly related to the degree of suture asymmetry, F (1, 72) = 1.04 (p = 0.31). The covariate points of dental asymmetry was not significantly related to the degree of suture asymmetry, F (1, 72) = 0.68 (p = 0.41). There was no significant main effect of ancestry on degree of asymmetry in suture closure after controlling for age and points of dental asymmetry, indicating that degree of suture asymmetry in those of European ancestry and those of African ancestry was in general the same, F (1, 72) = 0.12 (p = 0.73). After controlling for age and points of dental asymmetry, there was no significant main effect of sex on degree of suture asymmetry, indicating that the degree of suture asymmetry in males and females was in general the same, F (1, 72) = 0.23 (p = 0.64). There was no significant interaction effect between the ancestry and sex of the subject, F (1, 72) = 0.05 (p = 0.83). This indicates that the degree of suture asymmetry of subjects of different ancestries in general did not differ between males and females. Table 16 presents the results of the tests of between-subjects effects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.904	1	.904	26.741	.000
Age	.035	1	.035	1.043	.310
PDA	.023	1	.023	.675	.414
Sex	.008	1	.008	.225	.637
Ancestry	.004	1	.004	.124	.726
Sex * Ancestry	.002	1	.002	.047	.828
Error	2.435	72	.034		

* = Interaction Effect

Table 16: Mixed Model ANOVA I Tests of Between-Subjects Effects

Tests of Within-Subjects Effects

There was no significant main effect of suture site on degree of suture asymmetry, indicating that the degree of suture asymmetry at all 13 suture sites was in general the same, F (12, 864) = 1.26 (p = 0.24). There was no significant interaction effect between suture site and PDA, indicating that the degree of suture asymmetry at different suture sites did not vary according to points of dental asymmetry, F (12, 864) = 0.63 (p = 0.82). There was no significant interaction effect between suture site and sex, F (12, 864) = 0.44 (p = 0.95). This indicates that the degree of suture asymmetry at different suture sites did not vary significantly according to whether the subject was male or female. There was also no significant interaction effect between suture site and ancestry, indicating that the degree of suture asymmetry at different suture sites did not vary according to whether the subject was of European or African ancestry, F (12, 864) = 0.81 (p = 0.64). Finally, there was no significant interaction effect on degree of suture asymmetry between suture site, sex, and ancestry, F (12, 864) = 0.67 (p = 0.79).

There was a significant interaction effect between suture site and age on the degree of asymmetry in suture closure, F (12, 864) = 2.64 (p = 0.002). This indicates that the profile of suture asymmetry across different suture sites was different for different age categories. This may indicate that there was a significant relationship between age-at-death and degree of suture asymmetry at some sites but not at others. The results of the tests of within-subjects effects are reported in Table 17 below.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Suture_site	3.940	12	.328	1.258	.238
Suture_site * Age	8.274	12	.689	2.642	.002
Suture_site * PDA	1.960	12	.163	.626	.821
Suture_site * Sex	1.370	12	.114	.438	.949
Suture_site * Ancestry	2.529	12	.211	.808	.643
Suture_site * Sex * Ancestry	2.086	12	.174	.666	.785
Error(Suture_site)	225.475	864	.261		

* = Interaction Effect

Table 17: Mixed Model ANOVA I Tests of Within-Subjects Effects

Mixed Model ANOVA II Results

Due to the absence of a correlation between points of dental asymmetry and degree of asymmetry in suture closure and the desire to consider other variables that might be contributing to variation and obscuring such a relationship, a second mixed model ANOVA was conducted. The sample used in this study is drawn from two collections composed of individuals that are very different in terms of time period and socioeconomic status. To explore the possible effect of these differences on the degree of asymmetry in suture closure, skeletal collection of origin was included as a variable in this second ANOVA. All subjects were specified as either a 0 (Bass Collection) or a 1 (Hamann-Todd Collection).

Although sex and ancestry showed no significant effect on degree of asymmetry in suture closure in the first ANOVA, they were once again included as between-subjects factors in this

ANOVA because of the differing distribution of these variables between the two collection samples. Skeletal collection of origin was included as a third between-subjects factor. Age at death was included as a covariate because it was anticipated that there might once again be a significant interaction effect between age at death and suture site. Finally, the predictor variable of interest in this study, points of dental asymmetry, was included as a second covariate.

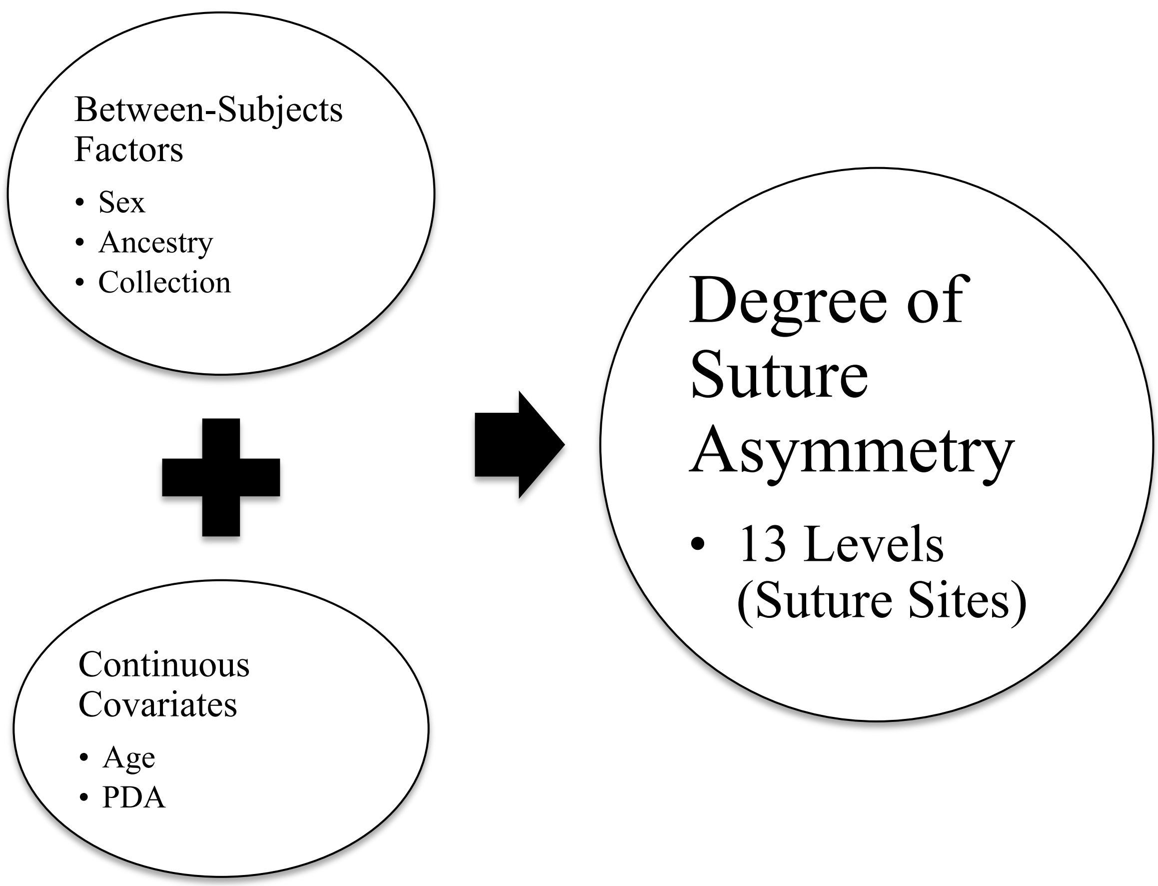

Figure 11: Variables Included in Mixed Model ANOVA II

Assumptions

The results of Mauchly's test of sphericity are presented in Table 18. Mauchly's test indicated that the conditions for sphericity were met, $\chi^2(77) = 97.9$, $p > .05$. Therefore, sphericity was assumed in the following analysis. Levene's test (Table 19) showed that for the degree of asymmetry in cranial suture closure, the variances were equal at the parietomastoid site, $F\ (7, 70) = 1.42$, $p > .05$, the occipitomastoid site, $F\ (7, 70) = 1.70$, $p > .05$, the inferior sphenotemporal site, $F\ (7, 70) = 2.05$, $p > .05$, and the endocranial midlambdoid site, $F\ (7, 70) = .08$, $p > .05$. Levene's test statistic was significant at the following sites, indicating that the assumption of homogeneity of variances was violated at those sites: squamosal, $F\ (7, 70) = 7.21$, $p < .05$, pterion, $F\ (7, 70) = 4.44$, $p < .05$, sphenofrontal, $F\ (7, 70) = 5.36$, $p < .05$, superior sphenotemporal, $F\ (7, 70) = 7.36$, $p < .05$, ectocranial midlambdoid, $F\ (7, 70) = 7.76$, $p < .05$, ectocranial midcoronal, $F\ (7, 70) = 2.83$, $p < .05$, endocranial midcoronal, $F\ (7, 70) = 4.12$, $p < .05$, incisive, $F\ (7, 70) = 2.31$, $p < .05$, and transverse palatine, $F\ (7, 70) = 2.37$, $p < .05$.

Although the assumption of homogeneity of variance was violated at 9 of the 13 suture sites in the second ANOVA, it was once again deemed inadvisable to transform the data for the reasons discussed above in relation to violation of the assumption of normality. Robust tests would once again be preferable, to ensure accuracy in the face of these violations of the assumption of homogeneity of variance. Although robust tests are recommended for use in the next stage of research, time constraints made it impossible to utilize them in the current study. Because ANOVA is relatively robust to violations of the assumption of homogeneity of variance when group sizes are approximately equal (Nimon, 2012), as they are in the current study, the results produced by the second mixed model ANOVA will still be cautiously evaluated here.

Within Subjects Effects	Mauchly's W	Approximate Chi-Square	df	Sig.
Suture_site	.216	97.897	77	.056

Table 18**:** Mixed Model ANOVA II Mauchly's Test of Sphericity

Suture Site	**F**	**df1**	**df2**	**Sig.**
Parietomastoid	1.417	7	70	.213
Squamosal	7.206	7	70	.000
Occipitomastoid	1.703	7	70	.122
Pterion	4.444	7	70	.000
Sphenofrontal	5.364	7	70	.000
Inferior Sphenotemporal	2.049	7	70	.061
Superior Sphenotemporal	7.360	7	70	.000
Ectocranial Midlambdoid	7.761	7	70	.000
Endocranial Midlambdoid	.078	7	70	.999
Ectocranial Midcoronal	2.828	7	70	.012
Endocranial Midcoronal	4.124	7	70	.001
Incisive	2.308	7	70	.035
Transverse Palatine	2.367	7	70	.031

Table 19: Mixed Model ANOVA II Levene's Test of Equality of Error Variances

Tests of Within-Subjects Effects

All effects are reported as significant at $p < .05$ and presented in Table 20. The main effect of suture site on degree of asymmetry in cranial suture closure was not significant, F (12, 816) = 1.31 (p = 0.21). Once again, there was no significant interaction effect between suture site and PDA, F (12, 816) = 0.81 (p = 0.64), or suture site and sex, F (12, 816) = 0.34 (p = 0.98). There was also no significant interaction effect between suture site and ancestry, F (12, 816) = 0.99 (p = 0.46), or between suture site, sex, and ancestry, F (12, 816) = 0.34 (p = 0.98). There was no significant interaction effect between suture site and collection F (12, 816) = 1.14 (p = 0.33).

There was no significant interaction effect between suture site, collection, and sex F (12, 816) = 0.87 (p = 0.58). In addition, there was no significant interaction effect between suture site, collection, and ancestry, F (12, 816) = 0.96 (p = 0.49). Finally, there was no significant interaction effect between suture site, collection, sex, and ancestry, F (12, 816) = 0.67 (p = 0.78).

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Suture_site	4.101	12	.342	1.312	.206
Suture_site * Age	7.924	12	.660	2.535	.003
Suture_site * PDA	2.544	12	.212	.814	.636
Suture_site * Collection	3.556	12	.296	1.138	.326
Suture_site * Sex	1.054	12	.088	.337	.982
Suture_site * Ancestry	3.101	12	.258	.992	.455
Suture_site * Collection * Sex	2.728	12	.227	.873	.575
Suture_site * Collection * Ancestry	2.992	12	.249	.957	.489
Suture_site * Sex * Ancestry	1.067	12	.089	.341	.981
Suture_site * Collection * Sex * Ancestry	2.095	12	.175	.670	.781
Error(Suture_site)	212.560	816	.260		

* = Interaction Effect

Table 20: Mixed Model ANOVA II Tests of Within-Subjects Effects

Tests of Between-Subjects Effects

Once again, as demonstrated by Table 21, the main effect of age on degree of suture asymmetry was not significant, F (1, 68) = 0.002 (p = 0.97). The main effect of PDA on degree of suture asymmetry was also not significant, F (1, 68) = 0.74 (p = .039). The main effect of sex on degree of suture asymmetry was not significant either, F (1, 68) = 1.20 (p = 0.28). There was no significant interaction effect between collection and sex, F (1, 68) = 1.00 (p = 0.32), or between collection and ancestry, F (1, 68) = 0.1 (p = 0.76). There was also no significant interaction effect on degree of suture asymmetry between sex and ancestry, F (1, 68) = 0.0 (p = 0.99).

