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Variability of the Pattern of Aging on the Human Skeleton: Evidence from Bone Indicators and Implications on Age at Death Estimation

ABSTRACT: Age at death assessment of adult skeletons is one of the most difficult problems in forensic and physical anthropology. Two fundamental sources of error are described: the complex variability in the process of skeletal aging and methodological bias. Taking into account these limits, we developed a new scoring system for the auricular surface of the ilium and the pubic symphysis. In order to address a large variability, we examine reference samples from Europe, North America, Africa, and Asia. Data were processed using Bayesian prediction in order to classify specimens in age range categories. Results show that combining indicators do not perform better than the auricular surface used as a single indicator. Morphological changes with aging are variable between Asian, African, and European populations, confirming the necessity to use population-specific standards. Bayesian prediction produces reliable classification and is applicable for subjects over 50 years old, a real methodological improvement.

KEYWORDS: forensic science, forensic anthropology, skeletal age estimation, bone indicators, human aging variability, Bayes' theorem

Accurate estimation of age at death is a prerequisite for forensic identification and unbiased paleoanthropological studies. It is only with unbiased methods that meaningful statements can be made. For past populations, a reliable estimation of age at death in skeletal material is a fundamental condition to develop a demographic profile but also to discuss biology of past people and their burial practices. One of the goals of a forensic investigation is to estimate the age of a single target individual. Methods elaborated in forensic sciences are most often based on specific population standards. Those populations represent individuals originating from the major geographical regions of the world. But the variability between individuals within the same population is often underestimated (1).

Thus, methods for estimating the age of adult skeletons is still a continually developing area in forensic or archaeological fields. Adult age estimates are based on "wear and tear" indicators such as skeletal degeneration and dental and bone remodeling. Most of indicators of age have been tested using various skeletal collections of known age. The level of reliability and accuracy in age assessment are highly variable between studies (2), and it appears that no stable method exists (3–5). Thus, we are beginning to accept that methods of age assessment are flawed and that it is necessary to establish the fundamental sources of error.

The main source of problem is the nature of human senescence. Senescence is characterized by an accumulation of metabolic disorders and decreased probability of survival (6). This process of aging is universal and progressive. But age-related processes show great variation in level and degree of change both within and between populations with increasing age (7). Individual senescence is determined by a complex set of ongoing interactions (genes-culture-environment) that contribute to his specific life history. Variation in the biological aging process has profound effects on age-at-death assessment. If we want to improve age estimation, we have to take into account this phenomenon. The relationship between chronological age and skeletal age indicators is neither constant nor linear, which is why adult ages at death cannot be estimated with accuracy from skeletal data (5). Skeletal changes have some relationship with age, but this relationship is governed by many factors (4).

Any method must give identical results independent of the observer. The intra- and inter-observer errors have to be assessed systematically (8). It is the ability to identify the pattern of changes of an age indicator that ultimately determines the usefulness of an age assessment method. Reproducibility by investigators with or without limited experience is needed (9).

With the exception of the multi-regional reference collection created by Suchey (10), most methods, especially the histologically based, are elaborated on the basis of approximately 100 individuals from the same population. Both limited sample size and mono-regional sample do not allow one to take into account the whole range of variability of a population. That is the reason why, when a new method is elaborated, its reliability must be evaluated on a completely independent sample of known age-at-death both from the same population and from different populations.

Methods of age-at-death assessment are based on the assumption that the underlying biological basis of the age/indicator relationship is constant across populations. Therefore, the age of any unknown or target individual can be estimated from observations of the skeletal indicators. Yet, age changes are not uniform across

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populations (11). The reference sample provides the basic information on age development underlying to a sample or an individual of unknown ages. To each stage of evolution of an age indicator, for instance, the cranial suture corresponds to a mean age in the reference population. This mean age depends, to a large extent, on the age structure of the reference population. It means that distribution for an archaeological sample will be close to the age distribution of the reference sample (12–14). In forensic investigations, the estimate of the age for a single target individual depends also on the reference sample, even if population-specific aging methods are developed.

Data processing methods are also open to criticism. As an example, most aging techniques use linear regression to correlate the morphological score of one indicator and chronological age. The equation of this regression line is used to convert unknown values of the age indicators into predicted ages. But, the poorer the correlation, the greater is the bias (15). There is a systematic trend towards overestimating the age of the young adults and underestimating that of older individuals. Given that the correlation between biological data and age is low (16,17), it represents a fundamental limitation to this predictive technique.

