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**PAPER**

**ANTHROPOLOGY**

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# A Bayesian Approach to Age Estimation in Modern Americans from the Clavicle*

**ABSTRACT:** Clavicles from 1289 individuals from cohorts spanning the 20th century were scored with two scoring systems. Transition analysis and Bayesian statistics were used to obtain robust age ranges that are less sensitive to the effects of age mimicry and developmental outliers than age ranges obtained using a percentile approach. Observer error tests showed that a simple three-phase scoring system proved the least subjective, while retaining accuracy levels. Additionally, significant sexual dimorphism was detected in the onset of fusion, with women commencing fusion at least a year earlier than men (women transition to fusion at approximately 15 years of age and men at 16 years). Significant secular trends were apparent in the onset of skeletal maturation, with modern Americans transitioning to fusion approximately 4 years earlier than early 20th century Americans and 3.5 years earlier than Korean War era Americans. These results underscore the importance of using modern standards to estimate age in modern individuals.

**KEYWORDS:** forensic science, forensic anthropology, age estimation, clavicle, skeletal maturation, secular change, transition analysis, probit regression, Bayesian statistics

Rigorous testing and evaluation of forensic methods is essential in all fields of the forensic sciences, particularly since the landmark *Daubert* decision of 1993 (1–3). In forensic anthropology, the dynamic nature of human skeletal variation adds another dimension to the evaluation of standards, namely the importance of using modern skeletal samples to develop forensic standards. Indeed, recent documentation of secular change in long bone length and cranial dimensions illustrates this point (4–9). Increases in stature and earlier sexual maturation in many industrialized countries are due to a positive secular growth trend (10,11). Accelerated maturation has been documented primarily in terms of menarcheal age and pubertal onset (11–30), but secular changes in skeletal maturation have received little attention (31–34). Since sexual maturation is closely related to skeletal maturation, acceleration in pubertal onset may be indicative of acceleration in skeletal maturation (35).

Epiphyseal union is used to age sub-adult skeletons in forensic anthropology and bioarchaeology. Whereas adult age estimates from skeletal material are necessarily wide because of the nature of degenerative skeletal changes, sub-adult age estimates can be narrower while maintaining the same degree of accuracy because of the more predictable timing of epiphyseal union. Consequently, secular changes in maturation may impact forensic skeletal age estimates significantly. This study uses the medial clavicle to investigate secular trends in skeletal maturation in the American population throughout the 20th century by comparing a modern autopsy sample to two earlier samples. The medial clavicular epiphysis is important in a forensic context because it can provide accurate age estimates beyond the fusion of other skeletal epiphyses, often into the mid to late twenties. The present study aims to provide updated standards for the American population using a Bayesian approach to derive robust age ranges for modern individuals; these age ranges will be tested on a separate population. Additionally, this study will evaluate the utility of two different scoring systems using associated observer error information.

### Background: Clavicle Development and Previous Studies

The medial clavicular epiphysis is the last to fuse (usually in the middle to late twenties). Medial epiphyseal ossification begins at the onset of puberty, but the epiphysis does not fuse to the shaft completely until some 10 years after its initial appearance (36,37). The epiphysis appears initially as a small speck of bone in the center area of the sternal end and spreads until it nearly covers the entire medial surface. Scheuer and Black (37) offer the following timeline for clavicular maturation: a well-defined medial flake appears between 16 and 21 years; the flake covers the majority of the medial surface between 24 and 29 years; complete fusion occurs between 22 and 30 years. Because of the extended developmental period of the medial clavicular epiphysis, the medial clavicle can provide accurate age estimates of young adults (38). This is useful in a forensic setting because young adults constitute a large portion of forensic casework. Additionally, the clavicle provides an opportunity to study skeletal maturation with a large sample size because adult skeletal material is more abundant than sub-adult material.

Among the earliest mention of medial clavicular epiphyseal fusion in the American population was Stevenson's (39) documentation of epiphyseal union in the arms, legs, and girdles using the Hamann-Todd Collection (Western Reserve Collection). Stevenson noted commencement of union as early as age 22 and completed union in all cases by age 28, although he did not mention sex

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differences in epiphyseal union. Several years later, Todd and D'Errico (38) published a more extensive study of the medial clavicle using a four-phase scoring system: (1) no union, (2) beginning union, (3) recent union with a scar, and (4) complete union (i.e., loss of all trace of the site of union). Their results indicated that union occurs between 18 and 29 years. The ossifying epiphysis typically begins to unite around age 21, and union is practically complete by age 25. They did not report any significant sex or race differences in their sample.

During the 1950s, McKern and Stewart (40) reported their findings on epiphyseal union in the Korean War dead; a portion of their report discussed the medial clavicle. They used a five-phase scoring system, adding a phase for "active" union to Todd and D'Errico's (38) earlier system: (1) no union, (2) beginning, (3) active, (4) recent, and (5) complete. McKern and Stewart (40) reported that union begins at age 18, possibly as early as 17, and most individuals fuse by age 25. They found clavicles with unattached epiphyses in individuals up to age 22; however, complete union did not occur prior to age 23, and all individuals had fused by age 30. Because the sample was comprised of men only, they could not investigate sex differences.

The first effort to provide modern standards for forensic anthropologists was Webb and Suchey's (41) study on an autopsy sample from the Los Angeles area. The sample consisted of skeletal material from over 800 autopsies from the late 1970s. Their four-phase scoring system differed from previous systems in that it placed more emphasis on the nonunion stages: (1) nonunion with no epiphysis, (2) nonunion with separate epiphysis, (3) partial union, and (4) complete union. They reported nonunion as late as age 25 in men and 23 in women. Fusion onset occurred in men from 17 to 30 years and in women from 16 to 33 years. Complete union was observed as early as age 21 in men and 20 in women, with all individuals fused by the early 1930s.

Black and Scheuer's (42) more recent study was performed on a compilation of skeletal material from the 18th to 19th century Spitalfields, St Bride's, and St Barnabus documented collections, as well as some material from the 20th century Museu Bocage Portuguese collection in Lisbon. Their five-phase scoring system is similar to Webb and Suchey's (41) in that it gives considerable attention to the nonunion phases: (1) distinctive ridges and furrows on the metaphyseal surface; no epiphyseal flake attached, (2) less ridges and furrows on the metaphyseal surface; no epiphyseal flake attached, (3) flake commencing fusion, (4) flake expanded across the metaphyseal surface, (5) complete fusion with no trace of a fusion line. The authors claim that the first two phases offer some resolution for distinguishing younger individuals around the age of 15. Their age ranges did not distinguish between men and women, and they found considerable overlap between samples. Phase 1 ranged from 11 to 17 years, phase 2 from 15 to 22 years, phase 3 encompassed 19–23 years, phase 4 individuals were between ages 23 and 28, and phase 5 individuals were 25+ years. The sample size was too small to make inferences about genetic/population differences and/or secular trends.

Although CT scans have been used to study epiphyseal fusion, most of these studies use slice thicknesses that are too thick to detect meaningful details about the various stages of fusion (i.e., thicknesses greater than 1 mm). For example, in one study, slice thickness ranged from 1 to 8 mm (36). The fusion process was divided into four stages: (1) nonunion without ossification of the epiphysis, (2) nonunion with detectable ossification of the epiphysis, (3) partial union, and (4) complete union of the epiphysis with the clavicular metaphysis. The ossified epiphysis appeared between 11 and 22 years, partial union was documented from 16 to 26 years, earliest complete union was at 22 years, and union was complete in all individuals by age 27. They found no statistically significant differences in men and women, possibly because of small sample size. However, scoring CT-scanned bones from scans of varying slice thicknesses should be approached with caution because details apparent in 1-mm slices may not be visible in 8-mm slices.

In sum, the medial clavicular epiphysis has been established as a reliable aging method for young adults. However, the existing studies employ various scoring systems, and there is no standard scoring system with established error rates. Furthermore, the most up-to-date information for the American population is from 1970s autopsies (41). The present study addresses each of these issues by using a large modern American sample to evaluate two scoring systems, examine observer error, and construct robust age ranges using Bayesian statistics.

## Materials and Methods

### *Samples and Scoring*

Two skeletal collections were scored for epiphyseal fusion (the William F. McCormick Clavicle Collection and the Hamann-Todd Osteological Collection). Additionally, McKern and Stewart's (40) raw data from the Korean War males are included as part of this analysis. The William F. McCormick clavicles are housed at the University of Tennessee in the Anthropology Department. This documented autopsy collection consists of approximately 2000 clavicle pairs from 1986 to 1998 autopsies in East Tennessee. The sample is 95% European American, 4% African American, and 1% Latino, Asian, and Native American, which roughly reflects the demographic composition of the East Tennessee area (43). A subset of 594 McCormick individuals aged 11–33 was scored for medial epiphyseal fusion (448 men, 146 women). This broad age range was chosen to ensure that a sufficient number of individuals were included from all stages of fusion (i.e., unfused, fusing, and fused).