The main effect of collection on degree of suture asymmetry approached significance after controlling for the effect of age at death and points of dental asymmetry, F (1, 68) = 3.55 (p = 0.06). This means that the degree of suture asymmetry in the Bass Collection was nearly significantly different from the Hamann-Todd Collection. The main effect of ancestry on degree of suture asymmetry after controlling for age at death and points of dental asymmetry was precisely on the borderline of significance, F (1, 68) = 3.98 (p = 0.05). This means that the difference between the degree of suture asymmetry in those of African ancestry and in those of European ancestry was nearly significant. After controlling for age at death and points of dental asymmetry, there was a significant interaction effect between collection, sex, and ancestry, F (1, 68) = 7.36 (p = 0.01).

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Intercept	14.043	1	14.043	35.009	.000
Age	.001	1	.001	.002	.969
PDA	.297	1	.297	.741	.392
Collection	1.423	1	1.423	3.547	.064
Sex	.482	1	.482	1.201	.277
Ancestry	1.597	1	1.597	3.982	.050
Collection * Sex	.402	1	.402	1.002	.320
Collection * Ancestry	.038	1	.038	.095	.759
Sex * Ancestry	5.660E-005	1	5.660E-005	.000	.991
Collection * Sex * Ancestry	2.953	1	2.953	7.362	.008
Error	27.277	68	.401		

* = Interaction Effect

Table 21: Mixed Model ANOVA II Tests of Between-Subjects Effects

CHAPTER 6: DISCUSSION

Frequency of Asymmetry in Cranial Suture Closure

It was predicted that asymmetrical cranial suture closure would be frequent and extreme enough in a sample of modern Americans to hinder estimation of age at death. Although extreme and moderate suture asymmetry are present in only a handful of individuals at each site, and several sites never displayed more than mild asymmetry (Appendix), further research into asymmetry in cranial suture closure is still warranted for several reasons. First of all, even a single case of extreme asymmetry could be highly relevant to the forensic anthropologist interested in positive identification.

If extreme asymmetry in cranial suture closure is present at a single suture site, depending on which side corresponds to the correct age estimate, the observer may obtain an inaccurate age estimate, which could hinder identification. For example, individual UT 17-00 demonstrates extreme asymmetry at the endocranial midlambdoid suture site. The individual is a male of African ancestry. Utilizing Equation 14 for "black males" in Nawrocki (1998, p 284), which incorporates the left endocranial midlambdoid suture site (LLZ), an age estimate of 17.93 ±10.5 years is obtained (Figure 12). However, if the right endocranial midlambdoid suture site (LRZ) is substituted for the left, an estimate of 32.99 ± 10.5 years is obtained. The individual's documented age is in reality 35 years, which falls within the range of the estimate obtained using the right side, but not within the range obtained using the left. Using the left side would thus produce an erroneous age estimate, which could hinder identification of the individual.

Individual	Ancestry	Sex
UT 17-00	Black (African)	Male

LLZ	0
LRZ	3
ASQ	1
LRQ	1
CRZ	2

Nawrocki (1998, p 284) Equation 14 for "Black Males:"
10.13(LRQ) – 10.98(ASQ) + 5.02(LLZ) + 9.39(CRZ) + 27.0 ± 10.5 years

Age estimate using LLZ: 17.93 ± 10.5 years
Age estimate using LRZ: 32.99 ± 10.5 years

Actual age at death: **35 years**

ASQ = Anterior Sagittal Suture Site (Nawrocki, 1998)
All other suture site abbreviations defined in Key to Symbols and Abbreviations on page xi
Figure 12: Calculation of Estimated Age at Death of Individual UT 17-91

Although extreme asymmetry was relatively infrequent in this sample, mild asymmetry was present in at least 12 individuals at every suture site. Even mild asymmetry has the potential to lead to an erroneous age estimate. For example, individual UT 17-91 is a male of European ancestry who demonstrates mild asymmetry in suture closure at the pterion site. Nawrocki's (1998, p 280) Equation 8 for "white males" incorporates the closure for pterion on the left side. Using the left side (which received a score of 1) produces an age at death estimate of 39 ± 11 years. The individual's actual age at death, 26 years, is not included in the estimate. Replacing the left side with the right side (which received a score of 0) produces an age estimate of 24 ± 11 years, which does include the individual's actual age at death. Once again, basing the age estimate on the left side produces an inaccurate age estimate that could hinder identification.

Individual	Ancestry	Sex
UT 17-91	White (European)	Male

PLQ	1
PRQ	0
ASQ	2

Nawrocki (1998, p 280) Equation 8 for "White Males:"
15.01 (PLQ) – 6.76 (ASQ) + 37.9 ± 11 years

Age estimate using PLQ: 39.39 ± 11 years
Age estimate using PRQ: 24.38 ± 11 years

Actual age at death: **26 years**

ASQ = Anterior Sagittal Suture Site (Nawrocki, 1998)
All other suture site abbreviations defined in Key to Symbols and Abbreviations on page xi
Figure 13: Calculation of Estimated Age at Death of Individual UT 17-00

Based on these examples, it is recommended that if both sides of the skull are available, the anthropologist should score both sides and compare each site bilaterally in order to identify any instance of mild, moderate, or extreme asymmetry. If a site is discovered to demonstrate asymmetry, the observer should avoid using a cranial suture age at death estimation method that incorporates the asymmetrical site if possible. Alternatively, the anthropologist should obtain two separate age estimates: one based on each side of the skull. The final age at death estimate should incorporate the full range of the estimates from both sides.

In some cases, the cranium may be fragmentary and no other age indicators may be present, making it necessary to utilize a suture site with asymmetrical closure in order to produce an age estimate. In the examples described above, even the age estimate based on the left side would have included the individual's actual age if the estimate had incorporated two standard errors instead of one. Therefore, if only one half of the cranium is available, the anthropologist should be careful to include the full range of two standard errors in the final age estimate.

Nawrocki (1998) recommends always incorporating two standard errors into the age at death estimate. Although this is certainly more accurate, it is also less precise. Some anthropologists feel that incorporating two standard errors produces an age estimate with a range that is too large to be useful in a practical setting. Following the procedure described above may produce an age estimate with a narrower range than one based on two standard errors. Ultimately, however, it is up to the individual anthropologist to use their discretion as to whether two standard errors should be incorporated in the age estimate or not.

It is important to note that the procedure for age estimation in cases of asymmetrical closure outlined above is based solely on anecdotal evidence. More research is needed to determine how effective these procedures are. They are recommended merely as interim measures to avoid some of the potential pitfalls of suture asymmetry, and thus aid in the identification of human remains. More research is also needed to determine whether the frequencies of mild, moderate, and extreme asymmetry in cranial suture closure demonstrated by this sample are reflective of the frequencies of asymmetry in the modern American population.

Although moderate and extreme asymmetry were both relatively rare in this sample, it is possible that the sample may not be truly representative of the target population: modern Americans. Issues with the size and composition of the sample and subsamples will be discussed in more detail below, and suggestions will be made to compensate for these problems when designing further research into asymmetrical cranial suture closure. In brief, the final study sample included individuals from both the historic Hamann-Todd Collection and the modern

Bass Collection. The frequency and location of suture asymmetry may differ between collections from different time periods. In addition, the overall sample size of 101 individuals is fairly small (Table 6). This increases the risk that the results obtained are due to sampling error, rather than the true state of suture closure in modern Americans. Finally, only two ancestral groups were examined in this study: African and European. The results cannot be extended to modern Americans of Asian, Native American, or Hispanic ancestry. The frequencies of mild, moderate, and extreme suture asymmetry may be significantly different in a sample that is more representative of modern Americans.

It was predicted that asymmetry in cranial suture closure would be frequent and extreme enough in a sample of modern Americans to hinder estimation of age at death. Although it is debatable whether the sample is truly representative of modern Americans, this hypothesis could not be rejected because even a single case of mild asymmetry has the potential to hinder estimation of age at death.

Age at death and Age x Suture Site Interaction

It was anticipated that age at death would have a positive correlation with degree of asymmetry in cranial suture closure. As an individual ages, there is more time for a suture site on one side to achieve complete or nearly complete obliteration, while the other side for whatever reason may never progress beyond mild closure or even complete patency. Thus an elderly individual would be more likely to have this extreme bilateral contrast in closure than a young adult whose sutures on both sides have not yet begun to close at all.

This prediction was not supported by the insignificant main effect of the covariate age at death on degree of asymmetry in cranial suture closure in both ANOVAs (Tables 16 and 21).

As an example, Figure 14 depicts the distribution of suture asymmetry scores at the squamosal suture site. It is clear that there were many scores of 0, or no asymmetry, in every age category. As age at death increases, the degree of suture asymmetry does not necessary increase as well. However, the interaction between age and suture site did have a significant effect on degree of suture asymmetry in both the first and the second ANOVA (Tables 17 and 20). The main effect of suture site was not significant in either ANOVA (Tables 17 and 20), indicating that the degree of suture asymmetry did not differ significantly between suture sites. Even a cursory glance at the frequency tables (Tables 25-37) and histograms (Figures 18-30) in the Appendix reveals that the percentages of no asymmetry, mild asymmetry, moderate asymmetry, and extreme asymmetry were very similar at each site.

The significant interaction between age and suture site could indicate that while the degree of suture asymmetry changes with age at some sites, it does not do so at others. The literature on suture closure reveals that some sites, such as the endocranial midcoronal, pterion, and sphenofrontal sites, are much more likely to achieve advanced closure with age than others. In fact, some sites, like the parietomastoid, occipitomastoid (Meindl and Lovejoy, 1985), and sqamosal (Meindl and Lovejoy, 1985; Falk et al., 1989) sites, rarely progress beyond mild closure. It makes sense that the former sites would be more likely to achieve a higher degree of asymmetry than the sites that never achieve more than mild closure, and thus do not achieve more than mild asymmetry.

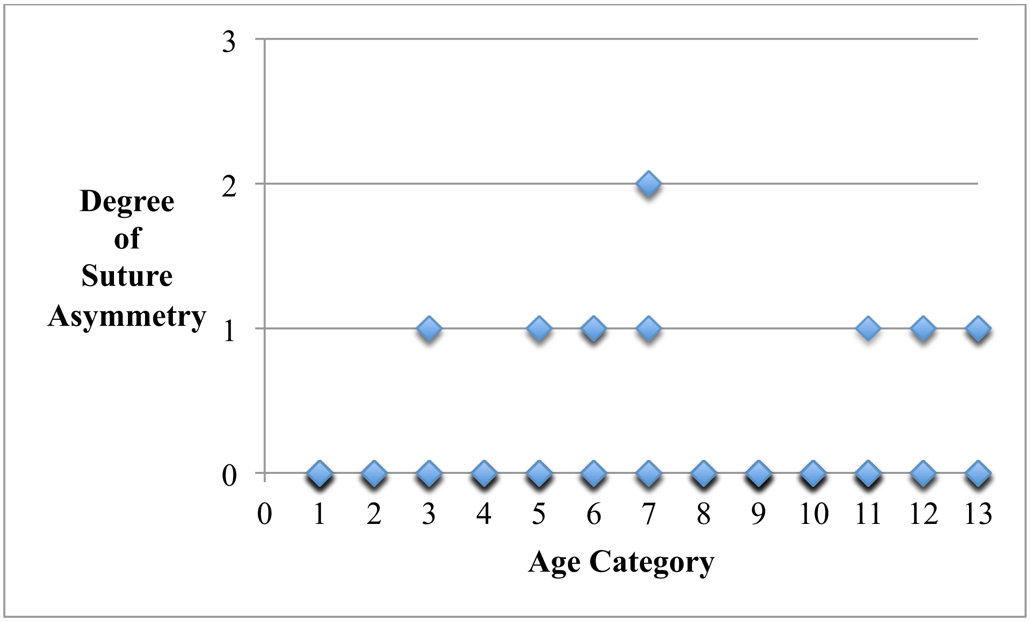

Figure 14: Scatterplot of Suture Asymmetry Scores at the Squamosal Suture Site

In the current study, it was not possible to determine which sites have a statistically significant relationship with age and which do not. Each suture site at each age category would have to be compared to every other suture site at every age category to look for differences. With 13 suture sites and 13 age categories, it would be extremely difficult to interpret the large number of pairwise comparisons involved. In addition, conducting so many pairwise comparisons would dramatically increase the likelihood of making a Type I error (Field, 2009). However, it would be possible to reduce the number of suture site levels by dividing the suture sites according to region (lateral-anterior, vault, palatine) and comparing the regions to one another. The number of age categories would also need to be reduced. For example, each age category could be assigned a range of one decade rather than five years, reducing the number of age categories by nearly half. Time constraints made it impossible to organize and analyze the data in this way in the current study, but it could certainly be done in the future.

It was predicted that there would be a positive correlation between age at death and degree of suture asymmetry. This hypothesis was rejected based on the absence of a significant main effect of age at death on degree of suture asymmetry, and thus an absence of a correlation between the two variables. However, based on the significant interaction effect between age at death and suture site, it appears that age at death does have some influence on degree of suture asymmetry at some suture sites or in some age categories. Therefore, it is recommended that age at death be included in future studies of suture asymmetry.

