Critical analysis of the factors affecting the "cranial suture aging method" using the Hamann Todd Collection

by

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Abstract

Cranial suture closure has been regarded as an unreliable method for age estimation due to the large amount of variability in the commencement, progression and termination of fusion. A preliminary study done on the J.C.B. Grant Collection (University of Toronto; Toronto, Ontario) showed that actual ages often did not fall in the age ranged produced by cranial suture aging. Accuracy was lost with increasing age. The Hamann Todd Skeletal Collection (Cleveland, Ohio) was used to examine the sagittal, coronal and lambdoid sutures in an attempt to determine the source(s) of variation. Sutural development is a moderate (to poor) predictor of age. In both the coronal and lambdoid sutures, significant sex-based and population-specific differences were noted. Black individuals had a stronger age-score relationship. Adolescents and adults up to 39 years of age showed a stronger age-score correlation than older individuals. Beginning twenty or thirty years before the turn of the century, the age-score relationship becomes strong, hinting at a secular bias. Individuals born from the late 19th century to the 20th century showed an age-score correlation stronger than all else reported so far. Progression is delayed in the oldest individuals dating to the earliest times. Black individuals had a significant height-score relationship in the sagittal while white subjects had a nearly negligible correlation. Adolescents showed the greatest correlation between height and synostosis. The negative trend indicates that taller people are associated with less development. Stronger age-score relationships were generally seen in underweight individuals. Individuals who used alcohol and/or narcotics for prolonged periods may be more likely to exhibit an obliterated sagittal suture. The presence of cranial features like wormian bones may be associated with a more predictable pattern of sutural development. Very light weight skulls were more likely to exhibit

greater fusion than extremely dense ones. The presence of the parietal foramina does not influence the rapid degree of closure seen in the obelionic region of the sagittal suture. Of all the sutural segments examined, the inferior coronal has the strongest age-score correlation. Progression in the internasal facial suture was rapid for the Hamann Todd sample, with average scores surpassing all three cranial sutures.

Preface

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1 Cranial sutures: An introduction

1.1 What is a suture?

To date, many definitions of the word "suture" exist. Sutures are fibrous tissues that hold the bones of the cranium in place, allowing for only a minimal amount of movement (Cohen, 1993). Sutures can be further classified as a suture area or suture proper (Moss, 1958). A suture area includes the adjoining bone edges and the soft tissue between them while the suture proper refers exclusively to the soft tissue. At sutural sites, continuous bone deposition and resorption take place, and with time, ossification, the process of becoming bone, occurs. This process is referred to as synostosis, and the degree of synostosis that has occurred is used by forensic anthropologists and osteoarchaeologists as a tool for estimating age at death of an individual.

Sutural biology suggests that synostosis should be a product of time. Theoretically, ossification in the suture proper intensifies with age, but to put this into context, it is necessary to discuss the mechanics of sutural development first. Pritchard *et al.*'s (1956) theory on sutural development is widely accepted: there are five layers in each adjoining bone, consisting of two cambial and capsular layers, which are separated by a vascular layer, making up the periosteum. Eventually with growth, the cambial layers become a single layer consisting of osteoblasts (bone-producing cells). The capsular layers become thicker and its fibres sit parallel to the bone margin (site of the suture). At this point, collagen fibres are situated evenly along a suture but with increasing age, the number of fibroblasts, located in the sutural connective tissue, decreases. Collagen fibres become less evenly distributed. The amount of connective tissue lessens with age as the marrow space in these bones (both cranial and facial) enlarges in size and quantity. As they reach the sutures, communication occurs between both parties, initiating synostosis.

Fusion occurs in two manners (Persson *et al.*, 1978): bone spicules develop at the margins and grow toward the adjoining bone. This can result in complete or partial fusion. Other times, thickets of calcified bone would form, either drifting unattached at the sutural site, or joined to the bone spicules (Cohen, 1993). These aggregates of cells would then bridge the adjoining bones. As this process occurs with time, during adulthood, it is evident that ossification progresses with age, but at varying rates.

1.2 The link between cranial suture closure and age: Is there one?

Observations on cranial sutures go back as far as Hippocrates (McKern & Stewart, 1957). Their application as an age indicator caught the attention of researchers after work done in the mid-1800s by Gratiolet, whose research showed that there was an association between age and cranial suture closure (Ashley-Montagu, 1938; Todd & Lyon, 1924). Since then, countless authors have performed original research in an attempt to test the age-suture-closure relationship and understand the mechanisms behind sutural biology with early works, like Todd and Lyon (1925a, 1925b, 1925c, 1924) to more recent publications, like Chiba *et al.* (2013).

Since the beginning, cranial suture closure has been regarded as an unreliable method for age estimation due to the large amount of variability in the commencement, progression and termination of sutural union, but McKern and Stewart (1957) argued that the difficulty in detecting the age-suture pattern was due to the small sample sizes used in early studies. Todd and Lyon (1924) were one of the first to use a relatively large sample size to study cranial synostosis; their first (of several) study on cranial sutures had a sample of 307 white males. Their research presented a definite positive relationship between age and cranial suture closure.

Three decades later, McKern and Stewart (1957) re-evaluated Todd and Lyon's methodology and tested its accuracy since the original methods were derived from certain exclusions and biases. For instance, Todd and Lyon (1925a, 1925b, 1925c, 1924) eliminated all subjects that exhibited abnormal closure patterns (e.g. early or delayed fusion, abnormal rate of union during fusion). Skulls with abnormalities in post-cranial skeleton growth were excluded as well. Also, in order to correct for the obscurity produced by idiosyncratic variation in closure rates and times, actual ages were not used. Rather, individuals were grouped into 3-year age intervals. Despite taking these precautions to avoid pattern obscurity, the authors were forced to conclude that it is difficult to deduce age from the degree of synostosis that has occurred in the skull at the time of death. Thus, even with an adequate sample size, the unreliability of cranial suture closure as an indicator of age persisted.

In the words of Cobb (1955): "Suture closure (both vault and facial) is a variable phenomenon and that age at which each specific suture should be found to have begun and to have completed closure cannot be categorically defined" (in McKern & Stewart, 1957, p.23). Singer (1953) provided a critical paper on vault suture progression in 100 Cape Coloureds, 190 Bantu, 20 White Germans, 60 North American Indians and 30 Eskimos, and firmly rejected the use of cranial suture closure. He reported "...the age of the individual at death cannot be estimated from the degree of closure of the various cranial sutures, whether taken individually or collectively or whether observed exocranially or endocranially" (Singer, 1953, p. 56).

So, the fundamental question is this: Is cranial suture closure influenced by age-related physiological processes, like the pubic symphysis or the auricular surface of the ilium? According to many authors, there exists a positive, but variable correlation between synostosis and age. In the work carried out by McKern and Stewart (1957) on American war casualties, they saw that the number of older crania with open sutures and the number of young crania with completely obliterated sutures were small. So, a relationship exists, but in order to discern chronological age from synostosis, the commencement and termination stages of union need to be associated with a particular age or age range. At the present time, this appears to be virtually impossible.

When the sample is highly controlled, as done by Todd and Lyon (1925a, 1925b, 1925c, 1924), such age ranges do emerge, but what happens when no exclusion factors are applied to the sample? For instance, in the Spitalfields sample used by Key *et al.* (1994), there were young individuals with obliterated sutures and old individuals with open ones. In this case, patterns will surely be obscured if all individual are included in the analysis. McKern and Stewart (1957) observed variability in closure commencement and termination in the sagittal, coronal and lambdoid sutures. The sagittal suture is a notable anomaly: 75% of individuals aged 17 to 18 years showed an open sagittal suture and 10% of males in the 31-40 year age group exhibited synostosis. An individual can easily be misclassified if age were solely based on closure in the sagittal suture. Also, the authors report that the number of individuals with a synostosed suture does not increase in frequency with age (McKern & Stewart, 1957). On the other hand, facial sutures were far less variable until the mid-twenties compared to the calvarial sutures. However, a solid method for age estimation could not be developed.

Early studies relied on macroscopic observations to test for age-synostosis relationship. A recent study (Chiba *et al.*, 2013) on Japanese forensic cases used multidetector computed tomography to document progress in the sagittal suture. Chiba *et al.* (2013) found that chronological age correlated well with sutural progression, with Pearson product-moment correlation coefficients as high as 0.79. In contrast, Wolff *et al.* (2013) report that age did not increase with progression in a suture in modern-day Hungarian autopsy cases. Age estimations had a tendency to over-age individuals under 30 years, while under-aging those over 40 years. Accuracy was consistently seen in those aged 31-40 years, but only 24% of the sample was aged correctly using sutures.

1.3 What affects cranial suture closure rates?

When Dorandeu *et al.* (2008) looked at the frontosphenoidal suture for age estimation, their prediction variability and R^2 value told them that one or more co-factors in addition to age impacted cranial synostosis. So, the answer to this question is numerous and can include sex, ancestry, genetics (idiosyncratic differences or interpopulation variation), nutrition, pathology, biomechanical stress and environment factors. To complicate matters, not all of these factors will be consistent across different populations. What impacts sutural union in one group may not be evident in another group.

1.3.1 Sex

There is much debate on the impact of sex on synostosis. Authors, like Dorandeu *et al.* (2008) [modern-day French autopsy cases], Perizonius (1984) [20th century Dutch sample from Amsterdam] and Acsádi and Nemeskéri (1970) [19th century Hungarian population] found no sex-based biases in their samples. Meindl and Lovejoy (1985) used the Hamann Todd Collection [American population, 19-20th century] for their research and concluded that sex and race did not bias age estimation. On the other hand, when Key *et al.* (1994) analysed the Spitalfields sample from London, England, they saw that sex-related differences in closure were apparent, especially in the coronal and sagittal sutures. Here, females exhibited a stronger relationship between synostosis and age. Males exhibited open or partially closed ectocranial (exterior surface of the skull) sutures in senescence more frequently than females. Conversely, Mann *et al.*'s (1991) study on the maxillary suture showed that males of both white and black ancestry exhibited more sutural obliteration than similarly-aged females. However, they noted that the rate of progression toward union in early adulthood was virtually the same in both sexes.

Earlier works, like Singer (1953) and Brooks (1955), support a sex-based influence on closure as well. Brooks (1955) found that cranial suture closure in females lagged behind the age-related changes observed in the pubis. Although this delay was present in males as well, there was a greater discrepancy between female pubic and cranial ages. In response to these mixed results, Key *et al.* (1994) concluded that sex-based differences in synostosis varies across populations, and the degree of dimorphism is reflected more extensively on the ectocranial surface rather than the endocranial (or interior) surface.

More recently, in Vijay Kumar *et al.*'s (2013) study on an Indian sample, synostosis occurred earlier in females on both the endocranial and ectocranial surfaces of the sagittal suture. The pattern was the same for the coronal and lambdoid as well. Chiba *et al.* (2013) documented sex-based differences in the strength of age-score relationships in the sagittal suture in a modern-day Japanese sample. If fusion is connected to genetics, then different populations may or may not show sex-based trends. If genetics plays a minimal role, then the contradicting results are rather puzzling.

1.3.2 Genetics

One of the major criticisms of cranial suture closure as an age predictor is the degree of variability seen in commencement, progression and termination. A genetic factor may explain this. Similar to the Spitalfields sample, Perizonius (1984) observed a few extremely old individuals with open sutures; he argued that these were not rare occurrences and hypothesized these cases to be the product of an unknown mechanism related to sutural biology. This author suggests that selection for open sutures may occur, although whether this impacts survivability is unknown. If such an impact exists, it is surely not negative since the individuals who exhibit this anomaly lived to advanced age. Most genetic studies have been done on children with premature suture closure (craniosynostosis). Recently, Wolff *et al.* (2013) showed that the msh homeobox 1 (MSX1): rs3821947 polymorphism is significantly related to synostosis in adults.

1.3.3 Nutrition and illness

Like sex and genetics, nutrition or malnourishment has the potential to alter the aging process, although more research is needed to verify this. In McKern and Stewart's (1957) analysis of the American soldiers who had died in the North Korean conflict, they saw that the bones of the prisoners of war or POWs (compared to those who were killed in action or KIAs) showed indications of malnutrition (e.g. light weight, osteoporosis) for a long period of time (up to 1.5 years before death). Interestingly, the authors carried their analysis out on a combined sample (POWs & KIAs), claiming that there were no substantial differences between the groups despite differing nutritional levels.

Illness, possibly the end result of malnourishment, may impact synostosis as well. Chronic illnesses that deteriorate the health of a person over a long period of time or diseases that disrupt metabolic function are probable causes of delays or acceleration in suture closure. For instance, Reilly *et al.* (1964) found that in one-third of rachitic children in their sample, premature closure and rickets occurred together.

1.3.4 Environmental impact: Secular change

Other factors outside of human biology, like the time period during which an individual lived in, can impact sutural union. Perizonius (1984) compared a Dutch population to the Hungarian population used by Acsádi and Nemeskéri (1970) and found that the latter exhibited earlier closure in every age group. Perizonius (1984) pointed to secular trends as a function of time period to explain this. He stated: "...the Hungarians died in 1955/56 while the Amsterdam inhabitants died between 1883 and 1909. The possibility of a secular trend caused by the rapidly changing way of life in the 20th century cannot be excluded" (Perizonius, 1984, p.215). Specifically, a secular trend can be seen in the treatment of different ancestral groups or availability of medical care to the poor class. These variables improved with time and can likely affect synostosis.

1.3.5 Biomechanical stress

The current consensus is that sutural growth occurs in a passive manner as a function of forces that cause separation (Cohen, 1993). Histologically, compression on facial bones is seen as bone resorption on the sutural margins of the bones involved. When the compression ceases, the sutures normalize. Tension causes bones to separate, making the space between them larger and causing increases in bone deposition at the margins. The sutures normalize once tensile forces are removed. Thus, if a cranium experienced no or limited biomechanical force over the course of life, the suture is expected to remain patent. The rate of sutural progression is controlled by the amount of force applied to it, which over time may increase, resulting in fusion.

1.4 Sutural sites and their relationships with age

Most cranial sutures are divided into multiple parts by researchers and these segments are scored independent of other parts on the same suture. These subdivisions are not arbitrary; different parts of a single suture can have faster or slower rates of closure (e.g. pars pterica lags behind the rest of the coronal regions; Todd & Lyon, 1924). Some sutural segments follow a route that is completely different from other parts of the same suture, as is the case with the pars obelica of the sagittal suture, pars pterica of the coronal suture and pars asterica of the lambdoid suture. Also, different segments of the same suture can have stronger or weaker correlations with age. According to Perizonius (1984), in 40 crania, aged 20-49 years, closure in ten endocranial suture sites (all sites on the coronal, and the two endsections of the sagittal and lambdoid sutures) were strongly correlated with age ($p < 0.001$). In the other six endocranial sites and eight ectocranial sites examined, significance was lower ($0.001 \le p < 0.05$). Furthermore, the author reported that correlations at the $p < 0.001$ level were non-existent in the 50-99 year subgroup, while five sites expressed significance at the $0.001 \le p < 0.05$ level. Interestingly, of these five, two were negative correlations (e.g. ectocranial endsections of the lambdoid suture). Even though Meindl and Lovejoy (1985) report that ectocranial sutures are a reliable way of predicting age in older individuals, Perizonius' (1984) negative correlations cause some doubt as to whether cranial suture closure can be used reliably to estimate age in individuals older than 50 years.

1.5 Techniques derived from cranial suture closure

The large amount of criticism around the use of cranial suture closure as an age estimator has not hindered researchers from using it or attempting to develop new techniques. At the present time, there are several accepted methods for qualitatively assessing age from the degree of synostosis reached by an individual at the time of death, and these include Masset (1989), Meindl and Lovejoy (1985), Baker (1984) and Acsádi and Nemeskéri (1970). These are, however, not without problems. Precise age estimations cannot be obtained from these techniques. Scoring cranial sutures remains a subjective process and intra-observer and assessment errors are heightened because of the unclear and broad nature of the scoring stages used in these techniques.

The most notable one, commonly used in North America, is Meindl and Lovejoy's (1985) method using vault and lateral-anterior sites for ectocranial sutures. According to Meindl and Lovejoy (1985), the lateral-anterior sutures are more reliable indicators of age than vault sutures. They exhibit prolonged closure and have smaller standard and mean deviations and age ranges than vault sutures. Preceding this is Perizonius' (1984) method, which incorporates both endocranial and ectocranial aspects. He devised separate scoring systems based on different sutural sites for individuals under and over the age of 50 years. Mann *et al.*'s (1991) study on maxillary suture obliteration proved to be an asset for aging commingled or fragmented remains. However, precise ages could not be determined; only age ranges were established.

Key *et al.* (1994) identified existing methods as problematic due to their tendency to rely on mean closure scores rather than individual suture closure sites. They argued that methods derived from individual suture closure sites would provide a way to check the accuracy of age estimations produced by cranial suture closure while simultaneously checking for interpopulation variation as well. Compared to the works preceding them, Key *et al.* (1994) devised a simpler scoring system, consisting of scores for only open, fusing and fused sutures. The reduction in steps was due to their Kruskal-Wallis analyses, which indicated that there were no significant differences in age between the Martin scores of 1 and 2, and 3 and 4 [scoring system used by Perizonius (1984)]. Dorandeu *et al.* (2008) looked at frontosphenoidal suture closure in French autopsy cases and developed a scoring system for age estimation that combined synostosis on both endocranial and ectocranial aspects of this suture.

1.6 Endocranial or ectocranial?

Todd and Lyon (1924, 1925b) concluded that synostosis on the endocranial aspect followed a more regular pattern compared to the ectocranial sutures; they favored the endocranial aspect for age estimation. Acsádi and Nemeskéri (1970) based their study on endocranial sutures as well. However, it is more practical to devise age estimation techniques based on the ectocranial aspect as it is readily visible and the skull need not be damaged (e.g. can be kept intact) in any way for observation. Meindl and Lovejoy's (1985) method involves the ectocranial surface exclusively and they argue that ectocranial sutures are better for aging older individuals. Subsequent studies (e.g. Key *et al.*, 1994) were in accord with Todd and Lyon's (1924, 1925b) conclusions. Key *et al.* (1994) saw that the average error in all the endocranial sites was much lower than the ectocranial sites. Furthermore, ectocranial sutures appear to be more greatly influenced by interpopulation variation (Key *et al.*, 1994; Perizonius, 1984). Endocranial sutures are less sensitive to sex-based differences (Key *et al.*, 1994). Thus, the research to date indicates that endocranial sutures are more reliable indicators of age estimation, although the ease of using Meindl and Lovejoy's (1985) technique trumps this to some extent.

1.7 The need for population-specific aging techniques

In Key *et al.*'s (1994) study on Spitalfields remains, they found that these individuals had delayed sutural closure. When they applied the Meindl-Lovejoy method, underestimation of age occurred. Thus, there was population-specific variation between the Spitalfields group and the sample from which Meindl and Lovejoy derived their method (Hamann Todd Collection). In fact, Key *et al.* (1994) demonstrate that a technique developed from one population may not be suitable for another population; Key and colleagues assessed the accuracy of three methods of age estimation using cranial suture closure (i.e. Meindl & Lovejoy, 1985; Perizonius, 1984; Acsádi & Nemeskéri, 1970) and found that all three exhibited poor correlations when applied to their target population for which known ages were available for comparison. In particular, they found that the Meindl-Lovejoy and Perizonius methods (based exclusively or partly on ectocranial sutures) were rather sensitive to interpopulation variation more so than the Acsádi-Nemeskéri method, which was based solely on endocranial sutures.

Furthermore, some authors (e.g. Aiello & Molleson, 1993; Boquet-Appel & Masset, 1982) have found that "age estimation techniques that work best are those where the age distribution of the test sample most closely resembles that of the reference population (that is, the population from which the technique was derived)" (Key *et al.*, 1994, p.204). One way of minimizing this is age intervals consisting of an equal number of individuals, but as mentioned by Key *et al.* (1994) and Meindl and Lovejoy (1985), this results in a loss of valuable data.

2 A test of cranial suture aging against other common aging methods

2.1 Introduction and methodology

In an effort to make methods more rigorous and to meet the legal requirements for evidence as outlined by the U.S. Supreme Court Daubert guidelines, extensive research needs to be done on developing more accurate and precise techniques for skeletal age estimations. Research needs to be done to improve the accuracy of existing methods like cranial suture closure. This is a way to ensure that analyses meet the scientific rigour when brought to the Canadian legal system.

The J.C.B. Grant Collection, housed at the University of Toronto (Toronto, Ontario), was used to determine the level of accuracy and precision associated with currently used age estimation techniques. The collection is comprised predominately of individuals of low socioeconomic status from Ontario, with documented age, sex and cause of death. Based on the death dates that were available, the specimens date to the 19th and 20th centuries, and are of European ancestry. The sample used here was aged, with an average age of 58.97 ± 17.80 years (range of 20 to 86 years), and consisted predominantly of males (93.9%). Unfortunately, a large number of skulls were not available for examination, but the specimens served as a basis for preliminary study.

The aging techniques tested here include the Meindl-Lovejoy method based on cranial sutures. The suture-based ages (lateral-anterior and vault age estimates) were compared to methods using the post-cranial skeleton to test the error rate of sutural ages (consult Appendix I for the sutural sites used by Meindl and Lovejoy, 1985). This included comparison of age estimations produced through sutural union with estimations generated from the pubic symphysis of the pubis (Brooks & Suchey, 1990; Suchey & Katz, 1986; Todd, 1921a, 1921b), the auricular surface of the ilium (Meindl & Lovejoy, 1989; Lovejoy *et al.*, 1985), and the sternal end of the ribs (Işcan *et al.*, 1984). Despite the small number of crania in this collection, this preliminary study sought to determine significant differences between estimated and actual age for each method. Does the actual age fall in the predicted age range? How often does it not? Which methods produce the most accurate ages? The least? How does cranial suture closure compare to the others in terms of accuracy and precision? The answers to these questions are essential, in order for current age estimation techniques to withstand scrutiny in the medico-legal system.

2.2 Results

2.2.1 Actual age and vault/lateral-anterior age estimates

Vault age (n=8), lateral-anterior age (n=9) and actual age (n=33) were compared. The mean age of the sample was 58.97 ± 17.80 years, but the estimated vault ages were lower ($\bar{x}$=48.57±2.39 years). However, the difference between the means was not significant (U=84.0, p=0.120, n=41). The mean age of the lateral-anterior estimations was 56.2 years, which is much closer to the actual age (U=117.0, p=0.348, n=42). Interestingly, the vault and lateral-ages were significantly different from each other (U=.000, p=.000, n=17). The small sample size is a concern here, but if the results are not biased, then it is problematic that a single method produces very different age estimates.

2.2.2 Pelvic aging methods: Suchey-Brooks method, the Todd system and auricular aging

A Mann-Whitney test was conducted between actual age and pubic age (n=31) based on the Suchey-Brooks method. The estimations were significantly different from each other (U=338.0, *p*=0.019, n=64). Pubic age was an underestimation of the actual age ($\bar{x}_{pubic}$=52.75±11.44 years; $\bar{x}_{actual}$=59.77±16.74 years).

The Todd system (n=15), which examines the pubis of the innominate bone as well, was used for comparative purposes against the Suchey-Brooks method. There was a significant difference between actual age and Todd pubic age (U=82.5, *p*=.000, n=48). The Todd system, like the Suchey-Brooks method, had a tendency to underestimate age. It is interesting to see that both methods based on the pubic symphysis underestimate age.

Like the pubic methods, auricular age estimates (n=26) were significantly different from the actual age (U=213.0, *p*=0.001, n=59). These ages had a tendency to be underestimations of the actual age. Based on these results, all pelvic traits generally appear to under-age the Grant individuals.

2.2.3 Aging and accuracy

Prediction error (PE) and percent prediction error (%PE) were used to establish the most accurate age estimators. The following formula was used: PE = [(actual - estimated age) / estimated age]. These values were then averaged to find a mean %PE value for each aging method. For vault ages, %PE was 32.7%; lateral-anterior ages, 21.1%; Suchey-Brooks ages, 30.7%; Todd ages, 51.2% (this does not include phase 10 subjects, 50+ years); auricular ages, 34.7% (not including Phase 6 subjects, 60+ years) and rib end aging, 43.6%. All the methods performed similar to each other in terms of accuracy, with the exception of the Todd method and rib end aging, which were the least accurate indicators of age. Lateral-anterior aging was less prone to error than vault aging.

The reason behind these high error rates is demonstrated graphically. The %PE of all five aging techniques increased with age (Figure 2.1-2.5). Although there were differences in accuracy across these methods, they all aged old individuals very poorly. This accounts for the high error rates seen above. For cranial sutural aging (both vault and lateral-anterior aging), results are not expected to be accurate if the individual exceeds 65 years of age (Figure 2.1).

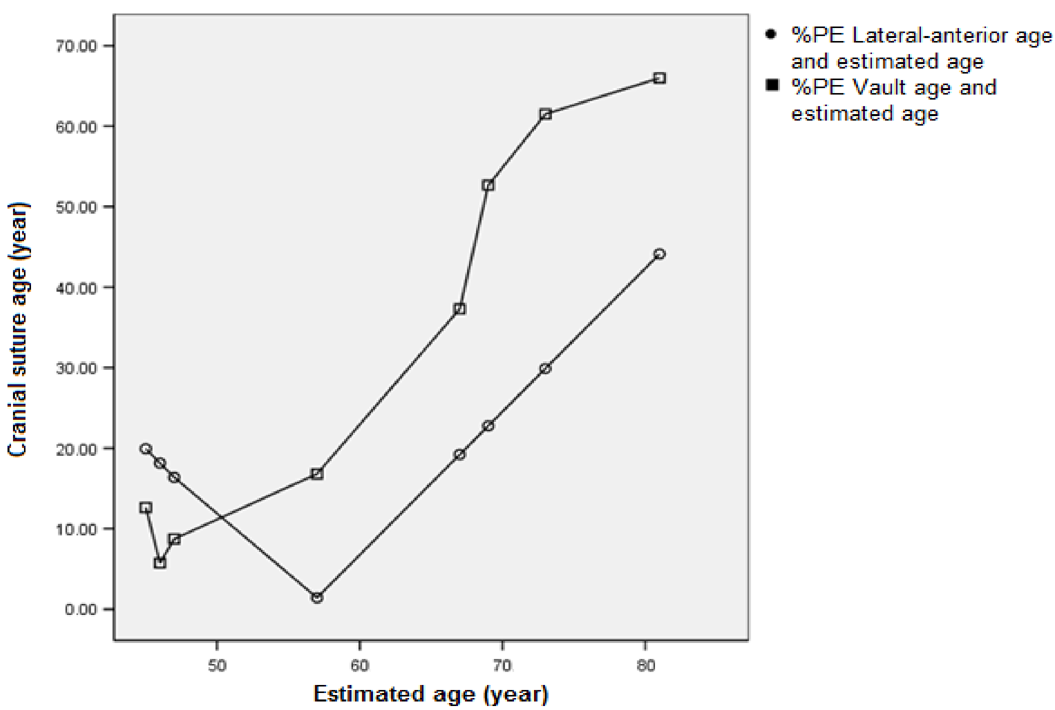


Figure 2.1 Increasing percent prediction error (%PE) with age for cranial suture aging (n=17).

Suchey-Brooks should not be used for very old people (70+ years; Figure 2.2). The Todd system aged individuals up to 50 years quite well, but since it does not provide discrete age categories after this, accuracy decreased (Figure 2.3). Auricular aging showed a high %PE for young individuals but generally, this method can be used for individuals up to 60 years of age (Figure 2.4). Figure 2.5 demonstrates that rib ends are good at aging young and middle-age individuals. Like the other aging techniques, the error rate increased in a linear fashion; the oldest individuals were most prone to incorrect age estimations, specifically individuals exceeding 60 years of age.

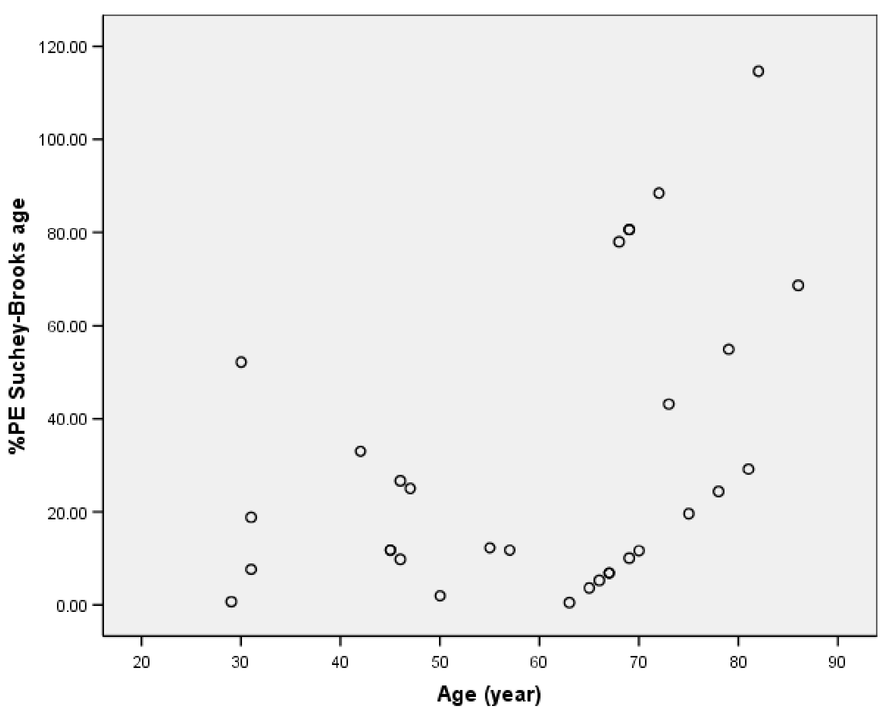


Figure 2.2 Increasing percent prediction error (%PE) with age for Suchey-Brooks aging (n=31).

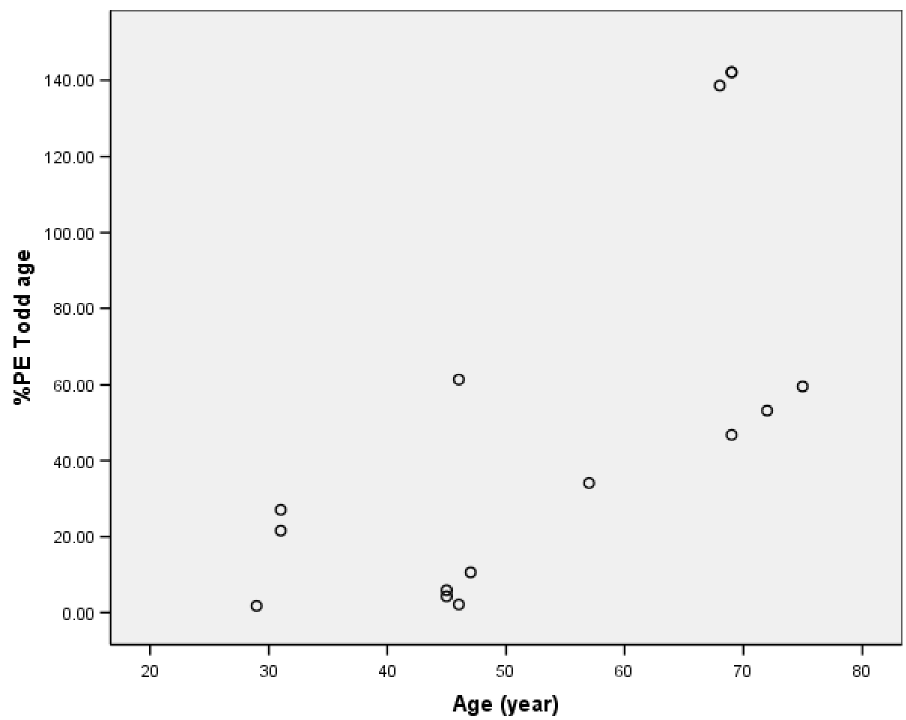


Figure 2.3 Increasing percent prediction error (%PE) with age for Todd aging (n=15).

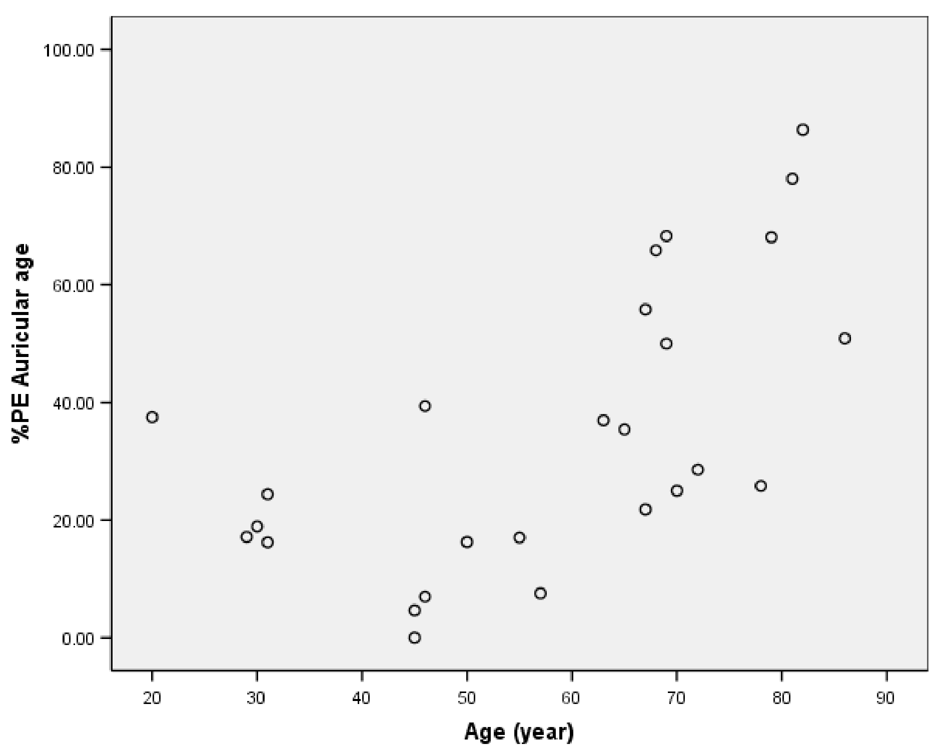


Figure 2.4 Increasing percent prediction error (%PE) with age for auricular aging (n=26).

