New Tools for Ancient Populations

Estimating Age-at-Death Distributions from Skeletal Remains by Calibrated Expert Inference

Jutta Gampe[1], George R. Milner[2], Jersper L. Boldsen[3], and Svenja Weise[1]

[1]Max Planck Institute for Demographic Research, Rostock, Germany
[2]Department of Anthropology, Penn State University, PA, USA
[3]Institute of Forensic Medicine, University of Southern Denmark, Odense

Extended Abstract
September 23, 2011

1 Introduction

Paleodemography aims at identifying the demographic patterns and parameters of past populations. Information about individuals that lived in those populations is mostly derived from archaeological finds. Physical anthropologists assess skeletal remains to estimate the distribution of ages-at-death, from which conclusions about mortality patterns in the past can be obtained. Age-estimation in paleodemography had been controversial and is hampered by several complications, a review of the fields and its problems can be found in Hoppa and Vaupel (2002).

Generally age-estimation proceeds in two steps (Koenigsberg and Frankenberg, 2002): One or several age-indicators, i.e., features of the skeleton that change with age, are studied for known-age skeletons. Such a reference sample allows to assess the distribution of the indicator(s) for given ages-at-death and the reference sample is the basis for a calibration procedure.

These age-indicators are then determined for the skeletal remains whose ages are unknown, however, the distribution of the indicator in an archaeological site is the composite of both the calibration relationship and the actual age-at-death distribution in the target population, which is to be estimated. Therefore the target quantity – the unknown age-at-death distribution – can only be estimated indirectly from the distribution of indicators, which make this problem statistically challenging. Ignoring this complication leads to so called 'age-mimicry' of the reference sample, which is one source of the scepticism that had been expressed towards the field in general Bocquet-Appel and Masset (1982).

In this paper we present a novel methodology for estimating age-at-death distributions from skeletons, *Calibrated Expert Inference (CEI)*. The method proposes a new indicator, the so called expert age, which allows an overall assessment of a skeleton but avoids the estimation of a multivariate calibration problem. Second the statistical methodology is adapted to the kind of information that is derived as expert age, which is commonly expressed as an interval that also incorporates the uncertainty of the osteologist's assessment (Milner et al., 2011; Gampe et al., 2011).

2 Expert Age and Calibration

The new indicator summarizes the anthropological assessment into a single interval, the expert age, and this interval also conveys the uncertainty that is linked to the assessment. Figure 1 show such expert ages for skeletons from the Portuguese Coimbra Identified Skeletal Collection. Two aspects of

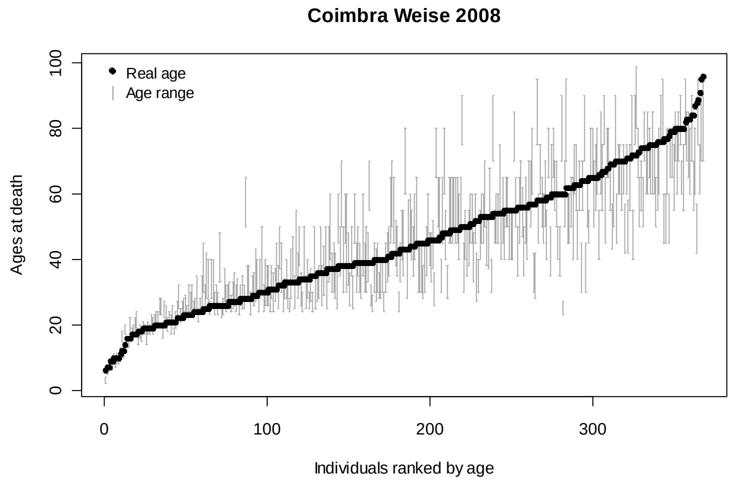

Figure 1: Skeletons, with sexes combined, arranged from youngest to oldest with known ages (dots) and estimated age ranges (lines) for examinations of the Coimbra skeletons.

the osteological component of CEI depart from common practice. First, numerous skeletal features are examined, not just a few anatomical structures such as, for adults, the pubic symphysis, iliac auricular surface, cranial sutures, and sternal ends of the ribs. Individually each characteristic provides limited information, but collectively they contribute a lot to the initial assessment of age. Second, the procedure relies on an observer's overall impression of skeletal age; that is, an experienced osteologist assesses many skeletal characteristics to produce a single indicator of age. That age indicator is not an age estimate, despite both being intervals that span anywhere from one (for infants) to many years (up to several decades for adults); the former is transformed statistically into the latter according to the procedure detailed in the following section.