Sex

It was predicted that degree of suture asymmetry would not differ significantly between males and females. The first mixed model ANOVA provided no evidence to support the influence of sex on degree of suture asymmetry. The main effect of sex on degree of suture asymmetry was not significant, and the interaction effect between sex and ancestry was also insignificant (Table 16). Although previous studies demonstrated a relationship between sex and the age at which certain suture sites achieve closure (Masset, 1989; Mann et al., 1991; Key et al., 1994; Nawrocki, 1998; Zambrano, 2005; Beauthier et al., 2010), whether this variable has any effect on the degree of asymmetry in suture closure at any given site is a different matter. Based on the first ANOVA, it would appear that it does not. However, the second ANOVA, which included skeletal collection of origin as an additional between-subjects factor, produced different results.

Although the main effect of sex on degree of suture asymmetry was not significant even when skeletal collection of origin was included as a variable, there was a significant interaction effect involving sex in the second ANOVA. The interaction between collection, sex, and ancestry was significant (Table 21). It is difficult to interpret significant three-way interaction effects, but this one may be related to the differing distributions of the two collection subsamples in terms of sex and ancestry, as demonstrated by Figures 15 and 16 and Tables 7 and 8. Although the overall study sample was carefully constructed to be evenly distributed according to these characteristics, the subsamples were not constructed in the same manner. This uneven distribution could be introducing a source of bias that contributed to the significant interaction effect between sex, ancestry, and skeletal collection of origin.

Ideally, future study samples should be drawn from only a single modern skeletal collection. If the limited availability of appropriate skeletal material makes it necessary to draw from multiple skeletal collections to construct a sufficiently large sample, the sample should be constructed so as to have an even distribution not only according to age-at-death, sex, and ancestry, but according to skeletal collection of origin as well, so as to remove this potential source of bias.

It was predicted that degree of suture asymmetry would not differ significantly between males and females. Based on the absence of a significant main effect of sex on degree of suture asymmetry, this hypothesis could not be rejected. Although the significant interaction effect between sex, ancestry, and skeletal collection of origin may be due to bias introduced by the uneven distribution of the collection subsamples according to sex and ancestry, it would be ideal to include sex as a variable in future studies of suture asymmetry to confirm the fact that it does not have an effect on suture asymmetry. Due to the limited availability of appropriate skeletal material, however, it may be necessary to examine only a single sex in the next stage of research in order to produce a sufficiently robust sample size.

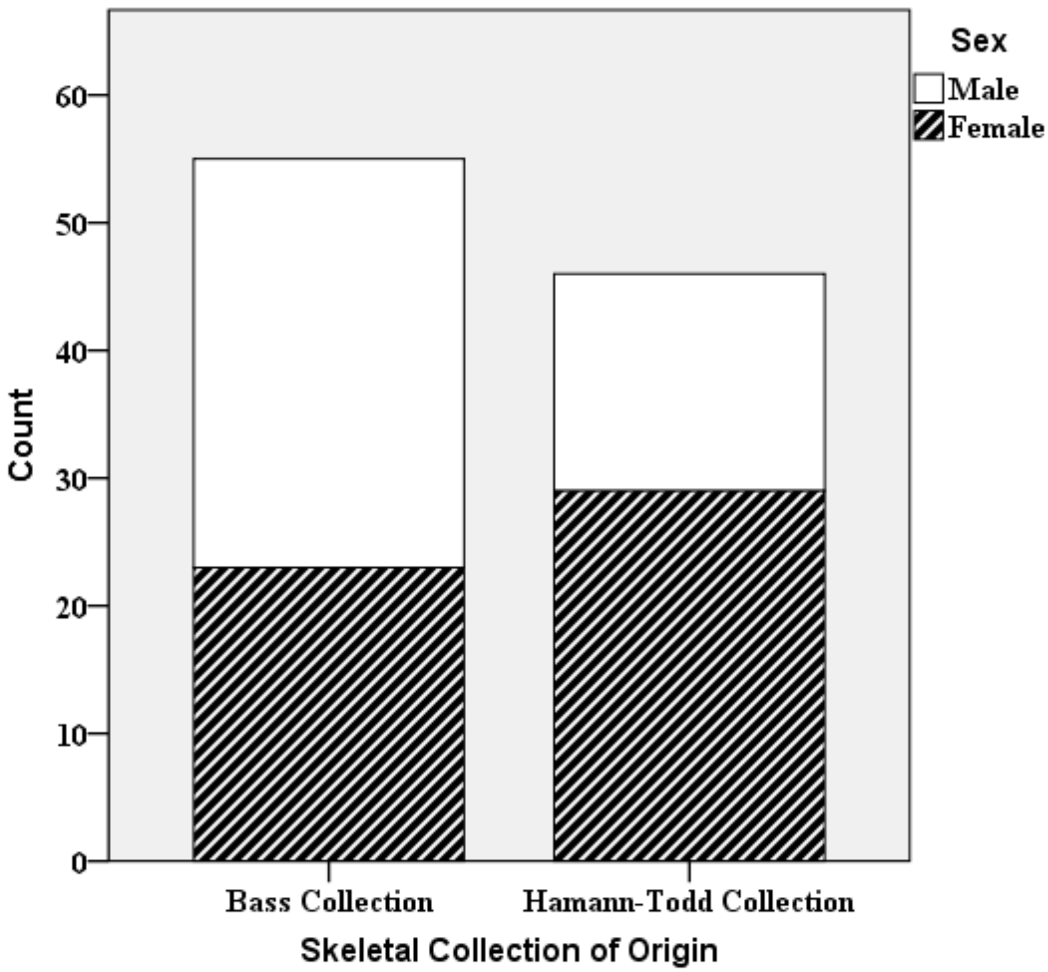

Figure 15: Sex Distribution by Collection Subsample

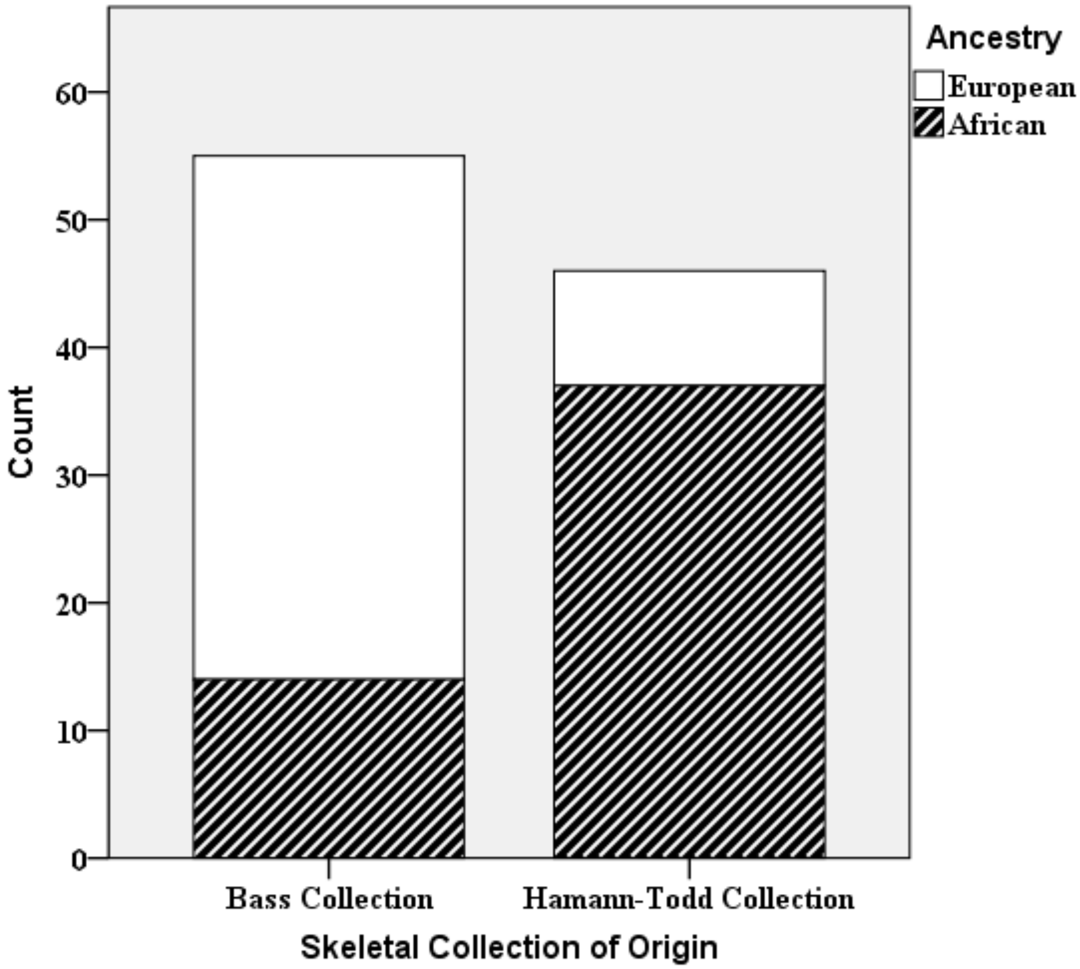

Figure 16: Ancestry Distribution by Collection Subsample

Ancestry

It was predicted that degree of suture asymmetry would not differ significantly between those of European ancestry and those of African ancestry. In the first ANOVA, the main effect of ancestry on degree of suture asymmetry was not significant, indicating that the degree of suture asymmetry was in general the same in those of European ancestry and those of African ancestry (Table 16). Table 22 is a table of means and associated standard errors for the main effect of ancestry on degree of suture asymmetry in the first ANOVA. The means are similar, and the 95% confidence intervals for the two ancestral groups overlap. In the second ANOVA, however, the main effect of ancestry is precisely on the borderline of significance (Table 21). Once the variation that is accounted for by the skeletal collection of origin is isolated from the variation caused by the rest of the factors, the significant main affect of ancestral origin on degree of suture asymmetry is revealed. Table 23 presents the means and associated standard errors for the main effect of ancestry on degree of suture asymmetry in the second ANOVA. Mean degree of suture asymmetry is higher in those of African ancestry than it is in those of European ancestry, and the 95% confidence intervals do not overlap as much as in the first ANOVA.

			95% Confidence Interval	
Ancestry	Mean	Std. Error	Lower Bound	Upper Bound
European	.287	.028	.230	.344
African	.302	.031	.241	.363

Covariates appearing in the model are evaluated at the following values: Age-at-death category = 7.08, Points of Dental Asymmetry = 2.03
Table 22: Ancestry Estimated Marginal Means ANOVA I

			95% Confidence Interval	
Ancestry	Mean	Std. Error	Lower Bound	Upper Bound
European	.243	.039	.165	.322
African	.349	.035	.279	.418

Covariates appearing in the model are evaluated at the following values: Age-at-death category = 7.08, Points of Dental Asymmetry = 2.03
Table 23: Ancestry Estimated Marginal Means ANOVA II

It is unclear why degree of suture asymmetry would differ between ancestral groups. Once again, it is possible that the significant main effect of ancestry in the second ANOVA is due to bias introduced by the differing ancestral distribution of the two collection subsamples. Alternatively, degree of suture asymmetry may truly differ between ancestral groups. This interpretation is supported by the results of studies by Key and colleagues (1994) and Sahni and colleagues (2005). Both studies demonstrated variation between ancestral groups in the timing of cranial suture closure (Key et al., 1994; Sahni et al., 2005). Although ancestral variation in the timing of cranial suture closure does not necessarily translate directly into ancestral variation in degree of suture asymmetry, in this case the evidence suggests that it does.

It was predicted that degree of suture asymmetry would not differ significantly between those of European ancestry and those of African ancestry. Based on the borderline significant main effect of ancestry on degree of suture asymmetry, this hypothesis was rejected. Therefore, it is recommended that ancestry be included as a variable in future studies if possible to identify and isolate any variation in suture asymmetry that it does cause. Once again, the limited availability of skeletal material may make it impossible to construct a sample with sufficient numbers of individuals of both African and European ancestry. Consequently, if the sample includes only one ancestral group, researchers should be careful not to assume that the results apply to other ancestral groups as well.

Skeletal Collection of Origin

As mentioned in Chapter 5, the two skeletal collections from which this study sample was drawn are very different in terms of time period and socioeconomic status. The skeletal remains in the Hamann-Todd Human Osteological Collection are from cadavers that were collected from several major Cleveland, Ohio area hospitals between 1912 and 1938 (Lovejoy et al., 1985). The majority of the individuals in this collection were born between 1825 and 1910 (Mensforth and Latimer, 1989). Based on the prevalence of "nutritionally dependent anomalies and pathologies listed in their medical records", El-Najjar and colleagues (1978, p 189) concluded that these individuals were members of a very low socio-economic group.

The WM Bass Donated Skeletal Collection is composed of remains that were donated by the deceased or the family of the deceased. Most of the individuals in the collection were born after 1940 (University of Tennessee Knoxville Forensic Anthropology Center), significantly more recently than those in the Hamann-Todd Collection. Most individuals in the Bass Collection were also members of higher socioeconomic classes than those in the Hamann-Todd Collection, with incomes that fell within the middle classes, and educational achievements of at least a high school diploma (Wilson et al., 2007). Clearly there are substantial differences in the composition of the two collections, and as a result, there are substantial differences between the two subsamples used in the current study.