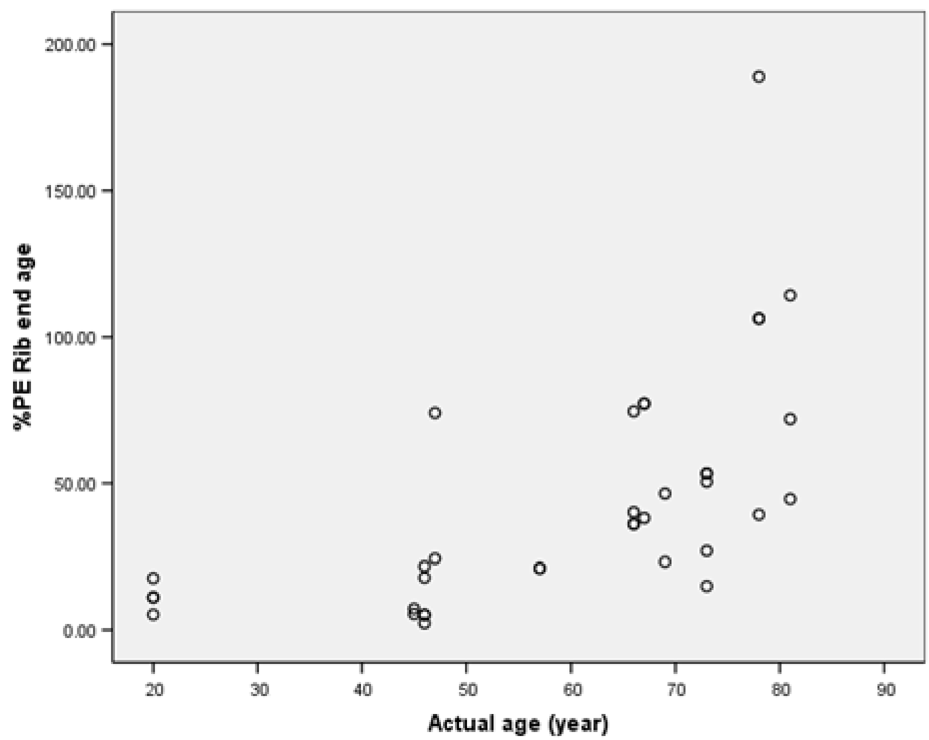


Figure 2.5 Increasing percent prediction error (%PE) with age for rib end aging (n=36).

2.2.4 Age range

The aging techniques examined here are not capable of producing a single age. Only age ranges are provided, and thus, comparing the mean ages of these age ranges will likely produce significant differences between estimates and actual age. Age range was considered here to verify the accuracy rates shown in the previous section.

When all age estimates were pooled (cranial [vault and lateral-anterior], pubic [Suchey-Brooks and Todd], and auricular ages), 57% of actual ages fell within their estimated ranges. The high number of incorrect estimations is slightly surprising since age ranges for many of these methods are quite broad. When individual aging methods were examined: vault ranges were correct 50% of the time (4 out of 8 individuals), 11% of lateral-anterior ranges were correct (1 out of 9 individuals), Suchey-Brooks was correct 84% of the time (26 individuals out of 31), 58 % of the Todd estimations were correct (18 out of 31 individuals) and 27% of auricular ages were accurate (8 out of 30 individuals).

Endocranial aging was considered here as well, but numeric ages were not calculated from sutural progression on the endocranial surface. Instead, adult broad categories (young, middle and old adult) were used (n=31). Only seven individuals were aged incorrectly (22%). When palatal sutures were examined (n=11), every age estimate fell in the broad category of 60+ years. Of these, five individuals were actually under the age of 60 years (54% aged correctly).

Age was estimated from several ribs belonging to 12 individuals as well. Out of 56 age estimations, which combined scores from pit depth, shape, and rim and wall configurations, 44% fell within the predicted range. When only pit depth was considered, 44% of 56 estimations were correct. Pit shape yielded the most amount of correct estimations (67%, n=57), followed by the rim and wall, where 59% of ages fell within the predicted age range.

In summary, actual ages fell within the Suchey-Brooks pubic age ranges most often followed by the Todd system. The Todd system was good at identifying 50+ years individuals but did not provide a specific age range for older adults. Rib end aging was reliable when only pit shape and rim and wall configurations were used. More actual ages fell within the age ranges predicted by the cranial vault aging system but lateral-anterior aging was associated with a smaller average error rate. The small sample size may be responsible for these contradicting results.

2.3 Concluding remarks and further explorations

Several methods of age estimation currently used in bioarchaeology and forensic anthropology were examined to test accuracy, with the primary focus demonstrating how cranial sutures performed by comparison. The pelvic indicators were the best indicators of chronological age, although underestimation occurred frequently. Cranial sutures performed very poorly compared to the other methods. This study indicates that vault sutures are more reliable at predicting age than lateral-anterior ones in the Grant Collection, contrary to Meindl and Lovejoy's (1985) study.

It is acknowledged that additional error in estimations may have resulted from the level of familiarity of the researcher with these techniques. Using a multifactorial approach, Milner and Boldsen (2012) demonstrated that their new aging method, transition analysis, did not out-perform experience-based estimations. This is partially the problem with current aging techniques used in anthropology. The lack of experience ensures that emerging anthropologists are less likely to produce accurate age estimations.

This preliminary study begs the question: why are cranial sutures such poor predictors of age? A closer examination of the factors influencing variability in sutural progression needs to be undertaken. Could these factors be controlled in order to increase the accuracy of cranial suture age estimations? The next section describes the research initiative undertaken to answer this.

2.4 Project outline

Sutural closure is a highly variable phenomenon. Many researchers have studied progression in one or more sutures, only to report that cranial sutures are only sporadically related to age, and consequently, should not be used for age estimation. Studies done by anthropologists in particular tend to focus solely on the presence or absence of age-synostosis trends. This study approaches this problem from a combined biological-anthropological point of view and attempts to find the factors that may cause variation in fusion. It is hypothesized that a number of variables are responsible for the high degree of variability seen in age estimations based on cranial sutures. Controlling these variables may restrict this variability and produce smaller age ranges. Progression in 276 skulls from Hamann Todd Osteological Collection housed at the Cleveland Museum of Natural History (CMNH) in Cleveland, Ohio was studied using a revised scoring system that tracks development in the entire suture, rather than a segment. The three primary sutures examined were the sagittal, coronal and lambdoid sutures.

Differences in age-score relationships between the following factors were noted: sex, ancestry, secular change, nutrition (e.g. overall health), stature, weight, body mass index, chronic and acute illnesses, alcohol and narcotics use, presence of cranial irregularities (e.g. wormian bones), skull density, and presence of biological features (e.g. parietal foramen). Lastly, segments of the sagittal, coronal and lambdoid sutures used in the Meindl-Lovejoy cranial aging system were scored and regressed against age to determine each segment's predictive power. Progression in cranial sutures was compared to one facial suture (internasal suture) as well.

2.5 The Hamann Todd Collection

The crania used in this study come from the Hamann Todd Skeletal Collection housed at the Cleveland Museum of Natural History (CMNH) in Cleveland, Ohio. The sample consists of 259 to 276 individuals, depending on the suture (Appendix II). The youngest individual is 15 years old while the oldest is 89 years. The average age for each suture group is approximately 50.2 ± 20.5 years, indicating that the collection is relatively aged. As shown by the Grant results, aging methods lose accuracy with increasing age, making the Hamann Todd sample ideal for tracking variability in sutural progression.

Information on sex, ancestry, birth and death year, cause of death, height and weight was taken from a database assembled by CMNH on the demographic characteristics of the collection. This information was initially amassed by the collectors from medical records, autopsy reports and in-lab examination of the cadavers. The sample consists of individuals who lived between 1830 and 1940. Males and females made up 58.7% (n=162) and 41.3% (n=114) of the sample, respectively. Three ancestral groups were included: white (n=170), black (n=104) and aboriginal (n=2).

2.5.1 Sources of error

Height and weight measurements may be subject to some error. For this study, these variables were taken to be representative of the subject's height and weight while alive. However, in some cases, the cadavers were not weighed immediately after death. Thus, decomposition and tissue loss may bias some of the weights. T.W. Todd measured height by using pulleys and ropes to suspend the cadaver from the ceiling. Stature was recorded with an anthropometer.

Some disparities in the stated age of the subjects do exist and may account for any error produced in the results. Specifically, ages ending in 0 or 5 have a higher likelihood of being estimations rather than the person's actual age.

2.6 A brief history of Cleveland

A brief history of Cleveland is recounted here in order to contrast the two centuries in question. Cleveland was founded in 1796 by Moses Cleaveland (Encyclopedia of Cleveland History, n.d.). During the 100-year time period that concerns the study subjects (1830s to 1930s), Cleveland went through dramatic population increases and its residents enjoyed a wide variety of technological innovations that forever changed their way of life. The growth of the city, however, brought with it the slums, civil unrest and disease as well.

The Hamann Todd subjects lived during a time of racial discrimination and social inequality. Living conditions tended to be poorer for black individuals compared to their white counterparts in the 19th and 20th centuries in America. Employment opportunities were minimal and they were restricted to the slums and subjected to unsanitary housing conditions (Encyclopedia of Cleveland, n.d.). The differences in standards of living were apparent even amongst the poor class. This would have reduced the survivability of black individuals and increased their chances of contracting disease.

In the early 1800s, terrible housing conditions were common in Cleveland (Encyclopedia of Cleveland History, n.d.). Some of the oldest individuals in the sample, born in the 1830s, would have likely lived under these unsanitary situations. At this time, the population of the city was 1075. In 1832, a cholera outbreak resulted in the death of 50 people. Despite poor living conditions, epidemic disease is not characteristic of early Cleveland; there were not many viral outbreaks. However, pulmonary tuberculosis was a deadly killer and claimed a number of individuals from the Hamann Todd Collection.

In 1850, the average life expectancy was approximately 40 years (Mapping History, n.d.). Depending on whether an individual lived past a particular age, their life expectancy was much higher. For instance, males who lived past 5 years of age were expected to live to 50-60 years. If they lived past 40 years, their life expectancy increased to 60-70 years. With females, those who lived past their child-rearing period could live up to 60-70 years. All the 1830s individuals used in this study lived past their 8th decade of life, which indicates that poor socioeconomic conditions did not hinder survival in all individuals. Even during colonial times (17th-18th centuries), many individuals lived to senescence (Volo & Volo, 2006), and so it is unsurprising to see very old individuals dating to the 1830s. From 1900 to 1941, the average life expectancy for all ancestral groups ranged from 49 to 63 years (Arias, 2006). The trends of the 1800s persisted in the early 20th century, but fewer deaths were seen in infancy and during childbirth (Mapping History, n.d.).

In 1849, Clevelanders, now numbering at approximately 17 000, were introduced to trains and streetlights (Encyclopedia of Cleveland History, n.d.). In 1850, a major source of employment, the Cleveland Iron Mining Company was established. A year later, the railroad was completed. A water system began operation in 1856, followed by the use of omnibuses a year later. An important innovation related to disease control, the sewer system was constructed in 1858, although the first sewage treatment plant did not open until 1922. By 1860, residents numbered at 43 417. A decade later, Cleveland became the 15th largest city in the nation, with a population of 92 829. After the civil war in the 1860s, Cleveland endured a massive influx of immigrants. It wasn't until 1904 that poor housing was linked to a variety of social and health problems. Building codes were created shortly after this, although no active campaign was undertaken to build more houses. As the population grew, the slums expanded as well. Civil unrest accompanied the growing city as seen by the railroad strike in 1877.

There were, however, efforts made to help the needy; the Women's and Children Dispensary opened the following year (Encyclopedia of Cleveland History, n.d.). In 1880, the year the Cleveland Telephone Co. opened, there were 160 146 people living in the city. Four years later, the first electric streetcars were in operation and the Electric Light Co. opened. Three years after the first mill strike in 1882, a second one occurred, followed by a streetcar strike in 1899, hinting that labor conditions remained unchanged. In 1890, the first cable cars began running. Cleveland was now the 10th largest city in the US (261 533 people). At the turn of the century, the population grew by another 100 000 people. Around this time, extraordinary advances in medicine occurred, although its availability to the poor was surely limited. In 1906, the first successful human blood transfusion was done. In 1910, Cleveland was the nation's 6th largest city, with residents numbering at 560 663. Street railways began running in the same year. In 1919, the May Day Riots occurred after a political demonstration supporting socialism and communism turned into mass violence and rioting, demonstrating civil unrest amongst Clevelanders.

Between 1900 and 1920, the population doubled in size to 796 841 people, making Cleveland the nation's 5th largest city (Encyclopedia of Cleveland History, n.d.). Although it was now a sprawling urban centre, the incoming immigrants were unskilled workers who quickly became incorporated into the slums. This only worsened the already deteriorating housing conditions of the poor. On the other hand, women's rights were becoming a major concern at this time and resulted in the League of Women Voters and the Maternal Health Association. The Cleveland Clinic was established in 1921, although it was not targeted at helping the poor. It wasn't until the late 1940s that the government opened a poorhouse and made medical care accessible and affordable to the poor. None of the subjects in this study were alive to witness this. The first buses, which may have served as a form of transportation for the working class and, perhaps even for the poor, began operation in 1925. In 1930, the population was 900 429. This prosperity was short-lived as the Great Depression left nearly one-third of workers without a job. In 1940, Cleveland's population declined for the first time to 878 366. From that time onwards, Cleveland has suffered a steady decline in population, reduced to a mere 396 815 people as of 2010.

2.7 Terminology

The definitions of a few terms are clarified here. Ancestral groups are referred to as *white* or *black*. The former is used to describe individuals of European background while the latter refers to people of African descent. *Population* refers to a broad group of people who exhibit biological (e.g. genetic) similarities. In this study, the terms *white* and *black populations* are used in a very general sense to convey the genetic differences between these groups. It is acknowledged that intra-group genetic variation may exist. The word *bias* is used in the general sense of the word (rather than statistically), implying a misrepresentation of specimens.

3 Sutural mapping: Tracking progression in the sagittal, coronal and lambdoid sutures

3.1 Introduction

This chapter examines synostosis by tracking the degree of ossification that has occurred in the three major sutures of the cranium (sutural mapping): the sagittal, coronal and lambdoid (Figure 3.1). The link between sutural progression and age was re-examined using a revised scoring method. Sex- and population-based differences in sutural progression were discussed as well. Although such analyses have been done before, it is necessary here to establish how strong the correlation between age and fusion is in an unrestricted (i.e. all individuals included) sample. That way, more restricted samples can be compared to the results of this chapter and the effects of individual variables on synostosis can be determined. Furthermore, using a revised scoring system may offer new information on age-fusion relationships.

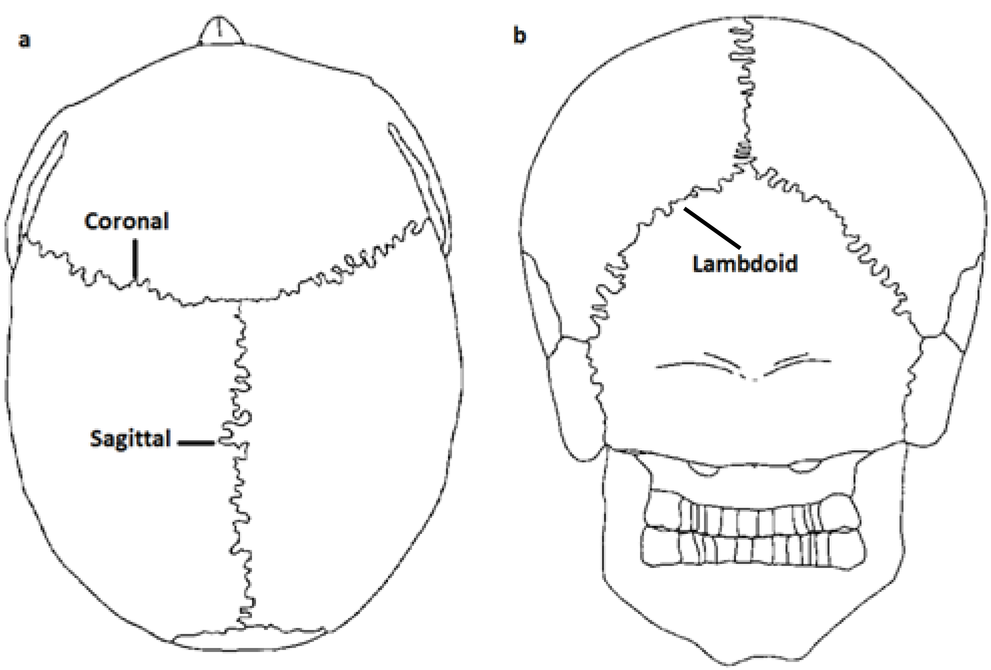


Figure 3.1 Illustration of a) sagittal and coronal, and b) lambdoid sutures on the cranium (superior and posterior views).

3.2 Methods

3.2.1 Scoring and weighted scores

A revised scoring system based on the Meindl-Lovejoy method was used to establish the degree of fusion reached in the suture (Table 3.1, Appendix III). The importance of using this particular scale is to track *exactly* (as allowed for by macroscopic observation) how much progression is reached by a certain age.

Table 3.1 A 5-point scale used to track sutural progression.

Stage	Description	Bone activity	Surface appearance	Meindl-Lovejoy[1] equivalent
1	Open	Suture is patent; no bony protrusions uniting the two sides	Open	0
2	Minimal closure	Bony spicules have formed and connect the two sides	There are many deep grooves	1
3	Significant closure	The bones are connected by larger masses of bone rather than spicules	The depth of grooves is just below the surface	2
4	Near obliteration	Significant fusion has occurred	Depth of the groove is very shallow, sometimes appearing as a faint line	2
5	Complete obliteration	All traces of the suture have been obliterated	Smooth bone layer	3

[1]Meindl and Lovejoy (1985)

Even though stages 4 and 5 have essentially undergone the same level of sutural closure, their surface appearance looks different, and this may be important for constructing age techniques based on sutures. Essentially, this scale is a more precise tracker of progression, because it addresses stages of closure not accounted for in the generalized Meindl-Lovejoy method.

Scoring began at the anterior tip of the sagittal suture (bregma) and proceeded posteriorly. For the bilateral coronal and lambdoid sutures, measurements began at the rightmost portion of the suture. Using a digital caliper, the suture was measured from the starting position to the point where there was a change in the appearance of the suture. At this point, the length of that segment (to the tenth decimal place) and its score were recorded in an Excel spreadsheet. The shape of the suture was simply described as 1. straight, 2. uneven (wavy), 3. serrated or 4. oscillating (highly serrated, as typically seen in the lambdoid suture).

Using the segment lengths obtained for each person's suture and their respective scores, a single weighted score was calculated and used in statistical analysis to determine the relationship between age and synostosis. The following formula was used to generate a weighted score between 1 (open) and 5 (complete obliteration):

Weighted score = [(segment 1/total suture length) x segment 1 score] + [(segment 2/total suture length) x segment 2 score] +... [(segment n/total suture length) x segment n score]

Using this means that a score is no longer a discrete variable like the Meindl-Lovejoy system; it is continuous instead. So, a score of 2.7 would mean that the suture is at minimal fusion but progressing toward significant closure. It allows for a more meaningful comparison of individuals as well. For instance, if scores of 1.6 and 1.9 were rounded, both individuals would be classified as exhibiting minimal fusion. Keeping the weighted score as a continuous variable shows that second individual shows more progression, however slight it may be. Thus, the exact stage of progression of a suture is not lost under broad categories.

3.2.2 Statistics

Spearman's rank order correlation was calculated by SPSS 14.0 to determine the strength of the relationship between weighted score and age, sex and ancestry. This was used rather than Pearson's correlation because most of the data are not normally distributed (the exception is the lambdoid suture). Furthermore, Pearson is sensitive to skewed data. In this study, there are many outliers, which cannot be justified for exclusion. Spearman is more suitable in this case since it is good at minimizing the effect of outliers. Lastly, even though weighted score is continuous, it is based on ordinal data and is interpreted categorically, making Spearman the appropriate method of determining correlation in this dataset.

The r_s value of a Spearman's correlation cannot be interpreted like Pearson's. It does not signify a linear relationship. Instead, the relationship is classified as monotonic, meaning that as one variable increases, the other can increase or decrease, but not strictly in a linear fashion. Thus, correlations should be interpreted based on strength (i.e. how strongly two variable are related). Due to the lack of normality, non-parametric Mann Whitney tests were conducted to compare average weighted scores of subgroups.

3.3 Results and discussion

3.3.1 Age and weighted score: The sagittal suture

Graphically, the correlation between age and the weighted score of the sagittal suture was poor (Figure 3.2). A two-tailed Spearman's rank order correlation produced a low but significant relationship (r_s= 0.30, p =.000, n=276). The r_s value suggests that development in the suture tends to increase as age increases in a moderately weak but positive fashion. The average weighted score for the sample was 3.50 ± 1.13. As shown by the standard deviation, there was a considerable amount of variation in the sagittal suture. Patent (open) sutures represented 7.2% of the sample, while completely fused sutures made up 15.2%. Open and fused sutures were more likely to occur in the sagittal suture. Figure 3.2 demonstrates the high degree of variability seen in the closure patterns in the sagittal, where even young individuals showed nearly obliterated or completely fused sutures.

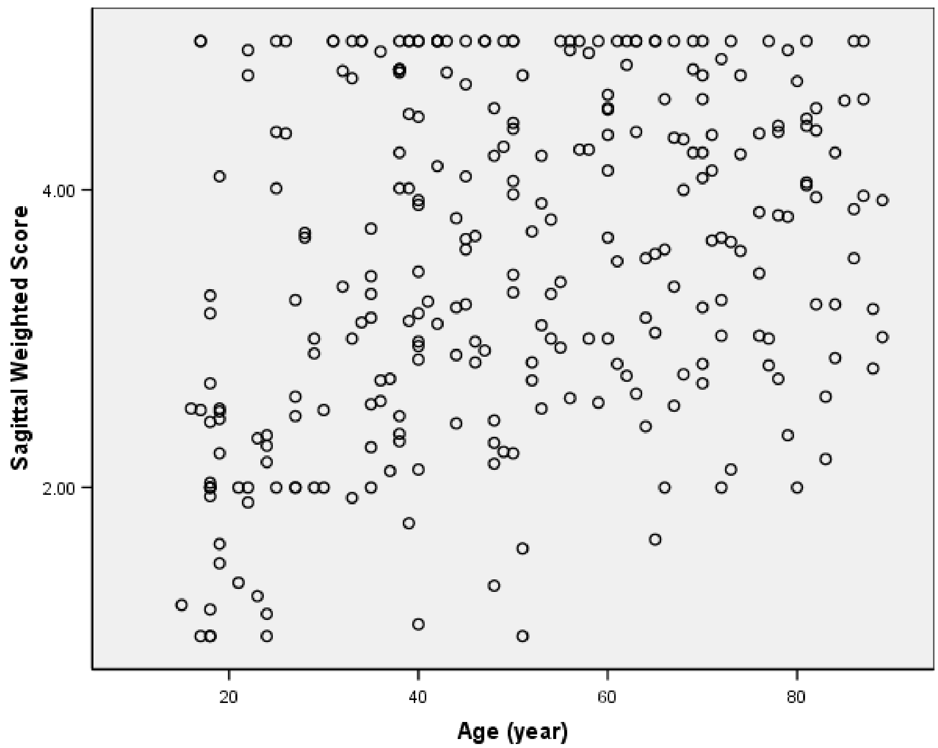


Figure 3.2 The positive, moderately weak relationship between age and weighted sagittal suture score of 276 individuals from the Hamann Todd Collection.

3.3.2 The coronal suture

Of the three sutures examined, the coronal suture exhibited the strongest age-score relationship (r_s=0.42, *p*=.000, n=264; Figure 3.3). Neither patency (0.8%) nor complete obliteration (3%) was common conditions in the coronal suture. With the exception of two individuals, scores below 2 (minimal fusion) were rare, and most weighted scores fell between 2 and 5. The average weighted score for the entire sample was 3.31 ± 0.80, suggesting that even though the sample is somewhat aged (average age of 45-50 years), significant fusion is the dominant condition of the coronal suture. This may indicate that complete obliteration may be more common amongst the oldest individuals rather than middle-aged adults.

Figure 3.3 shows no obvious age-related patterns, although the trend is stronger here than in Figure 3.2. Even though the average weighted score was greater in the sagittal, the coronal showed rapid progression as well, since patency was rarely observed.

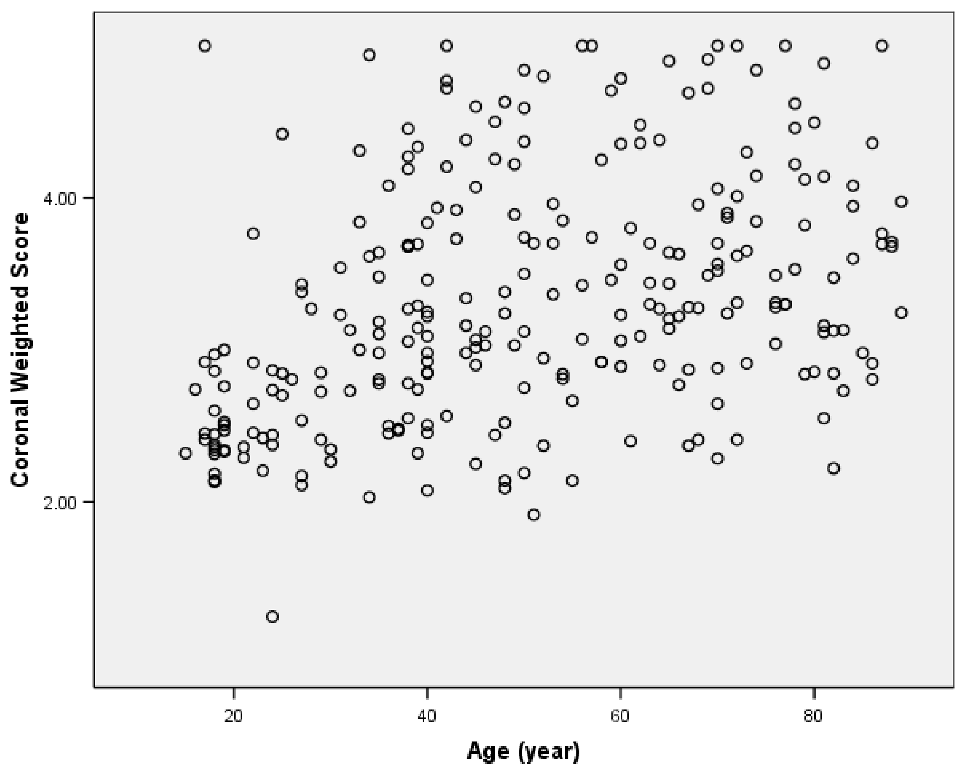


Figure 3.3 The positive, moderate relationship between age and the weighted score of the coronal suture score (n=264).

3.3.3 The lambdoid suture

The correlation between progression in the lambdoid suture and the age of a person was comparable to that of the sagittal suture (r_s=0.30, *p*=.000, n=259). The relationship was positive and significant, but fusion in the lambdoid appears to be as variable as the sagittal and coronal. However, Figure 3.4 shows that there is some linearity present in the youngest individuals. The average weighted score for the entire sample was 2.99 ± 0.77. Similar to the coronal (although less progression is seen here), most people in this sample had significantly fused lambdoid sutures. Patency was more common with the lambdoid than the coronal (5%), but complete obliteration was not (1.2%).

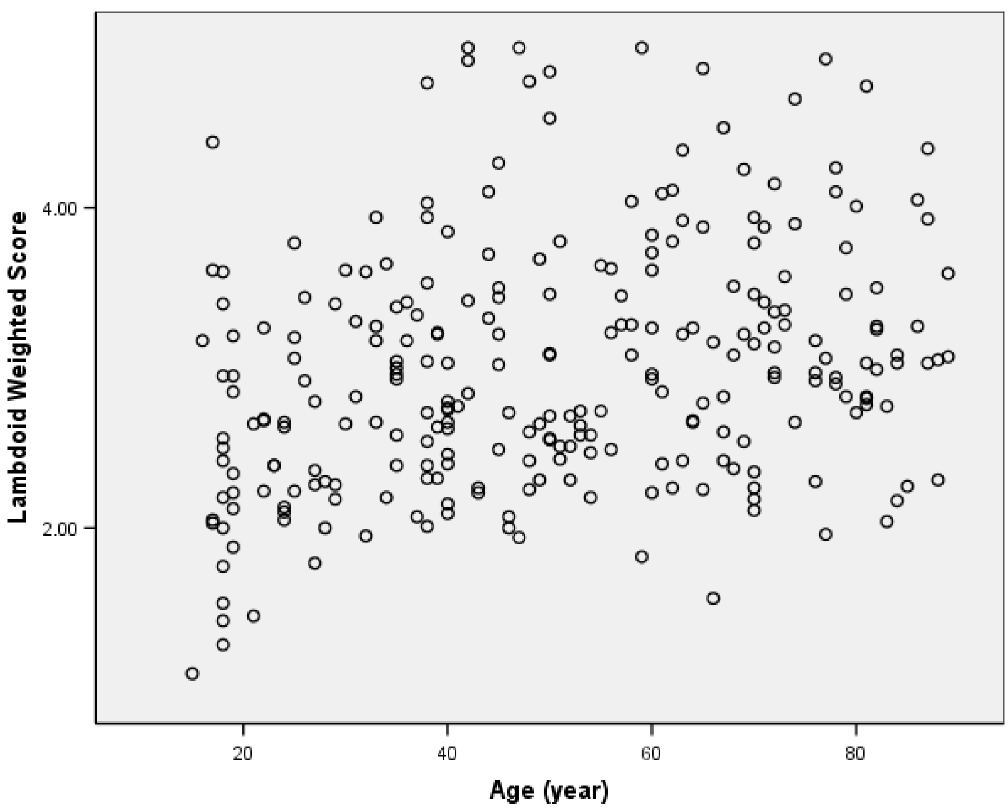


Figure 3.4 The positive, moderately weak relationship between age and weighted score of the lambdoid suture score (n=259).

These results support the conclusions of earlier studies like Singer (1953) and Cobb (1955) rather than recent works like Chiba *et al.* (2013). Sutures are highly variable and no identifiable age ranges can be deciphered from Figure 3.2-3.4.

3.3.4 Impact of sex

A number of authors report that sex-based differences in the progression of sutures is non-existent (e.g. Wolff *et al.*, 2013; Meindl & Lovejoy, 1985; Perizonius, 1984; Acsádi & Nemeskéri, 1970; Todd & Lyon, 1924). Brooks (1955) contradicts this; females exhibited patency longer than males. In fact, she recommended that cranial sutures not be used for aging in females due to its variability.

In this study, Spearman's rho showed weak to moderate correlations (Table 3.2). When the sample was divided by sex (n_{male}=162; n_{female}=114) in the sagittal suture, the male sagittal scores showed a stronger correlation to age than females (r_s=0.33, *p*=.000 and r_s=0.25, *p*=0.007 for males and females, respectively), but the difference in mean weighted score was not significant (U=8481.0, *p*=0.250). Females, however, showed greater overall progression ($\bar{x}$ =3.61±1.11) compared to males ($\bar{x}$=3.40±1.18). The age distribution of both groups is not significantly different, eliminating the idea that the presence of certain age groups accounts for the above results (U=8989.0, *p*=0.710).

The coronal suture, on the other hand, showed contradicting trends. Firstly, the weighted scores of males and females were significantly different from each other (U=6443.5, *p*=0.001). Males had a stronger age-score correlation compared to females (r_s=0.49 and 0.38 for males and females, respectively), but like the sagittal, females showed greater overall progression, with a mean weighted score of 3.52 ± 0.84 ($\bar{x}_{males}$=3.19±0.74). Patency was not observed in females; this indicates faster progression in females. Both sexes showed obliteration of the coronal, suggesting that synostosis is equally likely to occur in males and females.

Table 3.2. The Spearman rank order correlation (r_s) of the weighted scores of the sagittal, coronal, and lambdoid sutures and exclusion variables (age, sex, and ancestry), with their associated r_s values and sample sizes (n).