For a so called reference sample of known-age skeletons these age-indicators are calibrated. That is, the conditional distribution of the age-indicator, given the actual age of the skeleton, is estimated. We propose to use a regression model that allows for smooth, but possibly nonlinear mean functions as well as heterogeneous variance functions, so called generalized additive models for location, scale and shape (gamlss), see Rigby and Stasinopoulos (2005). This methodology also accepts interval-censored information and therefore is appropriate for the expert-age intervals. Figure 2 shows the calibration results for two different observers. The estimates were obtained by the R-package *gamlss* (see www.gamlss.org). As can be seen, the expert-age indicator shows a slightly bended mean-curve and its variability is highest around age 60. Truly old skeletons are recognized by the anthropologists with less uncertainty and low variance is found for the young.

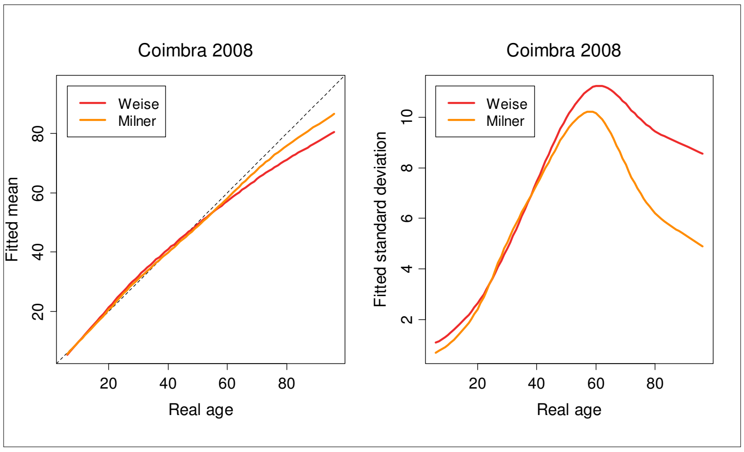

Figure 2: Calibration results derived by gamlss for two observers. Mean functions (left) and standard deviations (right).

3 Estimating the Target Distribution

When skeletons from the so called target population, whose ages are unknown, are assessed, the distribution of the expert-ages in this target sample is a compound of the calibration relationship and the actual (unknown) distribution of ages-at-death. If we denote the true age by a and the expert-age indicator by c, then the calibration step estimates the density $f(c|a)$ from the reference sample. The distribution $f(c)$ of the indicator in the target sample can be expressed as

$$f(c) = \int f(c|a)\, f_T(a)\, da$$

where $f_T(a)$ is the target age-at-death distribution. Hence $f_T(a)$ has to be estimated indirectly from the observed values of c.

We use a maximum-likelihood approach, which incorporates the gamlss-estimates for $f(c|a)$ and allows for interval observations via $\int_{lower}^{upper} f(c)\, dc$. Additionally the individual contributions are weighted by their uncertainty using the variance function from the calibration step (see Figure2, right).

To investigate the validity of the approach we simulated target-distributions by using skeletons from a different known-age collection (Bass Donated Skeletal Collection, University of Tennessee). In this way we are able to compare whether our procedure is able to recover the actual distribution.

In Figure 3 results from one scenario of this study are shown. The target distribution mimics a population structure (adults only) for medieval Denmark. The CEI method introduces higher variability as compared to what is obtained for exact ages at death, which is naturally expected, but offers unbiased estimates of the target distribution.

