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WHAT TO DO WITH LONG BONES: TOWARD A PROGRESSIVE PALAEOAUXOLOGY

ABSTRACT: There has been renewed interest in the study of growth of development of past populations by physical anthropologists over the past decade. A variety of approaches have been used in an attempt to bring some sense of statistical rigour to the use of linear growth as a proxy for health and well-being within a population. This paper presents an overview of these techniques, and then discusses alternative approaches for the analysis of skeletal growth data. Simply put, any observed distribution of anthropometric data can be thought of being composed of several underlying sub-distributions, which cannot be readily differentiated but may be of intrinsic interest to the skeletal biologist. Various techniques, including finite mixture analysis, can be used to estimate the contribution or proportion of those unobserved sub-distributions, and provide a potentially powerful, but as yet under-exploited avenue of investigations for future studies in palaeoauxology.

KEY WORDS: Palaeoauxology – Diaphyseal growth – Ageing – Osteology

INTRODUCTION

Since growth is the process by which variation occurs, it is not surprising to find a long history of growth-related studies in physical anthropology. Physical anthropologists are interested in understanding the variation in patterns of human growth and development to better understand observed morphological differences within and between populations. Such studies have examined human developmental patterns within wide spatial and temporal ranges. The basic assumption of palaeoauxological studies is that childhood growth reflects health and nutritional status better than any other index, a notion supported in the anthropometric literature which observes higher rates of morbidity and subsequent mortality associated with varying degrees of stunting and wasting in children.

Recognising that the subadult cohort contained a wealth of potential information on the evolution of human ontogeny, researchers were quick to apply techniques borrowed from anthropometric studies to both prehistoric and palaeoanthropological samples. Given the abundance of remains from archaeological populations relative to those of earlier hominids, it is not surprising to find that a large body of bioarchaeological studies have accumulated in the literature. Like anthropometric studies of living populations, studies of skeletal growth from archaeological collections make interpretations regarding the overall health and well-being of a population from the apparent growth of children. Since long bone growth is differentially affected by the nutritional and health status of the individual, osteologists have utilised cross-sectional analyses of long bone growth as a non-specific indicator of nutritional status, with observed differences between samples used as evidence for differential health status between entire populations, either geographically or temporally. It must be noted though, that growth-related measurements remain *non-specific* indicators of health, and are sensitive to many factors.

While there is a wealth of information on skeletal growth and development, physical anthropologists, for the most part, have been relatively selective in the kinds of data that have been explored for past populations. Many studies, particularly bioarchaeological studies, have been primarily descriptive in nature, with theoretical and methodological issues forming a secondary role in the literature (Hoppa, Fitzgerald 1999). As a result, there has been a relative paucity of hypothesis testing in palaeoauxological studies.

AN INTERPRETATIVE FRAMEWORK

Assessments of growth in length of the long bones are the most commonly employed assessment of growth in bioarchaeological analyses (e.g. Johnston 1962, Walker 1969, Merchant, Ubelaker 1977, Stloukal, Hanáková 1978, Molleson 1990, Lovejoy *et al.* 1990, Wall 1991, Hoppa 1992, Saunders *et al.* 1993, Miles, Bulman 1994, 1995, Ribot, Roberts 1996, Henneberg, Stenyk 1996). Less frequently but of equal interest, studies of appositional growth are made (e.g. Armelagos *et al.* 1972, Huss-Ashmore *et al.* 1982, Mays 1985, 1995, 1999, Saunders, Melbye 1990, VanGerven *et al.* 1985). Bioarchaeological studies need not restrict themselves, however, to traditional assessments of linear growth, and a handful of studies have undertaken more innovative approaches to palaeoauxological inquiry (Boldsen 1998, Clark 1988, Clark *et al.* 1986, Grimm 1990, Humphrey 1998, Porter, Pavitt 1987). Incorporating assessments of stress indicators in studies of growth provides further support for interpretation of health and well-being among past populations (e.g. Hühne-Osterloh 1989, Mays 1995, Nowak 1996, Ribot, Roberts 1996).