		Sagittal			**Coronal**			**Lambdoid**		
Variables	**Exclusion**	**r_s**	***p***	**n**	**r_s**	***p***	**n**	**r_s**	***p***	**n**
Sex	Males only	.334	.000	162	.492	.000	150	.253	.002	147
	Females only	.251	.007	114	.384	.000	114	.364	.000	112
Ancestry	Black indiv. only	.406	.000	104	.587	.000	103	.395	.000	101
	White indiv. only	.187	.015	170	.255	.001	159	.188	.019	156
Both	Black males only	.474	.000	56	.567	.000	55	.345	.011	54
	White males only	.237	.014	106	.370	.000	95	.164	.117	93
	Black females only	.326	.024	48	.566	.000	48	.405	.005	47
	White females only	.122	.338	64	.192	.129	64	.264	.036	63

Both sexes exhibited low correlations in the lambdoid, but females (r_s=0.36, *p*=.000, n=112) showed a stronger age-score correlation than males (r_s=0.25, *p*=0.002, n=147). In fact, females had significantly greater scores than males (U=6831.5, *p*=0.019). On average, females showed greater progression than males, where the mean weighted score was 2.86 ± 0.62 for males and 3.16 ± 0.90 for females. Females were more likely to exhibit obliteration.

It is interesting to note that there were no sex-based differences in the progression of the sagittal suture, although the opposite is true for the coronal and lambdoid sutures. Quizzically, Meindl and Lovejoy's (1985) study was based on the same collection but yielded no sex-based differences in fusion. The use of the entire length of the suture and the altered scoring system may have readily distinguished these subtle trends. There is no single sex-based trend that is consistent across these sutures. This explains why contradicting data is present in the literature. However, some trends were apparent in the Hamann Todd Collection. Even in the sagittal, females had greater overall scores than males, despite the lack of significance. This contradicts the results of many studies, like Hershkovitz *et al.*'s (1997) work, where females exhibited an open sagittal suture more often than males, but it lends support to others. It is interesting to note that even within the adolescent group, females showed a faster rate of development; the difference is significant in the sagittal suture (U=24.0, p=0.019, n=23) and coronal (U=27.0, p=0.015, n=24).

A potential complication may be that only parts of a suture may be impacted by sex (see Chapter 7). Zambrano's (2005) study found that age-score correlations were stronger for females in sutures of the vault and on the endocranial surface while males showed better correlations in the lateral-anterior sutures. The Hamann Todd individuals contradict Zambrano's (2005) results; the three sutures considered here are vault sutures (the midcoronal falls under both vault and lateral-anterior categories) but correlations were stronger in males in two out of three sutures. The important question is why it is necessary for the sutures of females to fuse faster. Two factors, which make females different from males, were addressed here.

3.3.4a Why females are different: Estrogen

The Hamann Todd data may suggest that different sutures may be influenced by different genetic and perhaps environmental factors. Each sex may react differently to these impacts due to physiological dissimilarity. For example, females have more estrogen in their bodies than males, which is a hormone that has been linked to limb bone growth and maintenance. James *et al.* (2009) tested the role of estrogen in synostosis in mice. They found that estrogen signaling through one particular estrogen receptor (ERα) was essential for synostosis to occur in the interfrontal suture (analogous to the human metopic suture). It is hypothesized that estrogen is closely associated with osteoblastic (bone-producing) activity in the cranium as well as in the appendicular skeleton. Since females carry a larger quantity of estrogen in their body, this is a potential explanation for elevated weighted scores. This may explain why females under the age of 50 years (before menopause) produced significant (but weak, $r_s \approx 0.33$) age-score correlations in all three sutures ($p<0.010$, n=60) while those over this age produced negligible and/or insignificant correlations (n=53-54). Current age estimation techniques do not account for these sex-based differences in sutural development.

3.3.4b Why females are different: Birth and synostosis

Females differ from males in their ability to give birth, which is an elongated physiologically stressful period of time. In the 19th and 20th century, pregnancy care (to the extent seen in modern times) was not available to the poor class. Consequently, this period of life may have been nutritionally deficient since the mother would have had to support herself and the child. Impacts of malnourishment are discussed in Chapter 6. Here, progression in the sagittal, coronal and lambdoid sutures is examined in females who had (or had not) given birth prior to death (n=52). No significant results were noted but greater progression was seen in females who had not given birth (n=32) in all three sutures. Aside from the coronal, where age-score correlations ranged from moderate (children) to low (no children), the other sutures showed negligible and/or insignificant relationships. The results were not biased by differing age distributions (U=289.0, p=0.560).

It is difficult to interpret these results. Due to the lack of significance (which may be due to the small sample size), it cannot be claimed that women who had given birth will show less progression than those who had not. If malnourishment is experienced, progression is expected to accelerate (as shown by the results in Chapter 6). Furthermore, pregnancy is associated with increased levels of estrogen, promoting bone development. It is possible that the women who had not given birth were not nutritionally fit enough to conceive. Thus, the women who had given birth were healthier in relative terms. This may explain why these women exhibited less sutural progression.

3.3.5 Ancestry

When the sample was divided according to ancestry (Table 3.2), black individuals exhibited a notably stronger age-score relationship in the sagittal suture (r_s=0.41, *p*=.000, n=104) than white individuals (r_s =0.19, *p*=0.015, n=170). A Mann Whitney test suggests that a population-based difference may exist; there was a significant difference between the average weighted scores of these two groups (U=7255.5, *p*=0.013). Both groups showed significant fusion progressing toward near obliterated conditions, but the sutures of black individuals were slightly less developed ($\bar{x}$=3.67±1.02 and 3.27±1.27 for white and black individuals, respectively). This may be influenced by the age distribution of the samples. The black subjects were, on average, younger with a mean age of 43.5 ± 21.7 years while the white individuals had an average age of 54.4 ± 18.7 years. These mean ages were significantly different (U=6085.0, *p*=.000). Although age distribution can influence average weighted score, it does not account for the stronger r_s correlation seen in black individuals relative to white subjects.

This bias was present in the coronal suture as well. The white group showed a weak trend (r_s=0.25, *p*=0.001, n=159) while the black individuals showed a much stronger correlation (r_s=0.59, *p*=.000, n=103). Although the results shown so far yield mostly moderately weak correlations, it is puzzling to see differences in the strength of the age-score relationship between different populations. Even more puzzling was the fact that the average weighted scores of the two groups were not significantly different (U=7480.5, *p*=0.444). As mentioned above, there was a significant difference between the age distributions of the white and black samples. The black sample had a larger number of adolescents than the white sample. Despite this, the mean weighted score and standard deviations of both groups were similar ($\bar{x}$=3.31±0.74 and 3.26±0.83 for white and black individuals, respectively). This suggests that the black subjects of the Hamann Todd Collection had a faster rate of sutural progression in the coronal than white individuals.

In the lambdoid suture, population-based differences were present as well. The age-score correlation of white individuals (r_s=0.19, *p*=0.019, n=156) were again superseded by black individuals (r_s=0.39, *p*=.000, n=101). However, average scores were not significantly different (U=6772.0, *p*=0.057), and white individuals exhibited more progression in the lambdoid ($\bar{x}$=3.05±0.70) than the black group ($\bar{x}$=2.89±0.85). Since the weighted scores for the lambdoid suture are normally distributed when converted to the logarithmic scale, a T test was used to verify this result. Surprisingly, a significant difference was noted (*t*=2.21, df=172.563, *p*=0.039). Since the parametric test is the stronger statistical measure, it is safe to assume that there is a significant difference in the weighted scores of both ancestral groups.

The presence of population-based differences is not surprising. Contradicting patterns have been seen in different ancestral groups. For instance, Cray *et al.* (2011) investigated sutural development patterns in the Aleutian Islands by comparing Paleo-Aleutians and present-day Aleutians, both of whom exhibit distinct cranial shapes (e.g. dolichocranic vs. brachycranic; long and short crania, respectively) and varying degrees of facial prognathism. They found that both groups exhibited similar ectocranial sutural development, and they suggest that sutural progression is independent of skull shape. Despite the temporal distance and difference in cranial morphology between both groups, genetic mechanisms remained unchanged. Even within a population, there is variation in synostosis. Goyal *et al.* (2011) examined the lambdoid suture via x-ray in males and females from Rajasthan and Punjab (i.e. states in India) to find that the suture closed at 80-81 years in the former and 55-65 years in the latter. The authors attribute this difference to climate, genetics, diet and life style differences.

The results show that different populations will exhibit greater progression in specific sutures. In the Hamann Todd sample, black individuals showed greater progression in the coronal but less development in the sagittal compared to white subjects. In the lambdoid, white individuals showed greater degrees of synostosis. When the age distribution of the samples was taken into account, it was evident that faster progression is seen in black subjects in all three sutures. Despite having a younger sample, black individuals showed average weighted scores that were similar to the older white individuals. Like sex, population-based differences in fusion are not accounted for in current aging methods using cranial sutures.

3.3.6 Combining sex and ancestry

When the sample was divided according to sex and ancestry (Table 3.2), black individuals continued to exhibit stronger correlations. In the sagittal suture, black males had the highest r_s value (r_s =0.47, *p*=.000, n=56), followed by black females (r_s=0.33, *p* =0.024, n=48). White males exhibited a moderately weak trend (r_s =0.24, *p*=0.014, n=106). All of these correlations were significant with the exception of white females (r_s=0.12, *p*=0.338, n=64).

In the coronal suture, the age-score correlations were weakest in white males (r_s=0.37, *p*=.000, n=95) and females (r_s=0.19, *p*=0.129, n=64). It was strongest in black males and females (r_s=0.57, *p*=.000, n=55, 48). Compared to the sagittal and coronal sutures, white females in the lambdoid had the greatest age-score correlation (r_s=0.26, *p*=0.036, n=63), while white males had the lowest correlation (r_s=0.16, *p*=0.117, n=93).

There were no concrete consistencies between the three sutures, although the same population-based differences were present in all three. Why white subjects would be more likely to have negligible age-score correlations is puzzling. It may be due to the differing age distributions of the sample, or perhaps there is a greater genetic diversity making up the white group. A large number of European groups could make up the white group. If these groups follow different sutural pathways, patterns will surely be obscured. On the other hand, it may be entirely environmental. After all, the subjects of the Hamann Todd Collection date to a period in American history where life would have been very different for white and black individuals. Potential explanations for this disparity are addressed in later chapters.

3.3.7 What influences the obliteration of a suture?

Sutures change in response to their environment (e.g. Cohen, 1993). A number of factors can influence sutural growth and development like muscle activity on sutures (e.g. Koskinen, 1977 in Cohen, 1993), trauma to the skull (e.g. Girgis & Pritchard, 1958), and movement of suture-containing bone through repositioning and/or transplantation (e.g. Markens & Oudhof, 1980; Giblin & Alley, 1944). Fusion can be manipulated experimentally to promote synostosis (Cohen, 1993). Damage to the suture itself can induce synostosis as well.

In addition to these external influences, the premature closure of sutures (craniosynostosis) has been linked to genetic factors in rabbits and mice (Cohen, 1993). Uterine conditions were altered in rabbits and monkeys to induce craniosynostosis. Hypervitaminosis D (in rabbits), A (in monkeys) and ethyl alcohol (in monkeys) treatment during pregnancy resulted in craniosynostosis in the infant.

In the Hamann Todd sample, some young individuals had fused sutures (Figure 3.5) while patent ones were seen in older persons. When all the individuals belonging to the 19th century with completely fused sagittal sutures were examined (n=30), great variability was seen in age, height, weight and ancestry. The age ranged from 26 to 87 years, the height varied from 1.54 to 1.85 meters (4.9-6 feet) and the weight ranged from 26 to 73 kg (57-161 lbs). Thus, completely obliterated sutures can occur in young and old people, short and tall people, and underweight and moderately-sized people. Interesting, although the sample does consist of some overweight people, none of these individuals showed complete fusion.

Figure 3.5 The completely obliterated sagittal suture of a 17-year-old white female (specimen no. 1606) from the Hamann Todd Collection.

3.3.8 Synostosis: Normal or abnormal?

The ultimate question is why a suture would fuse. In the Hamann Todd Collection, the sagittal showed the greatest number of synostosed individuals (15% of the sample). There were only 8 cases of obliteration out of 264 individuals in the coronal (3%). Obliteration in the lambdoid was even rarer (1%). This aligns well with the rate of craniosynostosis in modern populations; Grova *et al.* (2012) report that this condition is most often seen in the sagittal.

From a survivalist perspective, it is essential to know whether patency and fusion of a suture inhibits survival in any way. In the Hamann Todd sample, individuals in their ninth decade of life were found with patent sutures. Clearly in humans, patency does not interfere with survival. In mice, the interfrontal suture fuses some time after birth but the sagittal, coronal and lambdoid remain open during life (Grova *et al.*, 2012). In fact, there are antagonists present to limit the activity of bone morphogenetic protein, which is one of the growth factors responsible for osteogenesis (bone development) in a suture (Warren *et al.,* 2003). Also in mice, Furtwängler *et al.* (1985) found that apoptosis (programmed cell death) resulted whenever the distance between two osteogenic fronts (the margins of bones) shortened. This prevented the fronts from joining and ensured a patent suture.

On the other hand, there is evidence to support the idea that synostosis is the normal condition. Using animal models, sutures were removed from their original locations and transplanted to other areas of the body where they were no longer subjected to the biomechanical stresses associated with their original locations. Some experiments found that the fusions happened nonetheless (e.g. Watanabe *et al.*, 1957), while others achieved the opposite result (Prahl, 1968 in Cohen, 1993). Modern-day surgical intervention makes it possible to detach prematurely fused sutures in humans. However, re-fusion is common in these patients (Grova *et al.*, 2012). Arguably, since premature fusion has already occurred in these individuals, their sutures are more inclined to ossify because whichever factor(s) initiated synostosis in the first place has not been neutralized.

Fusion can be advantageous from a survivalist perspective. In peccaries, facial sutures fuse early in life. This strengthens the snout, which is necessary for the strenuous hooting and feeding activities carried out by these birds (Herring, 1974). Growth occurs even after the sutures have fused. Here, it is more adaptive to have a strongly constructed skull rather than a prolonged growth period. Depending on the species, the classification of synostosis as normal or abnormal varies.

3.3.9 Sources of error: Obliterated sutures

The important question is how linear plots can be produced between age and synostosis when individuals with obliterated sutures are present in the sample. Obliteration was clearly completed before death, but how long before death is uncertain. Thus, a separate analysis was done with 234 individuals from the Hamann Todd Collection, where individuals with completely obliterated sutures were removed. The r_s value was 0.40 (*p*=.000) for the sagittal, an improvement from 0.30. The coronal showed an improved trend as well (r_s=0.43, *p*=.000, n=256). For the lambdoid, the improvement was slight (r_s=0.31, *p*=.000, n=240). This shows that one of the reasons only weak and moderate correlations have been seen so far is partly due to the presence of obliterated sutures.

3.4 Conclusion

It is evident that sutural mechanics is a complex problem, influenced by multiple factors. Of these, this chapter tested the impact of age, sex and ancestry. Synostosis was a moderate (to poor) predictor of age in the sagittal, coronal and lambdoid sutures. Obscuring the pattern were young adults with fused sutures and older individuals with patent ones. In both the coronal and lambdoid, sex-based and population-specific differences were noted. The sagittal did not appear to be impacted by sex, but population-based differences may exist. The strength of the age-score correlation was dependent on ancestry; black individuals had a stronger age-score relationship. Current aging methods based on cranial sutures need to account for both sex and ancestry, particularly when using the coronal and lambdoid sutures.

4 Patterns in age groups

4.1 Introduction

In the previous chapter, synostosis in the sagittal, coronal and lambdoid sutures was shown to be poorly to moderately correlated to the age of a person using subjects from the Hamann Todd Collection. The purpose of this chapter is to determine whether certain age groups are more likely to present stronger age-score correlations. One theory behind the lack of concrete patterns in the previous analysis is that perhaps variability in synostosis increases with age. For example, older age groups may be less likely to correlate strongly with synostosis, making analyses where they are included devoid of any age-related patterns. The expectation is that significant, linear trends should not be seen within an age group, since age does not correlate perfectly with synostosis. However, it is predicted that variability in closure is restricted in younger individuals; stronger age-score trends are expected here. Lastly, the dominant sutural condition (i.e. the amount of fusion that has occurred) is examined for each age group in order to test if sutural progression increases with age.

4.2 Methods

Individuals in the sample were arbitrarily divided into decade-long age groups 1 to 8 (Table 4.1). The data were divided like this to isolate any trends that may characterize each decade. There was no biological rationale for organizing the ages in decades. The weighted scores used were calculated using the same formula shown in Chapter 3. The mean ages, standard error and standard deviation of each age group for all three sutures are shown in Table 4.1.

Table 4.1 Age groups, their associated age range, sample size (n), mean age and standard deviation for the sagittal, coronal and lambdoid sutures.

Age group	Ages (years)	$n_{sagittal}$	$n_{coronal}$	$n_{lambdoid}$	Mean age (year)	Std. deviation
1	15-19	25	25	25	17.9	1.0
2	20-29	29	26	28	25.0	2.5
3	30-39	41	40	37	35.6	2.7
4	40-49	45	44	39	43.9	3.1
5	50-59	35	31	32	53.5	3.0
6	60-69	38	35	36	64.1	3.0
7	70-79	36	36	36	73.8	3.2
8	80-89	27	27	26	84.0	2.9
Total		276	264	259		

4.3 Results and discussion

4.3.1 Age groups and age-score correlations

In the sagittal suture, when only groups 1 to 3 were examined, the r_s value was 0.42 (p=.000, n=95). When group 4 was added, correlation weakened slightly (r_s=0.38, p=.000, n=140). After this, the correlations were still greater than that of the entire sample and as more age groups were added, the r_s value started resembling that of the whole group, as expected. As predicted, age-score relationships were stronger in younger individuals (up to 39 years of age) in the sagittal suture.

As with the sagittal, correlations in the coronal suture were fairly weak and insignificant between age group and synostosis. When only age groups 1 to 3 were included (n=91), the correlation was 0.48 (p=.000). When additional age groups were incorporated, the strength of the correlation did not steadily decline, but it did not attain a higher r_s value either. This supports the idea that the age-score relationship is stronger in younger people in the coronal suture, and variability in closure happens more extensively after the age of 40 years.

The lambdoid consistently showed weak to negligible correlations for all age groups. Like the sagittal and coronal, the r_s value was strongest when only groups 1 to 3 were included (r_s=0.31, p=0.003, n=90), although the correlation was not as strong. Once more age groups were added to the initial three, the r_s value fell only slightly below that of the entire group correlation. Here, the strength of the age-score correlation stayed more or less consistent with age.

When sex and ancestry were taken under consideration, correlations improved, even for the lambdoid suture. Examining only age groups 1 to 3, white males had the strongest correlation in the coronal suture (r_s=0.59, p=0.011, n=18). Amongst white females, weighted score correlated moderately with age in the sagittal suture (r_s=0.55, p=0.014, n=19). Both the sagittal and coronal sutures yielded moderate age-score relationships in black males (sagittal: r_s=0.53, p=0.002, n=32; coronal: r_s=0.41, p=0.024, n=31). The lambdoid had a surprisingly strong correlation in black females (r_s=0.70, p=0.001, n=20), followed by the coronal (r_s=0.56, p=0.008, n=21). This demonstrated that the already limited variation in synostosis in youth and younger adults can be controlled further when sex and ancestry are accounted for.

4.3.2 Age groups and weighted scores

This section is a further examination of the trends seen in Chapter 3. Rather than looking at the entire sample, age groups were used to track changes in weighted score (Figure 4.1). Although the youngest, the average weighted score of adolescent group predominantly showed minimal fusion, rather than patency in the sagittal and lambdoid sutures. This may be biased by three individuals who showed near complete or fully complete synostosis (specimens 1606, 1711 and 2065). In the coronal suture, the adolescents were progressing toward significant closure.

Group 8, the oldest age group, showed not the first but the second greatest amount of fusion in the sagittal suture. Its score of 3.83 ± 0.86 translates to progression toward near obliterated conditions. Even amongst the coronal and lambdoid, the oldest individuals did not possess the greatest mean scores. Surprisingly, none of the older groups (groups 6+) were characterized by complete closure. The same patterns were seen in the coronal and lambdoid as well. In fact, in the lambdoid, complete obliteration was not seen in old individuals.

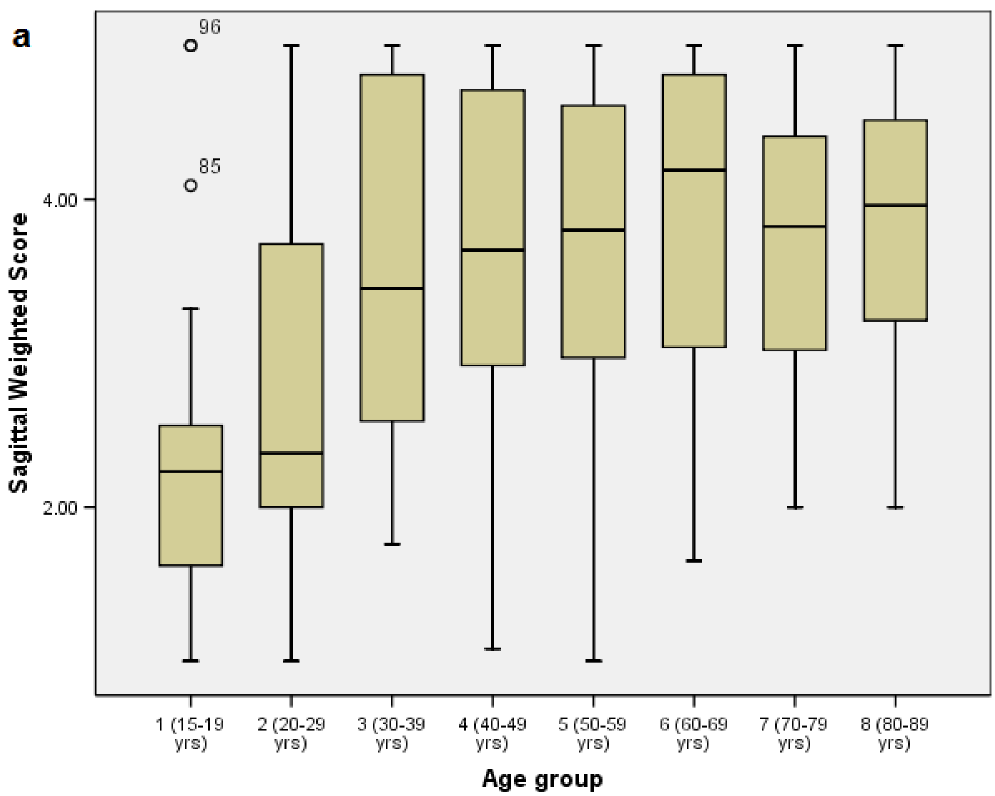
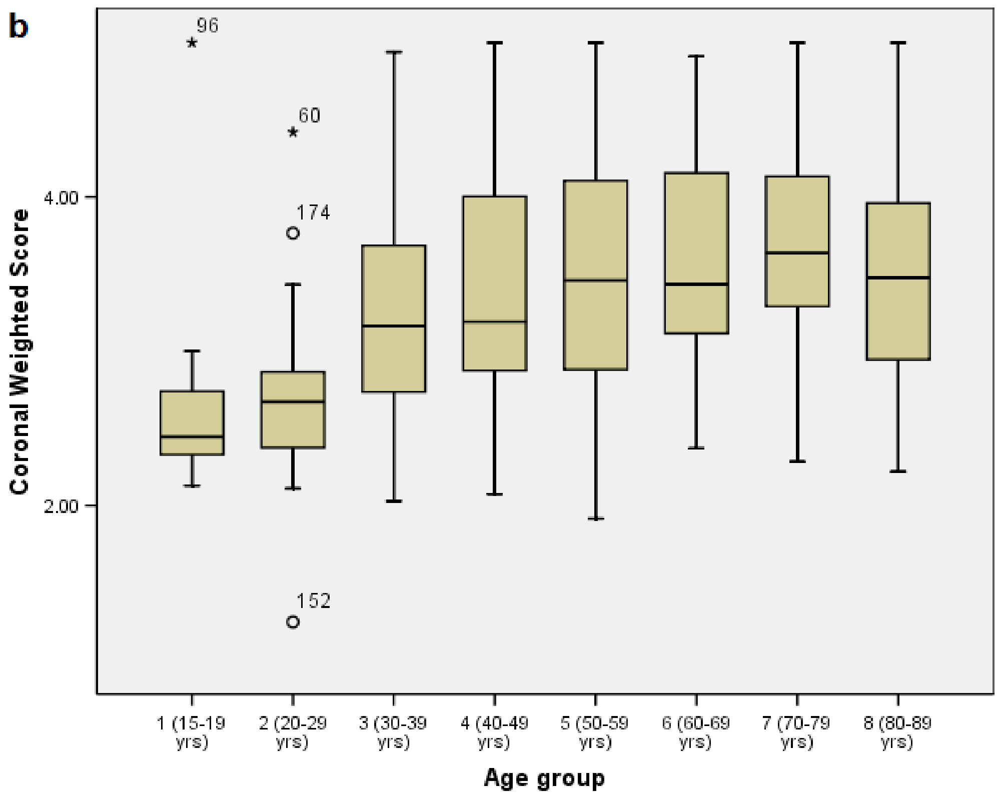


Figure 4.1 The weighted scores, median scores (shown by the horizontal line inside the bar) and outliers of the a) sagittal, b) coronal and c) lambdoid sutures for age groups 1 to 8.



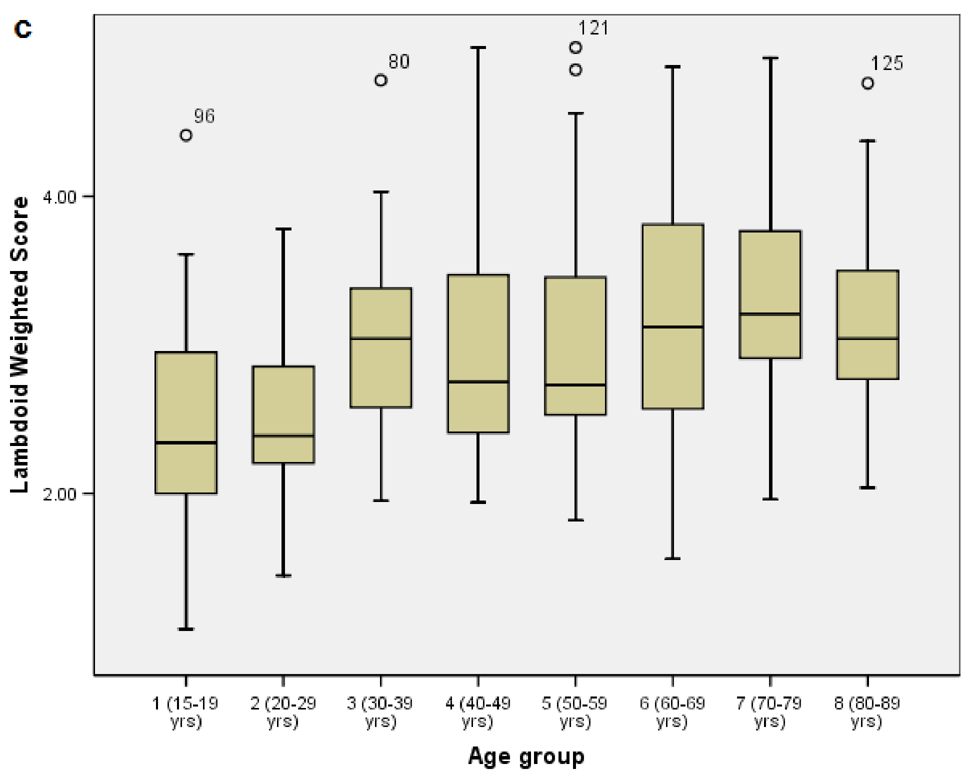


Figure 4.1 The weighted scores, median scores (shown by the horizontal line inside the bar) and outliers of the a) sagittal, b) coronal and c) lambdoid sutures for age groups 1 to 8.

A Mann Whitney test showed that the mean weighted scores of Figure 4.1 were significantly different from each other. The *p* values from multiple Mann Whitney tests are presented in Table 4.2.

Table 4.2 The statistical significance (*p*) of the weighted scores of age groups 1 to 8 based on Mann Whitney tests (2-tailed) for the sagittal, coronal and lambdoid sutures.

		Age group							
		1	2	3	4	5	6	7	8
		Sagittal							
	1	x	.237	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**
	2		x	.005	.003	.003	**.000**	**.001**	.002
	3			x	.855	.734	.322	.724	.660
	4				x	.849	.368	.790	.577
	5					x	.419	.931	.696
	6						x	.471	.674
	7							x	.702
	8								x
A		Coronal							
g	1	x	.210	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**
e	2		x	.002	**.000**	**.000**	**.000**	**.000**	**.000**
	3			x	.507	.198	.067	.008	.162
G	4				x	.579	.208	.056	.526
r	5					x	.797	.320	.944
o	6						x	.275	.691
u	7							x	.457
p	8								x
		Lambdoid							
	1	x	.460	.004	.013	.004	**.001**	**.000**	.003
	2		x	.003	.024	.004	**.001**	**.000**	**.001**
	3			x	.640	.923	.433	.166	.567
	4				x	.703	.239	.077	.192
	5					x	.480	.158	.430
	6						x	.581	.966
	7							x	.238
	8								x

*Bonferroni correction for multiple comparisons: α=0.00178 (p=α/n=0.05/28). Significant correlations are bolded.

In the sagittal, the adolescent group had a weighted score that was significantly different from nearly every other group. Individuals aged 20 to 29 years were an exception. Group 2 resembled groups 3, 5 and 8, but was very different from groups 6 and 7. This indicates that generally, individuals under the age of 29 years will show similar amounts of progression in the sagittal suture. Young adults and adolescents were not distinguishable from each other but together they were discernible from older individuals. Before the Bonferroni correction was applied, it could be seen that groups 1 and 2 were significantly different from every other group. Unfortunately, the remainder of groups could not be distinguished from each other. Thus, any age estimations devised from the sagittal suture can only conclude that the individual is either under or over the age of 30 years.

The coronal suture offered a binary classification of age as well, where the sample could be reliably divided as being young (groups 1 and 2) or older (group 3+). In the lambdoid, the adolescents' weighted scores were significantly different from older individuals (group 6 and 7, but not group 8). Individuals aged 20 to 29 years could be distinguished from groups 6 to 8. Individuals can be classified as being under or over the age of 59 years.

4.3.3 Dominant conditions

Certain age groups were characterized by a single sutural condition while others showed a mix of states. As shown in Figure 4.2a, minimal closure was the dominant condition, followed by patency and significant closure for group 1 in the sagittal suture. For individuals belonging to group 2, minimal fusion was predominant (Figure 4.2b). In as early as the 4th decade of life, complete obliteration becomes frequent (Figure 4.2c). This was true for group 4 as well (Figure

4.2d). In group 5, although obliteration was dominant once again, significant and nearly complete fusion were prevalent too (Figure 4.2e). In the remaining groups, complete obliteration was most frequently seen, followed by near obliterated conditions.

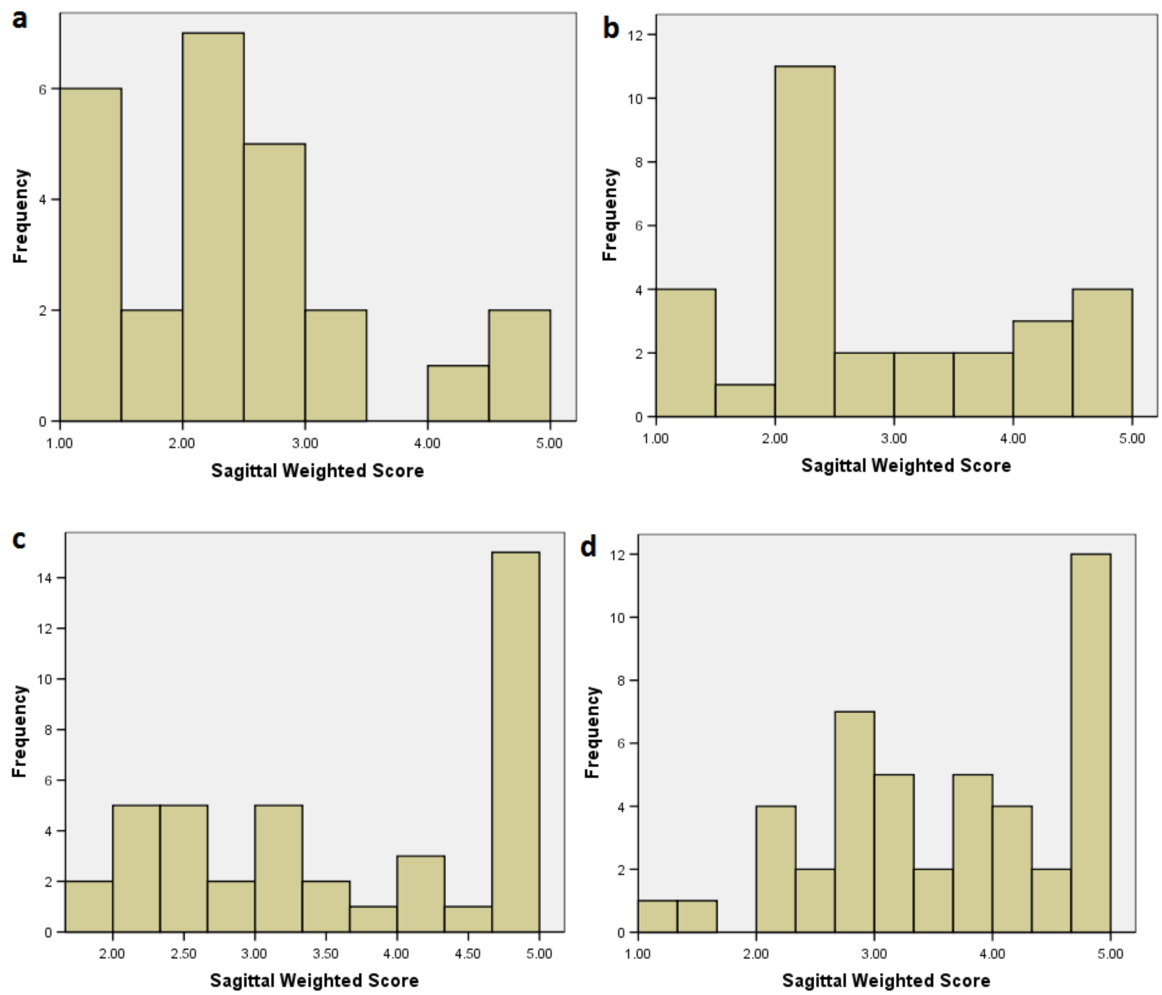


Figure 4.2 The frequency of weighted scores of the sagittal suture of different age groups, a) group 1, 15-19 years; b) group 2, 20-29 years; c) group 3, 30-39 years; d) group 4, 40-49 years; e) group 5, 50-59 years; f) group 6, 60-69 years; g) group 7, 70-79 years and h) group 8, 80-89 years.