The Hamann-Todd Human Osteological Collection is housed at the Cleveland Museum of Natural History. The collection consists of skeletal remains from approximately 3000 cadavers autopsied between 1912 and 1938. The collection is 62% European American and 38% African American. A subset of 354 individuals aged 11–30 were scored from this collection (255 men, 99 women). This sample was used to test ethnic differences in epiphyseal union, as well. Additionally, 341 men aged 16–33 from 1950 to 1952 Korean War fatalities are included in this analysis. These clavicles were scored as part of McKern and Stewart's government report *Skeletal Age Changes in Young American Males* (40), and the raw data are available online at http://konig.la.utk.edu/paleod.htm. In sum, the total study sample is comprised of clavicles from 1289 individuals from cohorts spanning the 20th century. The composition of this sample offers a way to control for population differences and examine secular trends the American population.

As discussed in the introduction, several scoring systems are available for use. Webb and Suchey's (41) system was unsuitable for this study because it was not possible to differentiate between phases 1 and 2 (i.e., nonunion with no epiphysis or nonunion with separate epiphysis). Because the clavicles were processed and dried before storage, it was not possible to discern whether an unfused bony epiphysis was present at any point during this curation process. Black and Scheuer's (42) system was suitable for use but differentiating between the first two phases proved challenging and subjective (phase 1: distinctive ridges and furrows on the metaphyseal surface; no epiphyseal flake; phase 2: less ridges and furrows on the metaphyseal surface; no epiphyseal flake); consequently, this system was omitted from the study. In the end, the clavicles were scored with McKern and Stewart's (40) five-phase system and with a three-phase system used by most forensic anthropologists, as well as for coding entries in the Forensic Anthropology Databank.

The five phases of McKern and Stewart's system are (1) no union, (2) beginning union, (3) active union, (4) recent union, and (5) complete union. Each of these phases is shown in Figs. 1–6. "No union" was scored if no remnant of the flake was fused to the shaft. Typically, the medial articular surface had a coral-like appearance (Fig. 1). A bone was scored as "beginning union" if the epiphyseal flake had commenced fusion to the medial articular surface, but less than 50% of the surface was covered by the flake (Fig. 2). "Active union" was scored if 50% or more of the surface was covered by epiphyseal flake, and fusion was actively occurring (Fig. 3). The epiphysis was considered actively fusing if the flake clearly appeared as a separate entity with some space between the edges of the flake and the bone surface (Fig. 4). "Recent union" was scored when the flake was completely fused to the shaft, but a trace of the fusion event remained in the form of a fusion scar and/or as small bony nodules on the outer rim of the medial surface (Fig. 5). A fusion scar should not be confused with the line left from the joint cartilage; this line is usually on the edge of the bone and not on the medial surface where fusion occurs. Finally, "complete fusion" was scored when no trace of the fusion event remained, and the articular surface was quiescent (Fig. 6). The three-phase system scores are (1) unfused, (2) fusing, and (3) fused. In this system, phases 2–4 in the McKern and Stewart system (beginning, active, and recent union) were lumped into the "fusing" stage.

*Observer Error*

To determine the best scoring system, a random sample of 51 clavicles was selected for intra- and inter-observer error tests. For the intra-observer error test, the 51 clavicles were scored by the principal researcher (Observer 1) 1 year after the initial scoring. To calculate inter-observer error, three independent observers with different experience levels scored the clavicles with each scoring system. Two of the independent observers (Observers 2 and 3) were experienced osteologists with advanced degrees; the third observer (Observer 4) had some osteology experience, but no experience scoring clavicular epiphyses. All observers were provided with the photographs and written descriptions included in this article and asked to score the clavicles using these aids solely. Each independent observer waited 1 week between scoring the clavicles with the five-phase system and the three-phase system.

FIG. 1—*No fusion. Note the coral-like appearance of the medial articular surface. From left: 12-year-old European American male, 10-year-old European American male, 12-year-old European American female.*

FIG. 2—*Beginning fusion. Flake commencing fusion; less than 50% of surface covered by flake. From left: 16-year-old European American male, 17-year-old European American male, 20-year-old European American female.*

FIG. 3—*Active fusion. Greater than 50% of the surface is covered by flake; fusion still actively occurring. From left: 22-year-old European American male, 25-year-old European American male, 20-year-old European American male.*

FIG. 4—*Active fusion. Note the visible gap between the epiphyseal flake and the bone surface.*

Spearman's rank correlation coefficients ($r_s$) were calculated to evaluate the consistency between observers' scores. A Bhapkar (44) test was used to test for overall marginal homogeneity and concordance among observer scores. Additionally, a McNemar (45,46) test was used to evaluate scoring bias between observers. This test compares the total frequency of observations above the main diagonal of the contingency table with the total frequency of cases below the diagonal. In instances of significant bias, marginal distribution histograms were constructed to visualize the directionality of the bias. Finally, a Spearman's rank correlation coefficient ($r_s$) was calculated to test the relationship between age and phase in each scoring system. Spearman's rank correlations were performed in Number Cruncher Statistical System (NCSS), and the Bhapkar and McNemar tests were performed with the MH program, which is available online at http://www.john-uebersax.com/stat/mh.htm.

FIG. 5—*Recent fusion. Arrows from left to right: fusion scar, bony nodule, bony nodule. From left: 23-year-old European American male, 23-year-old European American male, 25-year-old European American male.*

FIG. 6—*Complete fusion. From left: 36-year-old European American male, 49-year-old European American male, 37-year-old European American female.*

### *Probit Regression and Bayesian Analysis*

Transition analysis was conducted on the data to determine the average age at which the transition from one phase to the next occurs. The transition analysis was performed with Konigsberg's Nphases2 computer program, which is available at http://konig.la.utk.edu/nphases2.htm. The Fortran-based program performs a logistic regression wherein the intercept and slope are converted to the mean and standard deviation, respectively (47). Nphases gives an age-at-transition, which is the maximum likelihood estimate of the likelihood function provided by the probit regression. This estimate represents the average age at which an individual is most likely to transition from one phase to the next. Transition analysis has been used in the anthropological literature to study senescent changes in bone such as those at the auricular surface and pubic symphysis of the pelvis and the sternal rib ends (47–50). However, the phase systems used to score age-related changes in the medial clavicle meet the assumptions of transition analysis, and thus the method is applicable in this context. Namely, the fusion event can be represented in a series of invariant phases, and the morphological change is unidirectional with respect to those phases (47). One attractive feature of transition analysis is that it can be used to obtain robust estimates of age-at-fusion that are less sensitive to outliers than the traditional percentile method. To examine secular trends in skeletal maturation, separate transition analyses were performed on each skeletal sample (Hamann-Todd, McKern and Stewart, and McCormick). Furthermore, men and women were analyzed separately in each sample to investigate sexual dimorphism in epiphyseal union.

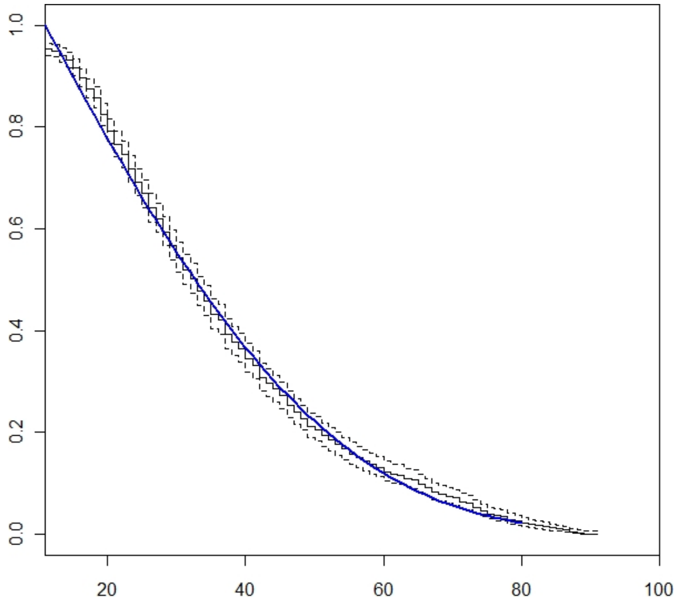


FIG. 7—*Forensic Data Bank Survivorship. Kaplan–Meier Survivorship with a 95% confidence interval (stepped lines) and Gompertz curve (solid line).*