Progress in the estimation of age-at-death involves greater awareness of the inherent biological variability and a better appreciation of the importance of systematic methodological bias. New methodologies should take into account the following points. Intra- and inter-observers error must be avoided by the elaboration of simple and scoring system and detailed publication (18,19). Age/indicator relationship varies among samples from different geographical regions (1). Thus, when elaborating a new method, it is necessary to observe samples of various osteological collections of known age-at-death (5) in order to obtain the widest variability of aging patterns. Aging differences related to sex must be analyzed. Data processing must be adequate to the complex nature of skeletal aging. The probability of belonging to an age category conditional on our knowledge of the indicator state is the most appropriate computation. The aim of new methodology should improve reliability instead of accuracy.

We propose here a new scoring system of the following current indicators: the pubic symphysis and the auricular surface of the ilium, which we prefer to call the sacro-pelvic surface of the ilium as it includes the retro-auricular area.

We observed the morphological changes of both indicators on several samples selected from identified collections from different geographical areas: Europe, North America, Asia, and Africa. We processed the data by Bayesian prediction. This technique allows a direct visualization of variability, since age-at-death is assessed by probabilities to belong to a chronological interval.

Materials and Methods

Observed Material

Four European collections from documented cemeteries were studied: Conchada Cemetery, Coimbra-Portugal (20); Spitalfields cemetery, London, Great Britain (21); Alcione Cemetery, Madrid, Spain; cemeteries from the canton de Vaud, Swizerland (22). The collections from Spain and Switzerland were entirely observed. They are composed of few and rather old individuals. We selected a sample from the Portuguese and British collection. We observed individuals of European origin from the Hammann-Todd collection, Cleveland, USA (23). From the Dart collection, Johannesburg, South Africa, two samples were selected, namely, individuals of African origin and individuals from European origin. And, finally, we observed an Asian sample from a Thaï collection, Chiang Mai, Thailand.

TABLE 1—*Osteological samples used in the study.*

Geographical Areas	Male	Female	Total
Portugal	59	67	126
Great Britain	85	78	163
Switzerland	103	48	151
Spain	26	38	64
USA (european origin)	57	56	113
South Africa	87	101	188
South-Africa (european origin)	24	22	46
Thaïland	34	29	63
Total	475	439	914

The number of individuals in each sample is given in Table 1.

New Scoring System

It has been claimed that histological age assessment from bone and teeth provide accurate data, but its early promise has not borne out (17,24,25). Microscopic techniques are not appreciably more accurate than macroscopic techniques (26). The methods used by forensic and physical anthropologists are the quick and cheap macroscopic methods. We chose to elaborate a new methodology from the pubic symphysis and the sacro-pelvic surface of the ilium. Current methods based on those indicators (27,28) involve morphological phase determination based on many features. Many blind tests of these techniques (3,21,29–31) found that both repeatability and reliability were low. Moreover, the method's applications are complex, especially for the sacro-pelvic surface for which application is too difficult to learn and master to yield satisfactory results (32,33).

We propose an alternative application to the initial methods of age-at-death based on these indicators. Each feature of each indicator is observed and processed separately with its own scale of variation. It simplifies the scoring system and, as a consequence, should improve the repeatability. It also allows one to combine the different features in a more objective way than the initial phase determination methods.

We observe four features on the sacro-pelvic surface: the transverse organization (two phases), the modification of the articular surface (four phases), the modification of the apex (two phases), and the modification of the iliac tuberosity (two phases).

Three features are examined on the pubic symphysis: the posterior plate (three phases), the anterior plate (three phases), and the posterior lip (two phases).

These new scoring systems are fully described with illustrations in Schmitt (32) and Schmitt and Broqua (33). Applying this new system reduces error between observers, since the similarity between two observers reaches 90% for each indicator. In previous studies (21,30), inter-observer errors were higher.

Before conducting a Bayesian prediction, we tested whether there were statistical differences between male and female for each feature considering each collection separately. Previously, we had to determine whether male and female groups had a similar age structure by a Kolmogorov Smirnov test. Non-parametric tests were used: the Mann-Whitney test for features' scores over 2 and the Fisher's exact test for the binomial features.

Data Processing: the Bayesian Approach

Bayes' theorem is commonly use in forensic science (34) and anthropology (14,35–40). Lucy and colleagues (40) have proposed a Bayesian prediction for individual age-at-death assessment. A strict implementation of Bayesian methods for continuous data would require the use of advanced technique of numerical analysis, but for ordinal-scale age categories and skeletal age indicators divided into discrete states, the Bayesian approach becomes simple and straightforward.