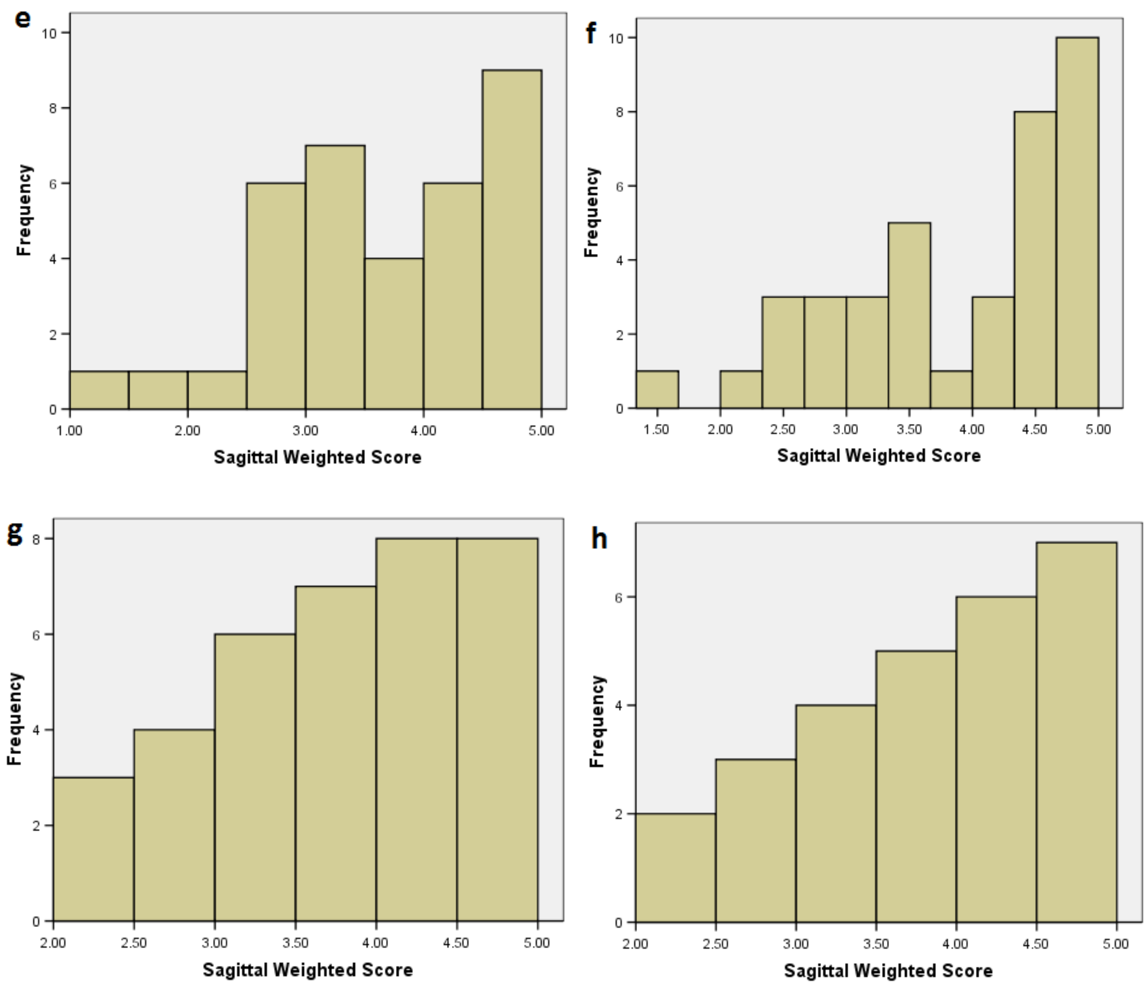


Figure 4.2 The frequency of weighted scores of the sagittal suture of different age groups, a) group 1, 15-19 years; b) group 2, 20-29 years; c) group 3, 30-39 years; d) group 4, 40-49 years; e) group 5, 50-59 years; f) group 6, 60-69 years; g) group 7, 70-79 years and h) group 8, 80-89 years.

Figure 4.3a shows that minimal closure is the dominant condition of the coronal suture amongst adolescents. In group 2, most sutures were minimally fused and progressing toward significant fusion (Figure 4.3b). Variability began in group 3, where individuals varied between minimal fusion and near obliteration, but significant fusion was most common (Figure 4.3c). This was true for group 4 as well (Figure 4.3d). Conditions were very variable for group 5; many individuals were progressing toward significant fusion or near obliteration or had undergone complete fusion (Figure 4.3e). Significant fusion was the dominant condition in group 6, disrupting the steady progression seen in the coronal suture so far (Figure 4.3f). The disruption was remedied in group 7, where progression toward near fusion is the dominant condition (Figure 4.3g). Group 8 was variable; conditions varied from progression toward significant fusion to nearly complete fusion (Figure 4.3h).

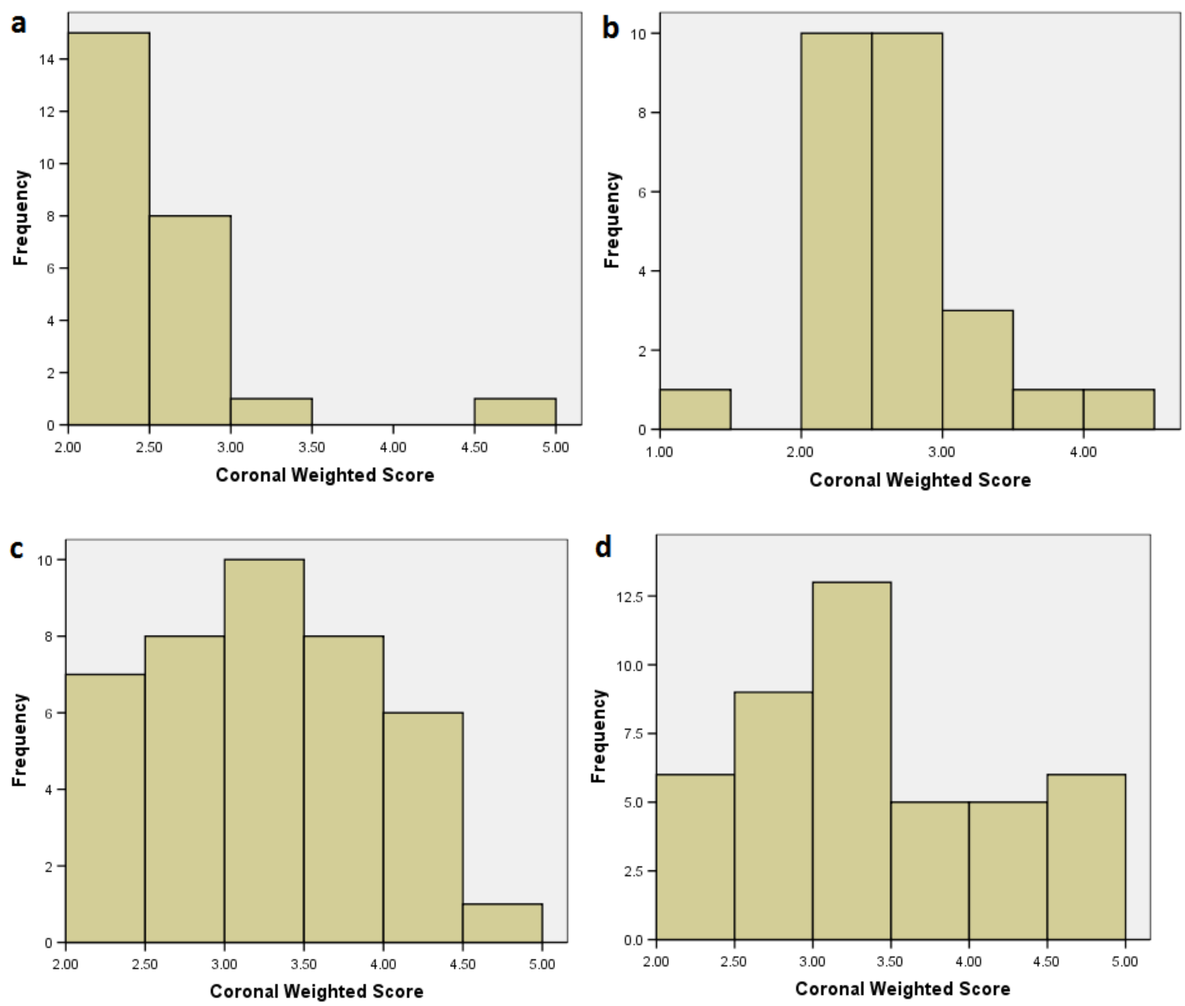


Figure 4.3 The frequency of weighted scores of the coronal suture of different age groups, a) group 1, 15-19 years; b) group 2, 20-29 years; c) group 3, 30-39 years; d) group 4, 40-49 years; e) group 5, 50-59 years; f) group 6, 60-69 years; g) group 7, 70-79 years and h) group 8, 80-89 years.

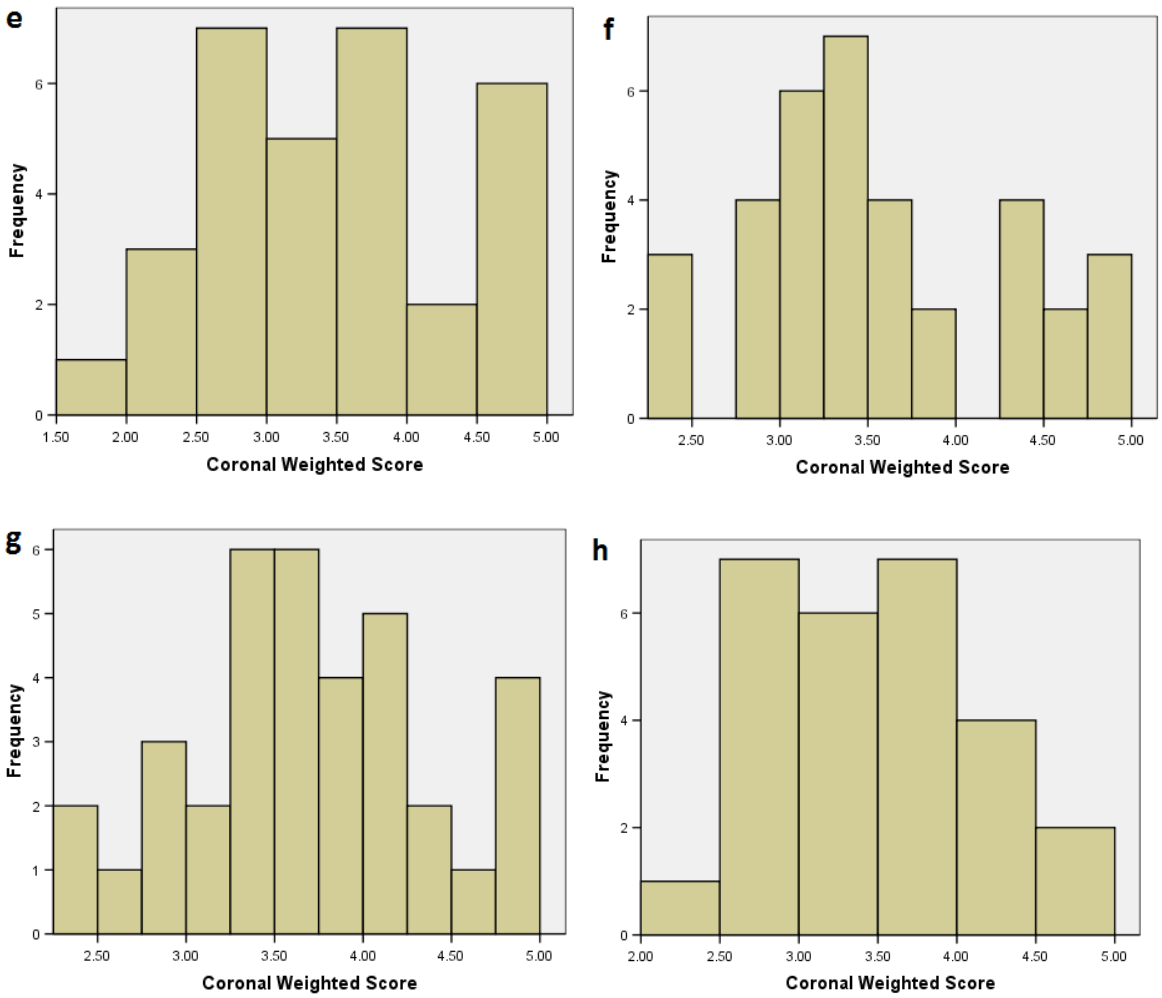


Figure 4.3 The frequency of weighted scores of the coronal suture of different age groups, a) group 1, 15-19 years; b) group 2, 20-29 years; c) group 3, 30-39 years; d) group 4, 40-49 years; e) group 5, 50-59 years; f) group 6, 60-69 years; g) group 7, 70-79 years and h) group 8, 80-89 years.

In the lambdoid suture, both group 1 and 2 were characterized by minimal fusion (Figure 4.4a, b). Significant fusion was the dominant condition in group 3 (Figure 4.4c). The linear trend was disrupted in group 4, where minimal fusion prevailed (Figure 4.4d). In group 5, most individuals started progressing toward significant fusion (Figure 4.4e). The same was true for group 6, but significant fusion and progression toward near obliterated conditions were common as well

(Figure 4.4f). Amongst the oldest individuals (group 7 and 8), significant fusion was the dominant condition (Figure 4.4g, h).

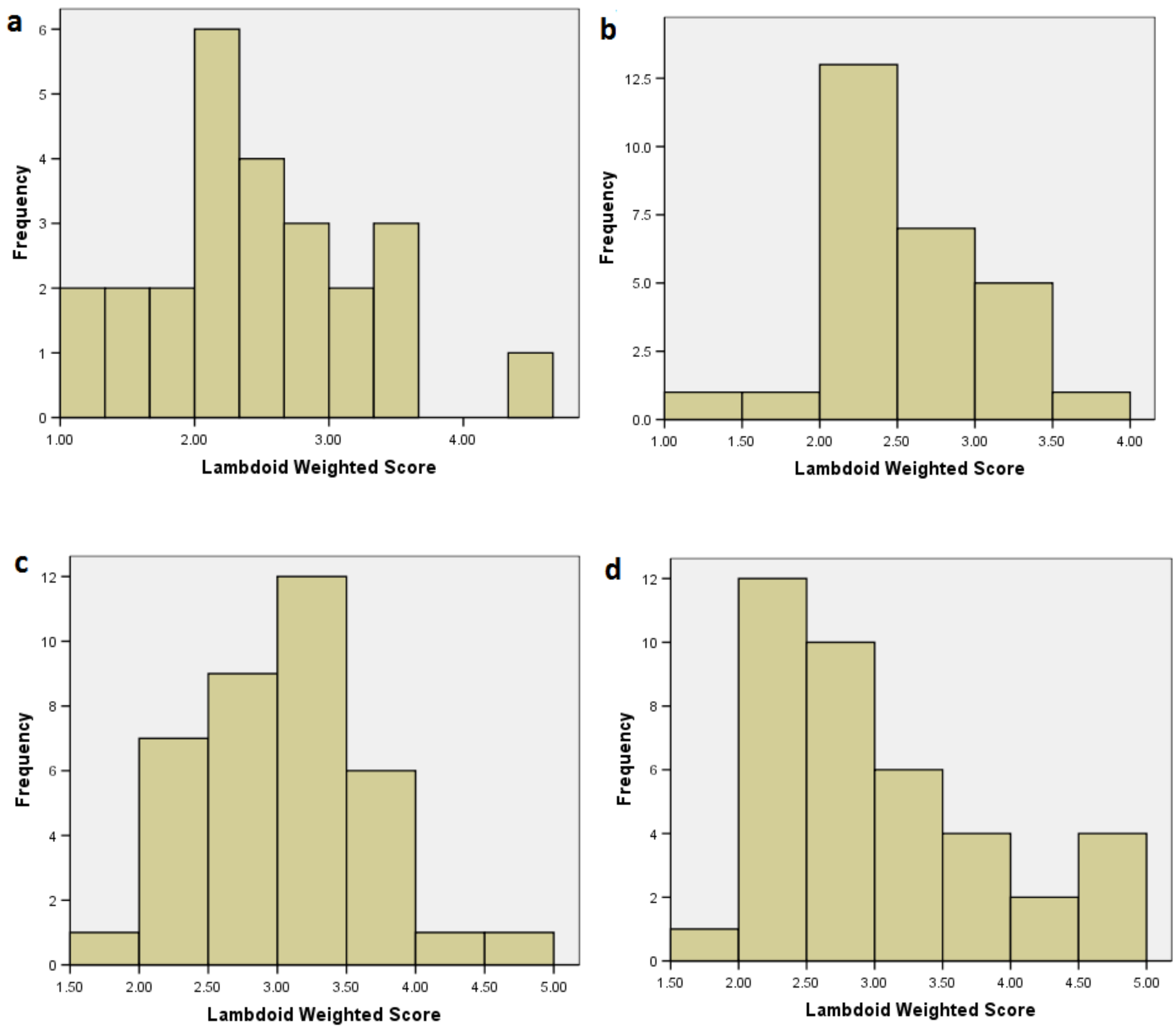


Figure 4.4 The frequency of weighted scores of the lambdoid suture of different age groups, , a) group 1, 15-19 years; b) group 2, 20-29 years; c) group 3, 30-39 years; d) group 4, 40-49 years; e) group 5, 50-59 years; f) group 6, 60-69 years; g) group 7, 70-79 years and h) group 8, 80-89 years.

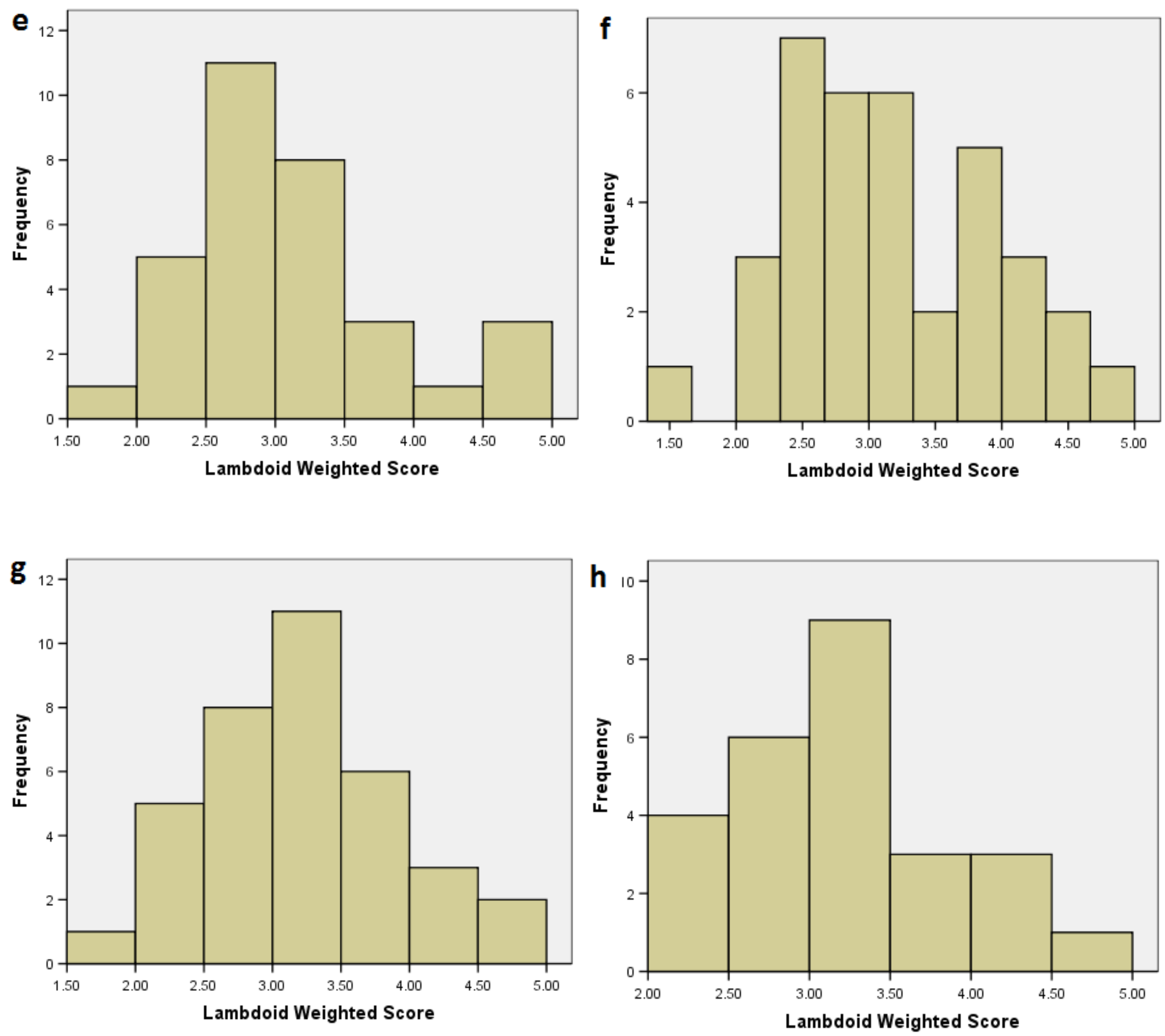


Figure 4.4 The frequency of weighted scores of the lambdoid suture of different age groups, , a) group 1, 15-19 years; b) group 2, 20-29 years; c) group 3, 30-39 years; d) group 4, 40-49 years; e) group 5, 50-59 years; f) group 6, 60-69 years; g) group 7, 70-79 years and h) group 8, 80-89 years.

4.4 Conclusion

The purpose of this chapter was to investigate whether variability as a function of age group may have masked any patterns between age and synostosis in the sagittal, coronal and lambdoid sutures. There is undoubtedly a large amount of uncontrollable variation in the progression of sutural development in the Hamann Todd subjects. If certain age groups exhibit more variation than others or if age groups are characterized by different rates of progression, then analyses done with a pooled sample will not yield strong correlations.

In this case, variation and rates of progression appear to be influenced by age group. Individuals belonging to groups 1 to 3 (adolescents and adults up to 39 years of age) showed a stronger age-score correlation than older individuals. This was documented in all three sutures. After this point, variability increased, masking patterns. Synostosis may be related to growth since adolescence and early adulthood show an accelerated rate of growth. Individuals belonging to groups 1 and 2 had weighted scores significantly different from older adults. Although age appears to correlate with synostosis, the trend was moderate (at best). Only binary classifications of age were seen. Cranial suture aging may be more reliably used in adolescents and young adults.

5 Secular changes in the fusion of the sagittal, coronal and lambdoid sutures

5.1 Introduction

So far, only biological variables, like sex and ancestry, have been explored in regards to synostosis in the sagittal, coronal and lambdoid sutures. Factors outside of human biology, like the time period during which an individual lived in, can impact sutural union. Perizonius (1984) compared a Dutch population to the Hungarian population used by Acsádi and Nemeskéri (1970) and found that the latter exhibited earlier closure in every age group. Perizonius (1984) pointed to secular trends as a function of time period to explain this. He stated: "...the Hungarians died in 1955/56 while the Amsterdam inhabitants died between 1883 and 1909. The possibility of a secular trend caused by the rapidly changing way of life in the 20th century cannot be excluded" (Perizonius, 1984, p.215).

This chapter explores the effect of secular changes in the Hamann Todd sample on synostosis. Secular change refers to any changes that occurred in one century that are not seen in another century, and includes standards of living, medical care availability, racial discrimination, etc. The Hamann Todd individuals chosen for study lived in the 19th and 20th centuries (1830s to 1930s). The sample predates the Hungarians studied by Acsádi and Nemeskéri (1970) while some of the subjects co-existed with Perizonius' (1984) sample. Life-altering innovations occurred during this period. This time period began with wretched housing conditions and high incidence of diseases like tuberculosis in Cleveland, Ohio, but eventually saw advances in medicine and improved standard of living, making it an interesting stretch of time to test the effects of secular changes on synostosis.

5.2 Methods

5.2.1 Sample

Of the 276 individuals used in this study, 251 individuals had information on birth and death dates. Individuals were first grouped by birth year as belonging to the 19th or 20th century in order to test the rate of progression of the sutures in question and determine differences between age-score correlations. The data were then arbitrarily divided by decade and each period was assigned a value of 1 to 9, where 1 was the earliest decade, 1830s, 2 was the 1840s, etc. to 8 being the 1900s. Group 9 was made up of individuals born in the 1910s and 1920s due to inadequate sample size in the latter group. This was done to pinpoint the origins of any trends.

5.3 Results

5.3.1 The 20th century

Figure 5.1 shows the relationship between the weighted score of the sagittal suture and age for individuals born in the 1900s (n=40). Although the trend was slightly stronger than the age-score correlations shown in the Chapter 3 (r_s=0.33, p=0.038, 2-tailed), a fair amount of variability continues to exist. A number of young individuals born in the 20th century had completely obliterated or nearly complete sagittal sutures (see squared portion of Figure 5.1).

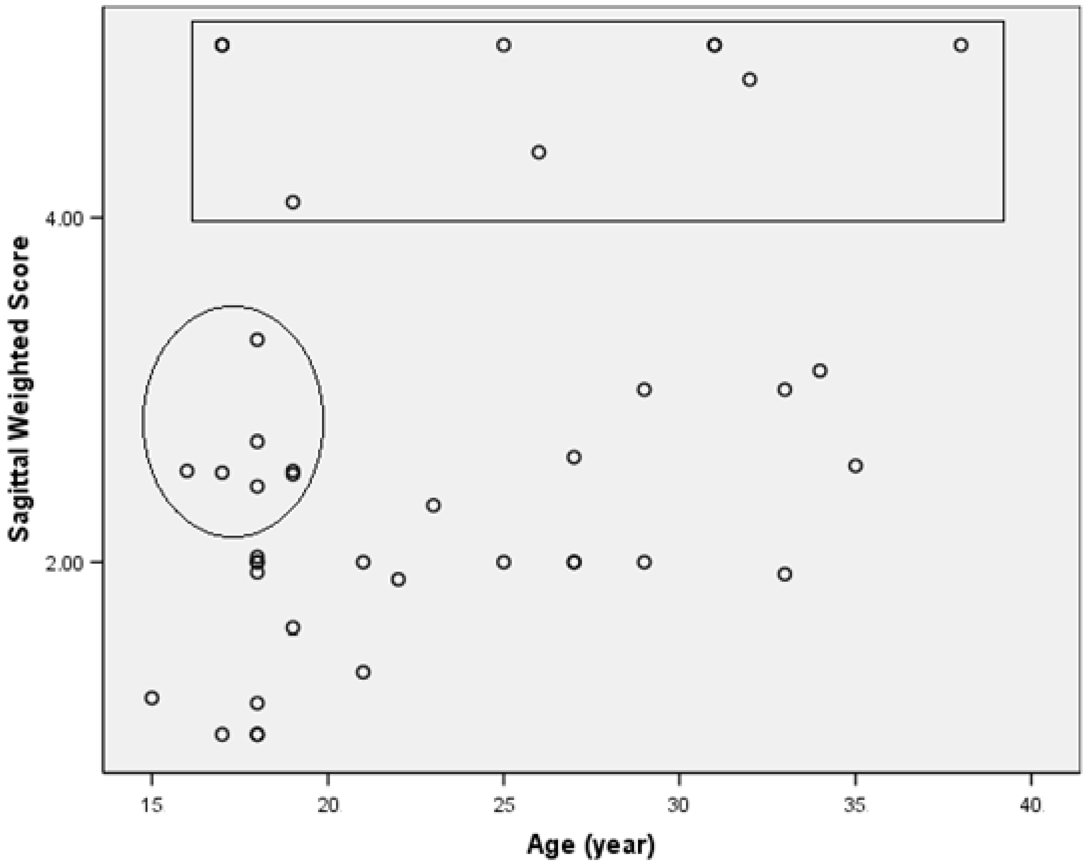


Figure 5.1 The relationship between the weighted score of the sagittal suture and age for individuals born in the 1900s (n=40). The highlighted areas represent individuals exhibiting premature synostosis.

In the coronal, a significant correlation was seen between age and weighted score amongst individuals born in the 20th century (r_s=0.40, *p*=0.011, n=40), resembling the correlation for the entire sample shown in Chapter 3. Figure 5.2 highlights the subjects that were a source of variability in the coronal suture. These individuals exhibited premature or delayed synostosis, thereby disrupting the otherwise linear trend.

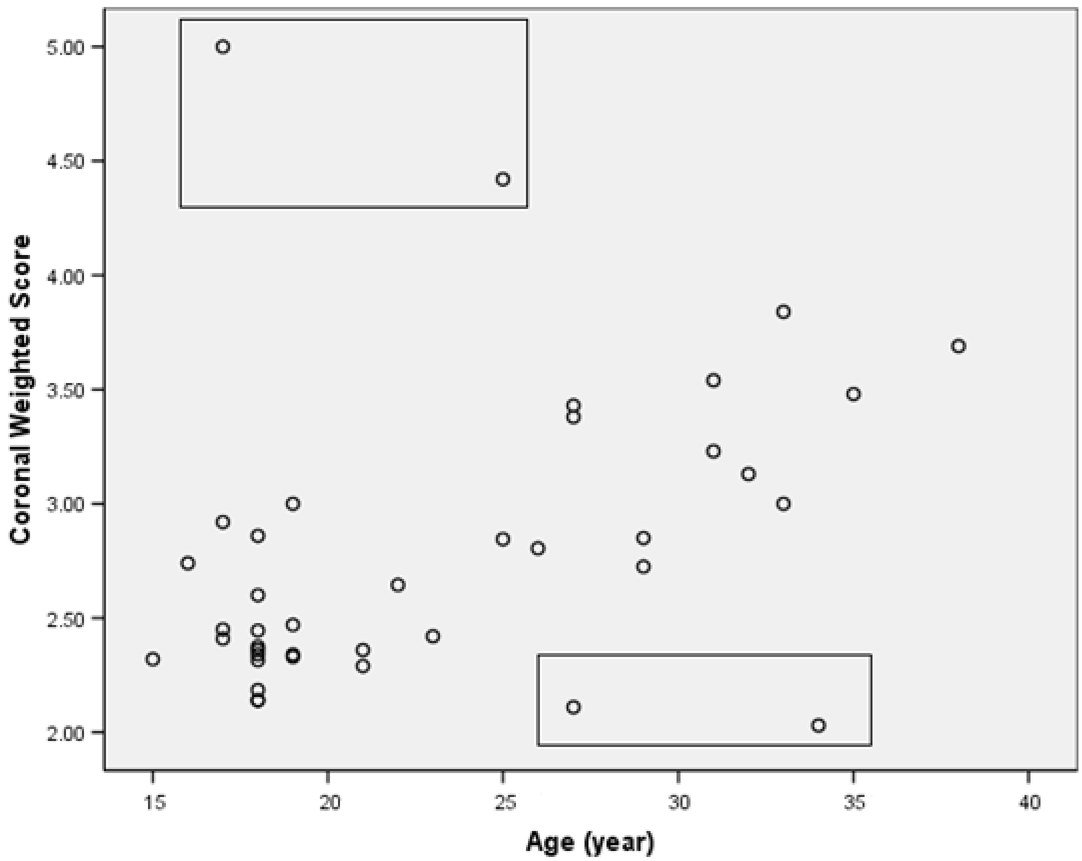


Figure 5.2 The relationship between weighted score of the coronal suture and age for individuals born in the 20th century (n=40). The squared area represents individuals exhibiting premature or delayed synostosis.

When four outliers were removed (2 over-developed and 2 under-developed coronal sutures), the correlation between age and weighted score was strong (r=0.83, *p*=.000, n=31). It is appropriate to use Pearson's correlation since graphically it can be seen that both variables are associated in the linear fashion. Although the trend is significant, the r^2 value is only moderately strong (0.69). A regression equation may cautiously be used to determine age from the degree of fusion that has occurred in the coronal for an individual born in the 20th century (age = 1.399 x weighted score + 0.060), but the error rate may be high. Additionally, it would be difficult to determined whether an under-developed or over-developed suture is present; this may under-or over-estimate age. Another potential source of error comes from the reduced sample size. After all, 11% of the sample had to be eliminated before a strong correlation could emerge.

The strength of the correlation between age and weighted score in the lambdoid was weaker than those of the sagittal and coronal sutures (r_s=0.28, p=0.122, n=40). Premature closure in the lambdoid suture is shown in Figure 5.3. As with the coronal, when outliers were moved (5 over-developed sutures), the age-score correlation was stronger and significant (r=0.63, p=.000, n=35).