A cumulative probit model on log age, or proportional odds model with a probit link, was used for the transition analysis. The cumulative probit model assigns the same standard deviation to each transition, and the natural log scale assures that the transition distribution is log normal (49). A Bayesian approach was used to obtain age ranges from the transition likelihood estimates (47). Bayes' Theorem can be stated as:

$$\Pr(a|c_j) = \frac{\Pr(c_j|a)f(a)}{\int_0^\infty \Pr(c_j|x)f(x)\mathrm{d}x} \qquad (1)$$

where $\Pr(a|c_j)$ is the probability that a skeleton died at age $a$ given it has characteristics $c_j$ (in other words, the probability of age given phase); $\Pr(c_j|a)$ is the probability that a skeleton with characteristics $c_j$ died at age $a$ (in other words, the probability of phase given age); and $f(a)$ is a probability density function for age (47,50). $\Pr(c_j|a)$ is obtained from the transition analysis performed in Nphases and is mathematically represented as:

$$\Pr(c_j|a) = \int_{-\infty}^{a} f(a|\mu_{j-1},\sigma)\mathrm{d}a - \int_{-\infty}^{a} f(a|\mu_j,\sigma)\mathrm{d}a \qquad (2)$$

where $f(a|\mu,\sigma)$ is the normal probability function of age $a$ with a mean $\mu$ and standard deviation $\sigma$; this function pertains to the transition distributions and is independent of the $f(a)$ from the informative prior in Eq. 1. The probability density function $f(a)$ (Eq. [1]) is obtained by fitting a Gompertz hazard model to an informative prior distribution to obtain hazard parameters $\alpha_3$ and $\beta_3$. The Gompertz hazard model is written as:

$$h(t) = \alpha_3(\exp\beta_3 t) \qquad (3)$$

where $h$ is the hazard rate, $t$ is age shifted by 11 years, $\alpha_2$ is the baseline mortality, and $\beta_3$ is the senescent component. Figure 7 contains a Kaplan–Meier survivorship curve of the informative prior (the Forensic Data Bank, or FDB) and the Gompertz curve using parameters from the FDB. Note that the Gompertz

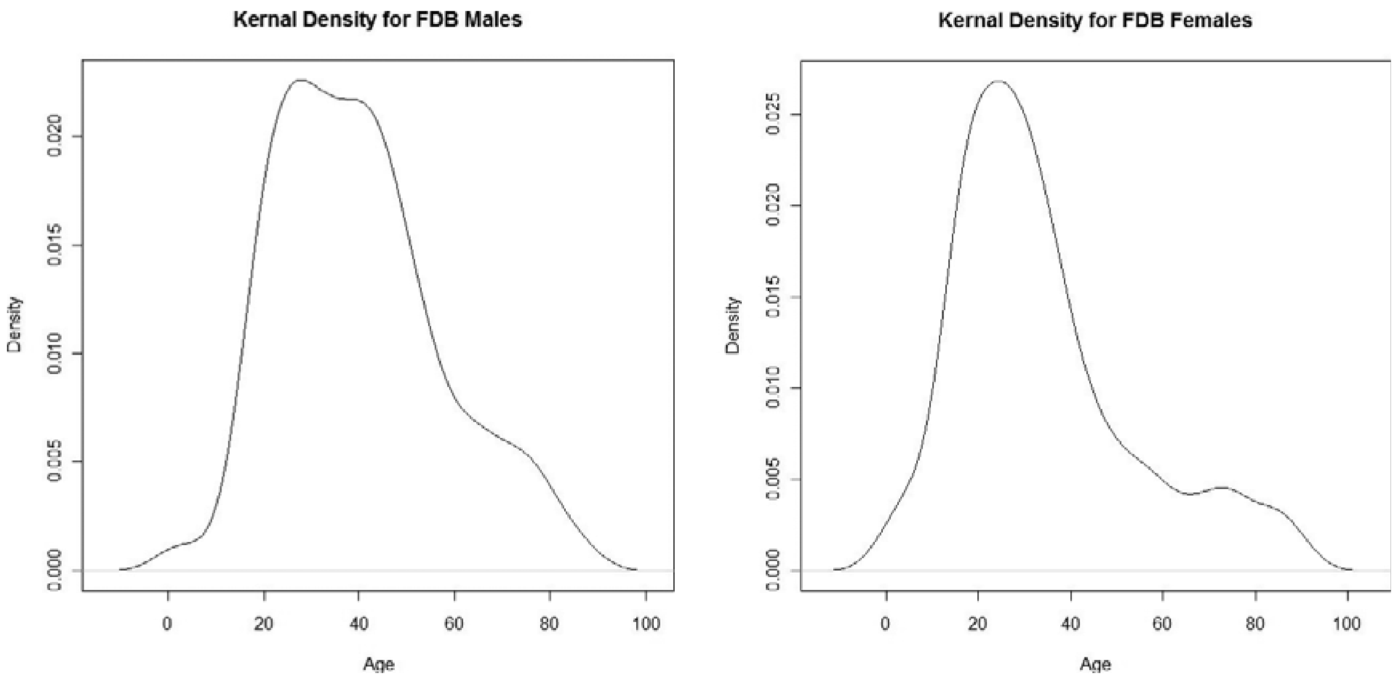


FIG. 8—*Forensic Data Bank age-at-death distributions. Kernal density plots.*

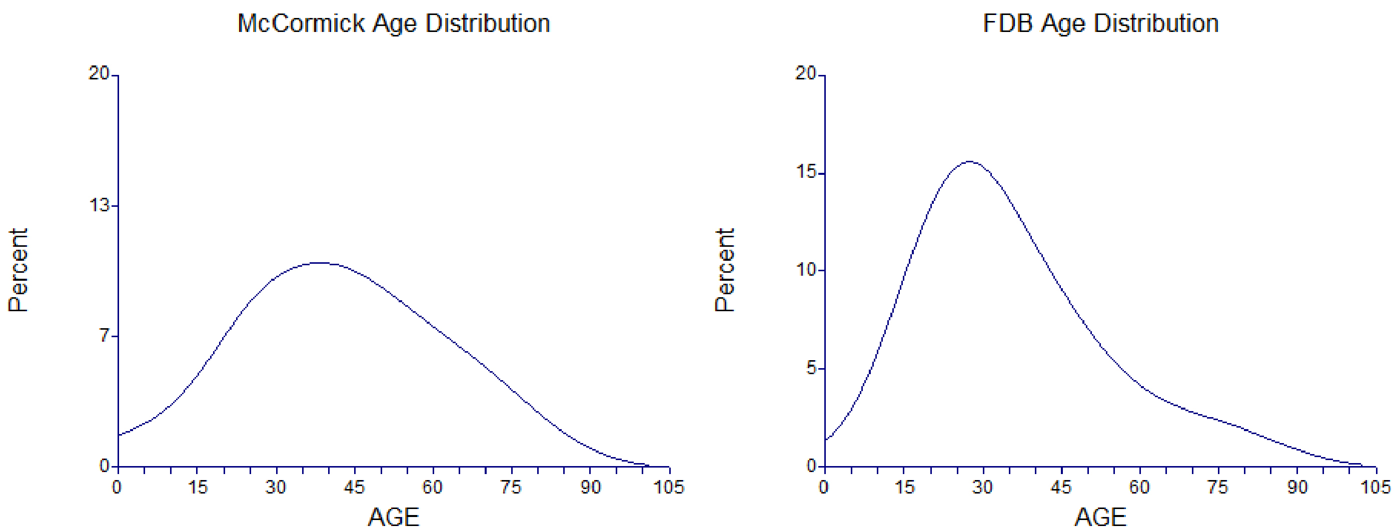


FIG. 9—*Age-at-death distributions for the McCormick autopsy sample and the Forensic Data Bank.*

distribution is an appropriate hazard model for FDB mortality. Figure 8 shows the differences between the men and women age-at-death distributions in the FDB. Consequently, separate hazards were run on men and women. The statistical package "R" was used to model the Gompertz distribution and to do the Bayesian analysis (http://www.r-project.org). "R" scripts for Gompertz hazards and for estimating the highest posterior density regions were adapted from scripts available at Dr. Lyle Kongsberg's webpage (http://konig.la.utk.edu).