The mathematical details of the procedure are fully described by Lucy and colleagues (40). Prior probability is the probability of an individual belonging to a defined age category, given no information other than the assumption that the individual is similar to the reference sample to be used. The likelihood is the probability of an individual with a particular score to belong to a given age, based on the age distribution of the reference set for that point's score. The posterior probability is the one related to an individual belonging to a particular age group, taking into account the prior probability and the likelihood (15). Age categories were divided by decades.

Crucial to the Bayesian approach is the selection of appropriate prior probabilities for each age category. There are several options. The use of the reference series as a source of priors can usually be ruled out for the reasons given in the introduction. One option is to assume a uniform prior probability of age (14).

From the posterior probabilities, Lucy and colleagues (40) estimate a median age-at-death. On the contrary, we choose to analyze directly the posterior probabilities distribution by age interval. For this purpose, we had to fix a threshold of probability for which we consider the correct interval. Different thresholds of classification were tested to retain the one that enables the highest number of individuals whose age at death is included in the interval. The threshold of 0.8 gives the best results. Table 2 shows a few examples of posterior probability distributions and the corresponding interval computation obtained with SPS indicator. Specimen A has 88.5% confidence to be between 20 and 29 years old, which corresponds to a narrower interval. Specimen B has 86.6 confidence to be between 30 and 59 years old. Specimen C is undetermined to the threshold of 0.8. Posterior probabilities are very close between age categories. Specimen D has 85% confidence to be over 60 years old.

We applied the Bayesian prediction on the sacro-pelvic surface (SPS). As pubic symphysis (PS) modification with age is not relevant from 40 years old (11, 42–44), we did not use it as a single criterion but by combining SPS and PS.

Results

Difference between Sex

Kolmogorov Smirnov tests indicate that male age-at-death distribution does not differ significantly ($p > 0.10$) from female age-at-death distribution, except for the Spanish sample, which is therefore excluded from this analysis. Then, we perform Mann-Whitney and Fisher's exact tests in order to test sex independence. The calculations yield p values more than 0.05 for each test concerning the pubic symphysis and the sacro-pelvic surface of the ilium. We accept the null hypothesis of sex independence.

Difference between Populations

For this analysis, five samples were considered: Portugal, Great Britain, USA, Africa, and Asia. The Spanish, Swiss, and African with European origin individuals were used for further analyses as independent target samples.

For each sample, we calculated the individual's posterior probabilities to belong to an age category. But, as it would have been incorrect to make estimates for individuals, which also appeared in the reference sample, we use a jackknife re-sampling strategy (44). Each specimen was removed in turn when its posterior probabilities were calculated on the basis of the other cases.

We tried, as far as was possible, and depending on the collection, to elaborate the homogeneous number of individuals in each age category. The last age category, ">60" was doubled compared to the ten-years-of-age categories since we considered the interval 60 to 80, except for the Asian sample, for which it was not possible. Table 3 summarizes the number of individuals selected for each sample.

Table 4 indicates the distribution of well-classified, misclassified, or non-classified individuals for SPS and SPS+PS. A well-classified specimen means that the interval computed by the Bayesian prediction includes the age category to which the specimen belongs. A not-classified individual means that the posterior probabilities do not reach 0.8 for any categories (see method). SPS used as a single age indicator gives similar results when combined with PS. If we do not consider non-classified individuals, the success of classification for European groups is around 86%. However, there are fewer no-classified individuals with SPS and PS combined, except for Africa. Indeed, the African group shows a high number of no classified individuals (44 to 53%). On the contrary, the whole Asian sample is classified.

TABLE 3—*Reference sample size for separate analysis.*

Indicators	SPS	SPS+PUS
Portugal	108	90
Great Britain	102	96
USA (european origin)	120	120
South Africa	126	120
Thailand	63	63

TABLE 2—*Posterior probabilities distribution and interval computation for SPS indicator.*

			Posterior Probability					
Specimen	Age Category	Age	20–29	30–39	40–49	50–59	>60	Computed Interval
A	20–29	21	0.885	0.082	0.033	0.000	0.000	20–29
B	30–39	37	0.104	0.313	0.323	0.229	0.033	30–59
C	40–49	42	0.089	0.260	0.297	0.212	0.142	Not classified
D	>60	96	0.000	0.011	0.019	0.120	0.851	>60