Knowing that the composition of the two subsamples is very different, it is possible that skeletal collection of origin is introducing an additional source of variation that the first ANOVA did not account for. To examine whether degree of asymmetry in cranial suture closure differed between the two collection samples, a second ANOVA was conducted with skeletal collection of origin included as an additional between-subjects factor (Figure 11). Each individual in the sample was designated as being drawn from either the Bass Collection or the Hamann-Todd Collection. The second ANOVA was then run with all of the same between-subjects factors, within-subjects factors, and covariates as the first ANOVA. The results of the second ANOVA were presented in Tables 20 and 21.

In the second ANOVA, the main effect of collection on degree of suture asymmetry approached significance (Table 21). It is possible that there was a difference between the two collections in terms of suture asymmetry, but that the difference was too small to achieve statistical significance. If so, this difference between the suture asymmetry in the historical Hamann-Todd Collection and the suture asymmetry in the modern Bass Collection could be the result of secular change. Secular change refers to change in a skeletal feature that occurs over the course of decades "due to an improvement or deterioration over time in factors such as nutrition, access to medical care, infectious diseases, etc." (Digangi and Moore, 2013, p 35). As Mensforth and Latimer (1989, p 461) point out, most of the individuals in the Hamann-Todd Collection lived "prior to the initiation and widespread use of antimicrobial drugs, hormonal replacement therapies, and nutritional dietary supplements." It makes sense, then, that any skeletal age indicator that is affected by nutritional status, medical care, or infectious diseases would also change over the course of decades.

Table 24 depicts the means and associated standard errors of the main effect of skeletal collection of origin on degree of suture asymmetry. The means do seem different, although as mentioned above, this difference approached significance at the .05 level. Although the confidence intervals overlap, they are not identical. This information seems to support the concept of differences in suture asymmetry between the two collection subsamples, and secular change is one possible explanation for such differences.

Collection	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Bass	.352	.034	.284	.420
Hamann-Todd	.240	.045	.150	.329

Covariates appearing in the model are evaluated at the following values: Age-at-death category = 7.08, Points of Dental Asymmetry = 2.03

Table 24: Skeletal Collection of Origin Estimated Marginal Means ANOVA II

A few studies do support the potential for secular change in the timing of cranial suture closure. Jantz and Meadows Jantz (2000) found considerable secular change in craniofacial morphology when they compared a sample drawn from the historical Terry and Hamann-Todd Collections with modern data from the Forensic Anthropology Data Bank. Although Jantz and Meadows Jantz (2000) did not specifically examine cranial sutures, the biomechanical model of cranial suture closure suggests that changing craniofacial morphology could also cause changes in the timing of cranial suture closure. Even more compelling, Masset (1989) notes that there appear to be small differences in suture closure between two Portuguese skeletal collections from different time periods. The individuals in the Lisbon collection died in 1876, while those in the Coimbra collection died between 1910 and 1936. Although the differences are small, they are statistically significant, and they do provide "presumptive evidence pointing in…" the direction of secular change in the timing of cranial suture closure (Masset, 1989, p 98). If secular change in the timing of cranial suture closure is occurring, secular change in asymmetrical suture closure could also be occurring. Therefore, secular change is one possible explanation for the nearly significant main effect of skeletal collection of origin on degree of suture asymmetry found in the current study.

The definition of secular change provided by Digangi and Moore (2013) and cited above links secular change to changes in nutrition, medical care, and infectious diseases. Kroman and Thomspon's (2007) study supports the influence of pathological skeletal conditions (or the diseases or nutritional issues that cause those conditions) on the timing of cranial suture closure, and thus also supports the possibility of secular change in suture closure patterns. Masset (1989) notes that suture closure was more advanced in several individuals in the Lisbon collection who were employed in more sedentary jobs. He suggests that not only could the advanced suture closure be a result of a more sedentary lifestyle, but that a shift in the sedentary nature of daily life could be behind the secular trend in suture closure (Masset, 1989). Although there does seem to be some evidence of the influence of medical and nutritional factors on suture closure, the mechanisms by which changes in disease, nutrition, or access to medical care would cause changes in suture closure are unknown.

Although secular change involves changes in nutrition, access to medical care, and the prevalence of infectious diseases, socioeconomic differences could also cause differential nutrition, medical care, and infectious disease rate. Because the majority of individuals from the Hamann-Todd collection were from a lower socioeconomic group than the majority of individuals in the Bass Collection, socioeconomic differences rather than change over time could explain the nearly significant difference in mean degree of suture asymmetry between the two subsamples.

Alternatively, the nearly significant main effect of skeletal collection of origin on degree of suture asymmetry may both be the result of bias introduced by the differing distributions of the Hamann-Todd and Bass subsamples according to age at death, sex, and ancestry (Tables 7 and 8). To determine whether secular change or socioeconomic differences are really present, the sample would need to have been constructed so as to have an even distribution not only according to age-at-death, sex, and ancestry, but according to skeletal collection of origin as well. This would allow the researcher to legitimately parcel out variation between the various factors and determine whether there is in fact a difference in suture asymmetry between two collections from different time periods and socioeconomic groups. Finally, the nearly significant main effect of skeletal collection of origin on degree of suture asymmetry could be the result of a combination of secular change, socioeconomic differences, and bias introduced by the differing distributions of the two subsamples.

Points of Dental Asymmetry

The main goal of this research was to examine whether asymmetrical antemortem tooth loss causes asymmetrical cranial suture closure. The variable points of dental asymmetry (PDA) was created to represent asymmetrical antemortem tooth loss. It was predicted that there would be a positive correlation between PDA and degree of suture asymmetry. The main effect of PDA was not significant in either ANOVA (Tables 16 and 21). This indicates that regardless of whether the effect of skeletal collection of origin on degree of suture asymmetry is accounted for, there is no evidence of a relationship between PDA and degree of suture asymmetry. There are several reasons why this may have occurred.

First, the first null hypothesis may be true and there is in fact no relationship between asymmetrical antemortem tooth loss and asymmetrical cranial suture closure. Perhaps asymmetrical suture closure is caused by biochemical and genetic rather than biomechanical factors, as suggested by the research of Opperman and colleagues (Opperman et al., 1993, 1995, 1996, 1997, 1998, 1999, 2000; Opperman, 2000). Perhaps the biomechanical changes caused by asymmetrical antemortem tooth loss are not extreme enough to affect suture closure at the sites considered here. Alternatively, perhaps Falk and colleagues (1989) were correct about the cause of asymmetrical cranial suture closure in rhesus macaques. They suggested that minor asymmetries in the shape of the brain and skull, known as cranial petalias, were the cause of asymmetrical suture closure (Falk et al., 1989). It is possible that this is true for humans as well.

Therefore, future research should identify and test other possible causes of asymmetrical cranial suture closure.

Second, it is possible that there is a relationship between asymmetrical cranial suture closure and asymmetrical antemortem tooth loss, but that the variable "points of dental asymmetry" is not an adequate measure of asymmetrical antemortem tooth loss. The fact that four of the five suture sites (parietomastoid, occipitomastoid, sphenofrontal, superior sphenotemporal) that displayed extreme suture asymmetry are located in close proximity to the attachment sites of the muscles of mastication is suggestive of a connection between suture asymmetry and mastication. It could be that the length of time spent masticating with dental asymmetry is extremely important to whether the sutures are affected. Viewing the state of antemortem loss at the time of death provides no information on when in the course of the individual's life each loss occurred. Consequently, the variable PDA does not account for the length of time spent masticating with dental asymmetry. Longitudinal radiological studies that allow for the simultaneous in vivo examination of suture closure and dental asymmetry may be the only way to address this issue, but there would be numerous logistical difficulties in the design of such studies.

It is also important to bear in mind that the biomechanics of mastication are extremely complex. Numerous factors are involved, and it may be naïve to try and reduce all of those factors to a single variable. For example, if the maxillary third molar was lost antemortem on the left, but the maxillary second molar was lost antemortem on the right, the individual was assigned two points of dental asymmetry (Figure 17). In reality, however, these two opposing points of dental asymmetry might essentially cancel each other out. The variable PDA thus does not account for such “balanced asymmetry.” The next stage of research should incorporate a better understanding of the biomechanics of mastication, and a better way to measure asymmetrical antemortem tooth loss should be designed.

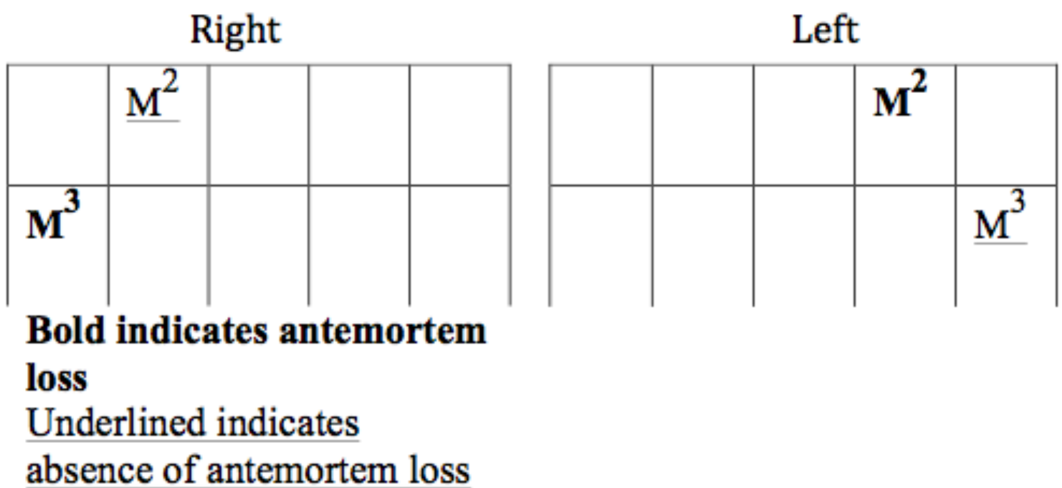

Figure 17: Demonstration of “Balanced Asymmetry”

Alternatively, PDA may be an adequate measure of asymmetry in antemortem tooth loss, but the role of the anterior teeth in mastication may have been unfairly dismissed in the design of this study. Only the asymmetry of the molars and premolars was incorporated in the points of dental asymmetry variable in this study. Although incisors and canines are not responsible for grinding actions, they do have very important functions, in the course of which they do transmit force to the cranium through the muscles of mastication. The next stage of research should therefore incorporate the entire dental arcade rather than just the molars and premolars. Fortunately, dental data were originally recorded for all teeth in the current study, so further data collection would not be necessary for the individuals in this sample.

It was anticipated that there would be a positive correlation between points of dental asymmetry and degree of suture asymmetry. This hypothesis was rejected based on the absence of a significant main effect of PDA on degree of suture asymmetry. It was also predicted that the relationship between PDA and degree of suture asymmetry would vary according to suture site. This hypothesis was also rejected based on the absence of a significant interaction effect between PDA and suture site in both ANOVAs (Tables 17 and 20). Although this study produced no evidence of a relationship between asymmetry in antemortem tooth loss and asymmetry in cranial suture closure, further research into the possible relationship between the two factors is warranted because the variable points of dental asymmetry may not accurately represent asymmetry in antemortem tooth loss. A research design that incorporates a variable that better represents asymmetry in antemortem tooth loss may provide support for the concept of a relationship with asymmetry in cranial suture closure.

Study Limitations

This study was limited by the availability of skeletal material. As a result, not only was the overall sample size relatively small, but the group sizes were small as well, consisting of only two individuals in each age at death, sex, and ancestry category (Table 6). Small sample and group sizes increase the risk that the results obtained are due to sampling error rather than true between-group differences. In addition, in order to fill all of the groups, individuals from two different skeletal collections had to be used. The differing time periods and socioeconomic statuses of the individuals in the two skeletal collections introduced an additional source of variation into this study. The differing distributions of the two subsamples according to age at death, sex, and ancestry introduced yet another potential source of variation. In the next stage of research, the individuals in the sample should be drawn from only a single modern skeletal collection. Due to the limited availability of skeletal material, it will most likely be impossible to examine both sexes and multiple ancestral groups. However, focusing on only a single sex and a single ancestral group should allow for the construction of a much larger sample and therefore decrease the risk of sampling error.

In addition to the limitations in sample size and composition, this study is limited in that it does not include an examination of intra-observer and inter-observer error. Although previous studies (Meindl and Lovejoy, 1985; Nawrocki, 1998; Zambrano, 2005) have shown that the suture closure scoring scale used here involves low rates of both types of error, the error rates for the collection of the dental data used in this study have not been quantified. The next stage of research should be designed to incorporate multiple observers and a test for inter-observer error. Additionally, the dental data should be collected twice by each observer with at least two weeks between collection dates in order to test for intra-observer error.

Furthermore, this study did not examine whether asymmetrical suture closure and asymmetrical antemortem tooth loss are directional in nature. Although Falk and colleagues (1989) found that advanced suture closure occurred more frequently on the right in rhesus macaques, Key and colleagues (1994) did not find directional asymmetry in suture closure in the London Spitalfields Human Collection. Živanović (1983) does not report on the presence or absence of directionality in asymmetrical closure in his samples of modern Europeans and East African Bantu. Determining whether suture asymmetry is directional in nature could shed light on the likely causes of such asymmetry. For example, Falk and colleagues (1989) suggest that the directional asymmetry present in their sample of rhesus macaque endocasts was related to minor brain and skull asymmetries known as cranial petalias. In the context of dental asymmetry, determining whether advanced closure on one side tends to occur in conjunction with antemortem loss on the same or opposite side could provide support for the idea of a relationship between asymmetrical cranial suture closure and asymmetrical antemortem tooth loss.