The FDB was selected as an informative prior for the Bayesian analysis because of its similarity to the target population (i.e., forensic anthropology cases). An informative prior permits the selection of appropriate values for $f(a)$ that are independent of the skeletal samples and eliminates the biased influence of the reference sample age structure (47,51). An alternative would have been to use a uniform prior, which has a flat age distribution and assumes that the unidentified individual (i.e., forensic case) has an equal probability of being any age (51). However, this is not the case in a forensic context (or in any demographic context, for that matter). Furthermore, the age-at-death distribution from a typical medical examiner's office differs from the age-at-death distribution of a typical forensic anthropology caseload. Consider, for example, the fact that medical examiners are required to autopsy infant deaths; these cases are not part of a forensic anthropology caseload. The difference between the age-at-death distributions in medical examiner and forensic anthropology cases is illustrated in Fig. 9, where the McCormick age distribution was obtained from autopsy records (a portion of which were used for the present study), and

TABLE 1—*Observer error.*

| | 1 | | | 2 | | | 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| Observer | Diff* ($r_s$)† | B‡ ($p$)§ | $p_M$¶ | Diff* ($r_s$)† | B‡ ($p$)§ | $p_M$¶ | Diff* ($r_s$)† | B‡ ($p$)§ | $p_M$¶ |
| 5-phase system | | | | | | | | | |
| 1 | 1 (0.99) | 6.80 (0.15) | 1.00 | | | | | | |
| 2 | 11 (0.93) | 9.49 (0.05) | 0.25 | | | | | | |
| 3 | 5 (0.96) | ** | 0.45 | 13 (0.93) | 6.54 (0.16) | 0.78 | | | |
| 4 | 16 (0.89) | 11.68 (0.02) | 0.06 | 20 (0.88) | 19.38 (0.001) | 0.004 | 19 (0.88) | 15.50 (0.004) | 0.003 |
| 3-phase system | | | | | | | | | |
| 1 | 1 (0.96) | 1.02 (0.60) | 1.00 | | | | | | |
| 2 | 2 (0.92) | 2.08 (0.35) | 1.00 | | | | | | |
| 3 | 4 (0.86) | 3.22 (0.20) | 0.25 | 6 (0.79) | 5.54 (0.06) | 0.38 | | | |
| 4 | 11 (0.68) | 1.32 (0.52) | 0.51 | 11 (0.68) | 3.19 (0.20) | 0.51 | 9 (0.75) | 0.00 (1.00) | 1.00 |

This table offers several measures of inter- and intra-observer error and scoring bias. Observer 1 was used to test intra-observer error.
*Actual number of scoring differences between observers.
†Spearman's rank correlation coefficient ($r_s$).
‡Bhapkar chi-squared/Bhapkar coefficient of concordance (B).
§$p$-value associated with the Bhapkar concordance coefficient.
¶$p$-value from McNemar ($p_M$).
**Covariance matrix could not be inverted; Bhapkar test could not be performed.

the FDB distribution was obtained from forensic anthropology caseloads throughout the United States. Konigsberg et al. (49) recommend that the prior is a "reasonable [guess] at what the possible age should be for an individual case prior to an osteological analysis" (544). In that the FDB provides *a priori* knowledge about the age-at-death distribution from US forensic anthropology caseloads, it is an appropriate prior for the purposes of this study.

The Bayesian analysis combines the transition analysis likelihood estimates with the hazard parameters from the Gompertz-modeled FDB to obtain the posterior density regions for each phase, which are equivalent to the most likely age-at-death in each phase. Note that these age ranges are not confidence intervals around mean ages, but instead probability estimates of the most likely age-at-death (50). These age ranges were tested on 12 individuals from the University of Tennessee's William M. Bass Donated Collection. Finally, Student's $t$-statistics were used to evaluate differences between the sexes and between birth cohorts. The $t$-statistics were calculated using the maximum likelihood estimates of the transitions and the corresponding standard errors from the log-normal transition ages:

$$t = \frac{\overline{x_2} - \overline{x_1}}{\sqrt{se_2^2 + se_1^2}} \quad (4)$$

## Results

### *Observer Error*

The Spearman's rank correlation coefficient between age and phase for the McCormick, Hamann-Todd, and McKern and Stewart samples are 0.88, 0.80, and 0.81, respectively, for the five-phase scoring system and 0.83, 0.75, and 0.75 for the three-phase scoring system. All of these coefficients indicate a strong positive relationship between age and phase in both scoring systems. The observer error tests show that the three-phase system is less subjective than the five-phase system (Table 1). The three-phase scoring system resulted in fewer absolute differences between observers than the five-phase system (44 differences versus 85 differences, respectively). Nonetheless, only 4% of the total differences involved scoring discrepancies greater than one phase.

Whereas the Spearman's rank correlations were slightly higher with the five-phase system, the $p$-values from the Bhapkar concordance test were considerably higher with the three-phase system, thereby indicating more consistent and reproducible results with the three-phase system. Moreover, conversations with observers who scored the clavicles revealed that all observers found the three-phase system easier to use. As expected, the least experienced observer's scores exhibited more inconsistencies across comparisons. Furthermore, although no significant bias was detected in the three-phase system scoring, the five-phase system presented significant bias in two instances ($p_M < 0.05$) and near-significant bias in one instance ($p_M = 0.06$). The marginal distribution histograms in Fig. 10 assist in visualizing the directionality of this bias. Specifically, the bias is apparent in scores from observer 4 in phases 3 and 4 (active and recent fusion); observer 4 has a tendency to assign lower scores than the other observers. These results suggest that the five-phase system requires more osteological experience than the three-phase system; consequently, the three-phase system is more easily applied, regardless of experience level.

However, the five-phase system can provide a means of fine-tuning age estimates, particularly estimates based on multiple age indicators. For example, beginning fusion is likely to represent an individual at the younger end of the age range. In fact, all individuals in the beginning fusion stage were under 25. Likewise, recent fusion is likely to represent an individual on the older end of the age range; no individuals in the recent fusion stage were under 20 years of age. In fact, the authors recommend consulting the age ranges provided for recent fusion in the five-phase system in instances where a fusion scar is present.

### *Epiphyseal Union*

A Student's $t$-test with a 95% confidence interval was applied to the Hamann-Todd sample to test for significant ethnic differences in the transitions. None of the transitions were significantly different for African American males versus European American males in either the five-phase or the three-phase system. The small female sample size for some of the transitions precluded testing each transition in the five-phase system for women. Nonetheless, there were no significant differences between African American and European American females in the three-phase system. Consequently, ethnicities were pooled in this analysis.

Tables 2–4 present the descriptive statistics from each sample with both scoring systems. Means and standard deviations are given

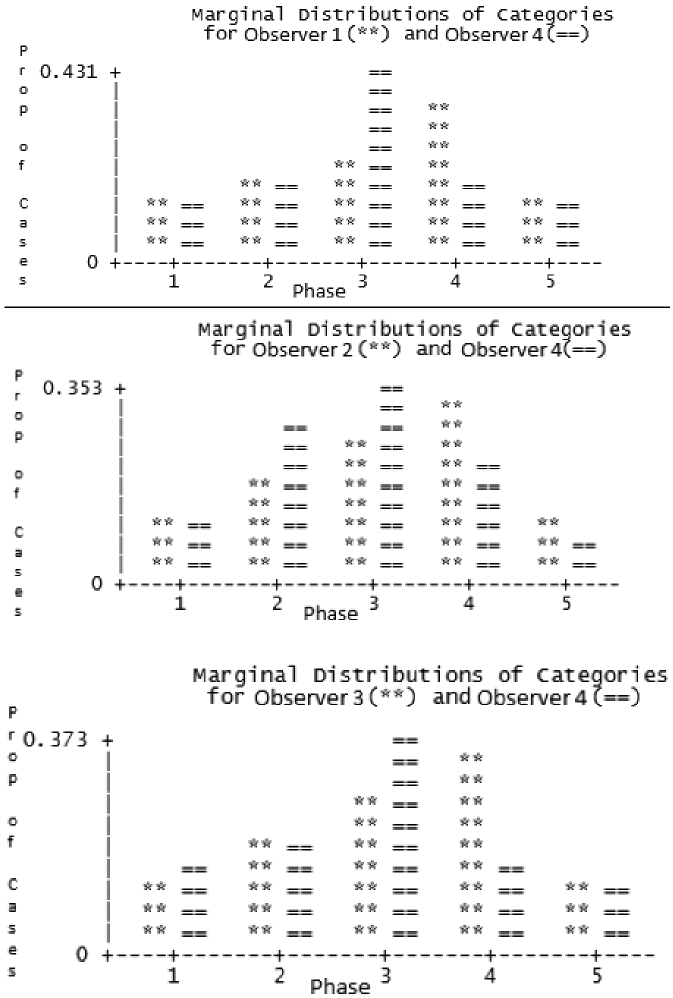


FIG. 10—*Marginal distribution histograms. These histograms show comparisons in which significant scoring bias was apparent. Overall, observer 4 had a tendency to assign lower scores than the other observers using the five-phase system.*

for each phase. However, note that the means for the first and last phases are artifacts of the upper and lower cut-off ages and should not be considered a true reflection of the variation in those phases. Age ranges derived from the raw data are included in the last column; these broad age ranges encompass the full range of variation in the data sets, including any outliers. Table 5 presents the results obtained from the transition analysis; the ages in this table are the maximum likelihood estimates of the age at which an individual transitions from one phase to the next (i.e., the age at which the transition is most likely to occur). As the transition analysis was applied with a cumulative probit model, all transitions are assigned the same standard deviation.