TABLE 4—*Number of individuals well classified, misclassified and not classified in each sample for SPS and SPS+PS.*

	SPS			
	Misclassified	Well Classified	Not Classified	Total
Portugal	12	78	18	108
Great Britain	12	75	15	102
USA (European origin)	15	92	13	120
South Africa	18	53	55	126
Thailand	9	54	0	63
	SPS+PS			
	Misclassified	Well Classified	Not Classified	Total
Portugal	12	75	3	90
Great Britain	12	75	9	96
USA (European origin)	14	93	13	120
South Africa	10	63	47	120
Thailand	12	51	0	63

A close inspection of the classification reflects the variability of the indicators of aging pattern. Tables 5 to 9 indicate the successful classification obtained with the sacro-pelvic surface of the ilium for each population observed.

For the age category 20–29, 10/14 individuals from Portugal individuals are classified in the corresponding age range. For the remaining groups, intervals go from 20–39, 30–49, or 20–49. The specimens belonging to the 30–39 and 40–49 decades are well clas-

TABLE 8—*Assigned chronological interval for well classified individuals from South Africa.*

Actual Age Category	Assigned Age Category 20–39	20–49	>40	>50	>60	Actual Total
20–29	4	6	0	0	0	10
30–39	1	2	0	0	0	3
40–49	0	1	5	0	0	6
50–59	0	0	5	5	0	10
>60	0	0	9	13	2	24
Assigned total	5	9	19	18	2	53

TABLE 5—*Assigned chronological interval for well classified individuals from Portugal.*

Actual Age Category	Assigned Age Category 20–29	20–39	20–49	30–39	30–49	40–49	40–59	>40	>50	Actual Total
20–29	10	1	3	0	0	0	0	0	0	14
30–39	0	1	8	1	1	0	0	0	0	11
40–49	0	0	4	0	1	1	1	5	0	12
50–59	0	0	0	0	0	0	0	0	11	11
>60	0	0	0	0	0	0	0	4	26	30
Assigned total	10	2	15	1	2	1	1	9	37	78

TABLE 6—*Assigned chronological interval for well classified individuals from Great Britain.*

Actual Age Category	Assigned Age Category 20–29	20–39	30–49	30–59	40–49	>40	>50	>60	Actual Total
20–29	7	6	0	0	0	0	0	0	13
30–39	0	5	3	2	0	0	0	0	10
40–49	0	0	3	3	3	4	0	0	13
50–59	0	0	0	2	0	3	3	0	8
>60	0	0	0	0	0	9	11	11	31
Assigned total	7	11	6	7	3	16	14	11	75

TABLE 7—*Assigned chronological interval for well classified individuals from North America.*

Actual Age Category	Assigned Age Category 20–29	20–39	20–49	30–49	30–59	>40	>50	>60	Actual Total
20–29	3	6	8	0	0	0	0	0	17
30–39	0	1	6	1	7	0	0	0	15
40–49	0	0	4	2	2	7	0	0	15
50–59	0	0	0	0	1	6	7	0	14
>60	0	0	0	0	0	7	15	9	31
Assigned total	3	7	18	3	10	20	22	9	92

TABLE 9—*Assigned chronological interval for well classified individuals from Thailand.*

Actual Age Category	Assigned Age Category 20–39	30–49	30–59	40–59	>40	>50	50–59	>60	Actual Total
20–29	2	0	0	0	0	0	0	0	2
30–39	1	2	1	0	0	0	0	0	4
40–49	0	2	1	1	10	0	0	0	14
50–59	0	0	4	0	2	7	1	0	14
>60	0	0	0	0	7	10	0	3	20
Assigned total	3	4	6	1	19	17	1	3	54

sified in larger intervals. Most of the individuals of the 50–59 decade are classified as being over 40 years old in every sample. None of the subjects who belong to the last age category (>60) are classified under 40 years old. In the Portuguese sample, 26/30 individuals over 60 years old are identified as being more than 50. With the English and American groups, the posterior probabilities distribution enables to classify many of them in the exact age category. Few are identified in the precise age category in the African and Asian samples. European groups follow the same trend of classification. The middle age categories present the most variable aging pattern. Moreover, the undetermined individuals belong quite systematically to those age ranges. The classification in a precise interval is limited to extreme age categories.

The African sample presents peculiar results. Most of the individuals are not classified. Posterior probabilities distribution is quite similar in each age category. Young individuals belonging to the 20–29 age category are classified in widest chronological intervals (20–39 or 20–49) compared to other samples. The Asian group presents the same pattern, but there are few young individuals in this collection.