Although would be relatively simple to format the data so as to incorporate in the degree of suture asymmetry which side demonstrated more advanced closure, ultimately it was not done in this study. This is because PDA, the measurement of antemortem tooth loss used in this research, does not express whether the antemortem loss occurred on the right or the left. Therefore, there was no way to compare the direction of dental asymmetry with the direction of suture asymmetry. In the next stage of research, a new variable should be designed to measure asymmetry in antemortem tooth loss. This new variable should incorporate directionality in such a way that it can be determined whether advanced suture closure on one side tends to occur in conjunction with antemortem loss on the same or opposite side.

Finally, this study was limited in that the data violated both the assumption of normality and the assumption of homogeneity of variance. Rather than being normally distributed, the data were highly positively skewed as demonstrated by visual examination of the histograms in the Appendix. Violation of the assumption of normality has the potential to increase both the Type I and Type II error rates (Field, 2009). Meanwhile, the assumption of homogeneity of variance was violated at one suture site in the first ANOVA, and at nine suture sites in the second ANOVA. Violation of the assumption of homogeneity of variance has the potential to increase the Type I error rate (Nimon, 2012). Although ANOVA is relatively robust to violations of both of these assumptions when the group sizes are similar (Donaldson, 1968; Lunney, 1970; Nimon, 2012), as they were in this study, robust statistical tests should be used in place of ANOVA in the next stage of research because robust tests are accurate even when their assumptions are violated (Field, 2009).

In sum, this study was limited both by the materials used and the methods employed. The potential relationship between asymmetrical antemortem tooth loss and asymmetrical cranial suture closure has never been examined before, making this study by definition a preliminary one. Although the information provided by this study is valuable, identification of study limitations allows for better research design in the future. Therefore, the next stage of research will be carefully designed so as to compensate for the limitations identified and discussed here.

CHAPTER 7: CONCLUSIONS

In the current study, extreme bilateral asymmetry in cranial suture closure was relatively rare but still present in at least one individual at five suture sites. Mild asymmetry was present in at least twelve individuals at every site. Although the frequency of suture asymmetry is relatively low in this sample, even a single case of asymmetry, be it mild, moderate, or extreme, has the potential to produce an erroneous age at death estimate and thus hinder the identification of the individual. The procedures for dealing with asymmetrical closure described in Chapter 6 are recommended as provision measures to avoid some of the potential pitfalls of suture asymmetry. Further research into the frequency and degree of asymmetrical cranial suture closure is warranted, however.

The sample used in this study may not be truly representative of the target population of modern Americans. The individuals in the sample were drawn from two different skeletal collections: one modern, and one historic. In addition, the modern skeletal collection primarily contains individuals of higher socioeconomic status than the historic skeletal collection. The differences between the two collections may have resulted in the sample used in this study failing to be representative of modern Americans. In addition, the overall sample size of 101 individuals is relatively small, which increases the potential for sampling error. Only two ancestral groups were incorporated into the sample, and there are many other ancestral groups in the modern American population. It is possible that the frequency and degree of asymmetrical suture closure would be different in a more representative sample.

Although it was predicted that there would be a positive correlation between age at death and degree of suture asymmetry, this hypothesis was rejected based the lack of a significant main effect of age at death on degree of suture asymmetry. However, there was a significant interaction effect between age at death and suture site, indicating that there is a relationship between age at death and degree of suture asymmetry at some suture sites or in some age categories. It was not possible to explore this interaction effect in detail in the current study, but age at death should be incorporated into future studies of suture asymmetry to account for any relationship it may have with degree of suture asymmetry.

It was predicted that degree of suture asymmetry would not differ significantly between males and females. This hypothesis could not be rejected due to the absence of a significant main effect of sex on degree of suture asymmetry. The only interaction effect involving sex was the interaction between sex, ancestry, and skeletal collection of origin. Although this result could be related to bias introduced by the differing distribution of the two collection subsamples according to sex and ancestry, sex should be incorporated into future studies of suture asymmetry if possible in order to account for any sexual dimorphism in asymmetrical suture closure. Unfortunately, due to the limited availability of appropriate skeletal material, the next stage of research will likely focus on a sample consisting of individuals of only one sex. Consequently, it will be impossible to draw conclusions about variation in suture asymmetry between males and females in the next phase of research.

It was predicted that degree of suture asymmetry would not differ significantly between individuals of European ancestry and those of African ancestry. This hypothesis was rejected due to the significant main effect of ancestry on degree of suture asymmetry in the second ANOVA. Although it is possible that this result is due to bias introduced by the differing distribution of the subsamples according to ancestry, ancestry should be included in future studies of suture asymmetry to account for any variation in suture asymmetry between ancestral groups. Unfortunately, it is once again unlikely that multiple ancestral groups can be incorporated into the next phase of research due to the limited availability of skeletal material. Consequently, the results obtained in the next stage of research cannot be extended to other ancestral groups.

Due to differences in time period and socioeconomic status between the two skeletal collections used to construct the sample in this study, skeletal collection of origin was included as a variable in the second ANOVA in order to examine whether degree of suture asymmetry varied between the two collections. The main effect of skeletal collection of origin on degree of suture asymmetry approached significance, indicating that there was a nearly significant difference in degree of suture asymmetry between the Hamann-Todd subsample and the Bass subsample. This could be an expression of secular change, differing socioeconomic status, or a function of the differing distributions of the subsamples according to age at death, sex, and ancestry. Alternatively, all of the above factors could be involved in producing this effect. A possible future avenue of research is an examination of secular change in degree of suture asymmetry. Such a study would require two subsamples from the same geographic region and similar socioeconomic statuses, one modern and one historic. Both subsamples would need to have similar distributions according to age at death, sex, and ancestry. Due to the very specific nature of the subsamples required, an examination of secular change will only be possible when sufficient skeletal material is available.

It was predicted that there would be a positive correlation between degree of suture asymmetry and points of dental asymmetry. Due to the absence of a significant main effect of PDA on degree of suture asymmetry, this hypothesis was rejected. This study provided no evidence of a relationship between asymmetrical antemortem tooth loss and asymmetrical cranial suture closure. There are several possible explanations for this result. First, the null hypothesis may be true and there is no relationship between asymmetry in antemortem tooth loss and asymmetry in cranial suture closure. Consequently, in the future, other possible causes of suture asymmetry should be identified and tested.

Second, there may be a relationship between asymmetry in antemortem tooth loss and asymmetry in cranial suture closure, but the variable PDA may not be truly representative of asymmetry in antemortem tooth loss. The fact that four of the five suture sites that demonstrated extreme suture asymmetry are located in close proximity to the attachment sites of the muscles of mastication does support a connection between suture asymmetry and the masticatory apparatus. Because the biomechanics of mastication are so complex, it is difficult to reduce them to a single variable. The length of time spent masticating with asymmetry in antemortem tooth loss may be an important factor in whether asymmetry in cranial suture closure occurs. Furthermore, the variable PDA does not account for cases of "balanced asymmetry" in which asymmetrical antemortem loss of a tooth on one side is essentially cancelled out by antemortem loss of a different tooth on the opposite side. Finally, only asymmetry in the posterior teeth was examined in this study. In the next stage of research, a new variable should be designed that not only incorporates the anterior teeth but also accounts for balanced asymmetry in antemortem tooth loss.

This study was limited both by the materials examined and the methods employed. Not only was the overall sample size small, but the age/sex/ancestry group sizes were small as well. As a result, the potential for sampling error is high. To build a more robust sample size and increase the group sizes, it may be necessary in the next stage of research to examine individuals from a single sex and ancestry category and with a more limited range in age at death. In addition, to further increase the group sizes, fewer age at death categories can be utilized by extending the range of each age category to include ten years rather than five. Finally, as previously mentioned, the sample used in the current study included individuals drawn from collections that differed in terms of time period and socioeconomic status. Only modern individuals of similar socioeconomic statuses should be included in the sample in the next stage of research in order to remove the possibility that secular change or socioeconomic status is affecting the results.

The current study did not incorporate tests for intra-observer and inter-observer error. In the next stage of research, multiple observers and repeated observations should be included so as to allow for tests of intra-observer and inter-observer error. In addition, this study did not examine whether asymmetrical antemortem tooth loss and asymmetrical suture closure are directional in nature. In the next research phase, a new variable to represent asymmetry in antemortem tooth loss should be designed that allows for the examination of directionality. Directionality in asymmetric suture closure should also be examined, and compared to any directionality in antemortem tooth loss, so that any relevant trends or patterns can be identified. Finally, the data in this study violated a number of statistical assumptions. In the next phase of research, the data should be analyzed using robust statistical tests that are not as sensitive to violations of assumptions as the analysis of variance.

In sum, a number of questions remain regarding the causes and functions of normal and anomalous cranial suture closure. Very little research has been done to determine the frequency and causes of asymmetrical cranial suture closure. Although it produced no evidence of a correlation between asymmetrical antemortem tooth loss and asymmetrical cranial suture closure, this study was the first step in the direction of exploring one possible cause of asymmetrical closure. Ultimately, a better understanding of the causes of asymmetrical cranial suture closure will allow for the refinement of cranial suture age at death estimation methods and the improved identification of individuals that is every forensic anthropologist's goal.

APPENDIX

		Frequency	Percent
Valid	No asymmetry	77	76.2
	Mild asymmetry	20	19.8
	Moderate asymmetry	3	3.0
	Extreme asymmetry	1	1.0
	Total	101	100.0

Table 25: Frequency of Suture Asymmetry at the Parietomastoid Site

		Frequency	Percent
Valid	No asymmetry	75	74.3
	Mild asymmetry	14	13.9
	Moderate asymmetry	2	2.0
	Total	91	90.1
Missing		10	9.9
Total		101	100.0

Table 26: Frequency of Suture Asymmetry at the Squamous Site

		Frequency	Percent
Valid	No asymmetry	66	65.3
	Mild asymmetry	29	28.7
	Moderate asymmetry	3	3.0
	Extreme asymmetry	2	2.0
	Total	100	99.0
Missing		1	1.0
Total		101	100.0

Table 27: Frequency of Suture Asymmetry at the Occipitomastoid Site

		Frequency	Percent
Valid	No asymmetry	63	62.4
	Mild asymmetry	36	35.6
	Total	99	98.0
Missing		2	2.0
Total		101	100.0

Table 28: Frequency of Suture Asymmetry at the Pterion Site

		Frequency	Percent
Valid	No asymmetry	73	72.3
	Mild asymmetry	24	23.8
	Moderate asymmetry	2	2.0
	Extreme asymmetry	1	1.0
	Total	100	99.0
Missing		1	1.0
Total		101	100.0

Table 29: Frequency of Suture Asymmetry at the Sphenofrontal Site

		Frequency	Percent
Valid	No asymmetry	70	69.3
	Mild asymmetry	29	28.7
	Moderate asymmetry	2	2.0
	Total	101	100.0

Table 30: Frequency of Suture Asymmetry at the Inferior Sphenotemporal Site

		Frequency	Percent
Valid	No asymmetry	74	73.3
	Mild asymmetry	22	21.8
	Moderate asymmetry	1	1.0
	Extreme asymmetry	1	1.0
	Total	98	97.0
Missing		3	3.0
Total		101	100.0

Table 31: Frequency of Suture Asymmetry at the Superior Sphenotemporal Site

		Frequency	Percent
Valid	No asymmetry	74	73.3
	Mild asymmetry	26	25.7
	Total	100	99.0
Missing		1	1.0
Total		101	100.0

Table 32: Frequency of Suture Asymmetry at the Ectocranial Midlambdoid Site

		Frequency	Percent
Valid	No asymmetry	78	77.2
	Mild asymmetry	16	15.8
	Moderate asymmetry	2	2.0
	Extreme asymmetry	2	2.0
	Total	98	97.0
Missing		3	3.0
Total		101	100.0

Table 33: Frequency of Suture Asymmetry at the Endocranial Midlambdoid Site

		Frequency	Percent
Valid	No asymmetry	69	68.3
	Mild asymmetry	28	27.7
	Moderate asymmetry	4	4.0
	Total	101	100.0

Table 34: Frequency of Suture Asymmetry at the Ectocranial Midcoronal Site

		Frequency	Percent
Valid	No asymmetry	73	72.3
	Mild asymmetry	26	25.7
	Moderate asymmetry	2	2.0
	Total	101	100.0

Table 35: Frequency of Suture Asymmetry at the Endocranial Midcoronal Site

		Frequency	Percent
Valid	No asymmetry	86	85.1
	Mild asymmetry	12	11.9
	Moderate asymmetry	2	2.0
	Total	100	99.0
Missing		1	1.0
Total		101	100.0

Table 36: Frequency of Suture Asymmetry at the Incisive Site

		Frequency	Percent
	No asymmetry	66	65.3
Valid	Mild asymmetry	26	25.7
	Total	92	91.1
Missing		9	8.9
Total		101	100.0