Figures 11 and 12 show the age-at-transition distributions from the five-phase system for the McCormick and Todd samples. Note the greater separation between the phases in the McCormick sample versus the Todd sample, particularly between the first two transitions (no fusion-beginning fusion and beginning-active fusion). Figure 13 shows the age-at-transition distributions for each of the three samples using the three-phase system. These graphs illustrate that the onset of fusion in the modern McCormick individuals occurs considerably earlier than in the Todd and McKern and Stewart individuals. Additionally, the McKern and Stewart Korean War males are more closely aligned with the Todd males for the

TABLE 2—*McCormick individuals descriptive statistics.*

| Phase | *n* | Mean Age | Standard Deviation | Observed Age Range |
|---|---|---|---|---|
| *5-phase system* | | | | |
| Males | | | | |
| 1 | 34 | 15.0 | 2.18 | ≤18 |
| 2 | 72 | 19.3 | 2.31 | 13–24 |
| 3 | 83 | 22.4 | 2.26 | 17–29 |
| 4 | 52 | 25.9 | 2.66 | 22–32 |
| 5 | 207 | 29.5 | 2.58 | ≥19 |
| Females | | | | |
| 1 | 11 | 14.6 | 2.11 | ≤19 |
| 2 | 22 | 17.8 | 1.89 | 15–23 |
| 3 | 26 | 21.0 | 2.54 | 17–26 |
| 4 | 16 | 25.4 | 2.94 | 20–31 |
| 5 | 70 | 29.3 | 2.47 | ≥24 |
| Total | | | | |
| 1 | 45 | 14.9 | 2.14 | ≤19 |
| 2 | 94 | 18.9 | 2.29 | 13–24 |
| 3 | 109 | 22.1 | 2.40 | 17–29 |
| 4 | 68 | 25.8 | 2.72 | 20–32 |
| 5 | 277 | 29.5 | 2.55 | ≥19 |
| *3-phase system* | | | | |
| Males | | | | |
| 1 | 34 | 15.0 | 2.18 | ≤18 |
| 2 | 207 | 22.2 | 3.47 | 13–32 |
| 3 | 207 | 29.5 | 2.58 | ≥19 |
| Females | | | | |
| 1 | 11 | 14.6 | 2.11 | ≤19 |
| 2 | 64 | 21.0 | 3.77 | 15–31 |
| 3 | 70 | 29.3 | 29.9 | ≥24 |
| Total | | | | |
| 1 | 45 | 14.9 | 2.14 | ≤19 |
| 2 | 271 | 21.9 | 3.57 | 13–32 |
| 3 | 277 | 29.5 | 2.55 | ≥19 |

Means for the first and last phases are skewed by the upper and lower cut-off ages of the sample.

first transition, indicating that the secular trend toward earlier onset of skeletal maturation appears to have occurred during the last several decades.

Table 6 presents the *t*-test results for sexual dimorphism in epiphyseal union. Significant levels of sexual dimorphism are evident in many of the transitions, but sexual dimorphism was not consistently detected in all transitions. However, the magnitude of sexual dimorphism is not constant across all stages of growth and development, but sex differences in skeletal maturation have been documented in the literature (37,41,52). Accordingly, this analysis provides separate age ranges for epiphyseal union in men and women in instances where sex is a known variable.

Table 7 shows the *t*-test results for cohort differences in epiphyseal union for men and women, respectively. Significant differences were noted in all the transitions between the McCormick and Todd males and between the McKern and Stewart and Todd males. The most significant differences between the McCormick males and the McKern and Stewart males occur in the first transition. Likewise, the significant differences between the McCormick and Todd females occurred in the first transition (i.e., in the onset of epiphyseal union). The transition from no fusion to beginning fusion occurs approximately 4 years earlier in the modern McCormick individuals than in the turn of the century Hamann-Todd individuals (see also Table 5). Furthermore, McCormick males transition to beginning fusion an average of 3.5 years earlier than the McKern and Stewart Korean War males. Consequently, the majority of the secular change in the onset of fusion appears to have occurred during the last several decades. Furthermore, the secular trend is more

TABLE 3—*Todd individuals descriptive statistics.*

| Phase | *n* | Mean Age | Standard Deviation | Observed Age Range |
|---|---|---|---|---|
| *5-phase system* | | | | |
| Males | | | | |
| 1 | 48 | 20.1 | 2.70 | ≤25 |
| 2 | 24 | 22.7 | 2.38 | 17–28 |
| 3 | 63 | 23.4 | 2.39 | 18–29 |
| 4 | 45 | 27.1 | 2.59 | 22–30 |
| 5 | 75 | 28.7 | 1.76 | ≥23 |
| Females | | | | |
| 1 | 21 | 16.6 | 3.74 | ≤25 |
| 2 | 3 | 20.7 | 3.06 | 18–24 |
| 3 | 18 | 22.7 | 2.59 | 18–26 |
| 4 | 14 | 25.1 | 2.77 | 21–29 |
| 5 | 43 | 27.6 | 2.17 | ≥22 |
| Total | | | | |
| 1 | 69 | 19.0 | 3.43 | ≤25 |
| 2 | 27 | 26.7 | 2.66 | 17–28 |
| 3 | 81 | 23.3 | 2.44 | 18–29 |
| 4 | 59 | 26.7 | 2.75 | 21–30 |
| 5 | 118 | 28.3 | 2.34 | ≥22 |
| *3-phase system* | | | | |
| Males | | | | |
| 1 | 48 | 20.1 | 2.70 | ≤25 |
| 2 | 132 | 24.6 | 3.08 | 17–30 |
| 3 | 75 | 28.7 | 1.76 | ≥23 |
| Females | | | | |
| 1 | 21 | 16.6 | 3.74 | ≤25 |
| 2 | 35 | 23.5 | 2.99 | 18–29 |
| 3 | 43 | 27.6 | 2.17 | ≥22 |
| Total | | | | |
| 1 | 69 | 19.0 | 3.43 | ≤25 |
| 2 | 354 | 24.4 | 3.09 | 17–30 |
| 3 | 118 | 28.3 | 2.34 | ≥22 |

Means for the first and last phases are skewed by the upper and lower cut-off ages of the sample.

TABLE 4—*McKern and Stewart males descriptive statistics.*

| Phase | *n* | Mean Age | Standard Deviation | Observed Age Range |
|---|---|---|---|---|
| 5-phase system | | | | |
| 1 | 118 | 19.2 | 1.44 | ≤24 |
| 2 | 45 | 19.7 | 1.60 | 16–23 |
| 3 | 60 | 21.4 | 2.03 | 18–29 |
| 4 | 48 | 24.1 | 2.45 | 19–30 |
| 5 | 70 | 28.1 | 2.98 | ≥20 |
| 3-phase system | | | | |
| 1 | 118 | 19.2 | 1.44 | ≤24 |
| 2 | 153 | 21.8 | 2.69 | 16–30 |
| 3 | 70 | 28.1 | 2.98 | ≥20 |

Means for the first and last phases are skewed by the upper and lower cut-off ages of the sample.

apparent in the onset of fusion than in the later stages, particularly in women; fusion commences significantly earlier in modern Americans but terminates at roughly the same age as in earlier Americans.

Tables 8 and 9 present the age ranges obtained with the Bayesian analysis. This analysis used the men and women hazard parameters obtained from the Gompertz-modeled FDB (men: $\alpha_3 = 0.01587542$, $\beta_3 = 0.03239691$; women: $\alpha_3 = 0.03518139$, $\beta_3 = 0.01013983$) and the transition analysis maximum likelihood estimates (see Table 5) to obtain probability density functions and corresponding age ranges. Four different probabilities are given for each phase and for both scoring systems (50%, 75%, 90%, and 95%). These confidence regions are *not* confidence intervals of the mean; instead, they represent the probability that an individual falls within an age range given that their clavicle exhibits the morphology of a given phase. Since this sample was truncated at 11 years on the lower end and 33 years on the upper end, the age ranges for the first and last phases are expressed in terms of the oldest and youngest probable ages for those phases. Tables 10 and 11 show the results of the test on the William M. Bass individuals using both scoring systems. The test sample size is small and contains only one woman, so statistical inferences should not be drawn from this test. Furthermore, a forensic caseload would provide a more appropriate test sample for these standards. Nonetheless, the test illustrates that aging accuracy is better with the 90% and 95% probabilities than with the 50% and 75% probabilities. The age ranges resulting from the Bayesian analysis were successful in aging the majority of the cases using the 90% and 95% probabilities; therefore, these probabilities encompass an adequate proportion of the individual variability in fusion.