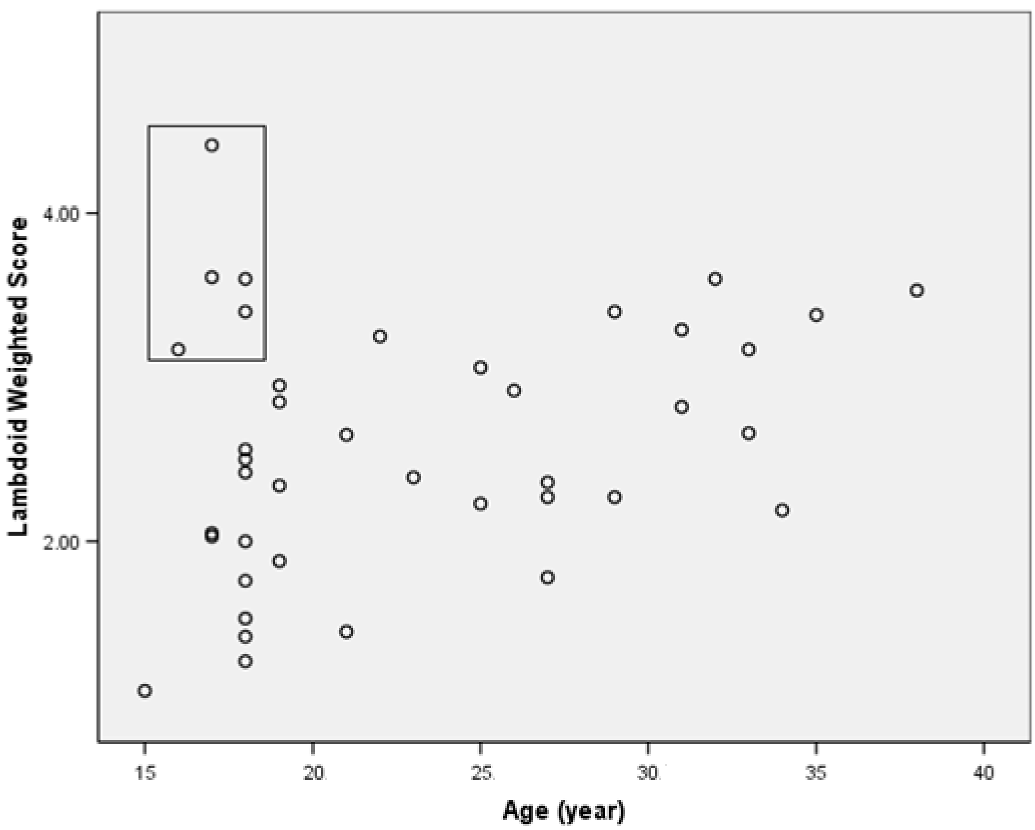


Figure 5.3 The relationship between weighted score of the lambdoid suture and age for individuals born in the 20th century (n=40). The squared area represents individuals exhibiting premature synostosis.

5.3.1a The 20th century anomalies

Individuals showing accelerated rates of closure consisted of adolescents and individuals in their 20s and 30s. Why did these individuals show rapid or delayed sutural progression? The answer is unclear. They were all born between 1900 and 1912 and died in the 1920s or 1930s. There was no particular sex-based bias (i.e. males and females were approximately represented equally), but seven out of nine subjects were of black descent. In terms of skeletal abnormalities, one person had lambdoid ossicles, although this appears to be a common finding amongst the Hamann Todd subjects. Five (fully grown adult) individuals were severely underweight (60-90 pounds), suggesting that either malnutrition took a toll on their health or that the cadavers' weights were determined after tissue loss had occurred. In fact, the adolescent subjects had greater weights than individuals in older age groups. Height, on the other hand, did not vary to a great extent, falling between 1.5 and 1.8 metres. Physically, none of the skulls were deformed. The early closure in these individuals cannot be explained by secular changes.

5.3.2 The 19th century

For individuals who were born in the 19th century, a nearly negligible trend emerged in the sagittal suture (r_s=0.166, *p*=0.016, n=211; Figure 5.4). The scattered pattern is very similar to the age-score plot presented in Chapter 3. This shows that the reason a definite trend did not emerge was due to the heavy presence of individuals from the 19th century, who exhibit greater variation than the 20th century group.

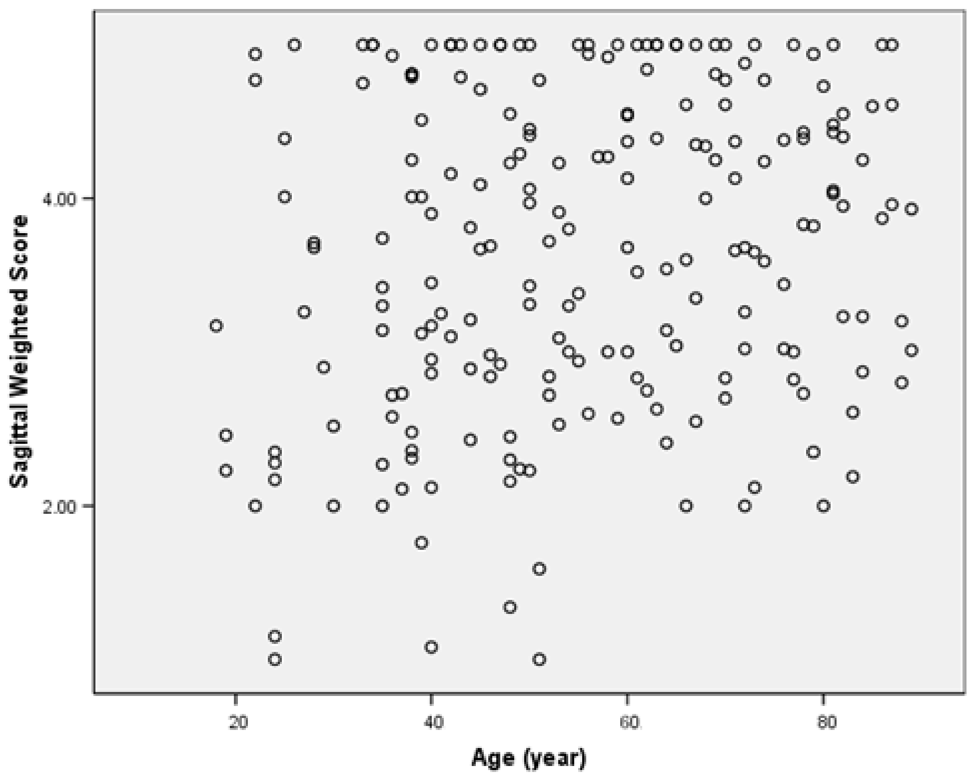


Figure 5.4 The weighted sagittal scores of individuals born in the 19th century regressed against age for the sagittal suture (n=211).

The age-score correlation for the coronal was somewhat stronger, but still weak (r_s=0.29, *p*=.000, n=199; Figure 5.5). Although significant, this correlation was much lower than that of the 20th century individuals. Figure 5.5 resembles the variability seen in Figure 5.4 for the sagittal suture.

The lambdoid suture followed a pattern similar to the other sutures. Although a significant correlation was present (r_s=0.22, *p*=0.002, n=196), Figure 5.6 demonstrates the high degree of variability in closure for the 19th century group. Since variability appears to be the norm in all three sutures, it is difficult to construct scatter plots without outliers, as done for the 20th century individuals.

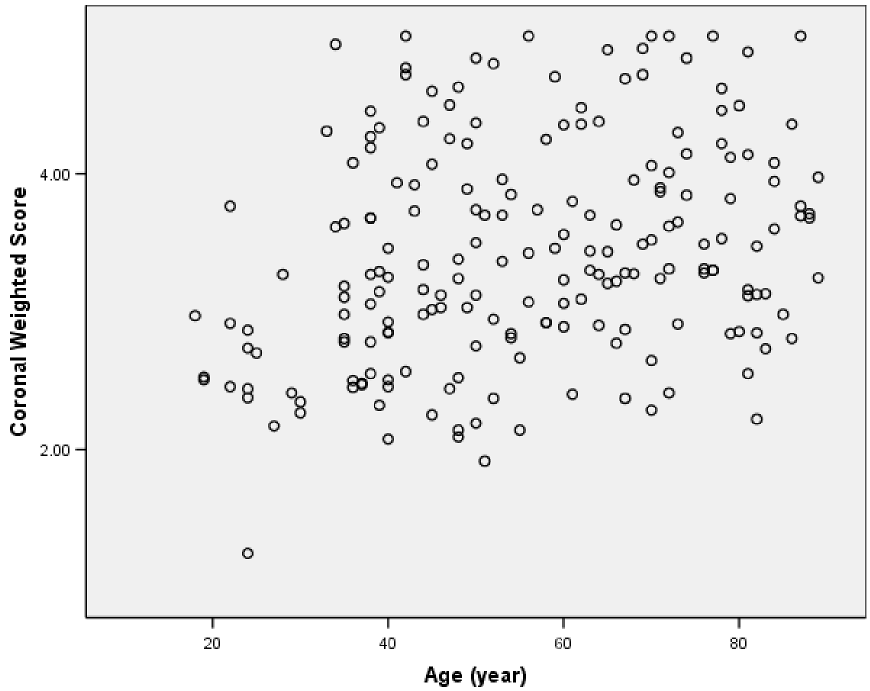


Figure 5.5 A weak age-score correlation in the coronal suture of individuals born in the 19th century (n=199).

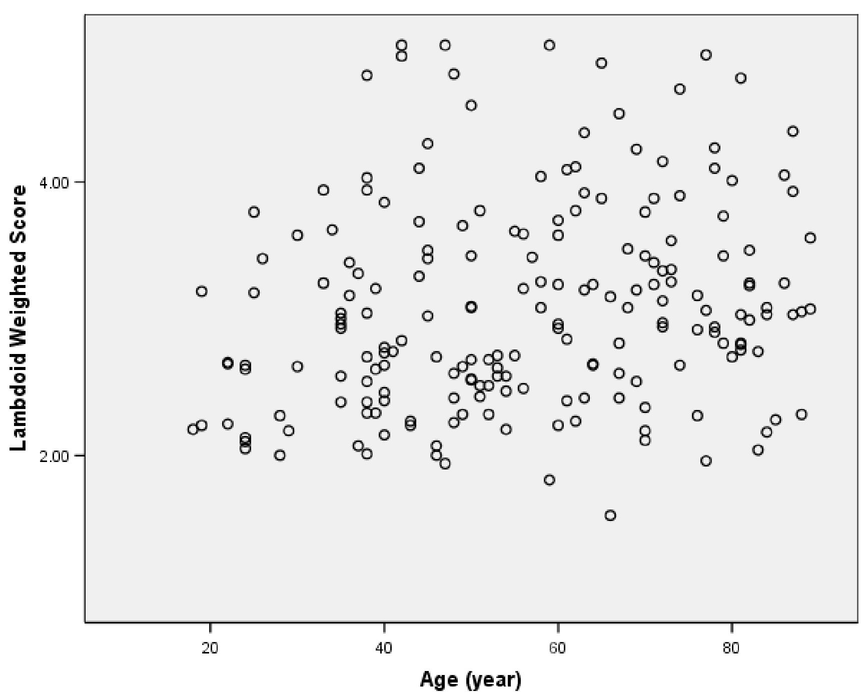


Figure 5.6 Scatter plot of the weighted scores of the lambdoid suture and age of individuals born in the 19th century (n=196).

Examining both centuries, the question that arises is this: why do individuals born in the 19th century have a more variable path to synostosis, unrelated to age? Why would the 20th century individuals have a stronger age-score relationship? Is the sample biased (e.g. not all age groups are represented)? After all, the 20th century group consisted of only people under the age of 40 years, while the 19th century group included both young and old individuals. Chapter 4 has already shown that less variability is seen in adolescents and young adults.

To answer this, progression in the three sutures was examined only in individuals born in the 19th century, belonging to age groups 1 to 3. Figure 5.7a shows a highly scattered plot for the sagittal with far more variability than seen in Figure 5.1. The coronal's trend was moderately strong (r_s=0.37, p=0.014, n=44). The lambdoid showed vague linearity; too many under-developed sutures were present (Figure 5.7c). Aside from the coronal, none of these plots had significant or strong correlations. When outliers were removed from the lambdoid plot (n=6), the correlation was moderate (r=0.49, p=0.002, n=38).

This suggests that the age distribution of the sample interfered minimally with the correlations seen in the 20th century individuals. The data suggests that in the 19th century, the age-score relationship in all three sutures was virtually non-existent. It appears that over time, progression in a suture, particularly in the coronal and lambdoid, was correlated more strongly with age in adolescents and young and middle-aged adults.

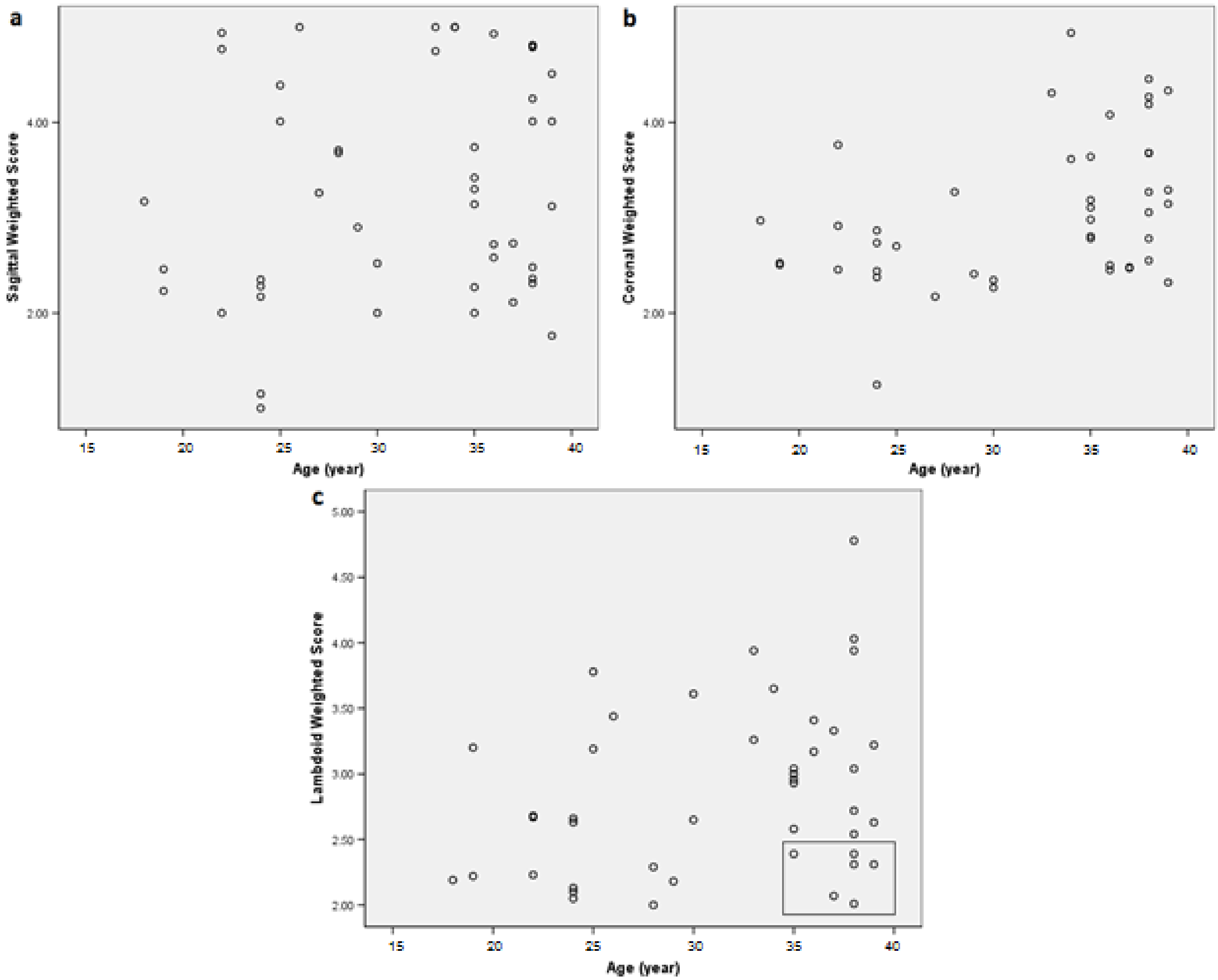


Figure 5.7 Age-score relationships for the a) sagittal (n=48), b) coronal (n=44) and c) lambdoid (n=44) sutures for individuals born in the 19th century, belonging to age groups 1 to 3. Boxed area shows individuals with under-developed sutures.

5.3.3 The late 19th century: From variability to strong correlations

The results suggest that age-score relationships were different between the 19th and 20th centuries. To pinpoint exactly when in time correlations start becoming stronger and significant, the decades were grouped. The age-score relationship in all three sutures becomes less variable beginning in the late 19th century. Table 5.1 presents correlations in a cumulative fashion.

In the sagittal, the greatest correlation was seen when all individuals born between 1880 and the 20th century are included. The same was true for the coronal (although moderate correlations started appearing in the mid-1800s). The lambdoid's greatest correlation was seen a decade later. It is evident that the trends seen in Figures 5.1 to 5.3 are not limited to the 20th century. Here, even though outliers were present, it is clear that the stronger trends between age and weighted score emerged in the late 19th century.

Table 5.1 Strength of age-score correlations as a function of time in the sagittal, coronal and lambdoid sutures.

Year	Sagittal (r_s, *p*, n)	Coronal (r_s, *p*, n)	Lambdoid (r_s, *p*, n)
1900+	.329, .038, 40	.398, .011, 40	.248, .122, 40
1890+	.448, .000, 70	.427, .000, 70	.360, .002, 69
1880+	.457, .000, 95	.508, .000, 91	.325, .002, 92
1870+	.404, .000, 142	.506, .000, 138	.276, .001, 135
1860+	.330, .000, 184	.495, .000, 176	.291, .000, 172
1850+	.341, .000, 213	.488, .000, 201	.329, .000, 200
1840+	.308, .000, 244	.430, .000, 232	.309, .000, 229
All years/whole sample	.298, .000, 276	.422, .000, 264	.297, .000, 259

5.4 Conclusion

A secular change appears to influence the impact of age on synostosis in the sagittal, coronal and lambdoid suture. This influence is marked at the turn of the century, beginning twenty or thirty years before this point. Progression appears to be slow in the oldest individuals dating to the earliest times. The rate of progression continues to climb after this, particularly in the 1870s and 1880s. This is in accord with Perizonius' (1984) observation on the Hungarian and Dutch samples, where the older Dutch sample exhibited delayed sutural closure. The consistency of this across all three sutures suggests that similar processes are at work across different sutures.

Although rates of progression and closure appear to be impacted by secular changes, synostosis continues to be a highly variable phenomenon and does not seem to be closely related to one's age. Individuals born from the late 19th century to the 20th century show an age-score correlation stronger than all else reported so far. This correlation does not spell out a definite connection between age and synostosis since the r_s value is only moderately strong. It does, however, pinpoint one of the external influences that may otherwise mask any potential connections between age and synostosis. This research shows that if age estimation techniques based on cranial sutures are used, the likelihood of obtaining an accurate age range is increased if the subject belongs to the late 19th or 20th century since stronger age-score correlations are seen here.

6 Nutrition and its affect on synostosis

6.1 Introduction

The effect of nutrition and overall health of an individual on synostosis is the focus of this chapter. There is an established connection between disease and synostosis. For instance, illness that results in metabolic disruption, like rickets, can cause premature fusion (Reilly *et al.*, 1964). The extent to which poor health can interfere with fusion has not been discussed. Stature and weight at death, alongside the author's remarks on skeletal abnormalities and cause of death (COD) were used to assess the general wellbeing of the Hamann Todd sample examined here. Previous research (e.g. Cardoso and Garcia, 2009) has shown that height is a reliable indicator of malnourishment, a chronic condition that would have likely severely impacted the lower class of Cleveland. Examining height can in the very least provide indications as to whether major disruptions occurred during childhood and/or pubertal years. Weight, on the other hand, is much more variable, but may disclose information about the health of an individual just before death.

The question this chapter explores is whether chronic health problems can impact synostosis. Individuals who are underweight or have below-average heights will be crucial to resolving this issue. Individuals with a chronic illness are examined as well to see whether being deficient in good health will alter the progression of a suture by accelerating or decelerating it. In addition to natural death, the effect of alcohol and drug intake will be studied as well. It is predicted that having long-term illness or malnourishment will impact the normal development of the suture. Specifically, it will accelerate the rate of progression.

6.2 Methods

Two indicators of health were examined here: height and weight. Although health conditions were poor in the 19th and 20th centuries, particularly for the lower class, which constitutes much of this sample, detailed information on the subjects' fitness is unknown, but cause of death was listed for many individuals. Many people in the sample died of an acute illness, which is predicted to have minimal influence on synostosis, compared to chronic illness.

The height and weight data were combined to calculate the Body Mass Index (BMI; weight (kg)/ height (m^2)) of the sample, which was used as a proxy for overall health status. Individuals were divided into underweight (<18.5), normal weight (18.5-24.9), overweight (25.0-29.9 kg/m^2) and obese (30.0+ kg/m^2) categories and fusion patterns were studied within these groups. Overweight and obese individuals were combined into a single group for statistical purposes due to low sample count in the latter. Individuals under the age of 18 years were not included. Although people were shorter in the 19th and 20th centuries, particularly the former, because BMI uses height to predict an ideal weight, it should be appropriate to use on the Hamann Todd sample. Thus, the health of the Hamann Todd sample will be described relative to modern populations.

It is, however, acknowledged that BMI may be a problematic indicator of health, as it does not differentiate between muscle and bone mass and body fat (Cole, 2003). Furthermore, it is dependent on age, sex and possibly ancestry (Gallagher *et al.*, 1996). For example, women have more body fat than men (even if their BMI is the same). Body proportions are not accounted for as well (e.g. individuals with short lower limbs tend to have high BMIs; Garn *et* *al.*, 1986). Furthermore, an individual with a normal weight-height ratio can still have metabolic disorders (St-Onge *et al.*, 2004).

Many of the skulls examined here had peculiar cranial features (e.g. wormian bones, epipteric bone, apical bone, bregmatic bone, oddly shaped skulls, and extremely light or dense skulls as determined macroscopically by the author). In order to see whether the presence of these features is associated with accelerated or delayed synostosis, subjects who possessed any deviations from the "normal" condition were separated from those without any extra features.

6.3 Some observations

6.3.1 Changes in stature over time

Table 6.1 shows average heights for age groups 1 to 8 for both the 19th and 20th centuries. The information in this table was used to determine whether significant differences in height existed between the two centuries. Age groups 1 to 3 were available for comparison in both categories. A Mann Whitney test indicates that the average height of these groups did not vary significantly across time (U=425.0, p=0.345), although individuals from the 20th century (n=38) were taller than the 19th century sample (n=26) [$\bar{x}$=1.65±0.02 m for the 19th century; $\bar{x}$ =1.69±0.01 m for the 20th century]. This may be an indication that very little increases in stature occurred with the passage of time. If stature can be used reliably to measure nutritional status, this may suggest that nutritional conditions remained consistent with time for the poor class.

Compared to the measured statures presented by McDowell *et al.* (2008) for present-day Americans (2003-2006) over the age of 20 years ($\bar{x}$=1.76 m and 1.62 m for males and female, respectively), it is not surprising that the Hamann Todd sample is shorter [$\bar{x}$=1.71 m (n=89) for males; $\bar{x}$=1.60 m (n=90) for females]. So, there is a difference in nutritional wellbeing between modern times and the past two centuries, but conditions did not change dramatically between the 19th century and early 20th century.

Table 6.1 Average height in metres for individuals of all age groups born in the 19th and 20th century (n=191).

	19th century		20th century	
Age group	Average height (m)	n	Average height (m)	n
1	1.76 ± 0.04	3	1.71 ± 0.02	18
2	1.74 ± 0.04	5	1.69 ± 0.02	12
3	1.61 ± 0.03	18	1.63 ± 0.02	8
4	1.66 ± 0.01	27	-	-
5	1.65 ± 0.01	21	-	-
6	1.66 ± 0.02	27	-	-
7	1.65 ± 0.02	27	-	-
8	1.63 ± 0.02	25	-	-

6.3.2 Sex, ancestry and stature

A Mann Whitney test shows that there was a significant difference between the height of males and females in this sample (U=1835.0, *p*=.000, n=201); males were taller ($\bar{x}$=1.71±0.08 m) than females ($\bar{x}$=1.60±0.08 m). The age distribution of both groups was not significantly different (both lying in the 40s). Amongst the males, black males ($\bar{x}$=1.73±0.08 m, n=41) were significantly taller than white males ($\bar{x}$=1.70±0.08 m, n=63; U=959.5, *p*=0.027, n=104). Black females (n=43) showed significant differences in height as well (U=747.0, *p*=0.006, n=95); they were taller ($\bar{x}$=1.63±0.06 m) than white women ($\bar{x}$=1.58±0.09 m). The opposite trend is seen in modern times where white individuals are slightly taller than black individuals (McDowell *et al.*, 2008).

Even though race-based inequalities persisted over the temporal spread of this sample, if considerable nutritional differences existed between these two groups, height does not reflect them. It is unlikely that the black sample had better levels of nutrition. It is possible that genetic factors (e.g. larger body size for black individuals) mask differences in nutritional status between these ancestral groups. Alternatively, black adults may have attained greater heights than their white counterparts through catch-up growth, where nutritional deficiency and growth delays in childhood are counteracted with a rapid growth phase in youth and early adulthood.

6.4 Results

6.4.1 Ancestry, height and synostosis

Height consistently showed negative trends when regressed against the weighted score of all three sutures. When all subjects were included, a weak but significant correlation emerged in the sagittal suture (r_s=-0.24, *p*=0.001, n=201; Figure 6.1). The coronal suture's weighted score correlated in a similar weak fashion to height (r_s=-0.25, *p*=.000, n=196). The weighted score of the lambdoid suture was poorly correlated to height (r_s=-0.18, *p*=0.014, n=189).

When the sample was divided according to ancestry, black individuals exhibited a significant relationship between weighted score and height in the sagittal (r_s=-0.32, *p*=0.003, n=84) while white subjects had a nearly negligible correlation (r_s=-0.17, *p*=0.062, n=115). The negative Spearman's rho was consistent across both groups, indicating that as one variable increased, the other decreased. In the coronal, a trend opposite to the sagittal was seen. White individuals had a weak but significant correlation (r_s=-0.27, *p*=0.004, n=111); black subjects had a weaker one (r_s=-0.22, *p*=0.046, n=83).

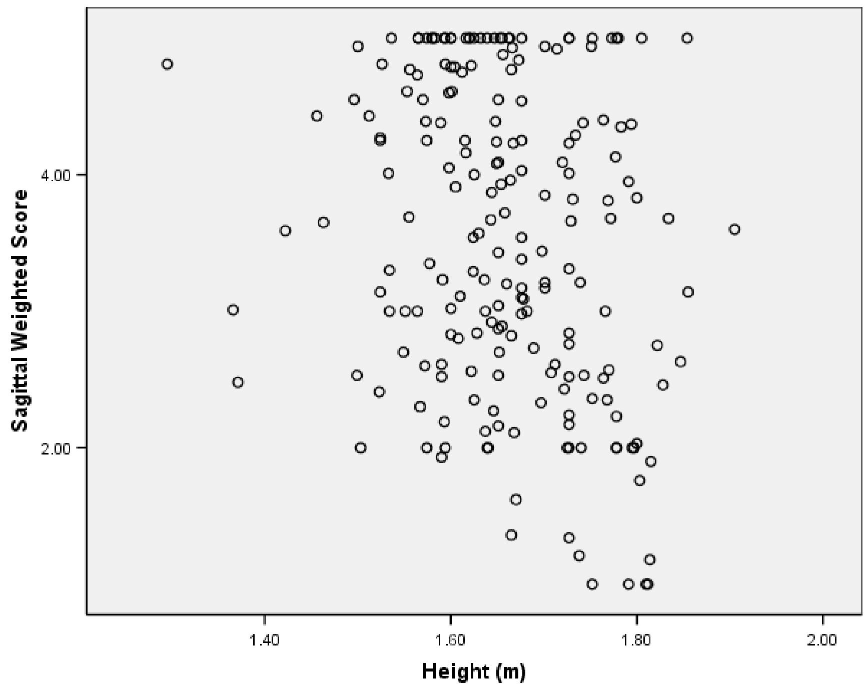


Figure 6.1 The negative, significant correlation between height (m) and weighted score of the sagittal suture for 201 subjects of the Hamann Todd Collection.

Unlike the other two sutures, the correlations in the lambdoid were very weak but consistent across both ancestral groups (r_s=-0.17, *p*=0.080, n=104 for white individuals and r_s=-0.18, *p*=0.110, n=83 for black individuals). The negative trend may suggest that individuals of greater heights are more likely to have patent or minimally fused sutures, although the weak correlations show that no definite pattern exists.

6.4.2 Sex, height and synostosis

Since height was significantly different between the sexes, separate analyses were conducted for males and females. In the sagittal suture, height was significantly, but weakly, related to weighted score in males (r_s=-0.25, *p*=0.01, n=104). In females, the correlation was negligible (r_s=-0.13, *p*=0.208, n=97). Both coronal and lambdoid sutures had nearly negligible or non-existent age-score relationships for males (r_s=-0.16, p=0.106, n=99 and r_s=0.035, p=0.740, n=94, respectively). For females, the coronal yielded a poor correlation once again (r_s=-0.19, p=0.067, n=97). Like the sagittal, the lambdoid showed disparities between the sexes; females had a weak but significant correlation (r_s=-0.22, p=0.034, n=95).

When the sample was divided by sex and ancestry, only black females showed a significant relationship between height and the weighted score of the sagittal suture (r_s=-0.31, p=0.044, n=43; white male, r_s=-0.23, p=0.071, n=63; black male, r_s=-0.24, p=0.137, n=41; and white female, r_s=0.04, p=0.751, n=52). In the lambdoid, black females had a significant correlation as well (r_s=-0.31, p=0.045, n=42), while in the coronal, all correlations were insignificant. Interestingly, even in the coronal, the black females had the highest r_s value (-0.23) of all the other groups examined, although the result was insignificant. The results did not favor a single conclusion about the relationship between sex, height and synostosis in these sutures. They are as complex and contradicting as the problem itself.

6.4.3 Age groups, height and synostosis

Since significant increases in stature did not occur temporally, subjects born in the 19th and 20th centuries were grouped and divided by age groups as done in Chapter 4. As shown in Table 6.2, height-score correlations ranged from poor to moderate and nearly all of them had a negative relationship. The adolescent group of the sagittal suture had the strongest correlation (r_s=-0.64, p=0.001, n=22; Figure 6.2), followed by that of the coronal (r_s=-0.53, p=0.011, n=22). Whether this is a product of the relatively small sample size or an actual trend is present is unknown.

Table 6.2. Correlation of height and weighted score of the sagittal, coronal and lambdoid sutures of subjects from the Hamann Todd Collection divided by age group.

Age group	Sagittal (r_s, *p,* n)	Coronal (r_s, *p,* n)	Lambdoid (r_s, *p,* n)
1	-0.64, 0.001, 22	-0.53, 0.011, 22	-0.12, 0.597, 22
2	0.16, 0.516, 18	-0.13, 0.606, 17	0.33, 0.175, 18
3	-0.19, 0.350, 27	-0.30, 0.135, 26	-0.15, 0.471, 25
4	-0.40, 0.037, 27	-0.24, 0.229, 26	-0.09, 0.688, 22
5	-0.06, 0.800, 21	0.15, 0.537, 20	-0.21, 0.383, 19
6	-0.11, 0.582, 29	-0.02, 0.911, 28	-0.18, 0.377, 27
7	-0.17, 0.350, 31	-0.13, 0.498, 31	-0.20, 0.274, 31
8	-0.20, 0.318, 26	-0.19, 0360, 26	-0.33, 0.107, 25

r_s, Spearman rank correlation; n, sample count

The 40-year-olds (from the sagittal group) showed a significant, moderate correlation as well (r_s=-0.40, *p*=0.037, n=27). The correlations of the remainder ranged from weak to being too low to be meaningful. The results did not show any concrete patterns, relating height to sutural development, although very young people may be an exception to this.

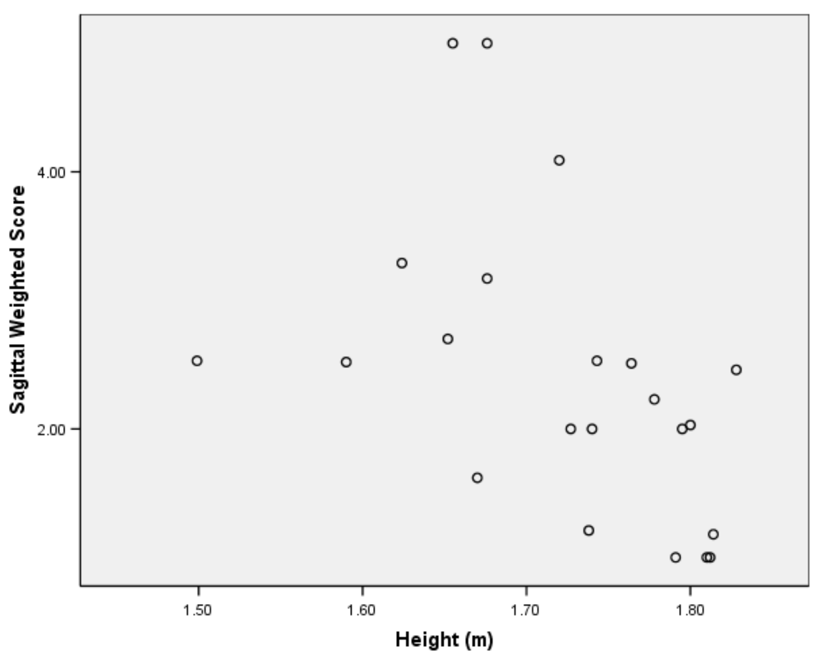


Figure 6.2 The inverse relationship between height and weighted score of the sagittal suture in adolescents (n=22).