Regardless of the specific focus, all studies of this nature necessarily adopt some interpretative framework to compare growth and age in the skeleton and the distributions of growth-related measures are examined in the context of some independent estimator of age – usually dental development. By doing so, a cross-sectional "growth curve" or skeletal growth profile (SGP) can then be constructed in order to examine the age-progressive trend in growth (*Figure 1*). The major limitation of cross sectional data is of course that it does not allow one to observe individual variability in the rate of growth or in the timing of the adolescent growth spurt (Tanner 1978). Individual variation in the timing of the adolescent growth spurt can be quite substantial, but when this data is represented by the average of many individuals all starting at different exact ages, the curve becomes spread out and its peak lowered. However, in comparative surveys of growth between two or more populations, there is often more concern with the means and variations of the group rather than the patterns unique to the individual (Eveleth, Tanner 1976). Nevertheless, researchers have attempted to examine the rate of growth by examining simple percentage increases in size by age (e.g. Hoppa 1992, Armelagos *et al.* 1972) or by taking the first derivative of a polynomial function fitted to the growth data (e.g. Lovejoy *et al.* 1990).

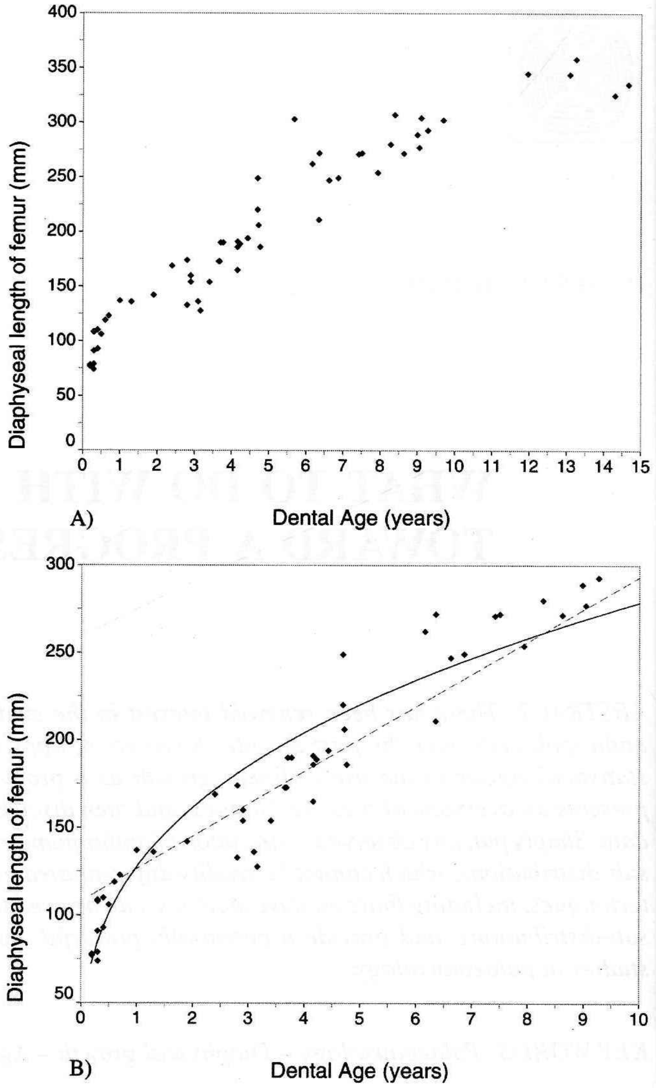

FIGURE 1. Skeletal growth profile (SGP) plotting diaphyseal length of femur against dental age. A) standard SGP, B) SGP illustrating the curvilinear nature of the data when very young individuals are included.

Another issue to be considered is the fact that almost all growth-related events have a positively skewed distribution relative to the mode, given that there are going to be more late than early maturers (Angel 1984, Angel *et al.* 1986). Because of this bias, Angel (1984) recommends avoiding means and using the actual distributions and modes of the data.

Once within such a framework, growth-related data can be explored visually, and possibly, by more rigorous quantitative techniques. However, the extent to which such techniques can provide meaningful interpretations depends greatly on the sample size and quality of the skeletal data being analysed. In the following section, some common forms of statistical analysis performed in growth-related studies are reviewed. In addition, alternative approaches are presented and their potential for palaeoauxological studies explored.