Independent Test of the European Model

As European samples follow the same trend of variation, a European model was created. We pooled the Portuguese, English, and North-American groups. We tested the model reliability on three independent target samples from Spain ($n = 77$), Switzerland ($n = 71$), and South-Africa with European origin ($n = 46$). The analysis of individuals' posterior probabilities shows that very few subjects are not classified: one Spanish, three Swiss, and two Africans from European origin. The Bayesian prediction enables classification of individuals in large but reliable chronological age groups. Ninety four percent of the Spanish group and 89% of the Swiss group are well classified. Those samples are made of individuals over 60 years old whose identification performs well with our methodology. Only 78% of the European origin individuals of South Africa are well classified. Five subjects who belong to the category 40–49 are misclassified as more than 50 years old. However, these results are very close to those obtained for European groups processed separately. A multi-regional European model is therefore appropriate for European population.

In order to ascertain the difference between Asian and European groups, the Asian sample was tested as a target on the European reference. As expected, the European model misclassified 13 individuals, and 5 were not classified at all. The age prediction performs worse when using European reference. This analysis confirms that bone indicators for morphological changes are specific of the Asian group.

Discussion

These results stress several important points. Distributions of posterior probabilities confirm the non-linear relation between bone indicators and age at death. Individuals who belong to middle age categories are classified in large chronological intervals. To reach a probability of 0.8, we have to consider two or three decennial age categories. Thus, accurate age-at-death estimation is out of reach for the samples studied herein. However, identification of individuals aged over 60 is particularly relevant. Indeed, archaeological samples that have been aged using skeletal morphological indicators show an absence of or at least very few older individuals. When testing the methods on the known age-at-death sample, the same trend (30–31) appears. Our methodology encounters this systematic bias.

Concerning the new scoring system, the retained features of morphological changes in the pubic symphysis and the sacropelvic surface are not sex dependent. Consequently, this system may be used for both sexes without risk of introducing measurable bias. This is in agreement with other publications for the sacropelvic surface (29,32). Various studies have clearly shown that the pubic symphysis morphological changes with age involve separate standards for each sex. Discrepancies between the sexes were demonstrated from 40 years old on (31,45) and are probably linked to the degenerative process. However, two of the features observed for this indicator are related to maturity rather than degeneration of the joint.

This work also approaches the relative value of using a multifactor technique versus a single technique. While multifactor technique is recommended by many authors (2,15,46,47), our results suggest that, as far as reliability is concerned, approaches that consider multiple indicators are not more outstanding than single criteria. Thus, we argue that it is better to take into account only a single factor—the most reliable indicator—as suggested by Saunders and colleagues (30). The sacro-pelvic surface turned out to be a useful single age indicator. Senescent biology of this criterion offers several peculiarities that make it an appropriate individual age indicator. Due to the histomorphological structure of the joint and its unique embryonic origin and development (41), the morphological changes extend beyond the fifth decade (28). Moreover, it is frequently preserved in archeological contexts (48–50).

The last point is the necessity to use population-specific standards. Morphological changes with aging in Asian and African samples are clearly different from European samples. However, European groups show the same trend of variation. Three European independent target samples were tested on a European model. Results confirm the similarities of morphological changes with aging among European groups.

Age estimation is a fundamental parameter of research in both forensic sciences and archaeological purposes. This topic suffers from many fundamental sources of error. This preliminary study demonstrates that is possible to avoid or reduce most of the bias, i.e., inter-observer errors in scoring, influence of the reference sample, and sex-dependent bone indicators.

The use of Bayesian prediction seems to be a useful tool to advance aging techniques, as demonstrated by previous studies (15,40). In our methodology, this tool allows a reliable classification by chronological intervals. Reliability may increase at the expense of accuracy, but we believe that the estimation of age at death needs to be free from empiricism and to make advances on well-defined bases. Identification of reliable intervals for each individual represents nevertheless crucial information for both forensic and physical anthropology topics.

This study also shows that a single standard of senescence for populations of different origins is not appropriate. Population-specific models are absolutely necessary. If this approach is possible for forensic investigation, it is not the case for past population studies. For those particular target samples, only one option remains: the use of a model including the widest variability of bone indicators of morphological changes. This kind of model is likely to provide high number of non-classified individuals, remaining the only way to preserve the reliability of the estimation.

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