The results (of the sagittal and coronal sutures) suggest that physical growth and synostosis may be connected. Cohen (1993) discusses a potential link between fusion and termination of growth. Does cessation of growth lead to sutural fusion? The answer is no; the brain stops growing well before the first cranial sutures start fusing during 3rd and 4th decades of life. Interestingly, growth does cease before the onset of fusion. For instance, growth in the face stops by 20 years of age, but the circummaxillary suture does not close until the 7th or 8th decade of life. It appears that sutural fusion does not immediately follow after the termination of growth. However, some of the young Hamann Todd individuals contradict this. Of all the age groups considered, the adolescents were the ones to experience dramatic growth and yet cases of obliteration were present here.

Greater growth would signal better health and environmental conditions. It seems that people who grow more during pubertal years maintain patency (or undergo minimal fusion). Those who do not reach their peak stature, perhaps due to malnourishment, are subjected to premature closure, which is not the natural state and can even be detrimental. For instance, craniosynostosis in infants can hinder survival without surgery. Recently, a gene was identified as the cause of non-syndromic craniosynostosis (Grova *et al.*, 2012). Although premature closure in infants may be genetic, there is most likely an environmental aspect to premature closure in adolescents; the association between weighted score and stature as a proxy for health is evidence of that. The ultimate question is why poor health would result in early fusion.

6.4.4 Weight and synostosis: Influence of sex and ancestry

The affect of weight on the weighted scores of the sagittal, coronal and lambdoid sutures was negligible (e.g. r_s=0.03, *p*=0.707, n=200 for the sagittal; Figure 6.3). As expected, there was a sex-based difference in weight in the sample; males ($\bar{x}$=58.6±13.79 kg, n=103) on average were heavier than females ($\bar{x}$=47.27±12.54 kg, n=97). Weight was significantly different between white (n=144) and black (n=84) subjects as well (U=3931.0, *p*=0.031). White individuals, on average, possessed greater weights than their black counterparts, but the white sample had older individuals, which may account for this difference.

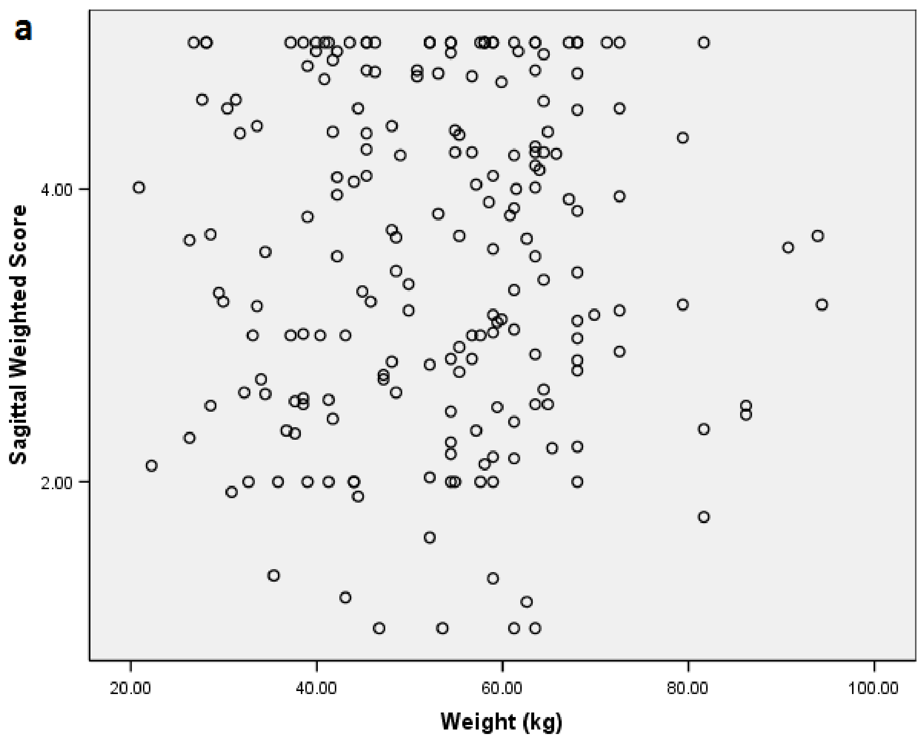
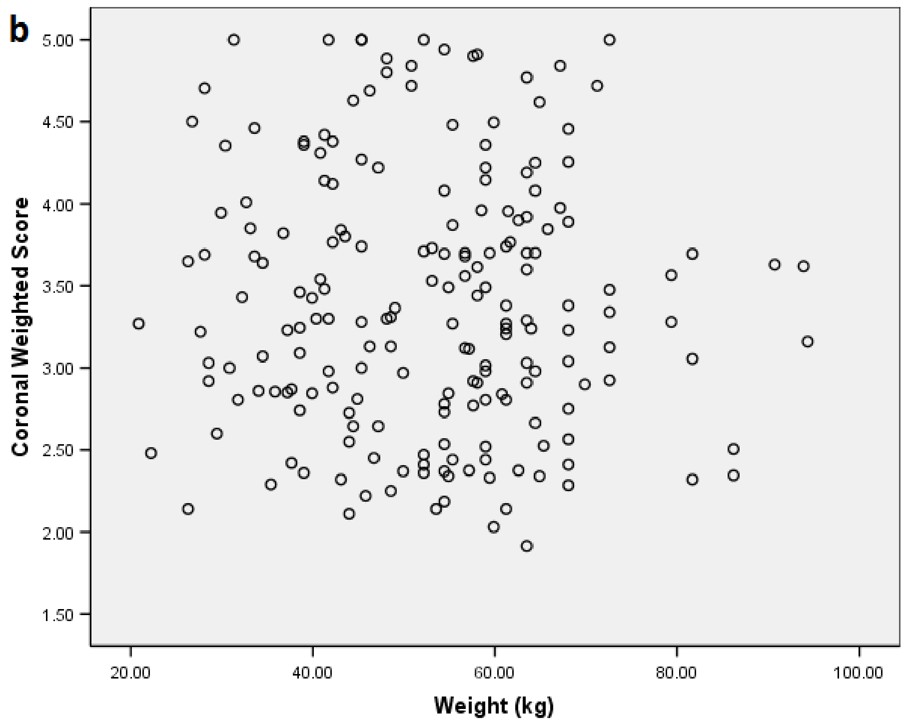
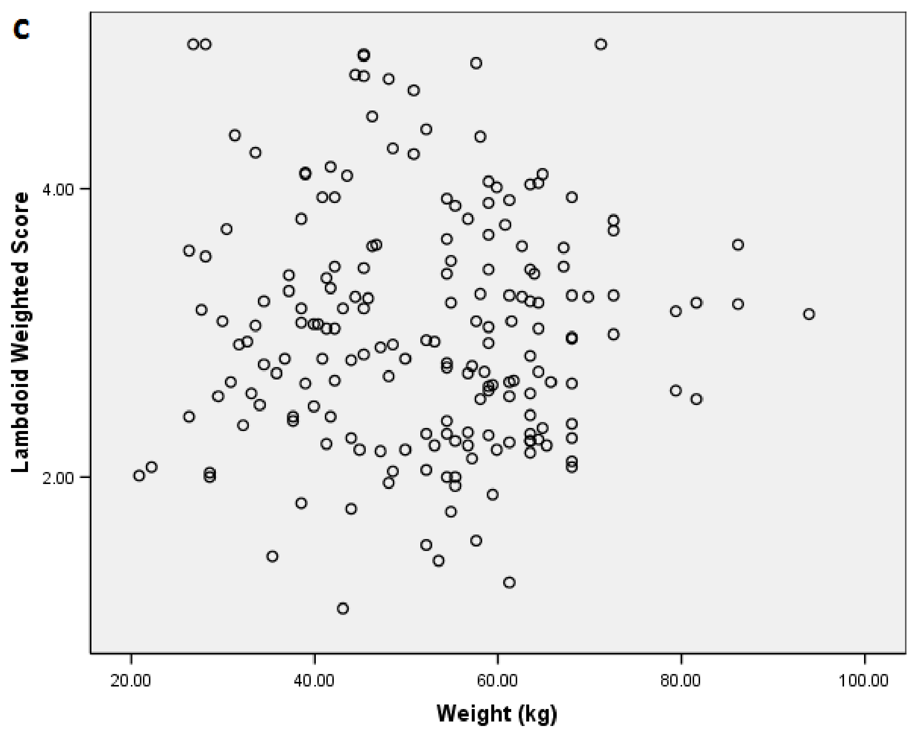


Figure 6.3 The negligible correlation between weight (kg) and weighted score of the a) sagittal (r_s=0.03, *p*=0.707, n=200), b) coronal (r_s=-0.03, *p*=0.628, n=195) and c) lambdoid sutures (r_s=-0.01, *p*=0.883, n=188).





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6.4.5 Body mass index

Weight cannot be assessed in the same manner as height. It is partially dependent on the height of a person, genetics, and nutritional status during growth periods, and cannot be reliably used to deduce health by itself. Also, weight gain does not stop at a fixed point in life like height; it fluctuates with time. A measure, like the body mass index (BMI), which combines weight with height, is a much more useful approach to test for malnourishment.

Most of the sample was either underweight (41%) or normal (44%) by modern standards. The sample consisted of 26 (13%) overweight and two obese individuals, which is surprising considering that the subjects belonged to the poor class, who lived during a period of squalor and malnourishment. Hence, it is possible that the obesity here could have been caused by illness. However, since cause of death was unnatural in the obese individuals, it was difficult to verify this.

6.4.5a BMI, age and synostosis

Keeping the weight category constant, the relationship between age and weighted score of the sagittal suture was examined. Amongst underweight individuals, the correlation was low, but significant (r_s=0.29, p=0.010, n=80). Normal individuals showed a weaker correlation (r_s=0.17, p=0.108, n=86). When the overweight-obese group was tested, the correlation was moderate but insignificant (r_s=0.36, p=0.058, n=28). Interestingly, when the two obese individuals were removed from the group, the correlation became stronger and significant (r_s=0.43, p=0.028, n=26). The results were not influenced by age distribution as the mean age of each group centred on the 6th decade of life and consisted of both young and old individuals.

The coronal showed moderately strong trends when BMI categories were considered. Amongst underweight individuals, correlations were significant and resembled that of the entire sample (r_s=0.44, *p*=.000, n=80). People of normal weight showed a lower correlation (r_s=0.31, *p*=0.005, n=81). The weakest correlation was seen in overweight and obese individuals (r_s=0.23, *p*=0.232, n=28).

In the lambdoid, the age-score correlation of underweight individuals resembled that of the entire sample (r_s=0.35, *p*=0.001, n=79) and the normal group was similar to the underweight individuals (r_s=0.34, *p*=0.002, n=81). Overweight and obese individuals showed a negligible correlation (r_s=-0.06, *p*=0.773, n=22).

It is surprising that in all three sutures, underweight individuals showed a significant and stronger relationship between age and score than the normal group. Only in the lambdoid was there no substantial difference. There was a sharp contrast between the sutures in regards to overweight and obese individuals; the sagittal showed a moderate correlation while the coronal and lambdoid had weak or negligible ones.

Being underweight may suggest malnourishment while being overweight may imply illness (e.g. diabetes, thyroid malfunction), and yet in the former group, the sutures, particularly the coronal, followed a more predictable pattern of closure. Could nutrient deprivation somehow trigger this? Why would healthy individuals have more variable closure patterns? Perhaps variability is the norm and age-related synostosis is abnormal. The same pattern was seen amongst youth earlier in this chapter. The presence of a stressor, such as malnourishment and chronic disease, may trigger premature closure or increase the rate at which closure occurs. That may explain why some adolescents in the Hamann Todd sample have obliterated sutures. If a completely fused suture is not the natural end result, then this would explain why old individuals in the sample show patency.

This, however, does not explain the patterns seen in the coronal and lambdoid sutures. In the coronal, overweight and obese individuals had very poor age-score correlations. In the lambdoid, normal individuals had correlations as strong as that seen in the underweight group, indicating that malnourishment may influence synostosis differently in different sutures.

None of the correlations were high enough to say that a definite link exists between progression in a suture and malnourishment and illness. When individuals under the age of 50 years with near-closure or complete obliteration scores were isolated (belonging to the sagittal group), individuals of every BMI group were present (n=33). Underweight individuals made up 36% (n=12) of the sample, normal individuals made up 44% (n=16) and the overweight group made up 5% (n=5). This suggests people of normal weight are just as likely to develop an obliterated sagittal suture as underweight people.

6.4.5b BMI and ancestry

As shown in Chapter 3, black individuals had a significant and stronger age-score relationship than white subjects. The results of this chapter suggest that malnourished or otherwise stressed individuals may be more likely to exhibit a stronger age-score relationship than healthy individuals (at least in some sutures). Examining ancestry-based trends in body mass index further supports this idea.

White individuals, on average, had significantly greater BMI scores than black individuals (U=3415.0, p=0.003, n=192). A fair percentage of black individuals were underweight, while more of the white subjects had normal weight or were overweight. This may answer why age-score correlations were so poor for white individuals in Chapter 3 while the opposite trend was seen amongst black subjects.

6.4.6 A case study: Evidence for the impact of malnourishment on synostosis

So far, it has been shown that malnourished people are more likely to develop stronger age-score correlations. Specimen number 529, a black female, aged 34 years, who was born in the late 1800s, demonstrates that extreme malnourishment may trigger complete obliteration of a suture in a very short amount of time. This individual died from marasmus, a condition where the health of a person rapidly deteriorates due to malnourishment. This individual offers an excellent opportunity to study the effects of extreme malnourishment (ultimately leading to death) on synostosis. This individual's adolescence was most likely not affected by this condition since her stature at death was not below average (1.60 m). According to modern standards, she had a normal BMI as well. It is probable that she was malnourished shortly (e.g. a matter of months) before her death, and yet her sagittal suture was fully fused. If the premature closure is connected to her malnourishment, this case may indicate that rapid fusion may occur over a short period of time in response to an environmental trigger. Interestingly, rats, fed on diets deficient in vitamin D and calcium, combined with biomechanical factors, were more likely to exhibit sutural obliteration (Engström & Thilander, 1985). Specimen 529 offers additional support that malnourishment can interfere with sutural progression, by accelerating closure rate, particularly in the sagittal suture.

6.4.7 Chronic and acute health conditions and their effect on synostosis

If illness does influence the progression of a suture, then the next step would be to look at cause of death. Of 276 subjects, 160 suffered from chronic illnesses that may or may not have influenced closure. There were 90 cases of sudden deaths, which ranged from natural deaths (e.g. acute illness) to suicides and homicides. The most prevalent types of disease involved the heart (e.g. atherosclerosis), lungs (e.g. pulmonary tuberculosis, TB) and kidneys (e.g. nephritis).

When subjects were divided as having short-term (including homicides) and long-term illness/causes of deaths, the differences in age-score relationship between the groups contradicted the results shown so far. In the sagittal suture, the age-score correlation was weak for people with chronic disease (r_s=0.24, p=0.002, n=158). The strength of the correlation was greatest in the coronal (r_s=0.36, p=.000, n=154), while the lambdoid resembled the sagittal (r_s=0.27, p=0.001, n=153).

In the acute group, the correlation was moderate in the sagittal (r_s=0.40, p=.000, n=90) and coronal (r_s=0.49, p=.000, n=83), and weak in the lambdoid (r_s=0.30, p=0.008, n=80). These results are inconclusive as there are a number of different interpretations. This may suggest that having a chronic illness weakens the age-score relationship, contrary to what was said previously. The strong correlation in the second group may be unreliable because medical history is not listed for these individuals. Thus, these people could have had a long-term illness but succumbed to death in another manner.

In general, the reliability of these results is somewhat questionable due to the lack of data. For instance, there is no data on the onset of a person's illness. Although some conditions are classified as chronic, the person may not have lived long enough in that state for the illness to affect synostosis, especially if proper medical care was not available, as was the case for these individuals.

To counteract this, individuals under the age of 50 years who had been bed-ridden prior to death were examined to test the effects of chronic illness on synostosis. The average weighted scores for bed-ridden individuals (n=10) was greater than that of similarly aged individuals (n=129-140). This was consistent across all three sutures. Due to the small sample size, the results need to be interpreted with caution, but they do lend support to the idea that chronic illness can accelerate synostosis.

6.4.8 Premature synostosis and illness

The next line of inquiry was to determine if certain illnesses occurred more frequently with cases of premature synostosis. Amongst individuals under the age of 50 years who had weighted scores of 4 or higher in the sagittal suture (n=47), cause of death was quite variable, although some illnesses were more prevalent than others. About 17% of subjects with premature closure (or near closure) had tuberculosis. Carcinoma (cancer) and syphilis made up 6% and 8% of the sample, respectively. Blood- and heart-related diseases made up 15% and pneumonia constituted 11%. There were two deaths associated with kidney failure, one with problems in the gastrointestinal tract and one case of marasmus (mentioned above).

There were only eight cases where complete obliteration of the coronal suture occurred, five of whom were younger than 65 years. Their cause of death was very variable (e.g. tuberculosis, asthma, lobar pneumonia, etc.). Specimen no. 3357 had an eroded hole on the right parietal due to tuberculosis, indicating that the disease had an effect on the cranium, but whether this or senescence influenced closure is unknown (the individual was 87 years old). In the youngest individual, specimen no. 1711, a black 17-year-old male who died of pulmonary TB, both the sagittal and coronal were obliterated. Although the cranium looked normal in form, this person likely suffered from some malnourishment, since the first molar, canine and incisors were eroded and pitted.

Complete obliteration in the lambdoid was even rarer than in the coronal (n=3). Here, cause of death ranged between cancer and hypertension. It appears that only the sagittal is likely to have complete fusion, particularly in young individuals. In the three lambdoid cases mentioned above, the sagittal suture was fully fused as well. Full closure solely in the lambdoid was not seen in this sample.

6.4.9 Unnatural deaths: Alcoholism and narcotics

In addition to homicides and accidents (15%) for which a medical history was not listed, unnatural deaths included chronic alcoholism and narcotism (11%). This is of interest because long-term alcohol and narcotics use can change brain structure. Whether this can in turn impact synostosis has not been studied. Interestingly, nearly every person under the age of 50 years whose cause of death was alcoholism or narcotics use had a completely obliterated sagittal suture, the youngest being only thirty-four years old (spec. 1747). When the sample was increased to include individuals in their 50s, the pattern was consistent there as well.

However, the pattern was not absolute. When individuals of all ages were examined (n=18), there were quite a few people without a nearly complete or fully obliterated suture (44%). There are a few explanations for this. Generally, older individuals had the greatest scores

(30+ year olds), suggesting that the longer a person had been using alcohol or drugs, the greater the degree of obliteration seen in the suture. Two of the lowest scores were seen in individuals under the age of 30 years. Specimen 3512 was 27 years old and died in 1939. Since Prohibition was in effect from 1920 to 1933 in the United States, this person could only have taken up serious drinking for a maximum of six years, assuming illegal alcohol was not acquired. However, it is clear that illegal alcohol was available to the lower class of Cleveland; specimen 1747 died eight years after the start of Prohibition due to alcoholism.

It may be argued that these results have very little to do with these individuals' vices, since synostosis is supposed to correlate with age. However, complete obliteration is not expected to be seen in the alcoholic/narcotics group because the age range is only 27 to 55 years (with one subject of senescence). Yet, complete fusion was present. Therefore, something, perhaps the prolonged use of detrimental substances like alcohol and drugs, was the trigger.

There were 17 cases of alcoholism and narcotics use in the coronal and lambdoid samples. Unlike the sagittal, complete obliteration was not seen here, although some reached near obliterated conditions. Alcoholism and narcotics did not seem to impact these sutures as they did in the sagittal. However, graphically, this group revealed a surprisingly moderately strong, linear trend (but weaker trends in the lambdoid) between age and weighted score (Figure 6.4). Although $p > 0.05$, the lack of significance may be due to the small sample size.

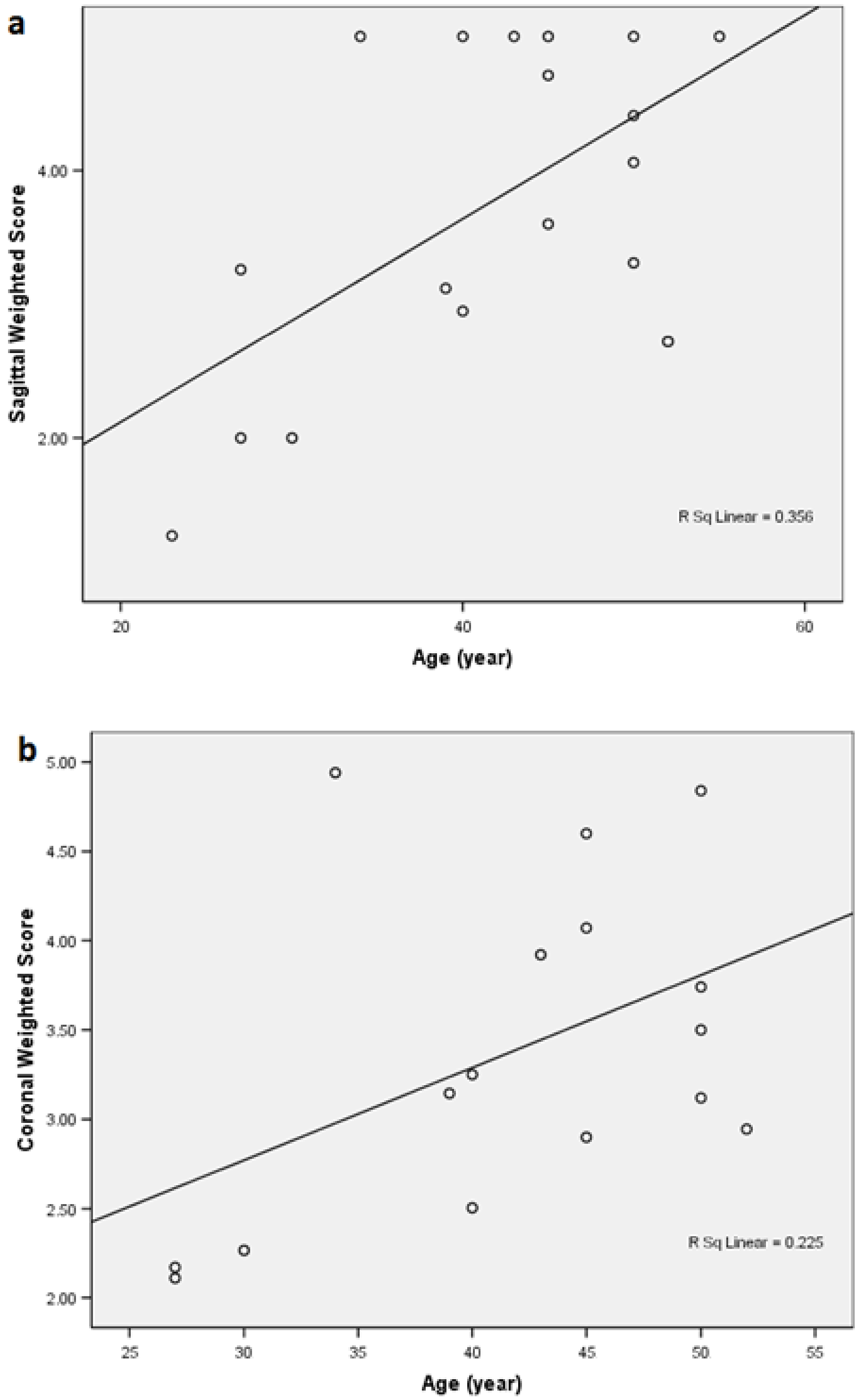
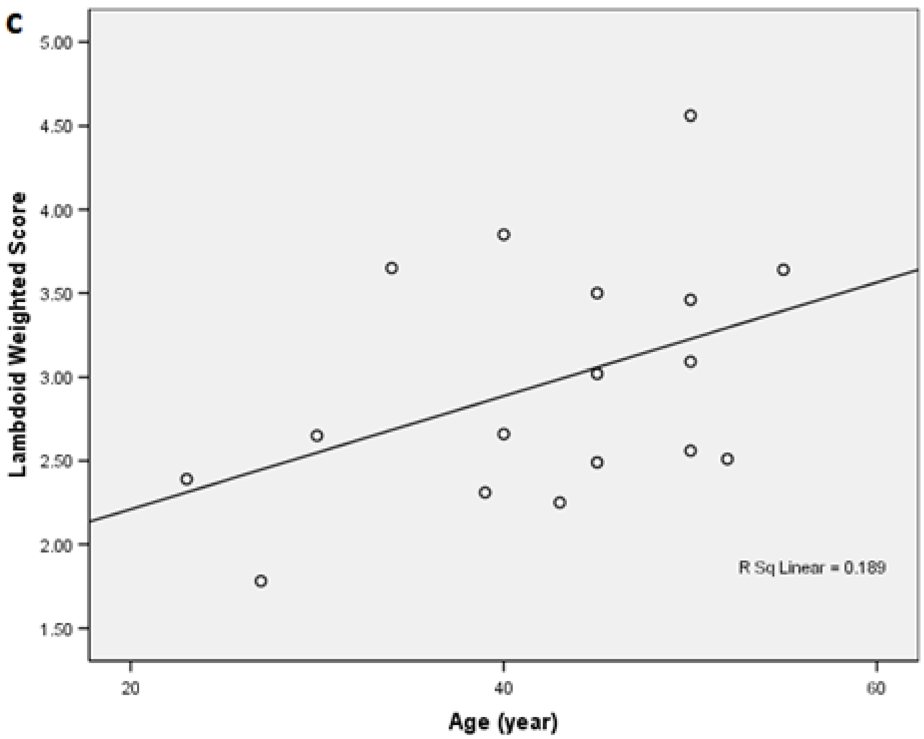


Figure 6.4 Moderate correlations between weighted score and age amongst individuals whose cause of death was alcoholism and narcotics use for a) sagittal (r_s=0.45, *p*=0.063, n=18), b) coronal (r_s=-0.43, *p*=0.081, n=17) and c) lambdoid (r_s=0.38, *p*=0.129, n=17).



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6.4.10 Cranial irregularities

Another variable that was tested was cranial irregularities. The purpose of this was to test whether the presence of certain features on the bone, like ossicles, would affect (or occur concurrently) the degree of synostosis reached at the time of death. Stotland *et al.* (2012) discuss the occurrence of wormian bones in association with craniosynostosis. These accessory bones are not themselves pathological but they are known to occur in concert with pathological conditions (e.g. hydrocephaly). In fact, they are associated with skull asymmetry, bone malformation, and patency in the metopic suture in adulthood. This may serve as an indicator of health problems. Unlike wormian bones, which develop from separate ossification centres, accessory bones like, the os incae (Inca bones), develop when the upper and lower parts of the occipital do not fuse (Hauser & DeStefano, 1989 in Stotland *et al.*, 2012).

The Hamann Todd sample had a high prevalence of wormian bones and other bony irregularities (40.2%). In comparison, previous population-based studies indicate that wormian bones occurred in 80% of Chinese skulls examined (Hauser & DeStefano, 1989 in Stotland *et al.*, 2012). About 25% of Inuit skulls had accessory bones, the lowest percentage seen across 14 different populations. There was no sex-based difference in the expression of wormian bones, but it occurred less frequently in older individuals.

In the Hamann Todd sample, individuals who were free of these additional features had a weak age-score relationship in the sagittal suture (r_s=0.16, *p*=0.002, n=165). The coronal and lambdoid had similar correlations (coronal: r_s=0.35, *p*=.000, n=156; lambdoid: r_s=0.31, *p*=.000, n=153). When only "irregular" individuals were examined, the correlation was much stronger in the sagittal (r_s=0.47, *p*=.000, n=111), but the strongest trend was seen in the coronal (r_s=0.52, *p*=.000, n=108). The lambdoid presented a weak correlation (r_s=0.28, *p*=0.004, n=106). It appears that the presence of extra bony features triggers or is associated with stronger age-synostosis correlations in the sagittal and coronal sutures. However, the correlation coefficient is not large enough to state that a definite relationship exists. It is interesting to note that again, the sagittal and coronal show similarities that are lacking in the lambdoid.

6.4.11 Skull density and synostosis

Sun *et al.* (2004) noted that in pigs fusion in the sagittal suture was caused by thickened, dense bone in that region of the cranium. An overgrowth of bone resulted in synostosis. This phenomenon was examined to see whether the pig model is applicable to humans. Skull density of the cranium was used with the expectation that highly dense skulls would be more likely to exhibit sutural obliteration. In the Hamann Todd Collection, some of the skulls were drastically lighter or denser than the majority. This was determined macroscopically by the author; weighing equipment was not used.

The degree of progression reached at the time of death was compared in these two groups. Only the coronal suture showed a significant difference; very light skulls exhibited greater degrees of fusion than very dense ones (U=5.0, p=0.002, n=18). The dominant condition in the light group was near completion while only progression toward significant fusion was seen in the dense group. In fact, despite the lack of significance, this was consistent in the sagittal and lambdoid sutures as well. However, this contradicts the pig data. Thickened bone is not associated with synostosis in humans.

The light group was older than the dense group ($\bar{x}$=62.2±5.2 and 44.4±8.3 years, respectively) but the difference was not significant (U=17.5, p=0.083). Extremely high and low skull densities were most prevalent in females. Despite the small sample size, these are interesting preliminary results. Age-score correlations in the sagittal suture for dense skull was strong (r_s=0.89, p=0.019), but the sample size of six is not adequate enough to argue that a definite relationship exists. Future research should test age-score correlation in light and dense skulls using a large sample size.

6.5 Conclusion

The effect of nutrition and overall health of an individual was quantified and regressed against progression in the sagittal, coronal and lambdoid sutures. Height consistently showed negative trends when regressed against the weighted score of all three sutures. There were, however, population-specific differences. For instance, black individuals had a significant height-score relationship in the sagittal while white subjects had a nearly negligible correlation. Adolescents showed the greatest correlation between height and synostosis. This suggests that physical growth and synostosis may be connected. The negative trend is of interest; it insinuates that taller people are associated with less development. Previous research (e.g. Cardoso and Garcia, 2009) indicates that taller people are associated with better nutrition and overall health, but this does not align with the results here. It may be presumptuous to assume that good health equates with regular patterns of closure. In fact, the results indicate that the opposite is true.

A number of other variables were tested as well to determine what can disrupt or trigger fusion. Stronger age-score relationships were generally seen in underweight individuals. Progression in individuals with chronic and acute illnesses was inconclusive, but premature closure was not associated with any particular disease. Individuals who used alcohol and/or narcotics for prolonged periods may be more likely to exhibit an obliterated sagittal suture. The presence of cranial features like wormian bones may be associated with a more predictable pattern of sutural development. Very light skulls were more likely to exhibit greater fusion than extremely dense ones. Thus, a number of patterns exist. The results indicate that the health of a person can influence sutural closure.

7 Biological features, synostosis in sutural segments and facial sutures

Three small studies were undertaken in this chapter. First, the effect of biological features on synostosis was examined. Next, the supposed age-related sutural progression in segments of the sagittal, coronal and lambdoid sutures that are presently used to generate age estimations was scrutinized. Finally, cranial sutures were compared to the internasal facial suture to discuss differences and similarities in development and progression between cranial and facial sutures.

7.1 Parietal foramina: Impact on the obelionic region of the sagittal suture?

7.1.1 Introduction and methodology

Sometimes segments of a suture may develop faster or slower due to the presence of a biological feature, like a muscle. Kokich (1976) examined the effect of the masseter muscle on the frontozygomatic suture and found it exhibited an increasingly irregular route toward union with age due to its association with the muscle. This is related to the masticatory strain hypothesis, which theorizes that suture closure is affected by mechanical forces like tension and compression brought on from mastication. Sun *et al.* (2004) theorize that the intense bone apposition as a result of mastication leads to fusion of the sagittal suture in pigs. In *Gorilla*, mastication correlated strongly with sutural fusion (i.e. more masticatory activity meant a higher occurrence of obliterated sutures; Cray *et al.*, 2011b). In humans, on the other hand, the location of the sagittal suture ensures that it is not impacted by muscle activity (Kanisius & Luke, 1994 in Wolff *et al.,* 2013).

Since mechanical forces pass through the mandible to the face and then reach the cranium, it would be a good adaptation for facial sutures to remain patent or unfused during life. For instance, the circummaxillary sutures may act as shock-absorbers for the masticatory muscles (Cohen, 1993). This does not always appear to be the case. Weasels, for example, have fused facial sutures despite the presence of powerful muscles of mastication. Studying the impact of large antlers on the frontal bone of cervids (deer), Sanchez-Villagra (2010) reports that the biomechanical stress involved in bearing these structures did not alter the sequence of synostosis in the cranium. These cervids followed a suture closure sequence similar to smaller cervids. Thus, a mixed set of results are present in the literature about the impact of biomechanical stress.