STATISTICAL ANALYSES OF GROWTH IN SKELETAL SAMPLES

As others have noted, the nature of the data used to construct SGPs often prevents adequate statistical comparison between population samples. Some have further argued that more powerful techniques are likely to reveal little more than is observable from simple examination of the graphs (Merchant 1973). In fact, Konigsberg and Holman (1999) have suggested that many previously published observations of significant differences in SGPs between archaeological samples probably are not actually significant, but rather the result of poor sample sizes and variability in dental age estimations. The latter point in particular, is seen as an often-ignored but important issue (Hoppa 1992, Lampl, Johnson 1997). Nevertheless, a variety of studies have made use of various statistical approaches for making interpretations regarding health and well-being in the past. Often in fact, there is more emphasis on attempting to describe the data and less emphasis on trying to understand the mechanisms responsible for or most likely to have produced the data. Freedman (1985) once criticised 'social scientists' for applying mathematical models to describe data rather than applying models to examine the behaviour of the process being investigated. Often the purpose is to "fit a curve to the data, rather than figuring out the process which generated the data" (Freedman 1985:348). Palaeoauxological studies must, in particular, be cautious of not falling into this trap.

Somatic growth during infancy follows a simple curvilinear path for which regression models can be applied (Bogin 1988, Johnston 1978). Deviations from the general path are often associated with malnutrition or disease, and children whose growth is abnormally affected by such factors tend to be easily identified. During the years of early childhood (1–4 years of age) somatic growth becomes standardised in its rate, achieving a steady, near-linear increase until the adolescent growth spurt (Maresh 1955, Johnston 1978). As a result, many studies of linear growth in skeletal samples have made use of regression analysis to aid interpretation of growth-related changes. In doing so, long bone size is the dependent variable and (often) dental age the independent variable. Simple linear regression can then be fit to the distribution, although the inclusion of very young individuals often requires a curvilinear fit (*Figure 1b*). Correlations are, not unexpectedly, very high. As with any statistical procedure, there are a number of assumptions built into ordinary least squares regression analysis that should be addressed. Since most of these assumptions focus on error (omitted variables, a non-linear relationship, non-constant error variance, correlation among errors, non-normal errors or influential cases), residual analysis is one way of assessing these problems. Normal-probability plots of residuals and scatter plots of predicted values versus residuals aid in assessing the validity of these assumptions (Hamilton 1992). Multicollinearity among independent variables may also be a problem and while most models are univariate, multivariate models will have some degree of correlation between independent variables, given that they are all a function of skeletal growth. The result being that the standard error of the estimated coefficients will be greater in multivariate than univariate models.

It can also be tempting to fit more complicated models although one must be cautious of such attempts, as very complicated models, relative to fairly simple data, serve to reduce the overall adjusted correlation. However, as with studies of modern growth data, there is still no clear consensus on the models to be fitted to skeletal growth data. Miles and Bulman (1994, 1995), recognising the problems with fitting complex curves to data, opted to fit a 5th order polynomial to their raw data, although a log-normal equation was used when comparing their results to other published summary data. Recently Humphrey (1998) has shown that the Gompertz equation provides a reliable description of human skeletal growth and that a modified Gompertz equation, in which the lower asymptote is forced to be zero, is less severely perturbed than the standard Gompertz equation by the removal of young individuals from the sample.

Another issue that has come to light for physical anthropology is the statistical validity of using ordinary least squares regression analysis for age-related data. While criticisms have been levied primarily at regression estimates for adult age (Akyroyd *et al.* 1999, Konigsberg *et al.* 1997) some discussion has focused on growth-related variables in skeletal samples. The greatest application of course, has been in the estimation of foetal or perinatal individuals (e.g. Fazekas, Kósa 1978, Olivier, Pineau 1960). Notwithstanding the problem of applying radiographic observations to osteological samples (Huxley 1998), much criticism has centred on the use of regression equations for age estimation in perinatal remains (e.g. Scheuer *et al.* 1980, Sellier, Tillier 1997, Konigsberg *et al.* 1997). For example, Fazekas and Kósa (1978) undertook extensive measurements on a sample of 138 foetuses of variable age and produced regression equations to predict overall body length from the size of a single bone. This in turn could be translated into a foetal age in lunar months from conception. However, their "material was not grouped according to the period of pregnancy, but on the basis of body length" (1978:31). While a well known correlation exists between foetal age and body length, the use of their regressions is circular given that long bone length is highly correlated with stature. Scheuer *et al.* (1980) developed regression equations to directly determine foetal age from the size of most of the long bones. Application of both techniques to archaeological and forensic specimens of different populations have produced less accurate results (Huxley, Jimenez 1996, Ubelaker 1987). However, Scheuer and co-workers state that while regression equations may not be universally applicable "one should not be deterred from at least trying to estimate the age of babies so frequently found in archaeological sites" (1980:263). The danger in this of course, is the potential for widely differing interpretations, as Konigsberg and colleagues have noted in a re-analysis of Owsley and Jantz's (1985) large Arikara perinatal sample. The original analysis used Scheuer *et al.'s* (1980) regression equations of known age on foetal length, to estimate gestational age for almost 500 perinatal individuals, and observed a large proportion of pre-term or small-for-age individuals. Konigsberg and colleagues (1994, 1997) using a different set of regression equations for length of age, and a maximum likelihood estimation technique, observed the bulk of the individuals falling at the 40 week or term period. The results are radically differing interpretations of population dynamics and perinatal mortality and health.