Table 37: Frequency of Suture Asymmetry at the Transverse Palatine Site

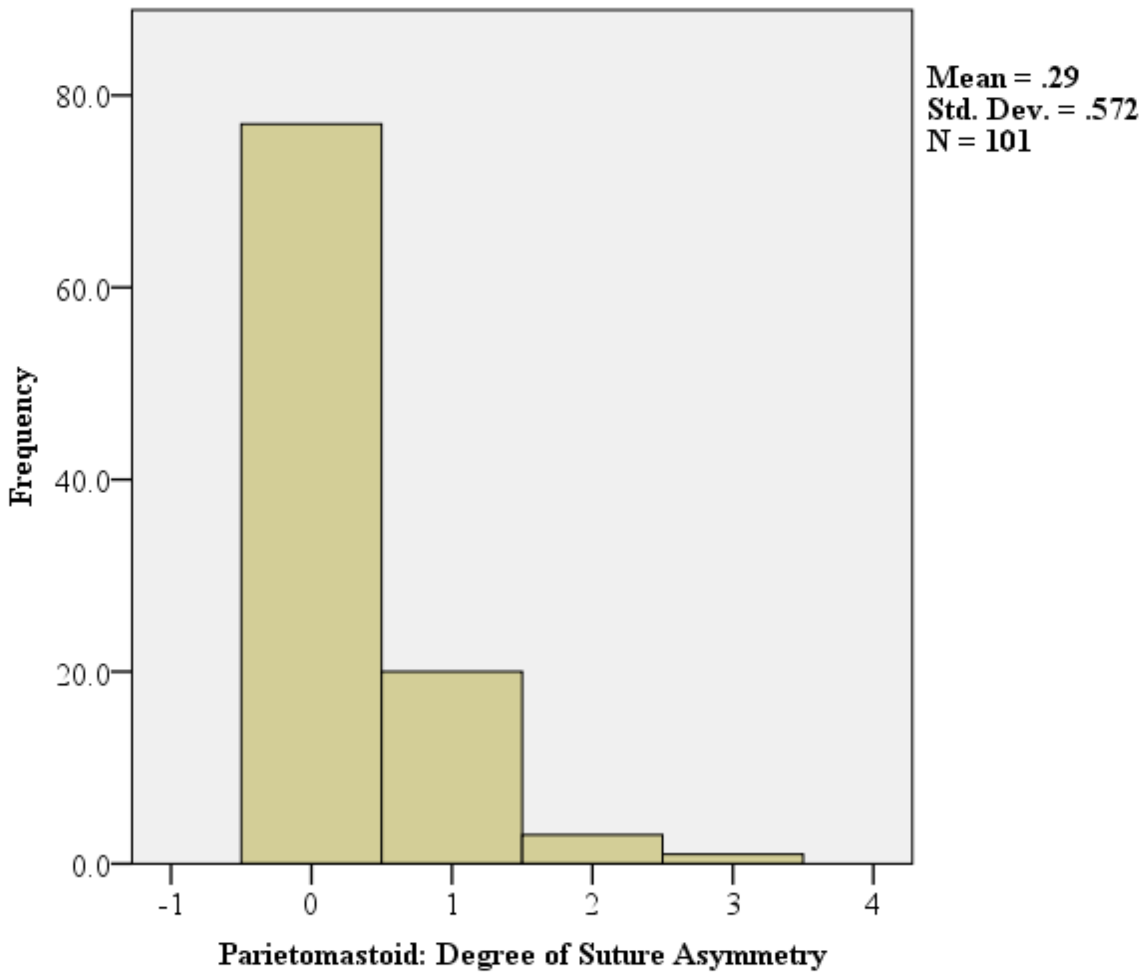

Figure 18: Histogram of Degree of Suture Asymmetry at the Parietomastoid Site

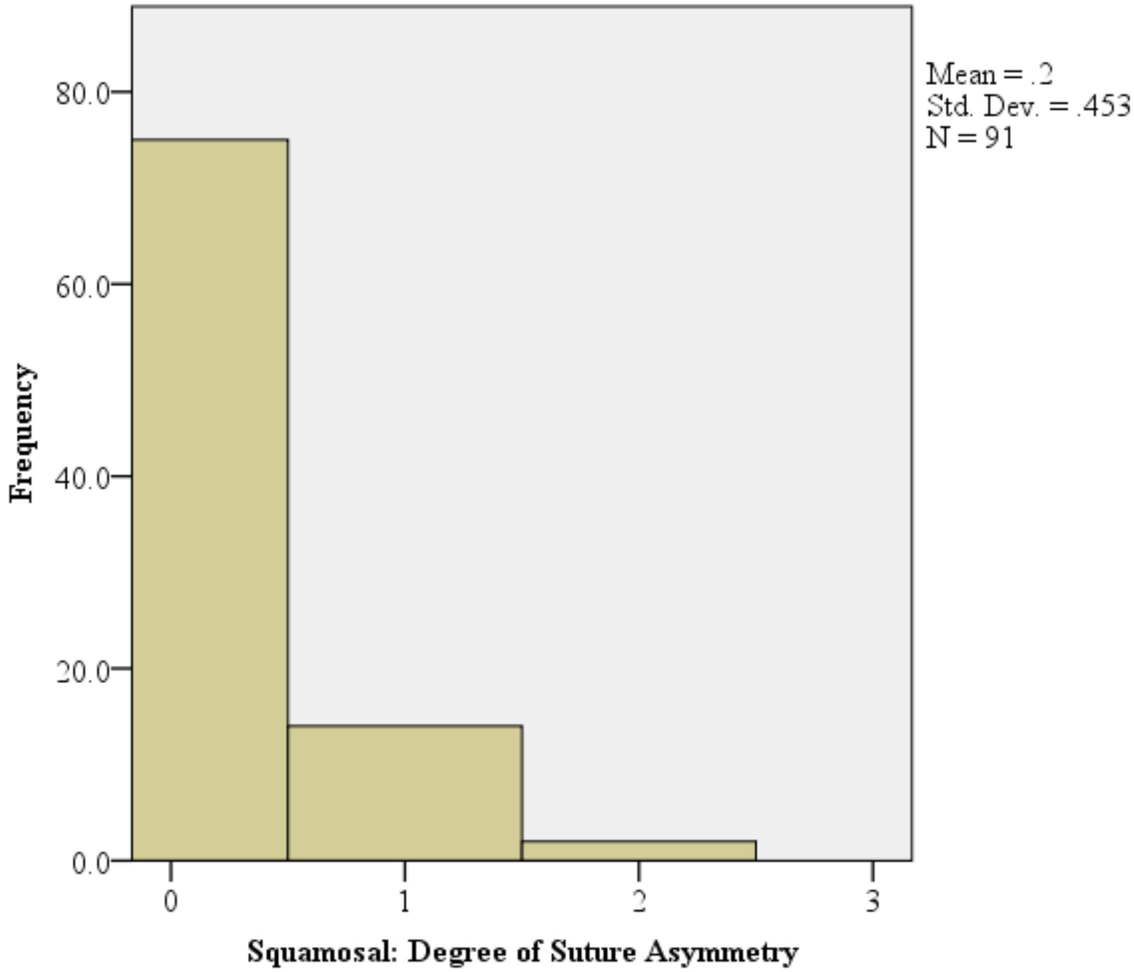

Figure 19: Histogram of Degree of Suture Asymmetry at the Squamosal Site

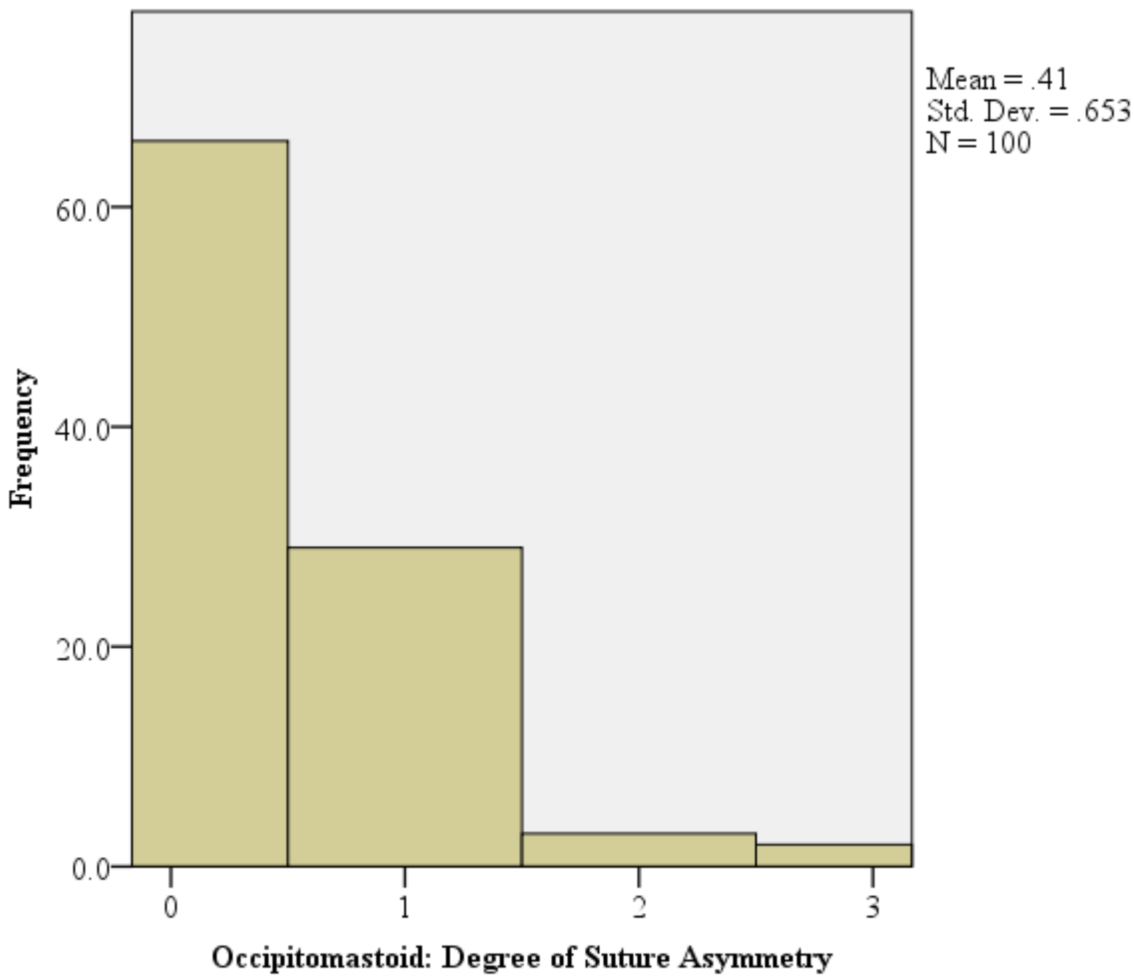

Figure 20: Histogram of Degree of Suture Asymmetry at the Occipitomastoid Site

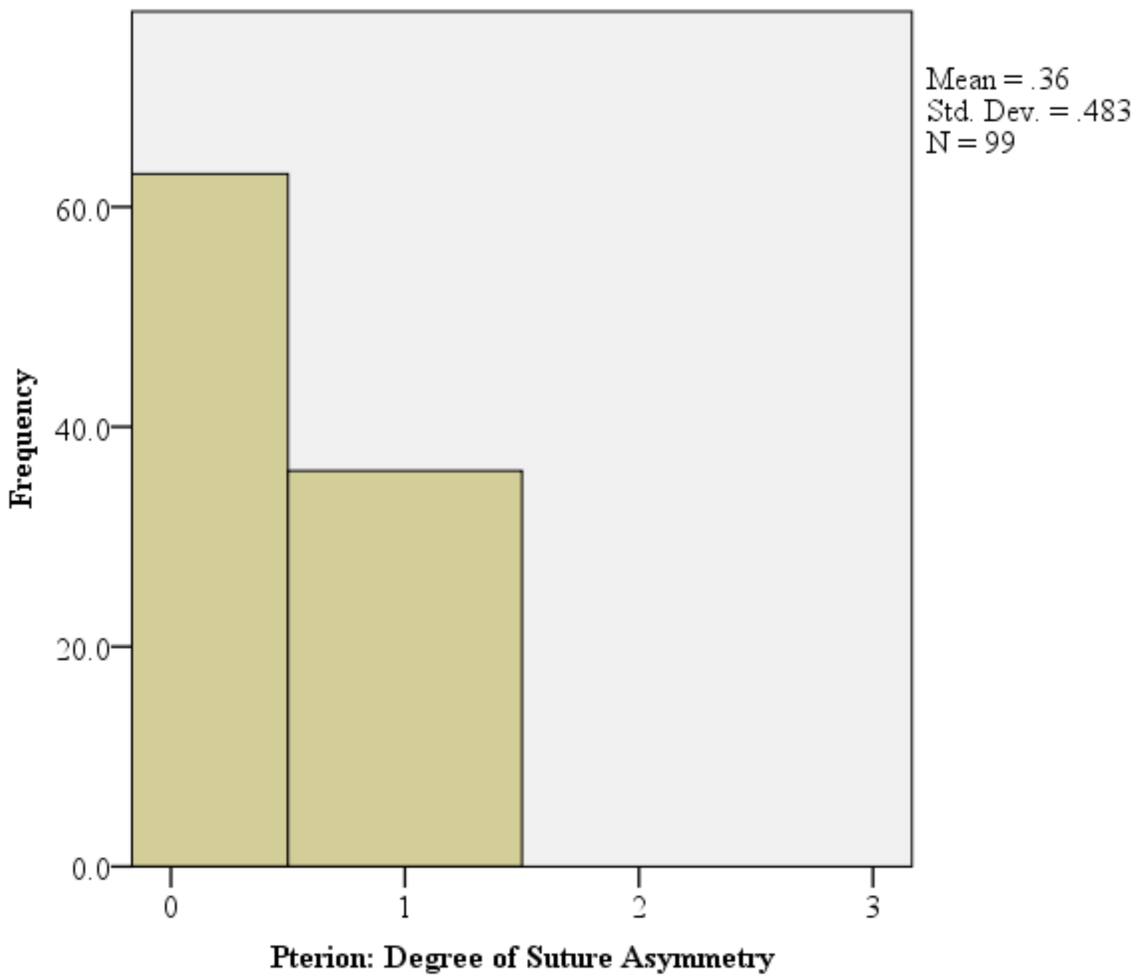