The focus of this section is the obelionic region of the sagittal suture, which is the portion described by Meindl and Lovejoy (1985) as occurring superior to the lambda (Figure 7.1). This segment has been observed to exhibit full or near-complete fusion while the rest of the suture remains in a state of incomplete synostosis (Todd & Lyon, 1924). According to Todd and Lyon (1924), fusion in the sagittal suture occurs first at the obelionic region.

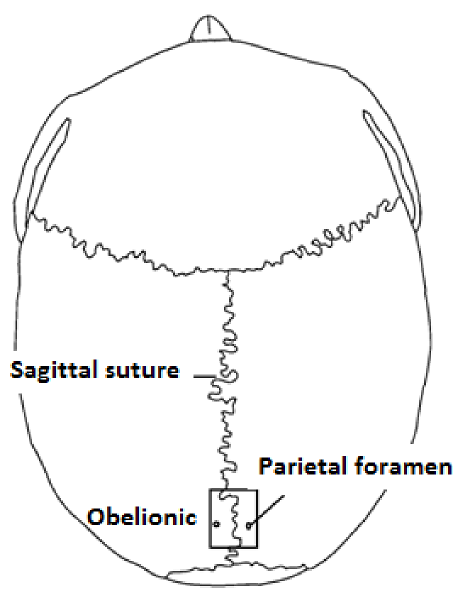

Figure 7.1 The obelionic region of the sagittal suture with parietal foramina.

To test whether the presence of the parietal foramen and the parietal emissary vein that passes through influences this early closure, 125 specimens from the Hamann Todd Collection were randomly selected and examined. Ninety-five subjects exhibited one or more foramina in the obelionic region while 30 did not. The degree of fusion reached was recorded to see whether there was a significant difference. This progression was recorded following the 4-point system outlined by Meindl and Lovejoy (1985) where a score of 0 is patency, 1 is minimal fusion, 2 is significant fusion and 3 is obliteration. For statistical purposes, these categories were re-named using a scale of 1 to 4. Figure 7.2 shows mean age, segment score, and their standard deviations for both groups. Both groups had similar mean ages, although the group with no foramina was slightly older. The same group had a slightly higher average score as well.

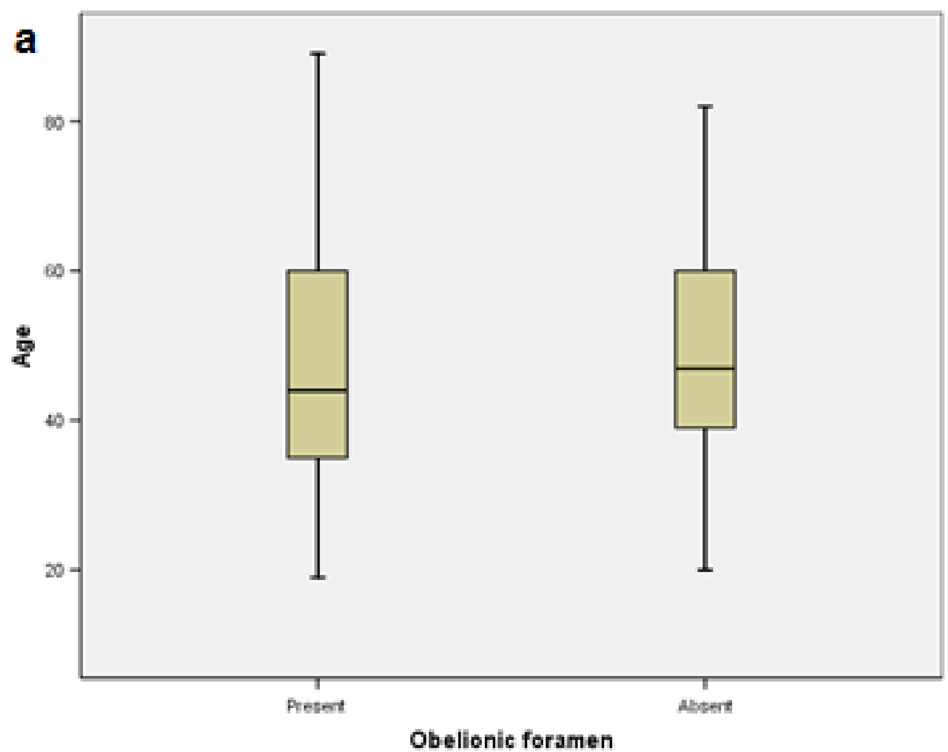

Figure 7.2 (a) Mean age (years) and (b) score of the obelionic region for individuals with and without parietal foramina.

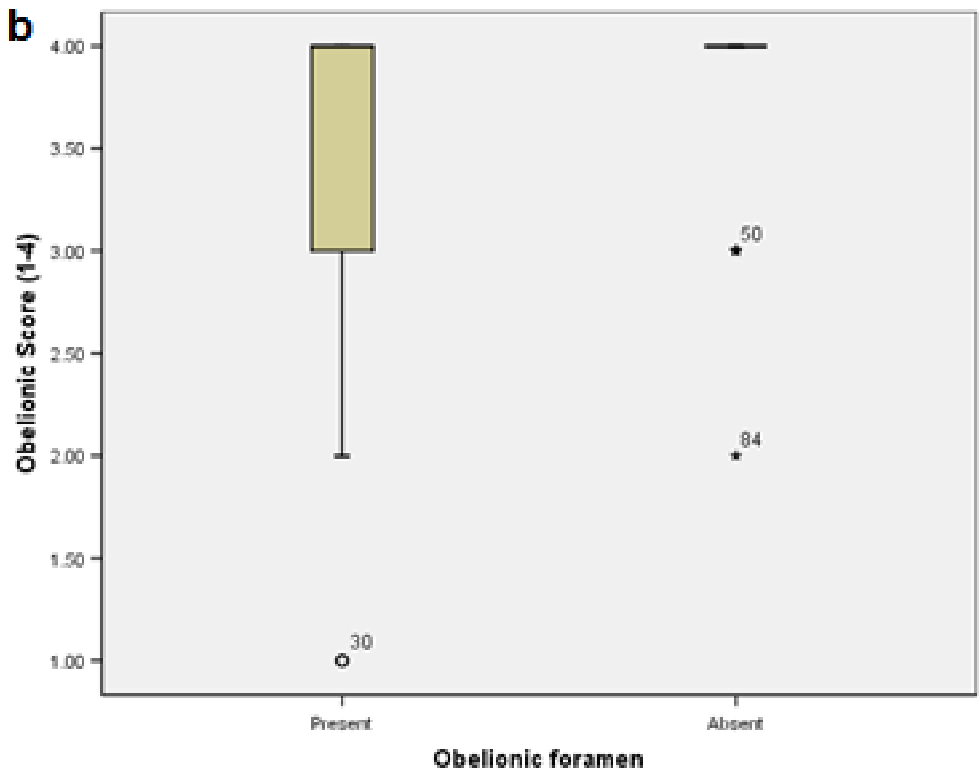

Figure 7.2 (a) Mean age (years) and (b) score of the obelionic region for individuals with and without parietal foramina.

7.1.2 Results

Is there a significant difference between degree of fusion achieved and the presence of obelionic foramina? A significant relationship did not emerge (U=1283.5, p=0.304, n=125). As shown in Figure 7.2, the average score of the obelionic region for both groups was very similar. It appears that the presence of the parietal foramina and the parietal emissary vein that runs through it did not trigger or influence in any other way the rapid degree of closure reached in the obelionic region of the sagittal suture. There was variation in the number of obelionic foramina present; this ranged from 0 to 2. The majority of subjects had two foramina. A Kruskal Wallis test indicates that the number of foramina was not correlated to synostosis in the obelionic (χ^2=1.644, df=2, p=0.440).

The observation that this region tends to fuse earlier than other areas of the sagittal was verified. Of 125 subjects, 89 achieved a score of 3 (complete closure) while 14 and 20 scored 1 and 2, respectively. Only two individuals showed patency. One of these individuals was only 21 years old; patency is expected here. However, the second subject was 87 years old. Despite this oddity, 71% of the sample exhibited a fully fused obelionic region. This supports the idea that the obelionic region is more likely to be obliterated compared to any other part of the sagittal suture. These results support Todd and Lyon's (1924) conclusion that the obelionic region is the point at which fusion commences in the sagittal suture. The shape of the suture segment further supports this conclusion. According to Cohen (1993), the greater the oscillation, the longer the suture has been open. In many of the Hamann Todd subjects, the obelionic region was straight (i.e. the suture was not serrated). Even though the sample was relatively aged, complete obliteration of other parts of the sagittal suture was not seen, and this favors the idea that the obelionic region does not stay patent as long as the rest of the suture.

7.2 Age-related patterns in segments of the sagittal, coronal and lambdoid sutures

In present-day aging methods based on cranial sutures, age is estimated from points along the suture. The resulting age estimations are often broad. Actual ages frequently do not even fall in these wide age ranges (see Chapter 2). The high error rate in aging with cranial sutures was traced back to progression in the individual segments used to generate these estimations. Fusion at different points of the sagittal, coronal and lambdoid sutures was examined to see whether one part of the suture is more likely to exhibit a linear age-related trend. In some of these segments, sex- and population-based differences noted in previous chapters were examined as well. Sutural progression was mapped in the following sutural segments: the obelionic, bregma and lambda of the sagittal suture; the inferior coronal, mid-coronal and bregma of the coronal suture; and the lambda and mid-lambdoid of the lambdoid suture (Figure 7.3).

It is important to track progression in individual segments of a suture, in addition to tracking development in the entire suture. After all, the most popular cranial aging technique, the Meindl-Lovejoy method, is based on these segments. Progression in segments is just as complicated as the whole suture, since different sections of the same suture can begin fusion at different times. Furthermore, the rate of progression may not be the same across these segments as shown by the work of Todd and Lyon (1924). In a study on rhesus monkeys that were injected with Ca-45 (a radioactive tracer), it was found that the same suture had differing rates of formation, proliferation and calcification at different locations (Yen & Shaw, 1963). This research showed that uptake of Ca-45 was different on both sides of the same suture in some cases, indicating that one bone was growing at a faster rate than the other.

The results shown below for patent sutures and the age groups associated with this condition are reliable. However, observations on obliterated sutures can be erroneous since the age at which obliteration occurred is unknown. As in the case of the specimen 529 mentioned in Chapter 6, if individuals proceeded from significant fusion to obliteration in a matter of months, the results presented here will have less error associated with them. However, this may not be the case for all individuals, and thus, the age estimations generated from an obliterated segment are not provided here.

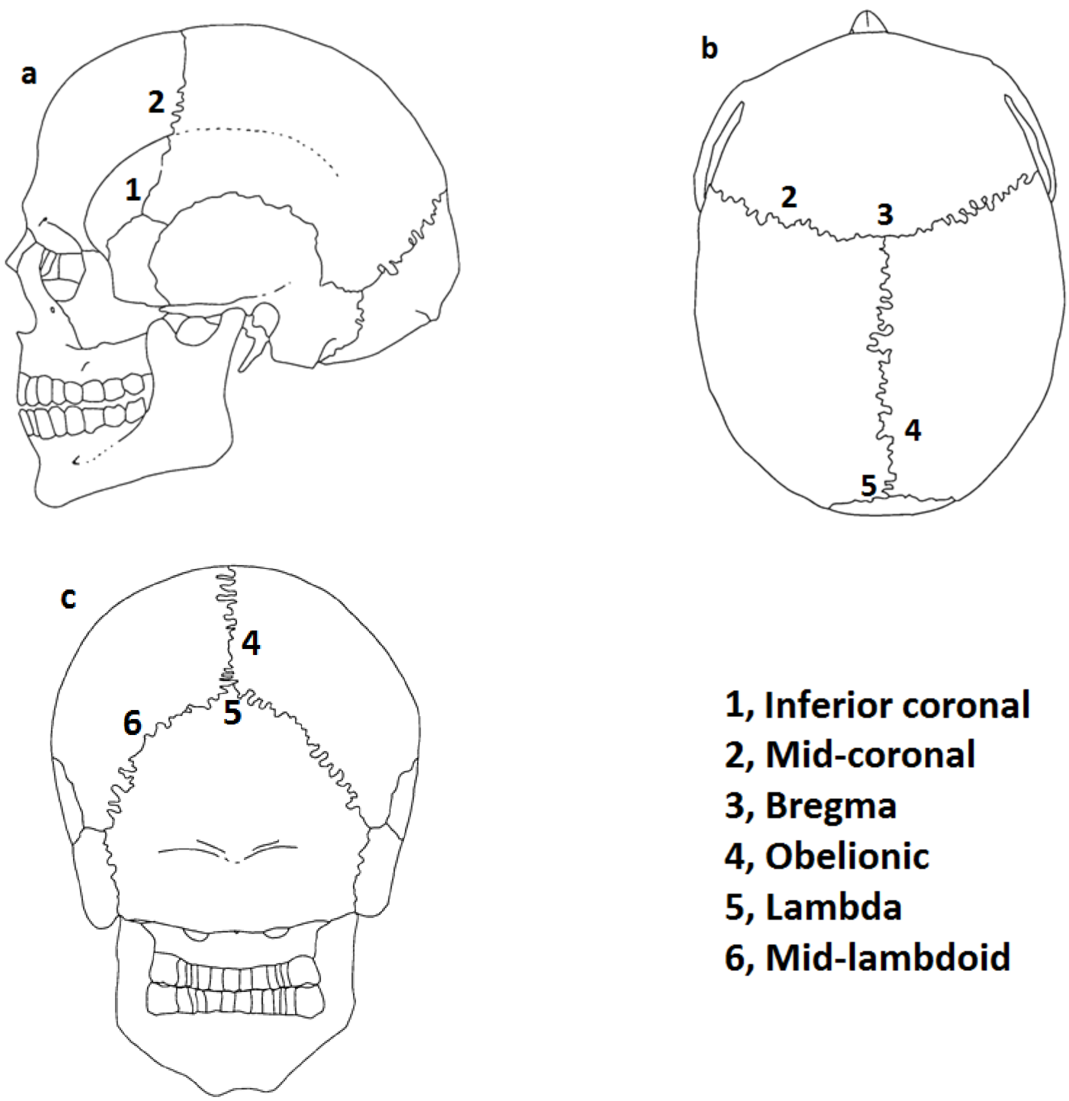

Figure 7.3 Location of sutural segment, showing a) lateral, b) superior and c) posterior views.

7.2.1 Obelionic

As shown in the previous section, the obelionic region of the sagittal is known to close more quickly than the rest of the suture. This was evident in the Hamann Todd sample, but how well does it correlate with age? This is important to know since the obelionic is used in current age estimation techniques. The strength of the correlation was comparable to the correlations for the entire sample presented in Chapter 3 (r_s=0.28, p=0.002, n=125); a weak but significant relationship was present. A patent obelionic was associated with individuals under 30 years, although some subjects in group 8 showed patency as well (Figure 7.4). Examining other segments of the sagittal, coronal and lambdoid (see below) will show that only in the obelionic was patency observed in very old adults. However, complete obliteration was the dominant condition in the obelionic, indicating that fusion occurred earlier.

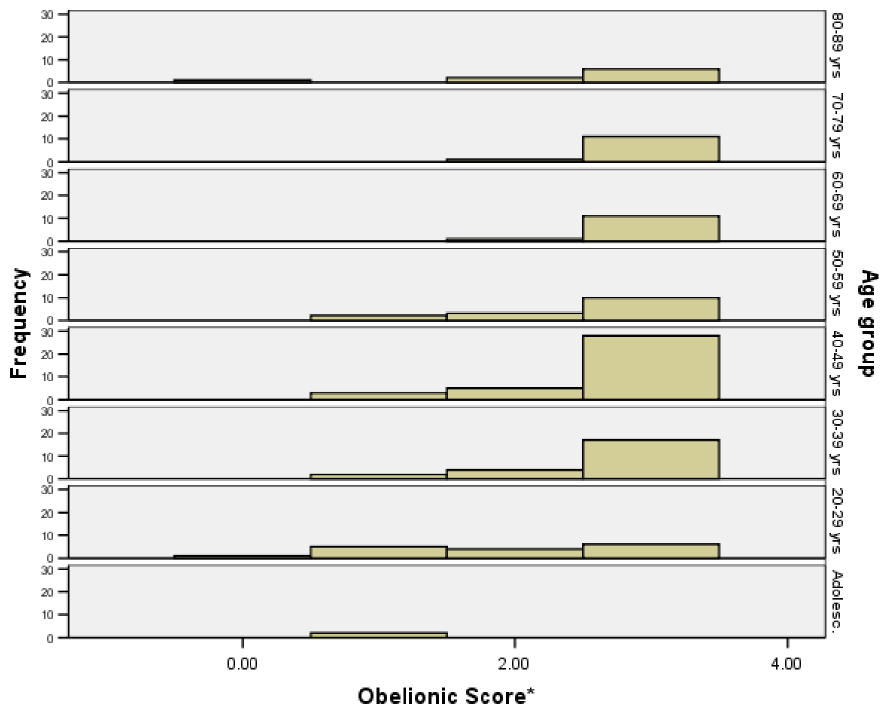

Figure 7.4 Fusion in the obelionic region of the sagittal suture (n=125).
*The Meindl-Lovejoy scoring system was used here; the rest of the segments were scored according to the system outlined in Chapter 3.

The obelionic surpassed both the bregmatic and lambda regions of the sagittal suture in terms of progression, with an average score of 3.56 ± 0.75 (significant fusion, progressing toward nearly complete fusion), even though the average age of the obelionic group was slightly lower ($\bar{x}$=48.20±3.60 years). Nearly all of the individuals in the sample showed significant or complete fusion in this region. Based on the Hamann Todd sample, the obelionic portion had a tendency to fuse at least by the late 20s, which means it cannot be used as an indicator of age in older individuals.

7.2.2 Bregma and lambda

Macroscopic observations showed that some general patterns have emerged in regards to fusion at certain points along a suture. In the bregmatic portion of the sagittal (Figure 7.3), a weak, significant trend emerged (r_s=0.22, *p*=.000, n=276). Figure 7.5 illustrates closure in 170 white males and females. Scores ranged from patency to significant fusion in adolescents. Age group 2 (20-29 years) showed more cases of minimal and significant fusion, although patency and complete fusion were seen here as well. Patency was not present in group 3, but reappeared in groups 4 and 5.

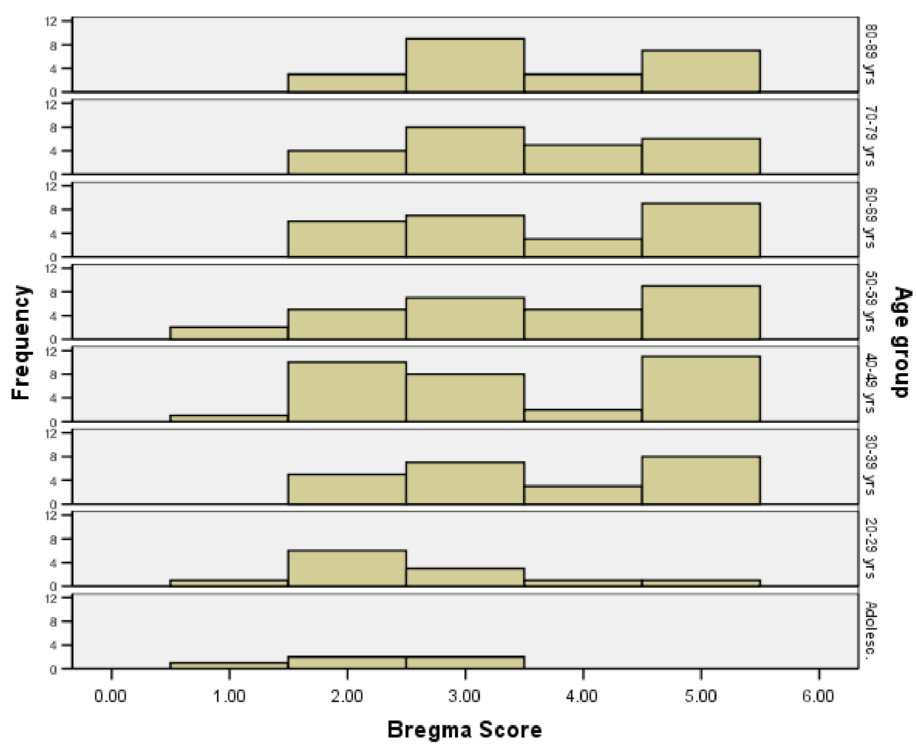

Figure 7.5 Fusion in the bregma region of the sagittal suture in white individuals (n=170).

A patent bregma can mean that the individual is under the age of 60 years. A minimally or significantly fused suture is difficult to interpret, as it is present in every age group.

The portion of the lambda made up by the sagittal suture was examined here (Figure 7.3). The lambda scores and ages were weakly related (r_s=0.19, *p*=0.001, n=276), and was the poorest of the three sagittal segments. Figure 7.6 shows sutural progression in the lambda in white individuals (n=170).

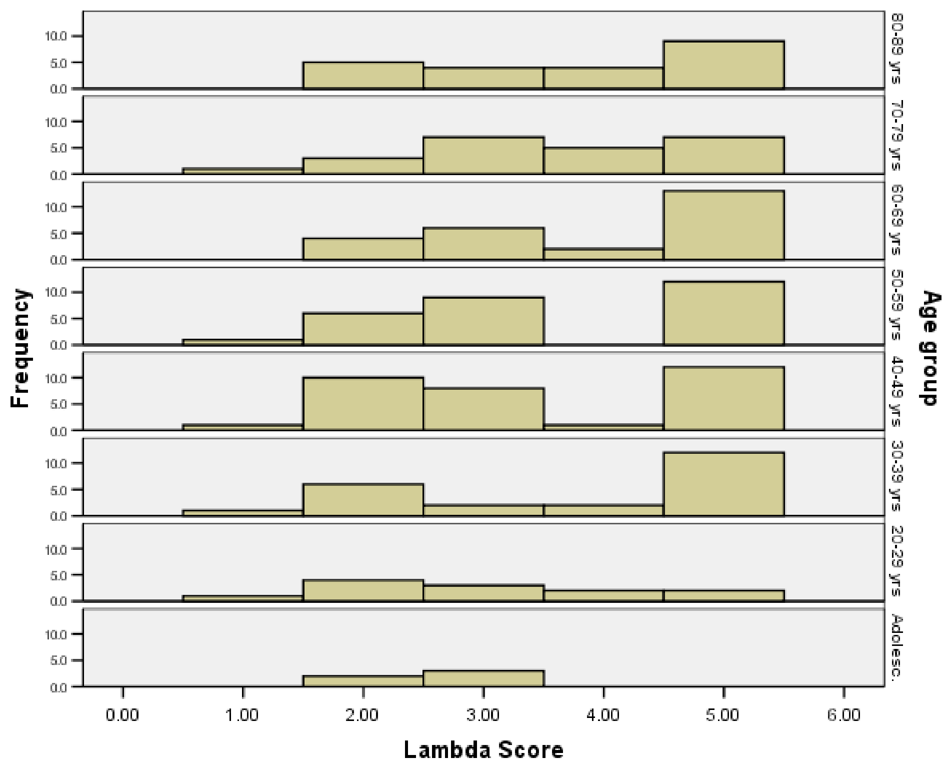

Figure 7.6 Sutural progression in age groups in the lambda region of the sagittal suture in white individuals (n=170).

Patency was seen in nearly every group so age cannot be determined based on this, although a patent lambda would mean the individual does not belong to group 8 (80-89 years). Significant fusion suggests that the individual is likely to be older than 40 years. The lambda appeared to be more variable than the bregma, even when the sample was limited to only one ancestral group. Incorporating black individuals into both Figures 7.5 and 7.6 produced a far more variable plot. For instance, complete obliteration was present in the adolescent group. This is of importance since current age estimation techniques make use of the bregma and lambda. It is not reliable to use these segments; their correlation with age is weak and insignificant.

On the other hand, both the bregma and lambda regions correlated very well with each other (r_s=0.63, *p*=.000, n=276). This indicates that development in different parts of a suture is more in-sync with each other than with age. This was verified by their mean scores, which were similar ($\bar{x}$=3.39±1.28 and 3.48±1.36 for the bregma and lambda, respectively).

7.2.3 Inferior coronal

The inferior coronal refers to the area of the coronal superior to the pterion (Figure 7.3). It is not used in current age estimation methods (although the pterion segment used in the Meindl-Lovejoy system is made up partially of this region), but as it is the starting point of the coronal suture and appears to fuse early in life (based on the Hamann Todd sample), it was considered here to see whether young and old individuals can be distinguished.

A moderately strong relationship was present between the score of the right inferior coronal and age (r_s=0.53, *p*=.000, n=153). It was the strongest correlation seen so far. Figure 7.7 confirms macroscopic observations made on the Hamann Todd sample; the inferior coronal fused early. This may suggest that the inferior portion is the starting point of fusion in the coronal. If the segment is patent, then the individual is likely under the age of 50 years. Minimal and significant fusion occurred in every age group, but appeared to be more common in groups 1 and 2.

Since the inferior coronal produced the best age-score correlation, the impact of ancestry and sex was examined. The trends listed above were apparent in both white and black populations. When the sample was divided by sex, young females showed more progression than similarly aged males, which supports the sex-related biases seen in Chapter 3. Significant fusion occurred more often in group 2 females than in males, where both minimal and significant fusion was more common. This was true for the adolescent group as well.

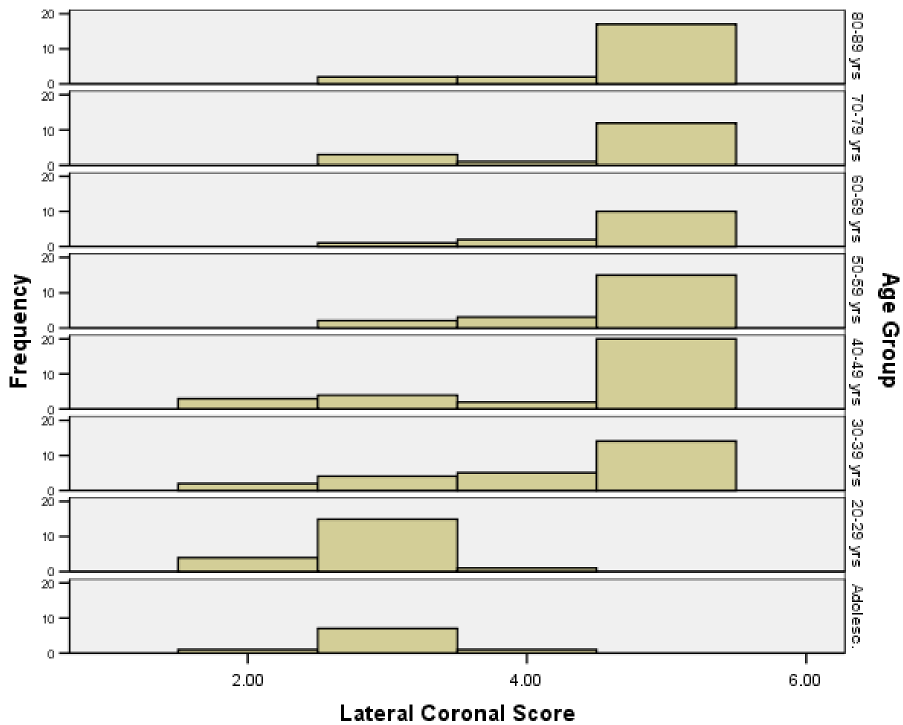

Figure 7.7 Fusion in the inferior coronal (n=153).

7.2.4 Mid-coronal

The mid-coronal score (Figure 7.3) and age were weakly related (r_s=0.17, *p*=0.040, n=153). Development was delayed in this segment, compared to the inferior coronal. Figure 7.8 shows trends that are the reverse of the inferior coronal. Patency was not seen in individuals over the age of 30 years. Obliteration in this segment was uncommon. The dominant condition was minimal to significant fusion in all groups, with most groups exhibiting a minimally fused mid-coronal. This was consistent in both sexes.

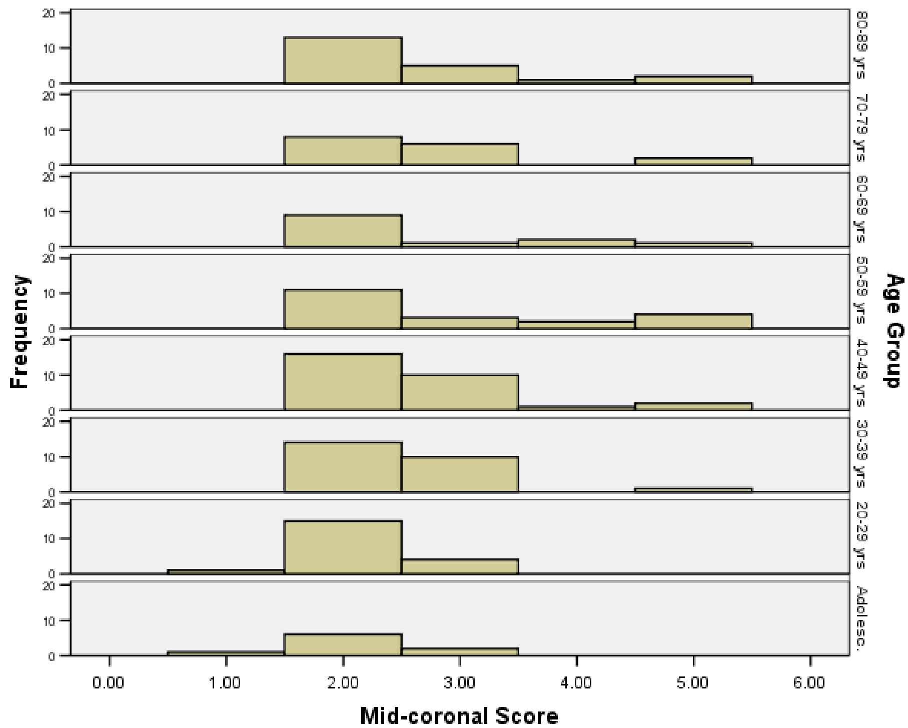

Figure 7.8 Fusion in the mid-coronal (n=153).

7.2.5 Bregma of the coronal

The bregmatic portion of the coronal (Figure 7.3) correlated more strongly with age than the mid-coronal (r_s=0.35, *p*=.000, n=153), but Figure 7.9 shows how much more variable it is.. A patent segment means the individual is likely under the age of 60 years. The dominant conditions were minimal and significant fusion, which makes this segment an ineffective indicator of age.

Like the inferior coronal, faster progression was seen in young females. On the other hand, adolescent males showed both minimal and significant fusion while females showed only the former. Patency was seen up to 60 years in black individuals, while in white subjects, patency was not observed past 30 years of age. Most individuals had a minimally fused bregma. Amongst individuals aged 80-89 years, significant fusion was dominant.

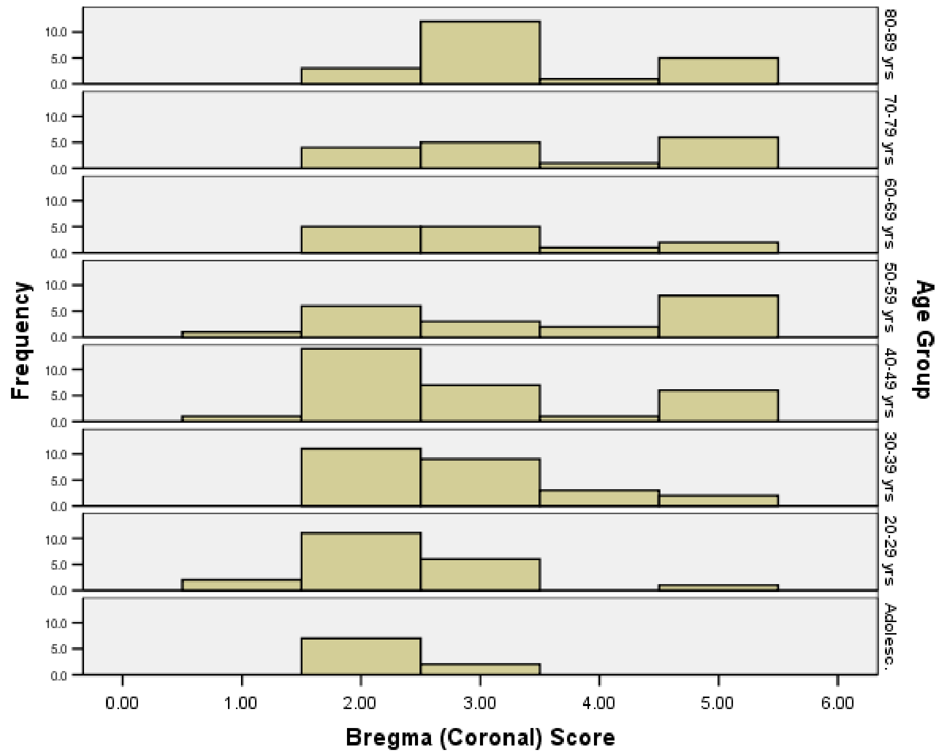

Figure 7.9 Fusion in the bregmatic region of the coronal (n=153).

It is interesting to note that the inferior coronal correlated to both the bregmatic region of the coronal and the mid-coronal in a moderate fashion (r_s=0.39, *p*=.000, n=153). Its progression was significantly related to the other two coronal segments, but it appears to pursue a different path. The inferior coronal showed the greatest amount of progression with the dominant condition nearing obliteration ($\bar{x}$=4.20±1.03). This was followed by the bregma region ($\bar{x}$=3.00±1.16) and the mid-coronal, which had similar average scores ($\bar{x}$=2.57±0.91). The bregma and mid-coronal correlated more strongly with each other than with the inferior coronal (r_s=0.43, *p*=.000, n=153). The Hamann Todd sample may indicate that fusion begins in the inferior coronal, followed by the bregma and mid-coronal, if all three segments are presumed to develop at similar rates. This is in accord with histological studies where surgically removed coronal sutures showed that synostosis spread from the inferior part of the suture (Cohen, 1993).