Another analytical technique that is commonly used to assess patterns of skeletal growth is ontogenetic allometry. More commonly used in palaeoanthropological studies (e.g. Dainton, Macho 1999, Hartwig-Scherer, Martin 1992, Jungers, German 1981, Shea 1992, 1995), this approach has seen only limited use in bioarchaeological analyses (e.g. Jungers *et al.* 1988, see also Buschang 1982). In general, an SGP is constructed for two growth-related variables and the allometric power equation is fitted to the data (Albrecht *et al.* 1993). Because its strength is the ability to examine inter-specific growth, it has been exploited little in bioarchaeological studies, despite most analyses recognising the problems of population specific adult size. Traditionally this problem has been addressed by constructing growth profiles as a percentage of mean adult long bone length or mean adult stature for individual populations (Goode *et al.* 1993, Hoppa 1992, Lovejoy *et al.* 1990, Saunders *et al.* 1993b, Wall 1991). Utilising mean adult long bone lengths has been recommended as this will take into account variation in limb proportions and differences in the regression equations utilised to reconstruct mean stature (Sciulli 1994, Hoppa, Saunders 1994). However, as Albrecht and colleagues (1993) have noted, the use of a simple ratio to control for population differences does not eliminate size correlations.

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If palaeoauxology is to really develop as a sub-discipline, then like palaeopathological studies a decade ago, it needs to move beyond the level of descriptive case studies. Despite reservations by some that more quantitative analyses are neither warranted nor possible, there are some potentially useful venues that are worth exploring before declaring growth studies non-statistical. One area which has considerable potential for exploitation is that of finite mixture analyses.