## Discussion

### *Secular Change in Skeletal Maturation*

Although maturational secular change has been well documented in terms of somatic changes (i.e., earlier menarche and development of secondary sex characteristics), changes in skeletal maturation have received little attention, primarily because of the lack of sizable sub-adult skeletal samples available for cross-cohort comparisons. In fact, age at menarche in western, industrialized populations has decreased over the past five decades by around 4–6 months per decade, and pubertal onset in American females occurs as early as 8–10 years of age (11,14,30,53). Consequently, we might expect to see related changes in skeletal maturation. The results of this study indicate that the average age at which epiphyseal union commences in the medial clavicle is 4 years earlier in modern Americans than in the American population from the early

TABLE 5—*Transition ages.*

| Transition | McCormick Males | McCormick Females | Todd Males | Todd Females | McKern & Stewart |
|---|---|---|---|---|---|
| 5-phase system | | | | | |
| None–Beginning | 16.19 ± 1.02 | 15.18 ± 1.03 | 20.59 ± 1.02 | 19.02 ± 1.03 | 19.70 ± 1.01 |
| Beginning–Active | 20.39 ± 1.01 | 18.87 ± 1.02 | 21.86 ± 1.01 | 19.78 ± 1.03 | 20.94 ± 1.01 |
| Active–Recent | 23.98 ± 1.01 | 23.10 ± 1.02 | 25.24 ± 1.01 | 23.22 ± 1.02 | 23.24 ± 1.02 |
| Recent–Complete | 26.09 ± 1.01 | 25.58 ± 1.02 | 27.94 ± 1.01 | 25.35 ± 1.02 | 25.99 ± 1.01 |
| SD | 1.10 ± 1.01 | 1.10 ± 1.01 | 1.12 ± 1.01 | 1.12 ± 1.01 | 1.11 ± 1.01 |
| 3-phase system | | | | | |
| None–Fusing | 16.15 ± 1.02 | 15.42 ± 1.03 | 20.50 ± 1.02 | 19.24 ± 1.03 | 19.73 ± 1.01 |
| Fusing–Fused | 26.03 ± 1.01 | 25.39 ± 1.02 | 27.91 ± 1.01 | 25.35 ± 1.02 | 26.01 ± 1.01 |
| SD | 1.11 ± 1.01 | 1.11 ± 1.01 | 1.12 ± 1.01 | 1.13 ± 1.02 | 1.12 ± 1.01 |

Maximum likelihood estimate of age-at-transition (±standard error) and standard deviations (SD) from the cumulative probit on log-age transition analysis.

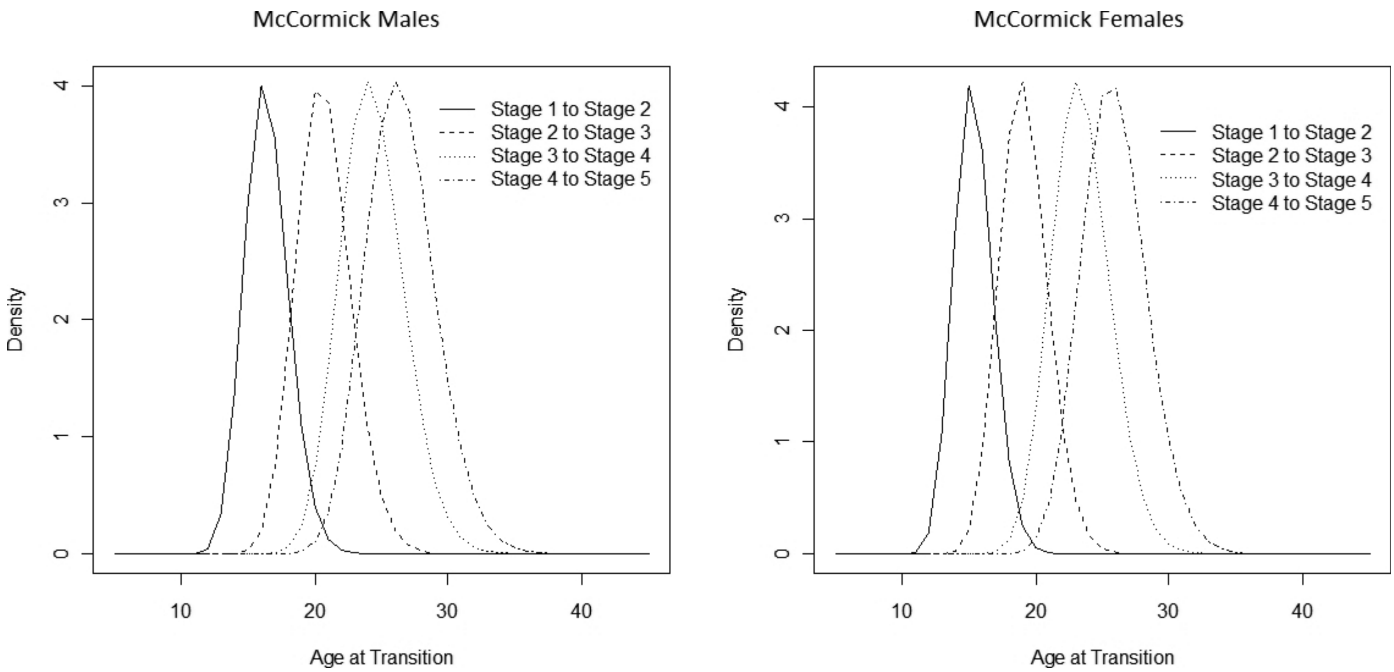


FIG. 11—*McCormick age-at-transition distributions. Transitions froms the five-phase system.*

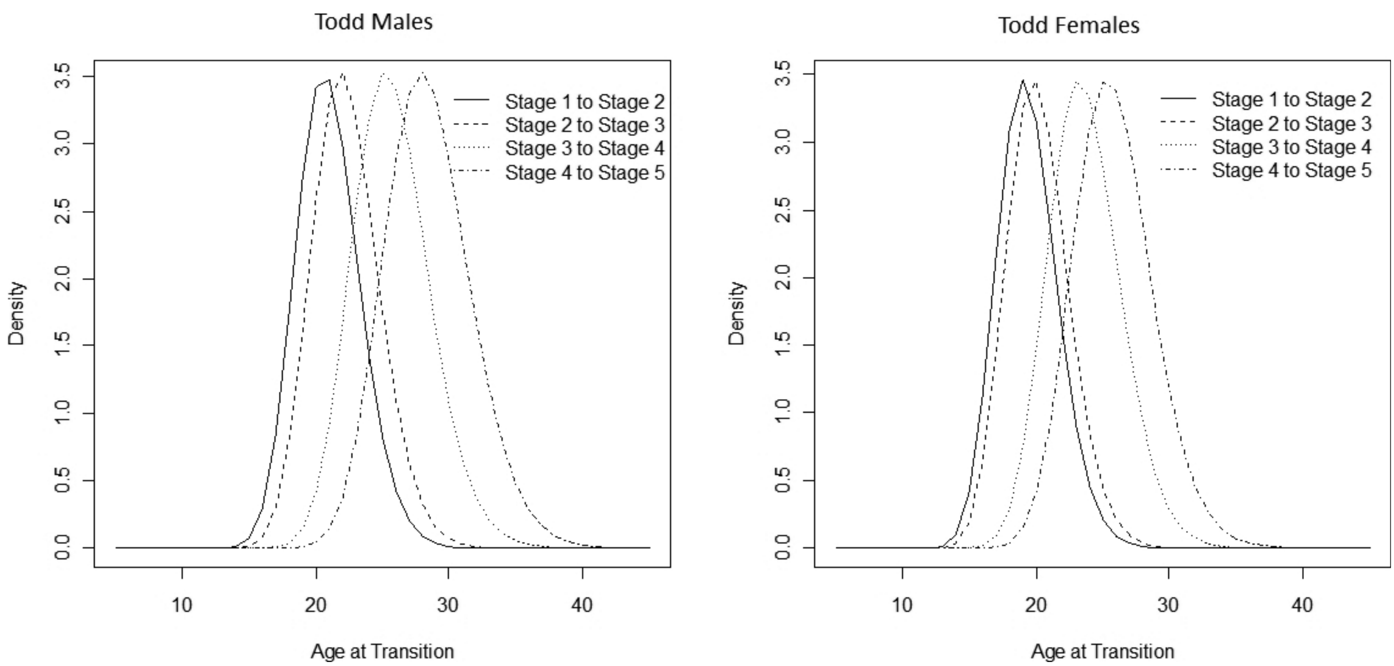


FIG. 12—*Todd age-at-transition distributions. Transitions from the five-phase system.*

20th century. Furthermore, comparisons between modern American males and American males from the Korean War era suggest that much of this acceleration has occurred during the latter part of the 20th century.