7.2.6 Lambda and mid-lambdoid

The lambda region of the lambdoid suture was assessed separately from that of the sagittal portion (Figure 7.3). Both the lambda (r_s=0.30, *p*=0.001, n=111) and mid-lambdoid (r_s=0.28, *p*=0.003, n=111) segments correlated significantly to age, but trends remain weak. Their correlation with each other was moderately strong (r_s=0.47, *p*=.000, n=111). Different parts of the lambdoid may not progress toward fusion at the same rate. The lambda was more developed with an average score of 3.15 ± 1.32 (significant fusion) compared to the mid-lambdoid's mean score of 2.56 ± 1.24 (progressing toward significant fusion).

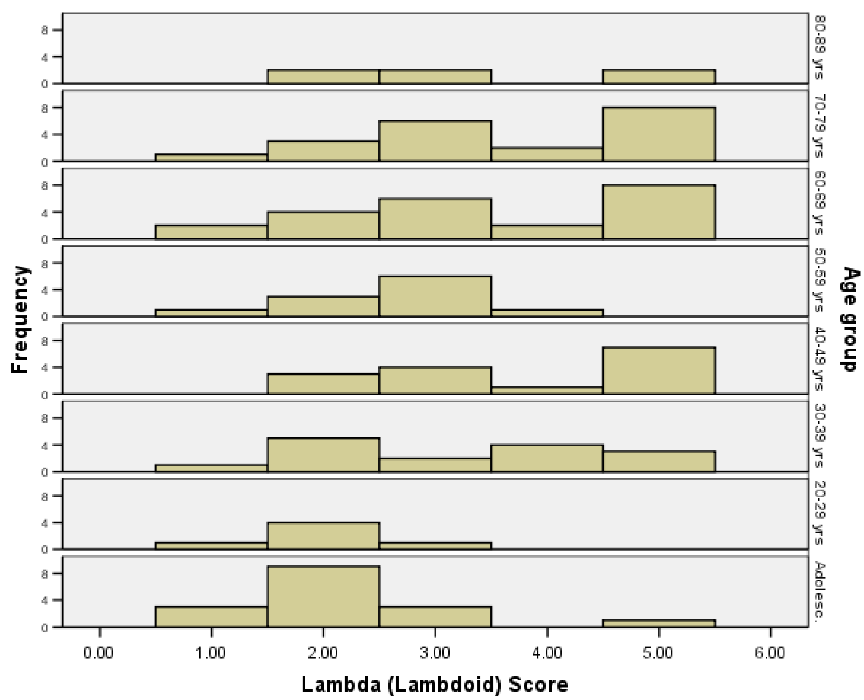

Figure 7.10 Fusion in the lambda region of the lambdoid suture (n=111).

Complete obliteration of the lambda was seen in adolescents (Figure 7.10), while patency was observed in nearly every group, except age groups 4 and 8. Thus, an individual with a patent lambda will be younger than 80 years old. The sample was not divided by sex; not every age group was represented in the males. Amongst the ancestral groups, minimal fusion in white individuals was seen as late as 79 years of age, while it stopped occurring ten years earlier in black subjects. In black subjects, obliteration was present in adolescents. Aside from this, patterns were consistent.

The mid-lambdoid (Figure 7.3) followed a somewhat similar pattern (Figure 7.11). Complete obliteration was not a dominant condition, even amongst the older individuals. Minimal and significant fusion was more common and was seen in all groups. Patency was observed in every age group except group 8. This segment of the lambdoid was not very helpful with age estimations.

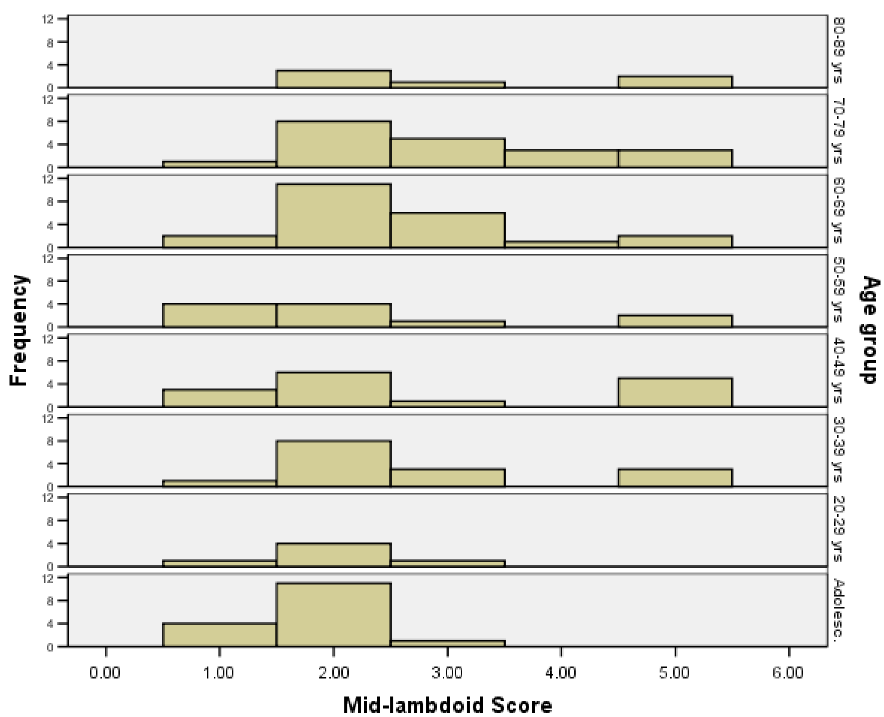

Figure 7.11 Fusion in the mid-lambdoid (n=111).

7.2.7 Concluding remarks

Comparing these results with other studies based on different populations, it is evident that synostosis follows different pathways across different groups. In a study done on a modern Indian population from Karnataka, Vijay Kumar *et al.* (2012) noted that in the sagittal, the anterior portion fused the fastest, followed by the posterior and middle sections. This does not align with the Hamann Todd Collection, where the posterior part containing the obelionic fused the fastest. On the coronal, the most inferior segment of the coronal began fusion first in the Indian sample, similar to the Hamann Todd group. In the Indian sample, faster progression was seen in the upper half of lambdoid, followed by the lower half. This is reversed in Hamann Todd, where the most inferior lambdoidal segments (at the base of the skull) were synostosed first.

Even though different paths are taken in different populations, there were similarities as well. For example, there was no bilateral variation in sutural progression (i.e. fusion was same in the right and left sides of the suture) in the Hamann Todd individuals or in the Indian group examined by Vijay Kumar *et al.* (2012). Sex-based differences in progression were present in the Hamann Todd sample. Females, particularly young women, generally showed greater progression than males. It is probable that females will be over-aged using present-day cranial aging techniques. Current aging methods should be refined to include population- and sex-specific patterns in sutural development. A method based on progression in the entire suture rather than segments is more likely to yield accurate age estimations across different populations.

7.3 Synostosis in facial sutures

7.3.1 Introduction: Cranial and facial sutures

It is evident that different sutures undergo synostosis at different rates and within these sutures, different segments start and end fusion at various times during life (Yen & Shaw, 1963). This section compared progression in facial and cranial sutures and discussed differences in development as seen in the Hamann Todd Collection and how these observations contradict trends cited in the literature.

Cranial and facial sutures develop differently. This was initially reported by Pritchard *et al.* (1956). By week 17 in utero, the fibrous periosteal capsules that envelope facial bones are fully formed. Cranial bones do not develop these structures until after birth. In utero, they are formed in a preformed fibrous membrane (ectomeninx). Koskinen-Moffett *et al.* (1983) report that the relatively more mature tissue of facial sutures in a fetus may be more capable of prolonging synostosis than the immature ones of cranial sutures (in Cohen, 1993).

This leads to differences in progression in adulthood. Facial sutures fuse late in life (e.g. 70-80s years), with the exception of the mid-palatal suture (Kokich, 1976), while cranial sutures close earlier. Since mechanical forces pass through the mandible to the face and then reach the cranium, facial sutures tend to remain patent or unfused during life. As mentioned previously, the circummaxillary sutures may act as shock-absorbers for the masticatory muscles (Cohen, 1993). Facial sutures are less prone to premature sutural closure compared to calvarial sutures. In fact, even when constraints are applied to the facial region, synostosis does not occur. When infants are subjected to this, catch-up growth occurs in the mid-facial region, preventing synostosis.

7.3.2 Methods

This section examined the internasal suture, the suture that connects the two nasal bones (Figure 7.12). Progression in this suture (as seen in the Hamann Todd sample) was illustrated here, following the methodology used for cranial sutures. The rate of progression was compared to cranial sutures in order compare and contrast facial and cranial sutures. The relationship between this suture and age was examined as well.

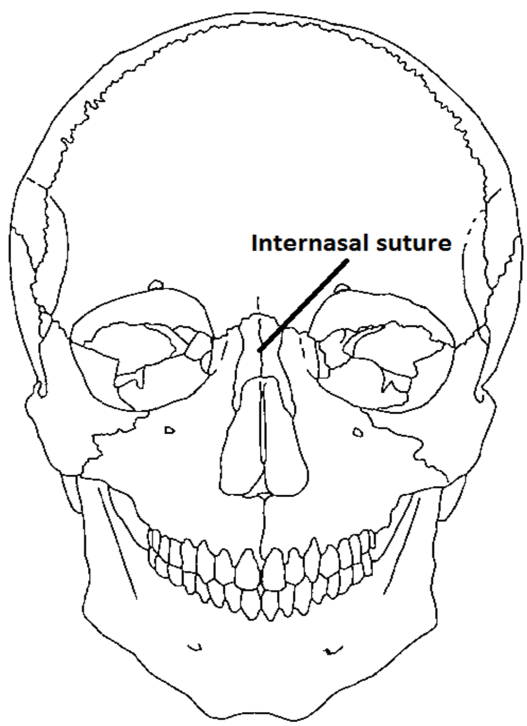

Figure 7.12 The internasal suture on the face.

7.3.3 Results

7.3.3a Progression in the internasal suture

Contrary to the generalization that facial sutures tend to remain patent, the internasal progressed quite rapidly in the Hamann Todd individuals. In 76 cases with an average age of 52.8 ± 15.5 years, the dominant condition was progression toward obliteration ($\bar{x}$=4.03±0.49). Since adolescents were not present in this sample, they were removed in the sagittal, coronal and lambdoid samples to ensure a similar age distribution and mean age. By comparison, all three sutures had lower scores than the internasal. The sagittal was beyond significant fusion, approaching near obliteration ($\bar{x}$=3.63±1.08). Both the coronal and lambdoid had undergone significant fusion, but less development was seen in the latter ($\bar{x}$=3.36±0.79 and 3.04±0.74 for the coronal and lambdoid, respectively). Furthermore, there was less variability in the internasal weighted score, as shown by the standard deviation.

Of importance here is the low socioeconomic status of the Hamann Todd individuals, which may explain why the internasal suture showed heightened progression even though this is not expected. As explained in Chapter 6, malnourishment, as well as biomechanical stress, can lead to sutural obliteration. The example used in Chapter 6 (rats fed on diets deficient in vitamin D and calcium and subjected to biomechanical stress) was observed in the internasal suture (Engström & Thilander, 1985). Engström *et al.* (1986) showed that rats fed with foods (e.g. soft foods) that did not put heavy stress on masticatory muscles were more likely to exhibit synostosis of the internasal suture. Being part of the lower end of the socioeconomic spectrum, the Clevelanders considered here would not have had access to expensive commodities; diet could have impacted progression in facial sutures.

7.3.3b Age-score correlations

The internasal did not correlate well with age (r_s=0.09, p=0.459, n=76), although Figure 7.13 shows some patterns that can be used to construct broad age categories. Complete fusion did not occur under the age of 30 years. This was similar to some of the histograms of sutural segments presented in the previous section for cranial sutures.

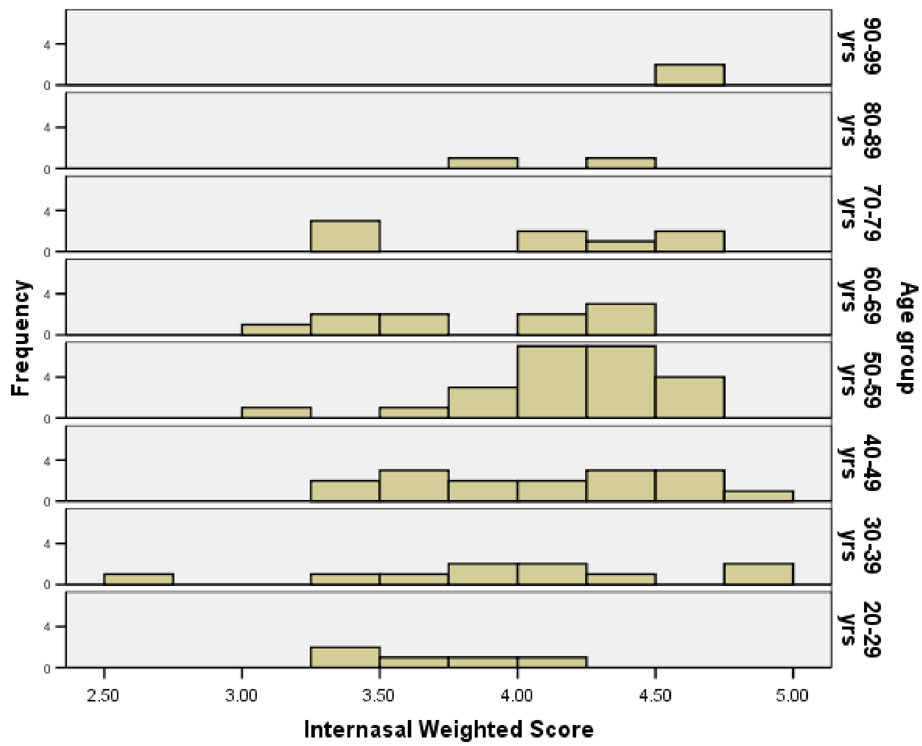

Figure 7.13 Sutural progression in the internasal suture (n=76).

However, in the internasal, even individuals in their 20s showed significant fusion, indicating that synostosis began early in life and progressed rapidly. In spite of this, obliteration in the entire length of the suture was not common, even in the oldest individuals. This is in agreement with the idea that facial sutures remain patent longer. In this sample, the entire suture did not remain patent, but small segments remained open even in senescence. The dominant condition ranged from significant fusion to near fusion and in most age groups both conditions occurred in similar proportions, making it difficult to determine age after 30 years.

Despite the different histological development between cranial and facial sutures, the Hamann Todd data showed that similarities exist in sutural progression during adulthood. An increase in variability in the forth decade of life appears to be consistent in both the internasal and calvarial sutural segments. The cranial sutures exhibited more concrete patterns though, making estimations based on the crania more accurate than those based on facial sutures. Although this assumption is based on one facial suture, examples from other studies support this. For instance, Mann *et al.*'s (1991) study on the maxillary suture showed that the suture was far too variable to infer age, although general patterns were seen.

7.4 Conclusion

The objectives of this chapter were three-fold. Firstly, the impact of parietal foramina on fusion in the obelionic region of the sagittal suture was determined. The presence of the foramina did not influence the rapid degree of closure seen in the obelionic. Although previous research on the masseter muscle demonstrates that the presence of the muscle altered the course of sutural progression, it seems that a large amount of force is needed to accelerate or delay progression. It is probable that the effect of the parietal foramina and the emissary vein that runs through does not exert a force comparable to the masseter muscle.

Next, multiple sites on the sagittal, coronal and lambdoid sutures, currently used in suture-based aging were examined in an effort to understand the high error rate associated with age estimations derived from cranial sutures. Many of these segments did not show strong age-score correlations. One exception is the inferior coronal, which is presently not used for age estimations. Graphing the degree of progression seen in each age group revealed some broad trends.

The last part of the chapter examined the internasal suture and compared progression in facial and cranial sutures. Progression in the internasal was rapid for the Hamann Todd sample, with average scores for the internasal surpassing all three cranial sutures. This stands in contradiction to past studies, which state that synostosis in the face is delayed. This may be related to malnourishment and diet.

8 Summary of finds

8.1 The Grant results: Examining cranial sutures

The relationship between cranial sutures and chronological age has been scrutinized for a long time. Many studies carried out through macroscopic observation have revealed weak (and sometimes contradicting) correlations (e.g. Singer, 1953). More recent radiographic works have concluded otherwise (Chiba *et al.*, 2013). A preliminary study done on the Grant Collection, cross-examining multiple aging techniques, demonstrated the need to critically re-examine cranial suture aging. The %PE was unsurprisingly high for both vault (32.7%) and anterior-lateral age estimations (21.1%). Only 50% of actual ages fell within the age ranges generated by vault sutures. The performance of lateral-anterior sutures was worse; only one out of nine crania was aged correctly. Age estimations lost accuracy with increasing age. Specifically, individuals over the age of 65 years were vulnerable (Figure 2.1) and this is problematic as there are no reliable aging methods for older individuals.

Although consisting of a small sample size, this preliminary study solicits a re-examination of cranial sutures, perhaps through a biological perspective. The need for this assessment lies with the fact that cranial sutures continue to be used despite their unreliability. After all, the Meindl-Lovejoy method is simple and sutural segments are easy to interpret and score, even for those new to aging techniques. Additionally, it is the only method available when only the cranium or cranial fragments are recovered. Hence, an extensive investigation of sutural biomechanics and the factors that influence synostosis may help refine this method.

8.2 Hypothesis and variables

Why are cranial sutures such poor predictors of age? It is evident that age is not the only variable affecting sutural commencement, progression and termination, which is why this method yields inaccurate age estimations. A critical analysis on the influence of environmental and biological factors on cranial sutures was undertaken in order to determine which variables cause variation in fusion. It was hypothesized that the high degree of variability is a product of a number of factors. These variables were controlled in order to reduce some of the variability and produce smaller age ranges. Differences in age-score relationships between the following factors were assessed: sex, ancestry, secular change, nutrition (e.g. overall health), stature, weight, body mass index, chronic and acute illnesses, alcohol and narcotics use, presence of cranial irregularities (e.g. wormian bones), skull density, and presence of biological features (e.g. parietal foramen).

8.3 Age, sex and ancestry

The first step was to establish the degree to which cranial sutures are influenced by chronological age in the Hamann Todd Collection. Synostosis was a poor to moderate predictor of age in the sagittal, coronal and lambdoid sutures. Patterns were not definite as there were very young people with fused sutures and older individuals with patent ones.

In both the coronal and lambdoid, sex-based and population-specific differences were present. In the coronal, males had a stronger age-score correlation compared to females (r_s=0.49 and 0.38 for males and females, respectively), but females showed greater overall progression with a mean weighted score of 3.52 ± 0.84 ($\bar{x}_{males}$=3.19±0.74). In the lambdoid, on the other hand, females (r_s=0.36, *p*=.000, n=112) showed a stronger age-score correlation than males (r_s=0.25, *p*=0.002, n=147). Females had significantly greater scores than males as well (U=6831.5, *p*=0.019). Progression in the sagittal, however, did not appear to be impacted by sex. Male sagittal scores showed a stronger correlation to age than females (r_s=0.33, *p*=.000 and r_s=0.25, *p*=0.007 for males and females, respectively), but the difference in mean weighted score was not significant (U=8481.0, *p*=0.250). Similar to the coronal and lambdoid, females showed greater overall progression ($\bar{x}$=3.61±1.11) compared to males ($\bar{x}$=3.40±1.18). Even though greater progression in females appears to be the overall trend observed in all three sutures, current cranial aging methods do not account for this. Using the same method for the sexes may explain the poor %PE values in Chapter 2. The first step in developing an accurate cranial aging method will be to construct a technique that is derived from the fusion patterns seen in each sex.

In addition to sex, the strength of age-score correlation was dependent on ancestry. Black individuals had a stronger age-score relationship. In the coronal, they had a faster rate of sutural progression as well compared to white individuals. In this study, only white and black individuals were considered using an adequate sample size. Other ancestral groups need to be considered in order to test the extent to which these differences are present. The presence of significant differences in other groups will verify that the ancestral differences observed here is not due to poor environmental conditions that resulted from disparities in socioeconomic status.

When the weighted scores of two Aboriginal individuals (females aged 34 and 35 years) were compared with the white and black individuals (belonging to age group 3) discussed in

Chapter 3, the Aboriginal scores were much lower. For instance, in the sagittal, average weighted scores were comparable in white (3.78±1.08, n=20; significant fusion progressing toward near obliteration) and black individuals (3.47±1.18, n=14), but the Aboriginal individuals exhibited minimal fusion (progressing toward significant fusion). A similar trend was seen in the coronal and lambdoid as well. Although only two Aboriginal individuals were used here, this may suggest that significant population-based differences may exist in sutural progression.

8.4 Age groups

The next step was to pinpoint the age(s) during which variation in synostosis becomes prevalent. Is a large amount of variation present in youth or does variability arise with increasing age? Subjects were divided into decade-long age groups in order to test whether variability would increase with age. The results showed that variation and rates of progression were, in fact, influenced by age group. Individuals belonging to groups 1 to 3 (adolescents and adults up to 39 years of age) showed a stronger age-score correlation than older individuals. This was documented in all three sutures. After this point, variability increased, masking patterns. This may be why older individuals are more likely to be incorrectly aged.

Average weighted scores for each age group did not increase perfectly with age, but a general linear trend was noted, particularly in the coronal and lambdoid. The sagittal showed the greatest difference in weighted scores across age groups. Individuals belonging to groups 1 and 2 had weighted scores that were significantly different from older adults. Although age appears to correlate with synostosis, the trend was moderate (at best). Only binary classifications of age were present. Cranial suture aging may be more reliably used in adolescents and young adults.

8.5 Secular changes

The Hamann Todd Collection is comprised of individuals from the 19th and 20th centuries, which allowed the effect of secular trends on synostosis to be tested. Sutural progression appears to be influenced by secular changes in the sagittal, coronal and lambdoid suture. This influence manifested close to the turn of the century, beginning twenty or thirty years before this point. The oldest individuals dating to the earliest times had the slowest rates of synostosis. The rate of progression accelerates after this, especially in the 1870s and 1880s. Individuals born from the late 19th century to the 20th century showed a strong age-score correlation. Although the correlation was only moderately strong, the results suggest that more accurate age ranges may be generated for individuals born in the late 19th or 20th century since less variability is seen here. Consequently, the use of sutural aging in archaeological specimens is not recommended.

8.6 Nutrition

Height, weight, body mass index and illness were used to assess the overall health of the Hamann Todd individuals and test the effects of malnourishment and disease on synostosis. Height consistently showed negative trends when regressed against the weighted scores of all three sutures. Black individuals had a significant height-score relationship in the sagittal while white subjects had a nearly negligible correlation. Adolescents showed the strongest correlation between height and synostosis. The negative trend suggests that taller people are associated with less sutural development. This may indicate that taller, healthier people are less likely to have fully synostosed sutures (suggesting that fusion is not normal) or the bone loss (and the consequent decrease in stature) that occurs with age may suggest that older individuals who have lost some of their peak height are less likely to have patent sutures (suggesting that fusion is the intended end product).

The BMI analyses showed that stronger age-score relationships were generally seen in underweight individuals, but complete fusion is likely to occur in any weight category. Early closure did not co-exist with any specific disease, but prolonged alcohol and/or narcotics use may trigger premature obliteration in the sagittal suture. The presence of cranial features, like wormian bones, may be associated with a stronger age-score relationship. Sutural progression was often more advanced in very light skulls compared to extremely dense ones. The results indicate that cranial structural characteristics (e.g. density) and the health of a person can influence synostosis.

8.7 Biological features

Proximity to biological features like muscles has been shown to alter the route of synostosis, like the masseter muscle and the squamosal suture (Kokich, 1976). Here, the suture followed a highly irregular pathway to fusion, indicating that the presence of the muscle and the biomechanical forces associated with mastication influenced the rate of progression. A similar structural set-up around other sutures may explain why variability is the norm for cranial sutures.

In the Hamann Todd individuals (and also in other collections; Todd & Lyon, 1924), it has been noted that obelionic portion of the sagittal has a tendency to fuse earlier than the rest of the suture. Whether this is due to the presence of parietal foramina (and the emissary vein that passes through) was tested. The presence of the foramina did not appear to cause the rapid degree of closure seen in the obelionic. Individuals with and without a parietal foramen experienced similar amounts of fusion. Another unknown trigger initiates early closure in the obelionic.

8.8 Synostosis in sutural segments

One reason why cranial sutures produce poor age estimations may be due to the hypothesis that the sutural segments used in current methods do not correlate well with age. Sutural progression was mapped in the following sutural segments to test this: the obelionic, bregma and lambda of the sagittal suture; the inferior coronal, mid-coronal and bregma of the coronal suture; and the lambda and mid-lambdoid of the lambdoid suture (Figure 6.2). These segments were more strongly correlated with each other than they were with age, particularly different segments along the same suture. Some internal mechanism ensures that most of these segments proceed toward synostosis following a similar pathway, but this progression is not a product of time. The inferior coronal, which forms part of the pterion segment used in the Meindl-Lovejoy system, exhibited the strongest age-score correlation.

8.9 The internasal suture

The last part of the study examined the internasal suture and compared progression in facial and cranial sutures. Internasal facial suture proceeded rather quickly toward synostosis in the Hamann Todd sample, with average scores surpassing the sagittal, coronal and lambdoid sutures. This contradicts the results of past studies (e.g. Cohen, 1993), where facial sutures remain patent even in senescence. The early closure may be a product of a soft diet.

8.10 Concluding remarks and future research

Synostosis is an unpredictable phenomenon dependent on multiple factors. This may be why age estimations generated from cranial suture aging are broad and often incorrect. This study sought to address some of these variables. Sex and ancestry appear to influence synostosis. Females tend to show greater fusion than males. The younger black subjects used here exhibited greater average weighted scores compared to the aged white sample, suggesting a population-specific disparity. A secular trend was present as well: age-score correlations became stronger with time, particularly after the 1870s. Stature correlated negatively with weighted score for all three sutures. Underweight individuals and those with cranial features like wormian bones were more likely to undergo greater sutural development. Skull density may have an impact as well, with extremely light skulls exhibiting well-fused sutures. Prolonged alcohol and narcotics use may trigger synostosis but further research with a larger sample needs to be done to verify this. Although biological features have been shown to interfere with sutural progression before, the parietal foramen does not induce the early closure seen in the obelionic region of the sagittal suture. The biological feature may need to be relatively large and be continuously used in order for biomechanical stresses to impact sutural development.

If cranial sutures are to be used in aging, formulae and/or scoring methods are more likely to yield accurate estimations if they account for the factors assessed here. The same technique should not be used for both sexes. Otherwise, females will be over-aged. Formulae should be population-specific as well to prevent over-aging black individuals. The extent to which populations should be divided (e.g. can some ancestral groups be combined?) needs to be tested. Cranial suture aging should be restricted to aging individuals born after the late 19th century. Unlike sex, ancestry and secular changes, health is a difficult variable to control. Although the skeleton can retain some evidence of health, malnourishment and chronic and acute illnesses may be difficult to assess in fragmentary remains. Aging individuals showing signs of malnourishment should be done with caution, as over-aging is likely here.

Despite critically analysing the impact of a number of factors influencing cranial suture closure, synostosis remains a complex problem. However, accurate age estimations may be constructed from age-score correlations if current aging techniques are revised to account for at least some of these variables.

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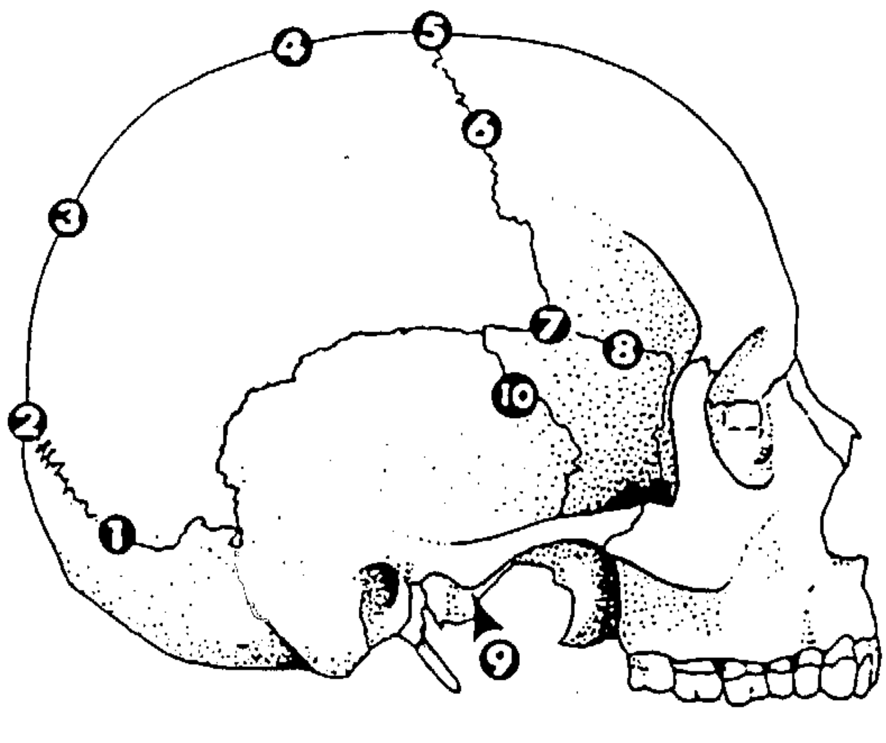
Appendix I Meindl-Lovejoy sutural segments

Ectocranial vault sites	Ectocranial lateral-anterior sites
1. Midlambdoid	6. Midcoronal
2. Lambda	7. Pterion
3. Obelion	8. Sphenofrontal
4. Anterior sagittal	9. Inferior sphenotemporal
5. Bregma	10. Superior sphenotemporal
6. Midcoronal	
7. Pterion	



Source: Meindl and Lovejoy, 1985, p. 60

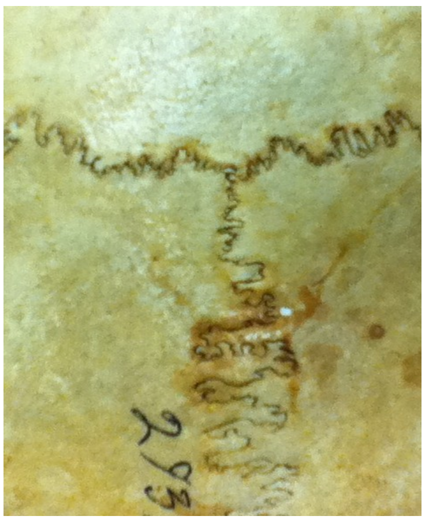
Appendix II Specimen List - Hamann Todd Collection

3470	3159	2293	2958	616	239	174	20
3455	3151	2254	2943	590	238	171	17
3391	3140	2244	2851	588	236	160	16
3382	3132	2184	2844	576	235	156	
3378	3123	2125	2840	543	234	155	
3359	3122	2071	2835	541	233	152	
3357	3118	2065	1684	540	229	148	
3352	3112	2059	1402	539	228	147	
3351	3111	2025	1340	538	227	130	
3340	3107	1974	1334	537	226	128	
3338	3099	1949	1333	536	225	118	
3336	3092	1938	1326	535	221	116	
3332	3088	1900	1219	534	219	100	
3327	3080	1889	1196	532	217	99	
3323	3075	1838	1195	531	216	97	
3318	3014	1747	1125	529	214	96	
3306	3005	1739	1021	528	213	94	
3297	2999	1711	981	525	212	91	
3288	2982	1606	967	524	210	88	
3286	2949	1590	965	523	208	87	
3283	2939	1581	927	512	207	79	
3278	2923	1540	773	506	206	78	
3274	2895	1418	762	497	204	74	
3269	2884	1367	759	437	199	73	
3256	2881	1350	757	420	198	69	
3234	2860	1140	752	410	197	67	
3223	2857	1138	751	399	195	58	
3221	2773	1097	748	397	194	57	
3214	2666	1041	739	381	193	55	
3210	2650	1012	721	340	192	53	
3186	2645	928	704	304	191	52	
3183	2643	854	703	254	190	50	
3182	2642	422	698	253	189	48	
3176	2589	3512	695	252	188	47	
3174	2558	3181	688	247	187	45	
3173	2496	3087	686	244	186	24	
3171	2478	3065	683	243	185	23	
3164	2395	3032	651	242	183	22	
3161	2310	3000	644	241	176	21	

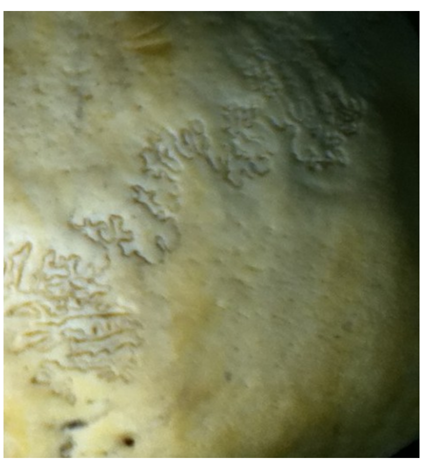
Appendix III Illustrations of stages of fusion

1

2



3



4

5

Source: Hamann Todd Collection, Cleveland Museum of Natural History.