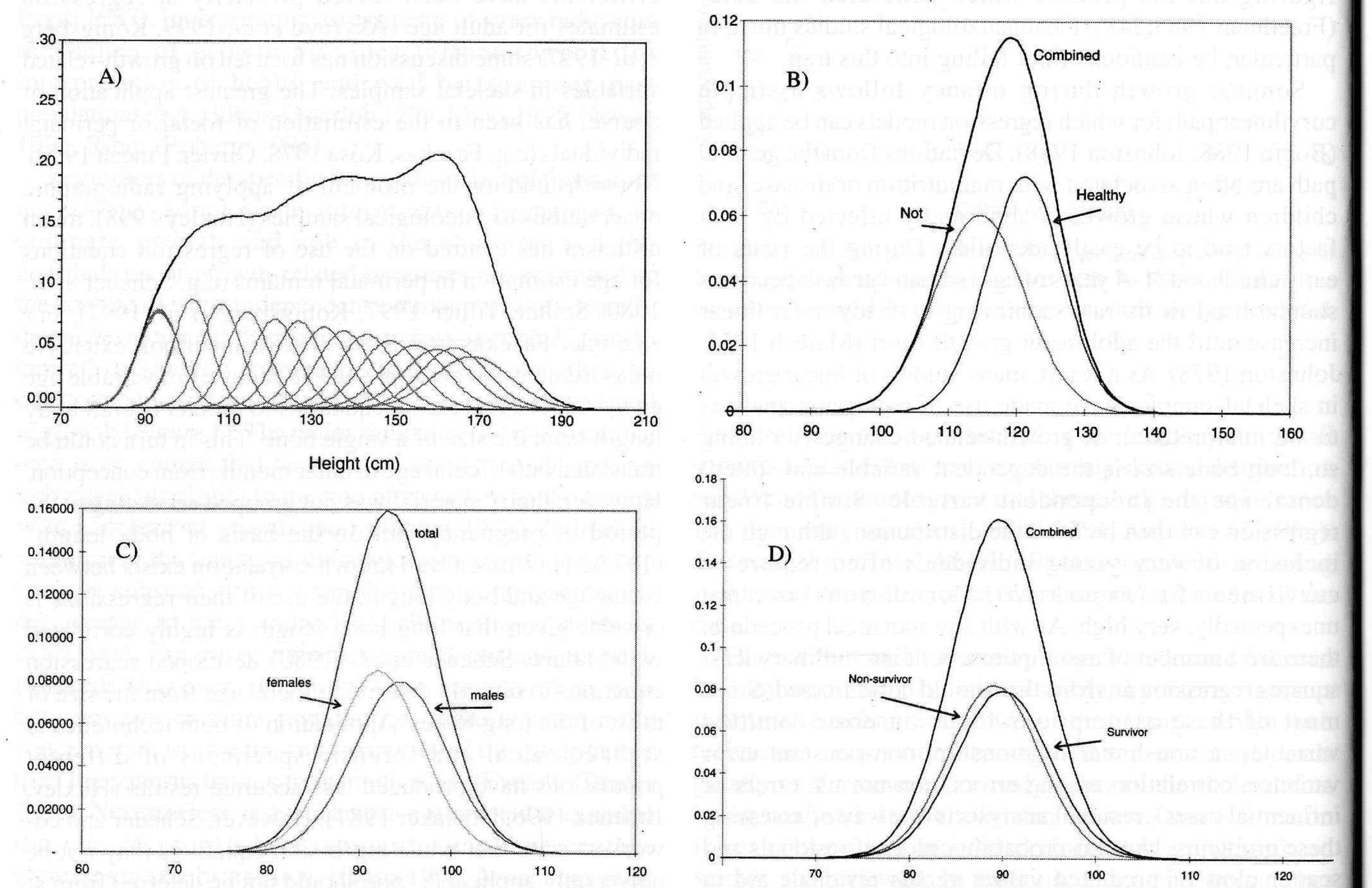

FIGURE 2. Distributions of height for age composed of various subsamples of: A) multiple age groups, B) healthy and non-healthy individuals, C) males and females, D) survivors and non-survivors.

The application of mixture analysis methods for analysing skeletal data is not new to physical anthropology. However, its application has found only limited exposure in the anthropological literature, dealing with discrimination of sex (Godfrey *et al.* 1993, Martin 1936, Plavcan 1994, see also Dong 1997) or taxa (Kramer, Konigsberg 1999, see also Pearson *et al.* 1992), and estimating age profiles (Hoppa *et al.* 1999). Simply put, mixture analysis techniques are statistical procedures that attempt to estimate the underlying subsamples that make up an observed distribution. For example, the observed distribution of children's heights is made up of a series of sub-distributions of height for various ages (*Figure 2a*). Similarly, the observed distribution of heights (or some other anthropometric measure) for a specific age group, can be thought of as being composed of sub-distributions of males and females (*Figure 2b*), healthy versus not-healthy individuals (*Figure 2c*) or survivors versus non-survivors (*Figure 2d*). In all these examples, it is the overall distribution that is observed, but it is the underlying distributions or their proportions that wish to be estimated.