Figure 21: Histogram of Degree of Suture Asymmetry at the Pterion Site

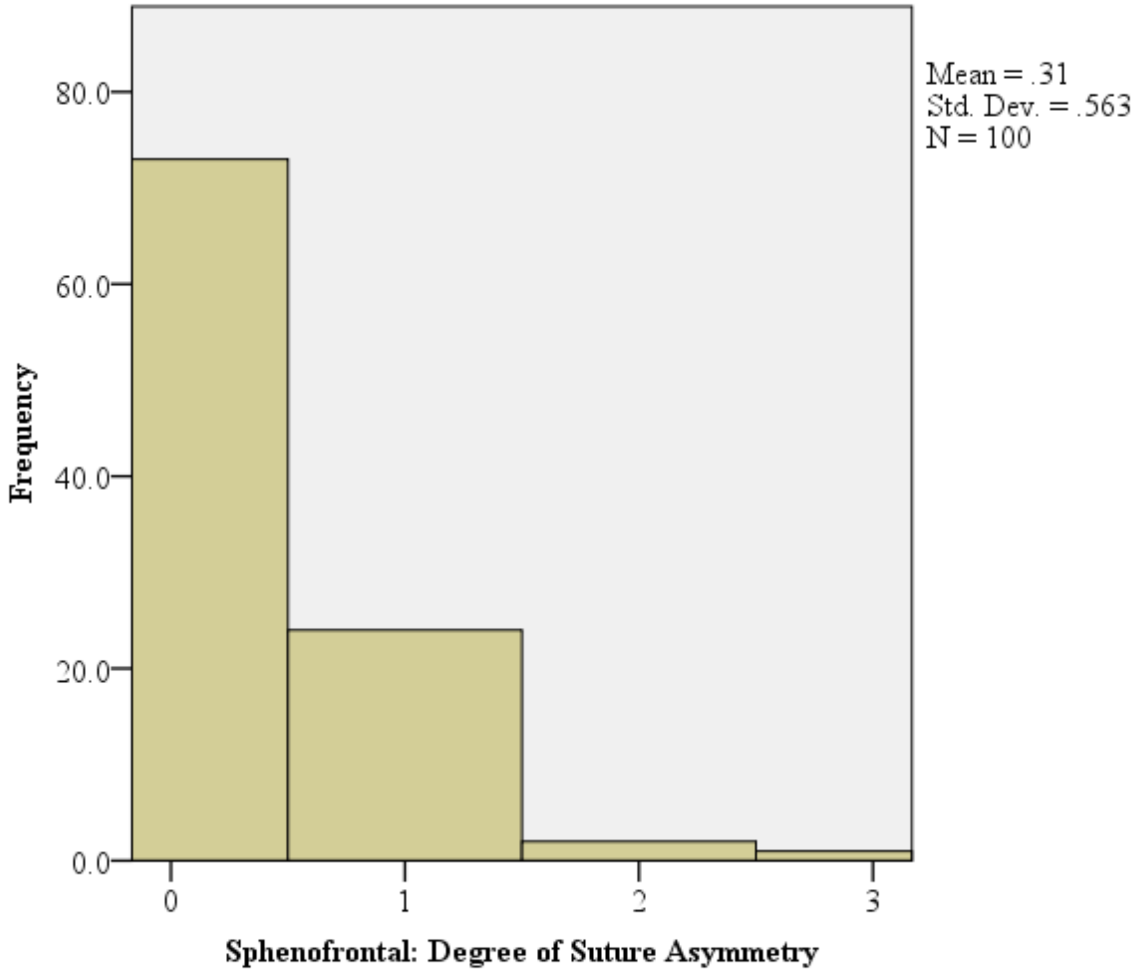

Figure 22: Histogram of Degree of Suture Asymmetry at the Sphenofrontal Site

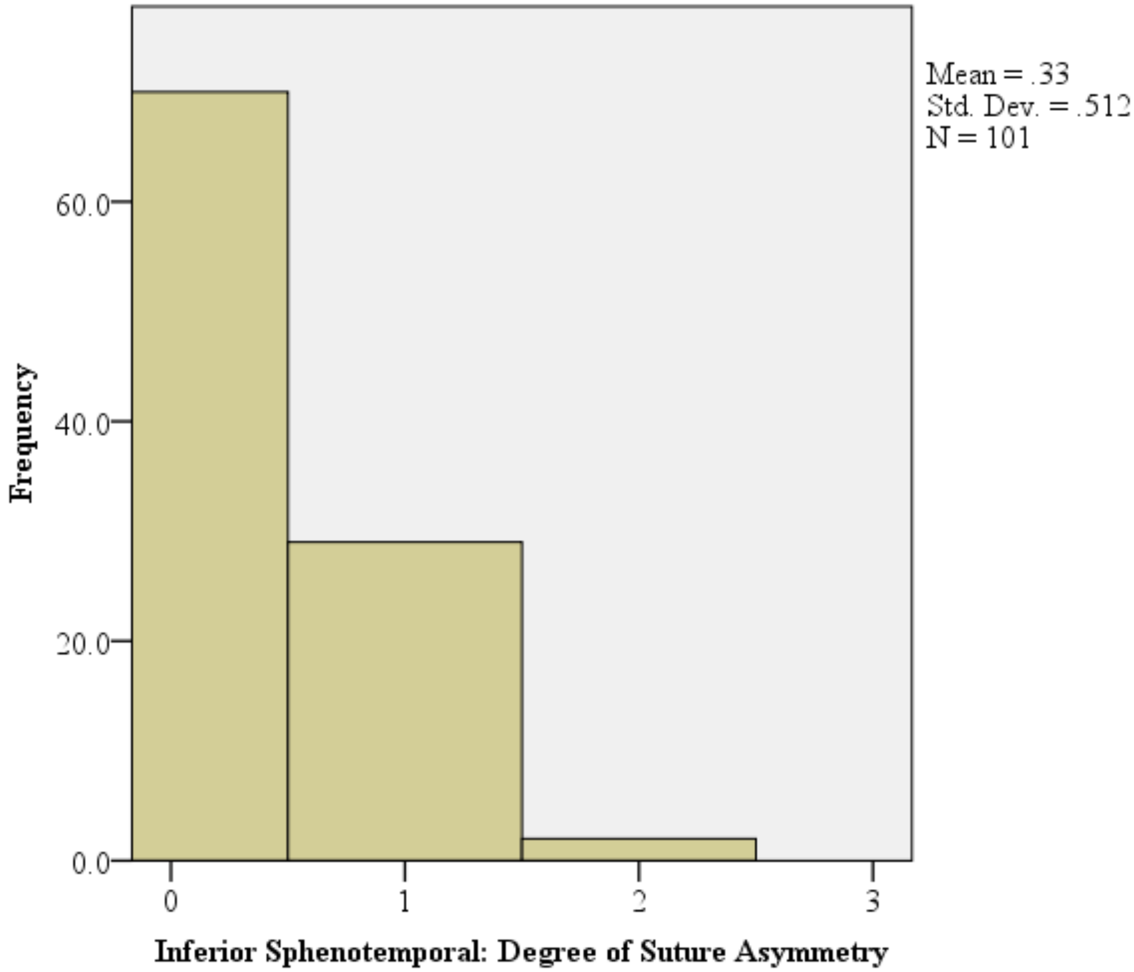

Figure 23: Histogram of Degree of Suture Asymmetry at the Inferior Sphenotemporal Site

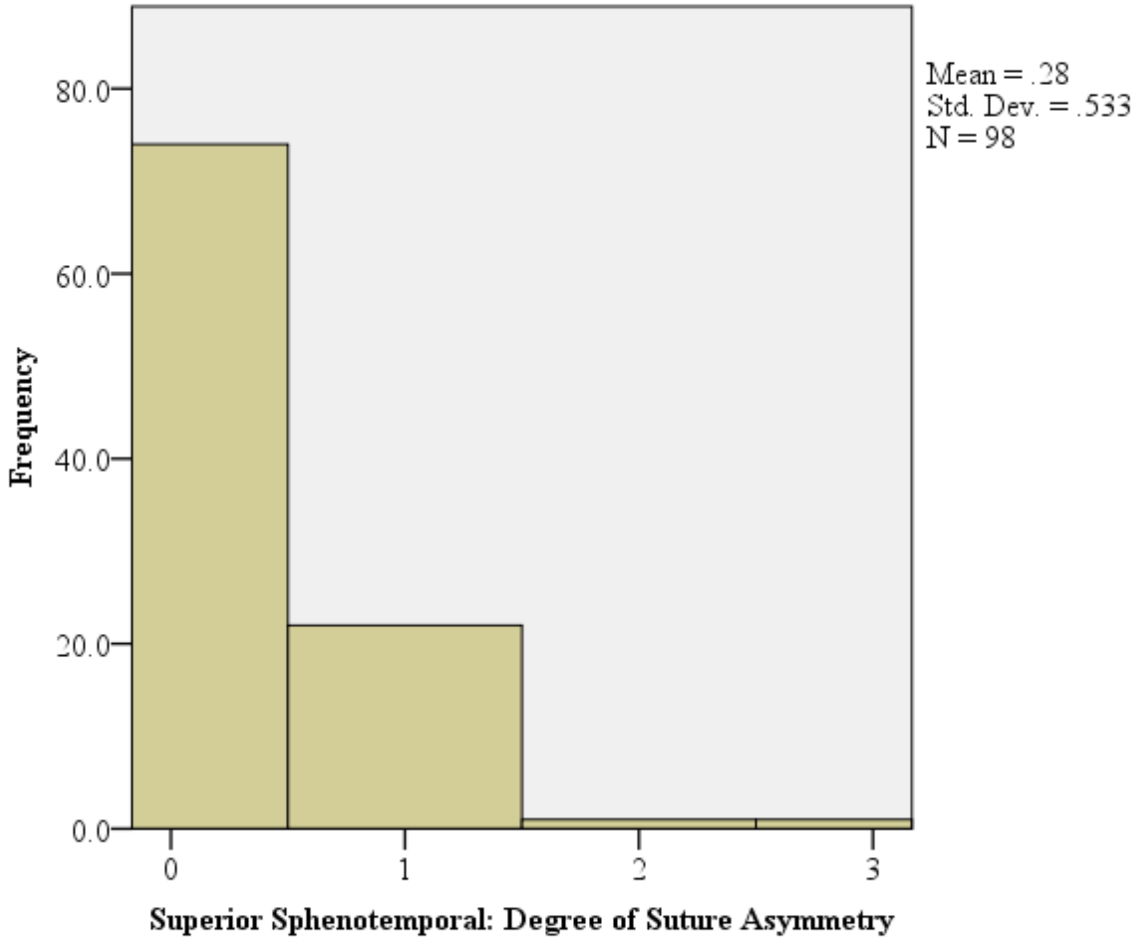

Figure 24: Histogram of Degree of Suture Asymmetry at the Superior Sphenotemporal Site