Reasons for secular changes in height, weight, and maturation are numerous; however, these changes are not necessarily caused by introducing growth-stimulation factors, but rather by eliminating growth-inhibiting factors (i.e., nutritional stress, environmental stresses, and disease) (14). Several factors contributing to body weight increases, overall health improvements, and accelerated maturation are stable caloric intake, reduced caloric expenditure, reduction in physical activity levels, increased calcium intake, introducing cereals at early age in infant diet, increased consumption of processed sugars and fats, improved socioeconomic status, improved health status, improvements in water and sanitation, elimination of infectious diseases, reduction in infant mortality, increased life expectancy, and reduction in family size (14). Furthermore, recent studies suggest that obesity has a significant effect on menarcheal age. Obese American females reach menarche earlier than normal weight females and are more likely to reach menarche before age

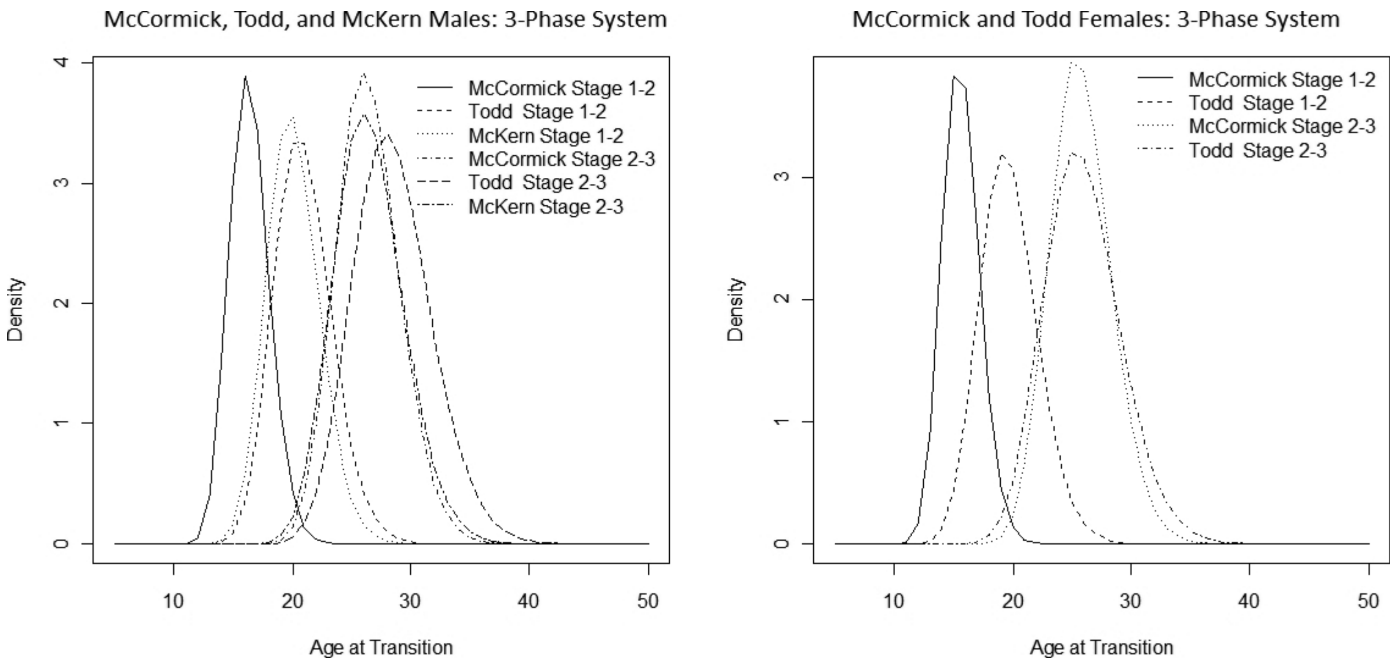


FIG. 13—*Three sample comparisons of age-at-transition. Transition distributions from three-phase system.*

TABLE 6—T-*tests for sexual dimorphism.*

| Transition | *t*-statistic | *p*-value |
|---|---|---|
| McCormick: 5-phase system | | |
| No–Beginning | 1.892 | 0.06 |
| Beginning–Active | 3.358 | <0.001 |
| Active–Recent | 1.729 | 0.09 |
| Recent–Complete | 1.056 | 0.29 |
| Todd: 5-phase system | | |
| No–Beginning | 1.942 | 0.05 |
| Beginning–Active | 3.210 | 0.001 |
| Active–Recent | 3.426 | 0.001 |
| Recent–Complete | 4.270 | <0.0001 |
| McCormick: 3-phase system | | |
| No fusion–Fusing | 1.362 | 0.17 |
| Fusing–Fused | 1.247 | 0.21 |
| Todd: 3-phase system | | |
| No fusion–Fusing | 1.802 | 0.07 |
| Fusing–Fused | 3.790 | <0.001 |

Degrees of freedom = ∞.

TABLE 7—T-*tests for secular trends.*

| | Males | | Females | |
|---|---|---|---|---|
| Transition | *t* | *p* | *t* | *p* |
| McCormick-Todd: 5-phase system | | | | |
| No–Beginning | 10.638 | <0.0001 | 5.308 | <0.0001 |
| Beginning–Active | 4.0873 | <0.0001 | 1.341 | 0.18 |
| Active–Recent | 3.378 | <0.001 | 0.185 | 0.85 |
| Recent–Complete | 4.531 | <0.0001 | 0.367 | 0.71 |
| McCormick-McKern: 5-phase system | | | | |
| No–Beginning | 10.265 | <0.0001 | – | – |
| Beginning–Active | 1.835 | 0.07 | – | – |
| Active–Recent | 2.187 | 0.03 | – | – |
| Recent–Complete | 0.258 | 0.80 | – | – |
| McKern-Todd: 5-phase system | | | | |
| No–Beginning | 2.547 | 0.01 | – | – |
| Beginning–Active | 2.761 | 0.006 | – | – |
| Active–Recent | 5.235 | <0.0001 | – | – |
| Recent–Complete | 4.130 | <0.0001 | – | – |
| McCormick-Todd: 3-phase system | | | | |
| No fusion–Fusing | 10.191 | <0.0001 | 5.182 | <0.0001 |
| Fusing–Fused | 4.490 | <0.0001 | 0.053 | 0.96 |
| McCormick-McKern: 3-phase system | | | | |
| No fusion–Fusing | 10.053 | <0.0001 | – | – |
| Fusing–Fused | 0.0250 | 0.98 | – | – |
| McKern-Todd: 3-phase system | | | | |
| No fusion–Fusing | 2.084 | 0.04 | – | – |
| Fusing–Fused | 3.807 | <0.001 | – | – |

Degrees of freedom = ∞.

12 (54). Similar obesity correlates have been reported in the European population (55) and in populations worldwide (56). In a forensic context, secular trends can affect age estimates derived from epiphyseal union because many skeletal aging standards were derived from documented collections of individuals born during the 19th and early 20th centuries. Age estimates based on reference standards from populations that have undergone significant positive secular change may be overestimates.

### *Using the Tables*

The tables in this study can be used to arrive at an age estimate in several ways. Table 2 provides age ranges based on the raw data. In some instances, these age ranges are extended several years because of the presence of a single outlier. For example, of the 207 McCormick males exhibiting complete fusion, one individual is 19, no individuals are between 20 and 22, two individuals are 23, one individual is 24, and then the frequency increases with individuals 25 years old and beyond. In other words, the 19-year-old outlier is not representative of typical fusion in that it constitutes a mere 0.48% of the variation. Nonetheless, some researchers argue that wide age ranges are necessary to address the unpredictable variation in individual cases (57,58). In addition, Table 2 could be used to devise age ranges based on the mean ± 1–2 standard deviations.

TABLE 8—*Male age ranges.*

| Phase | HPD | 50% CI | 75% CI | 90% CI | 95% CI |
|---|---|---|---|---|---|
| 5-phase system | | | | | |
| 1 | 12.7 | ≤13.7 | ≤15.2 | ≤16.6 | ≤17.4 |
| 2 | 18.2 | 16.8–19.8 | 15.9–21.0 | 15.0–22.2 | 14.4–23.0 |
| 3 | 22.2 | 20.6–23.9 | 19.5–25.2 | 18.5–26.6 | 17.9–27.5 |
| 4 | 25.1 | 23.4–26.9 | 22.3–28.2 | 21.2–29.6 | 20.5–30.6 |
| 5 | 34.7 | ≥29.1 | ≥26.9 | ≥25.1 | ≥24.1 |
| 3-phase system | | | | | |
| 1 | 12.6 | ≤13.7 | ≤15.2 | ≤16.6 | ≤17.4 |
| 2 | 20.9 | 18.3–23.5 | 16.8–25.4 | 15.6–27.3 | 14.9–28.5 |
| 3 | 34.8 | ≥29.1 | ≥26.9 | ≥25.0 | ≥24.0 |

Age ranges for modern males based on the highest posterior density regions from the McCormick sample.