Subadult age structure

Recently brought to the attention of physical anthropologists by Konigsberg and Frankenberg (1992, 1994) the age-length key method is a statistical technique designed to estimate age from size data. Originally developed for use in the fisheries industry (e.g. Kimura 1977, Kimura, Chikuni 1987, Macdonald, Pitcher 1979) this technique and alternative approaches clearly may be of interest to skeletal biologists interested in analogous information from diaphyseal length data. Traditionally, patterns of diaphyseal growth are recognised to be the least effective estimates of chronological age because of their sensitivity to population and health differences (Hoppa 1992, Ubelaker 1987). It is precisely for the latter reason in fact, that so many studies have attempted to describe diaphyseal length with respect to other independent age estimators. However, there has been much renewed discussion recently over the problems associated with extrinsic references standards on which these independent age estimations are based – that being the practice of applying modern dental developmental standards to pre-modern populations (Lampl, Johnston 1996). Coincidentally, there has been a movement toward the use of dental micostructure data on which to determine intrinsic rates of development, which would allow estimation of age while avoiding issues of inappropriate standards (Dean 1987, FitzGerald 1998, Shellis 1998) However, such techniques still remain time and labour demanding and as such, have seen only limited application on large archaeological samples (Antoine *et al.* 1999, FitzGerald *et al.* 1999, Huda, Bowman 1995, Reid *et al.* 1998). One possible solution is to employ a training sample based on a small random selection of individuals for whom dental microstructure estimates have been performed and use this information to estimate the overall age structure of the sample. For example, *Figure 3a* displays the frequency distribution of heights for a group of children. We know that the distribution is reflective of children aged 6 to 10 years, but do not know the precise proportion of individuals within each group. Using a small training sample of known-age individuals for this sample, we can use a fitted mixture distribution technique to estimate the underlying sub-samples of height for each of the 5 groups (*Figure 3b*).

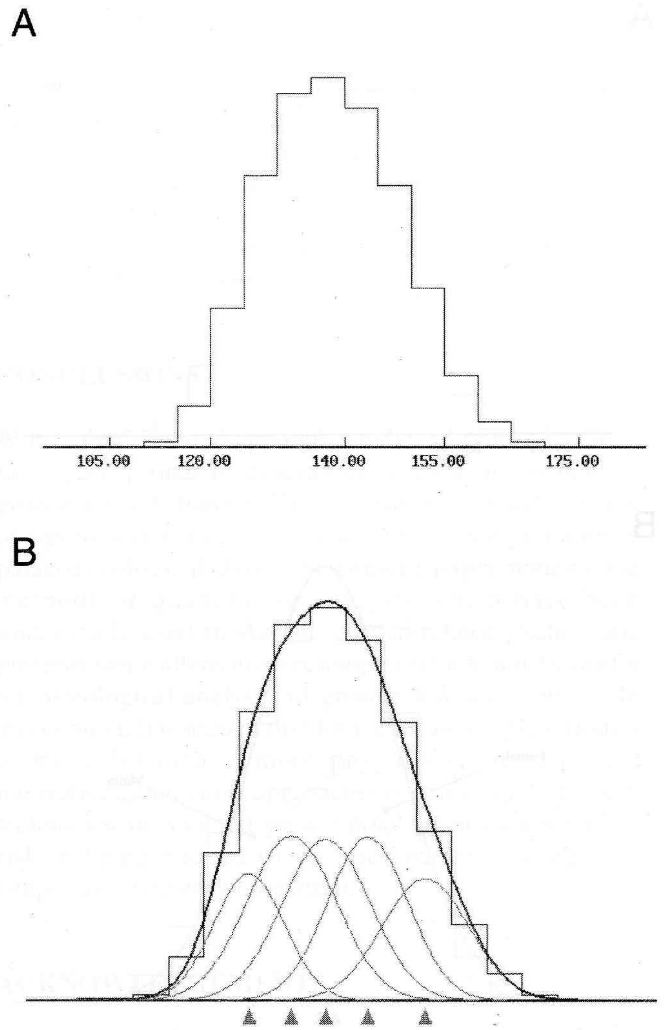

FIGURE 3. A) Distribution of heights for 6 to 10-year-old children. B) the estimated sub-distributions by age, using fitted mixture analysis.

Sex-specific patterns of growth

To the grief of many researchers, determination of sex from the skeleton has been restricted to those who have survived adolescence to manifest changes in the skeleton reflective of sex. Despite a variety of studies investigating sexually dimorphic traits in non-adults (e.g. Hunt 1990, Majo *et al.* 1993, Mittler, Sheridan 1992, Molleson *et al.* 1998, Rösing 1983, Schutkowski 1986, 1987, 1989, 1993, Weaver 1980) only a few have had sufficient levels of accuracy to warrant their application in osteological analyses. Showing great