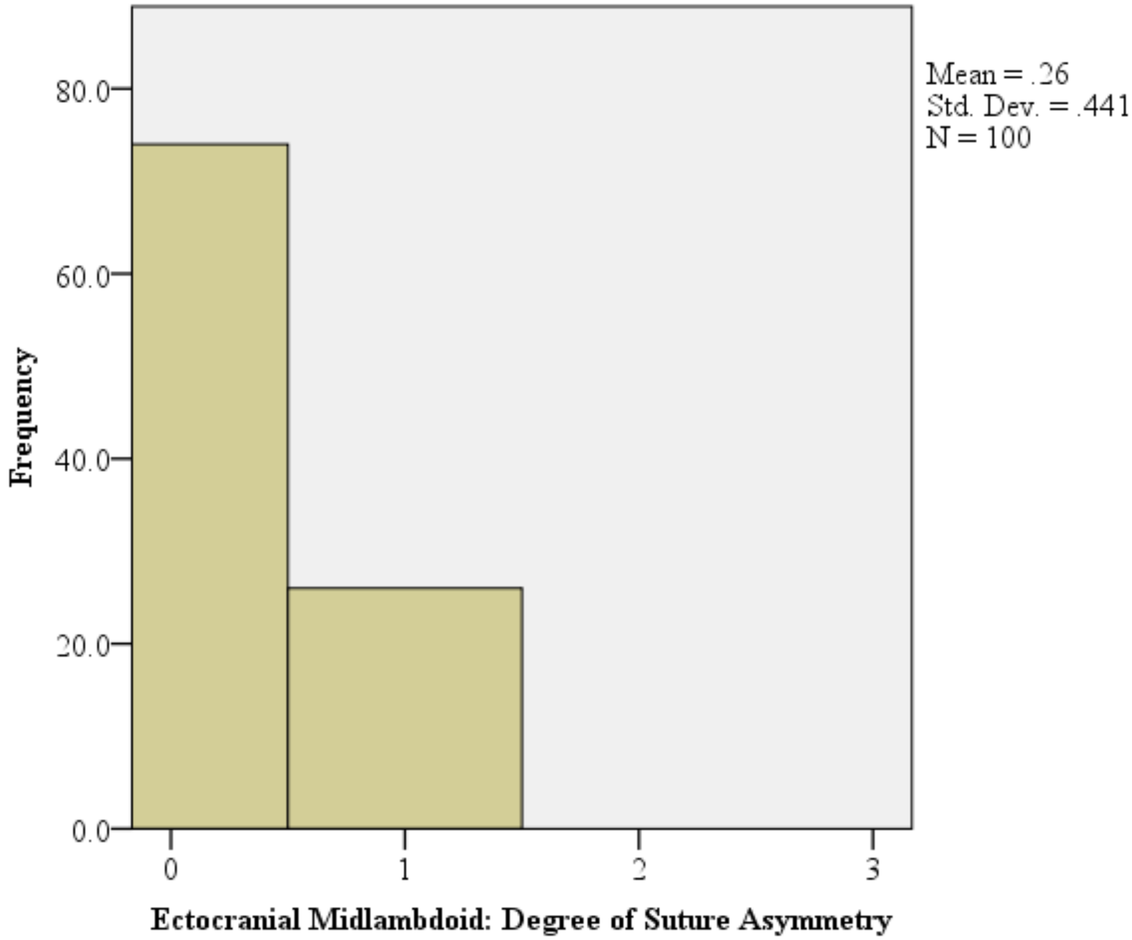

Figure 25: Histogram of Degree of Suture Asymmetry at the Ectocranial Midlambdoid Site

Figure 26: Histogram of Degree of Suture Asymmetry at the Endocranial Midlambdoid Site

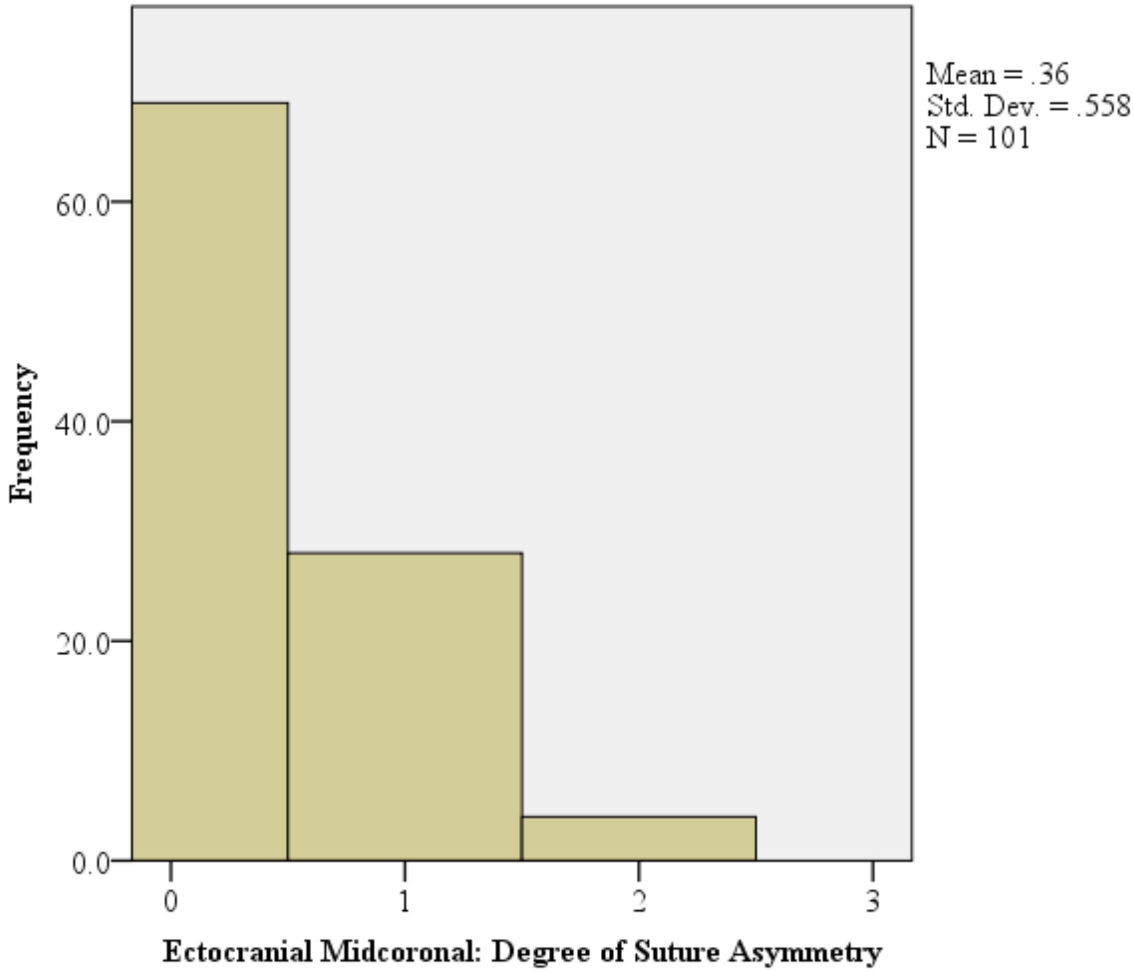

Figure 27: Histogram of Degree of Suture Asymmetry at the Ectocranial Midcoronal Site

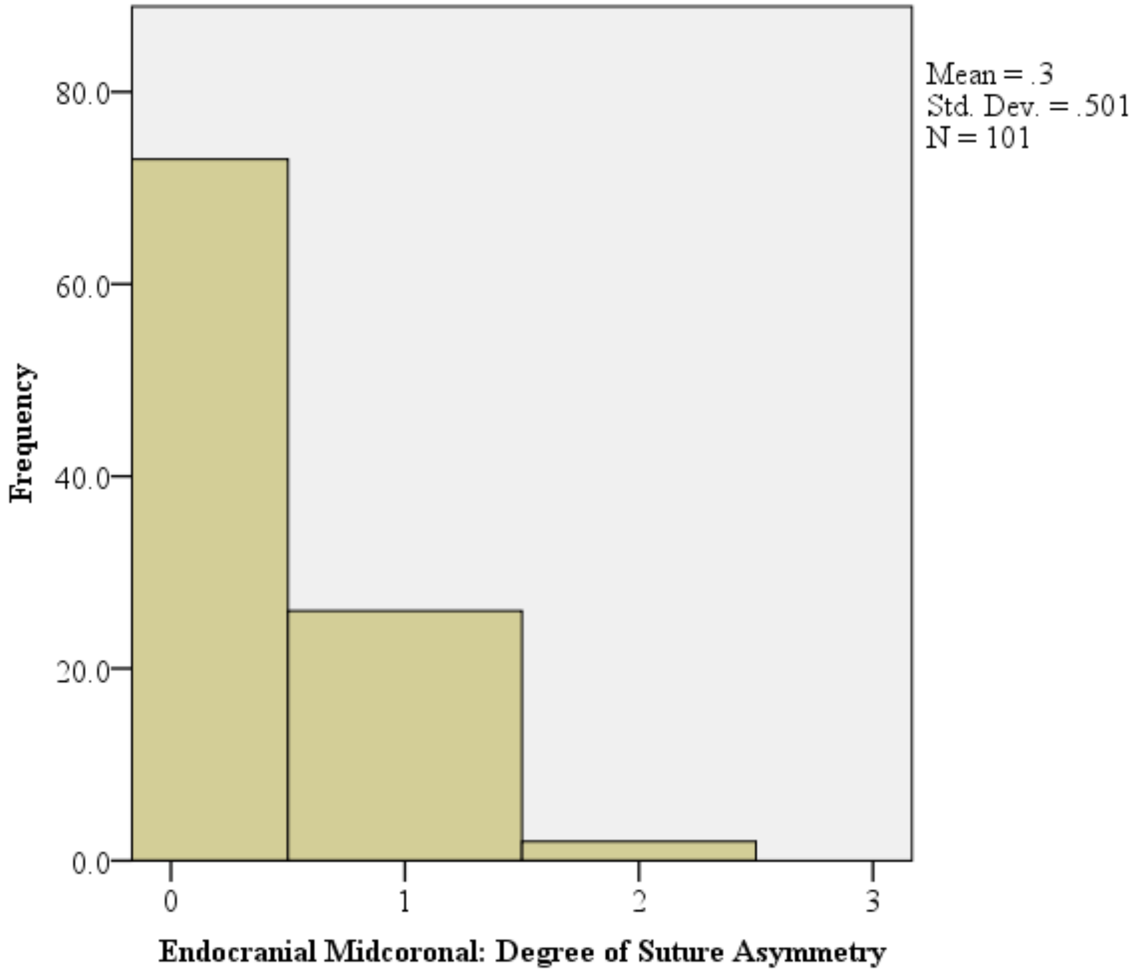

Figure 28: Histogram of Degree of Suture Asymmetry at the Endocranial Midcoronal Site

Figure 29: Histogram of Degree of Suture Asymmetry at the Incisive Suture Site

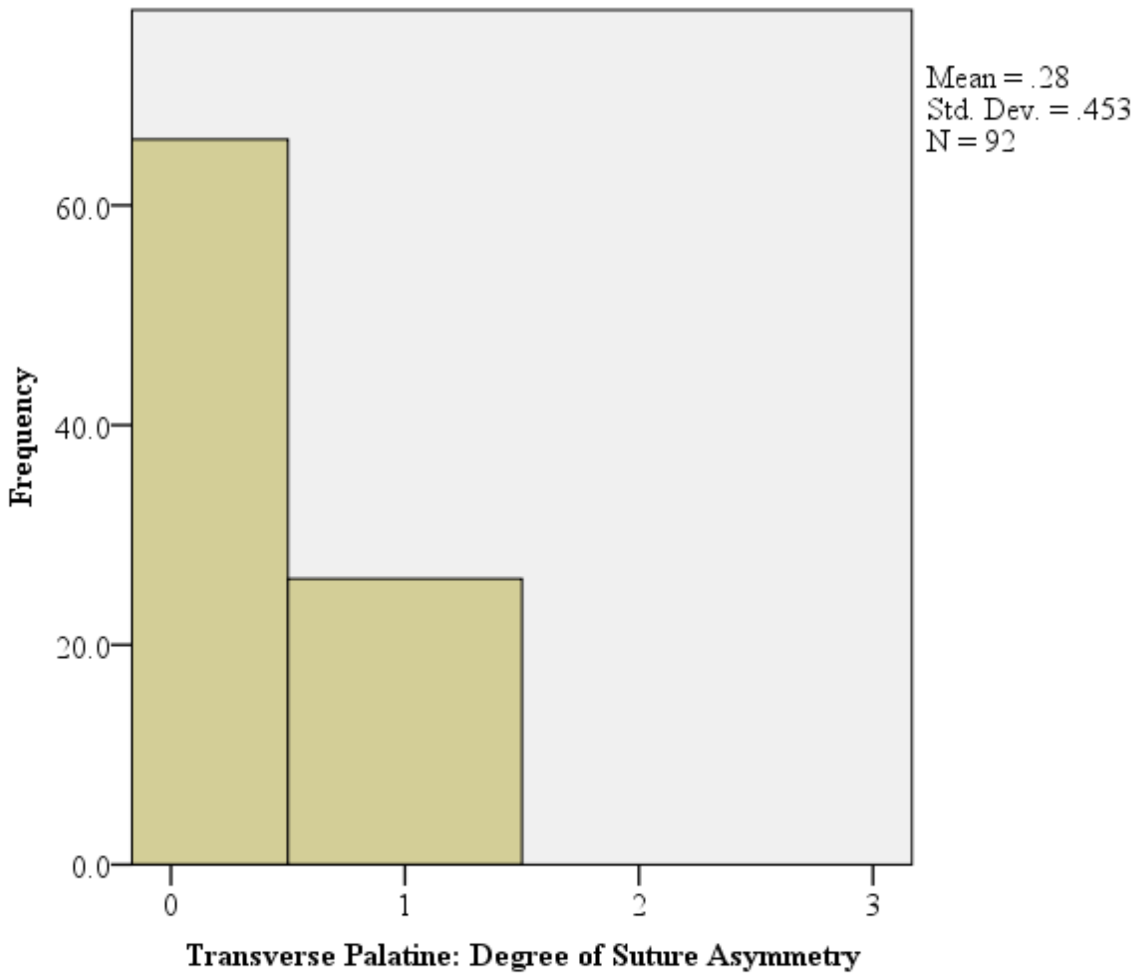

Figure 30: Histogram of Degree of Suture Asymmetry at the Transverse Palatine Suture Site

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