TABLE 9—*Female age ranges.*

| Phase | HPD | 50% CI | 75% CI | 90% CI | 95% CI |
|---|---|---|---|---|---|
| 5-phase system | | | | | |
| 1 | – | ≤13.1 | ≤14.3 | ≤15.5 | ≤16.2 |
| 2 | 16.8 | 15.6–18.2 | 14.8–19.2 | 14.0–20.3 | 13.5–21.0 |
| 3 | 20.7 | 19.2–22.4 | 18.2–23.6 | 17.3–24.9 | 16.7–25.7 |
| 4 | 24.1 | 22.6–25.8 | 21.5–27.0 | 20.5–28.4 | 19.9–29.3 |
| 5 | 30.1 | ≥25.9 | ≥24.3 | ≥23.2 | ≥22.5 |
| 3-phase system | | | | | |
| 1 | – | ≤13.2 | ≤14.6 | ≤15.8 | ≤16.5 |
| 2 | 18.8 | 16.8–21.9 | 15.7–24.0 | 14.6–25.9 | 14.1–27.1 |
| 3 | 30.1 | ≥25.7 | ≥24.1 | ≥22.9 | ≥22.1 |

Age ranges for modern females based on the highest posterior density regions from the McCormick sample.

TABLE 10—*Test of PDF age ranges.*

| Sex | Age | Score | Predicted 50% | Predicted 75% | Predicted 90% | Predicted 95% |
|---|---|---|---|---|---|---|
| M | 26 | 5 | ≥29.1 | ≥26.9 | ≥25.1 | ≥24.1 |
| M | 19 | 1 | ≤13.7 | ≤15.2 | ≤16.6 | ≤17.4 |
| F | 20 | 2 | 15.6–18.2 | 14.8–19.2 | 14.0–20.3 | 13.5–21.0 |
| M | 27 | 4 | 23.4–26.9 | 22.3–28.2 | 21.2–29.6 | 20.5–30.6 |
| M | 26 | 4 | 23.4–26.9 | 22.3–28.2 | 21.2–29.6 | 20.5–30.6 |
| M | 27 | 5 | ≥29.1 | ≥26.9 | ≥25.1 | ≥24.1 |
| M | 27 | 5 | ≥29.1 | ≥26.9 | ≥25.1 | ≥24.1 |
| M | 29 | 5 | ≥29.1 | ≥26.9 | ≥25.1 | ≥24.1 |
| M | 25 | 1 | ≤13.7 | ≤15.2 | ≤16.6 | ≤17.4 |
| M | 27 | 4 | 23.4–26.9 | 22.3–28.2 | 21.2–29.6 | 20.5–30.6 |
| M | 23 | 3 | 20.6–23.9 | 19.5–25.2 | 18.5–26.6 | 17.9–27.5 |
| M | 25 | 5 | ≥29.1 | ≥26.9 | ≥25.1 | ≥24.1 |

Test on 12 individuals from the William M. Bass Donated Collection using the five-phase scoring system.

However, as mentioned earlier, the descriptive statistics for the first and last phases are artifacts of the upper and lower cut-off ages and may not accurately reflect the variation in those phases. Furthermore, age ranges obtained with simple descriptive statistics use what Konigsberg et al. (49) refer to as a "hidden Bayesian approach" in that the reference sample also serves as the prior age-at-death distribution. This introduces the problem of age mimicry, whereby the age estimates of the target sample are influenced by the composition of the reference sample (47,51).

For these reasons, the authors have used a Bayesian approach to obtain conservative, statistically sound estimates that are less sensitive to the effects of age mimicry and developmental outliers (Tables 8 and 9). These issues, specifically age mimicry, were recognized as problematic in the paleodemographic literature over two decades ago and finally came to the forefront with the publication of a number of papers in an edited volume outlining the Rostock Manifesto (59). The Rostock Manifesto adequately pointed out the shortcomings of developing age ranges from seriated skeletal traits in a reference sample and applying these age ranges directly to a target population. Bayes' theorem was suggested as a way to arrive at probability-based age estimates using an informative prior. Although well established in paleodemography, this methodology has been adapted only recently in forensic anthropology (49,50,60). However, Bayes' theorem is just as effective at estimating individual age in a forensic context as it is in estimating the age structure of an archeological population, and we expect that the use of Bayesian methods in forensic anthropology will continue to increase in popularity (61,62). Because the informative prior used to develop the age ranges in Table 8 provides *a priori* information for forensic anthropology cases, these age ranges are most appropriate for a forensic anthropology caseload. Nonetheless, as shown in Table 10, the 90% and 95% ranges may work well in additional contexts; medical examiners may want to consult the maximum likelihood estimates in Table 5, as well. Of course, whenever possible age estimates in forensic cases should be based on multiple age indicators, particularly because individual areas of a given skeleton may be advanced or delayed relative to other areas (57,63).

TABLE 11—*Test of PDF age ranges.*

| Sex | Age | Score | Predicted 50% | Predicted 75% | Predicted 90% | Predicted 95% |
|---|---|---|---|---|---|---|
| M | 26 | 3 | ≥29.1 | ≥26.9 | ≥25.0 | ≥24.0 |
| M | 19 | 1 | ≤13.7 | ≤15.2 | ≤16.6 | ≤17.4 |
| F | 20 | 2 | 16.8–21.9 | 15.7–24.0 | 14.6–25.9 | 14.1–27.1 |
| M | 27 | 2 | 18.3–23.5 | 16.8–25.4 | 15.6–27.3 | 14.9–28.5 |
| M | 26 | 2 | 18.3–23.5 | 16.8–25.4 | 15.6–27.3 | 14.9–28.5 |
| M | 27 | 3 | ≥29.1 | ≥26.9 | ≥25.0 | ≥24.0 |
| M | 27 | 3 | ≥29.1 | ≥26.9 | ≥25.0 | ≥24.0 |
| M | 29 | 3 | ≥29.1 | ≥26.9 | ≥25.0 | ≥24.0 |
| M | 25 | 1 | ≤13.7 | ≤15.2 | ≤16.6 | ≤17.4 |
| M | 27 | 2 | 18.3–23.5 | 16.8–25.4 | 15.6–27.3 | 14.9–28.5 |
| M | 23 | 2 | 18.3–23.5 | 16.8–25.4 | 15.6–27.3 | 14.9–28.5 |
| M | 25 | 3 | ≥29.1 | ≥26.9 | ≥25.0 | ≥24.0 |

Test on 12 individuals from the William M. Bass Donated Collection using the three-phase scoring system.

### *Other Considerations: Ethnicity and Methodological Standards*

The standards proposed in this study were derived using skeletal samples from the American population. Significant ethnic differences between African Americans and European Americans were not detected in this analysis, possibly because the factors affecting growth are similar for the American population as a whole, regardless of ethnicity. Indeed, socioeconomic status is cited more frequently than ethnicity as the most influential variable in maturational differences (10,14,19,20,26–28,32,64–68). Schmeling and coworkers (69) argue that skeletal maturation occurs in stages that are the same for all ethnic groups; the critical factor that brings about differences in ossification rates is the socioeconomic status of a given population. Although a genetically determined potential of skeletal maturation may exist, this potential does not appear to depend on ethnicity. Instead, growth potential is realized under favorable environmental conditions (namely high socioeconomic status), and population affiliation appears to have no appreciable effect on skeletal age (70). In fact, regression analysis has shown a positive relationship between ossification rates and medical modernization, as well as economic progress (70,71). Nonetheless, the results presented here should not be applied to populations outside of the United States, especially those in which different growth environments may influence development and maturation. Furthermore, recent evidence suggests that Hispanic immigrants in the United States may be experiencing differential maturation because of ethnic differences, lower socioeconomic status, or a combination of these factors (31).

Another matter of concern in making developmental status comparisons is the method used to establish stage of union. Many skeletal maturation standards are based on radiographic studies of living individuals, and the appearance of the epiphyses on radiographs is not necessarily the same as they appear in dry bone (32,67). Additionally, many studies are beginning to use CT scans to establish age ranges for epiphyseal fusion. Commencement of fusion can be detected earlier with radiographs and CT scans than with dry bone observations (68). Consequently, forensic age estimates based on conventional radiographs should use standards developed from radiographs, whereas age estimates based on CT scans should refer to CT-based standards, and estimates based on dry bone observations should use standards developed from dry bone (32,63,72). Accordingly, the standards proposed in this study should be applied to dry bone observations only.

The results of this study call attention to the importance of using modern standards to assess the age of modern individuals. As the American population continues to change, particularly with the current obesity epidemic, forensic anthropologists will be charged with the task of evaluating how these changes in human biology affect our understanding of human skeletal variation. The dynamic nature of human populations necessitates constant research to ensure the most rigorous standards and current practices are available for use. Finally, age ranges derived using Bayesian statistics circumvent the issues of age mimicry and developmental outliers. Traditionally, these methods have been employed to establish standards for adult age estimation. However, they can be useful in sub-adult age estimation, as well, and a Bayesian approach should be considered in future evaluations of sub-adult skeletal aging.

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