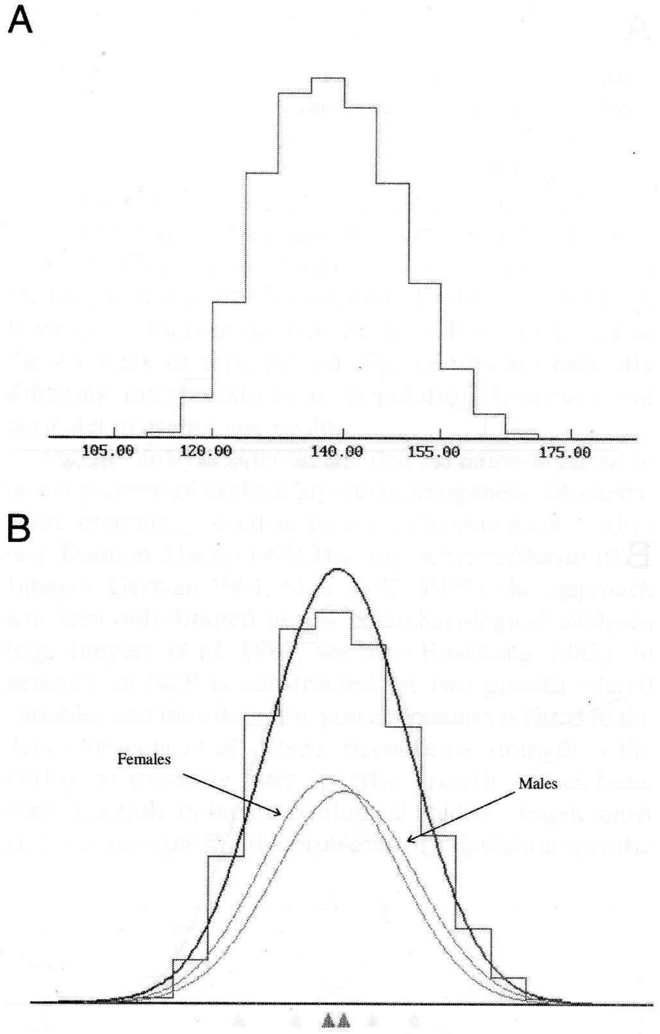

FIGURE 4. A) Distribution of heights for 6 to 10-year-old children. B) the estimated sub-distributions by sex, using fitted mixture analysis.

potential but still restricted by cost and time, is the possibility of determining sex by extracting ancient DNA from the bones or teeth of individuals (e.g. Faerman *et al.* 1995, Fattorini *et al.* 1989, Lassen 1997, Ovchinnikov *et al.* 1998, Stone *et al.* 1996). Somewhat more promising has been the discrimination of sex in non-adults from dental metrics (e.g. Alt *et al.* 1998, Black 1978, DeVito, Saunders 1990, Liversidge, Molleson 1999, Introna *et al.* 1993, Teschler-Nicola 1992). In particular, the use of metrics from the permanent dentition can be tested on a sample by sample basis, since some proportion of the subadult component will have at least a permanent M1 present. As a result, population-specific models can be developed and the use of discriminant function analysis or logistic regression techniques can use the adult segment (which can be accurately sexed) as a 'known sex' training sample on which to refine the model for the non-adults. This of course assumes that there is no mortality bias in the size of the teeth for non-survivors (i.e. subadults) as discussed below (although see also Guagliardo 1982, Perzigian 1975). This is illustrated in *Figure 4* which shows an overall distribution of height in children (*Figure 4a*) and the estimated sub-distributions of height for males and females (*Figure 4b*) based on a small training sample of known sex for height individuals.

Healthy versus not healthy – testing the Osteological Paradox

An issue that has had considerable attention for palaeoauxology is the fact that the subadult cohort associated with a burial sample are essentially non-survivors (Johnson 1968). That is, they represent individuals who for whatever reason have failed to survive the developmental phase to complete maturation and whose level or pattern of growth and development, therefore, might not reflect the true pattern of growth in the population. Long recognised as a theoretical obstacle by researchers, this issue re-emerged with the publication of the Osteological Paradox in which Wood and colleagues (1992) argued that skeletal samples are intrinsically biased because they are the products of selective mortality or non-random entry. Selective mortality relates to the fact that archaeological samples do not represent all susceptible individuals within a particular age cohort, but rather, only those individuals who have died at that age. If mortality in the age groups has differential links to reduced or abnormal growth, then there may be selection bias with growth observed in mortality samples under-estimating the normal pattern of growth which survivors underwent. The latter of course is unobservable by skeletal biologists, since survivors enter the adult segment of the skeletal sample after the growth process has ceased. However, from a review of the child survival literature with respect to growth, Saunders and Hoppa (1993) concluded that while there did appear to be statistically significant differences between the growth of survivors and non-survivors, the magnitude of this difference for cross sectional studies of long bone growth would be minimal, and likely less important than the error introduced by methodological issues like ageing standards.