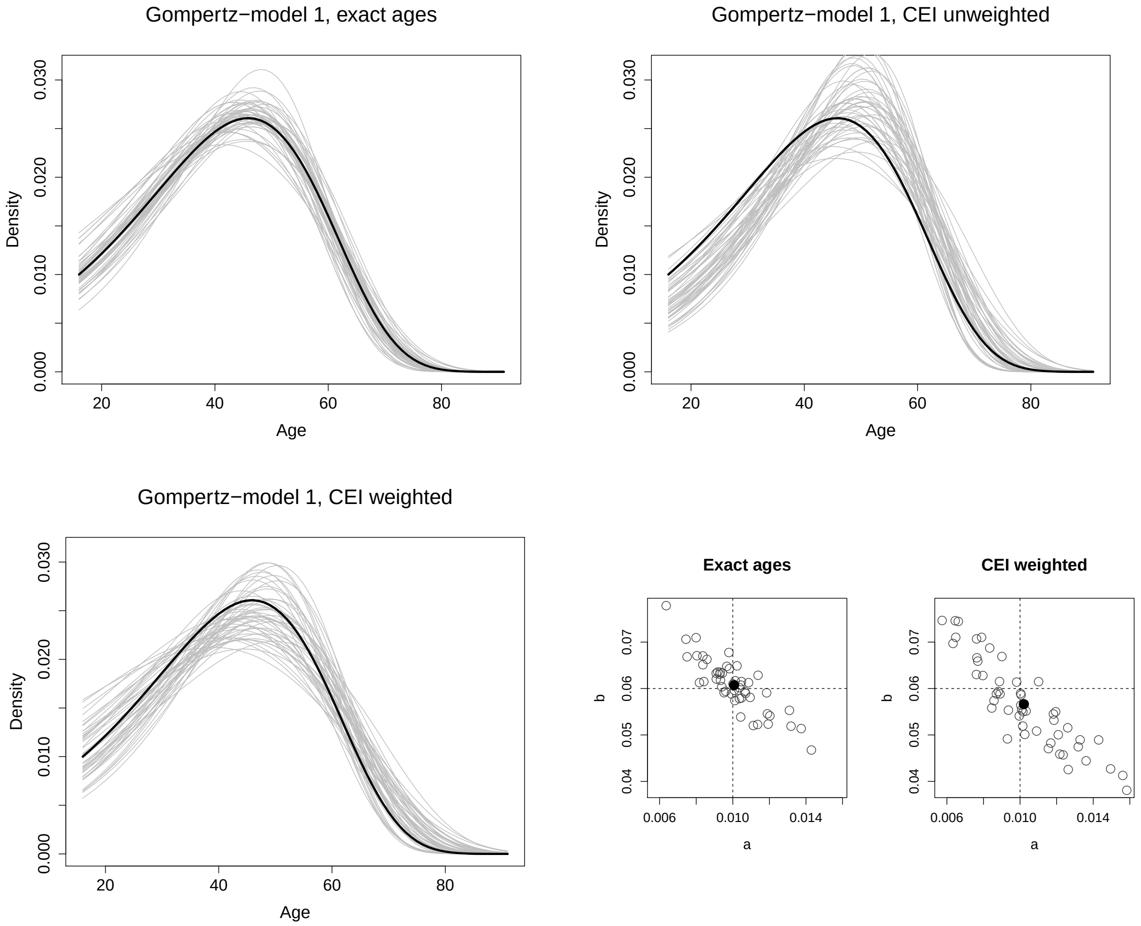

Figure 3: Sample size $n = 200$ for a Gompertz distribution with parameters $a = 0.01$ and $b = 0.06$, $s = 50$ replications. Top left: Results for MLE from exact ages. Top right: CEI estimates for unweighted likelihood. Bottom left: CEI estimates for weighted likelihood. Bottom right: Scatterplot of parameter estimates $(\hat{a}, \hat{b})$ for MLE from exact ages (left) and from weighted CEI estimates (right). The dashed lines mark the true values, the solid dots indicate the means for the 50 replications.

References

Bocquet-Appel, J.-P. and Masset, C. (1982). Farewell to paleodemography. *Journal of Human Evolution*, 11:321–331.

Gampe, J., Miler, G. R., Boldsen, J. L., and Weise, S. (2011). Calibrated expert inference: The statistical methodology. Preprint.

Hoppa, R. D. and Vaupel, J. W., editors (2002). *Paleodemography. Age Distributions from Skeletal Samples*. Cambridge University Press.

Koenigsberg, L. and Frankenberg, S. (2002). Deconstructing death in paleodemography. *American Journal of Physical Anthropology*, 117:297–309.

Milner, G. R., Boldsen, J. L., Weise, S., and Gampe, J. (2011). Calibrated expert inference: The osteological basis. Preprint.

Rigby, R. and Stasinopoulos, D. (2005). Generalized additive models for location, scale, and shape (with discussion). *Applied Statistics*, 54:507–554.