Nevertheless, an observed sample of growth-related data may still be reflective of a non-homogeneous group of individuals, some of whom may exhibit a different pattern of growth because of differing susceptibility or frailty. If supplementary information can be collected then statistical procedures might allow one to explore in more depth this hidden heterogeneity. Brought to the attention of skeletal biologists by Wood and colleagues (1992) the idea of hidden heterogeneity refers to the problem of unobserved variability in the relationship between dependent and independent variables. While this concept has been applied most often to the analysis of life-event history data, usually with respect to survivorship, it is clearly of relevance to interpretative analyses of differential growth.

If one has a subsample of individuals for which

palaeopathological information can be derived independently, such data can be used to estimate the proportion and distribution of each group. One can imagine, for example, a large sample of subadult long bone lengths for which a small sample of those individuals had been analysed for enamel hypoplasias and scored as present or not present. While this sample is smaller, it can still be used to create a matrix of bone length distributions and frequency of healthy versus non-healthy individuals. Using this information, one may be able to discern two distinct patterns of growth – one for healthy individuals, and one for non-healthy individuals. Of course, given the notion that the healthy are those who manifest chronic indicators of stress, and the frail are those that do not, the pattern might be opposite to that anticipated (Ortner 1991, Wood *et al.* 1992).

If palaeopathological data can be adequately assessed, the simple categorical relationships can be designed to group individuals into healthy versus not healthy (i.e. those within the subadult cohort without and with stress indicators present) and univariate logistic or multinomial logistic regression models estimated to predict membership is the observed group. How well the model is able to predict membership will reflect a relationship between the non-specific indicators of health, and the growth-related variables. Boldsen (1998) for example tested the hypothesis that childhood episodes of illness affected adult morphology in a Medieval Danish sample. By analysing size-independent aspects of adult morphology like residual height and principal component scores, Boldsen concluded that while episodes of illness did change some scores, they played no part in the formation of adult size. However, this analysis was based on survivors (adults) only. Comparison of survivors versus non-survivors is harder to assess since it means comparing growth-related variables in non-adults (non-survivors) and adults (survivors). This seriously reduces the types of variables that can be examined, but in theory, young adults may still have some growth-related processes in a stage of near completion. A better alternative might be to compare a growth-related variable which, rather than being not complete in adults, is complete in non-adults. For example, permanent molar size would fall into this category since observable differences in non-adults and adults may reflect health related differences representative of the non-survivor – survivor relationship that this comparison creates.

Ultimately, there are a variety of questions that researchers have been reluctant to ask, or thought unanswerable from skeletal growth data. With new techniques becoming available for analyses, palaeoauxological studies should begin to look toward a more progressive framework in which to place their data. In the last decade, palaeopathological studies in general, underwent a major shift in focus away from the individual case study, and toward more population-based hypothesis testing. If palaeoauxological studies are going to come into their own, then a similar shift away from the descriptive case study is necessary. More importantly, however, this venture is achievable. Palaeoauxology has enormous potential in terms of the kinds of questions that it can ask, and the variety of anthropological problems that it can contribute to. Further, there are substantial resources within other disciplines which we can draw on to help with this process. A few studies have already begun to reflect this move toward a more progressive palaeoauxology, but there is still room for improvement.

CONCLUSIONS

With a few recent exceptions, studies in palaeoauxology have been primarily descriptive in their assessment of growth-related changes. This is partly the product of a lack of rigorous statistical approaches to the interpretation of palaeoauxological data. The present paper reviews the methods of quantitative analysis which have been traditionally used in skeletal growth-related studies, and presents some alternative techniques which may be useful for osteological analyses of growth and development. In this context, it is argued that for palaeoauxological studies to move forward, a more progressive trend toward innovative quantitative approaches is necessary. Until such techniques are adopted, palaeoauxological studies run the risk of being nudged to the back-burner and regarded simply as interesting case studies.

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