CONFOUNDING FACTORS IN INTERPRETING FRACTURE FREQUENCIES IN SKELETAL POPULATIONS

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***Abstract*—The lifestyle of past populations can be reconstructed with help of several skeletal indicators. One such indicator is trauma. Trauma can be used for inferring about daily activities, subsistence strategy, division of labor, occupational hazards as well as warfare. Paleoepidemiology aimed at the evaluation of pathologies in populations provides a tool; however, since the tool is inferential and the living population does not exist anymore, it also brings some problems in the interpretation. This paper discusses these problem areas on a specific example of fracture frequency interpretations in skeletal populations. There are two main sources of interpretation confusion: methods and biology. Methodological problems are preservation, estimates of number of individuals, age, and sex, fracture recognition and diagnosis, and chronology of burial sites. Biological problems arise from processes of senescence, healing, and bone remodeling.**

***Key Words*—fracture frequencies, trauma, paleoepidemiology, skeletal populations, methodology, biology**

INTRODUCTION

MANY skeletal populations form museum collections and others are continuously excavated in order to prevent their definitive destruction from environmental factors and human activities, or as a result of academically driven excavations. Researchers use skeletal collections to answer specific questions. The majority of these questions are related to the life of a population from which the skeletons under study come from.

To answer such a question, researchers usually use several lines of evidence. One is to look at stress indicators manifested on the skeleton. This approach includes broad spectrum of skeletal characteristics from metabolic, congenital and dental defects to alterations of joints and indicators of trauma (Larsen 1999; Roberts and Manchester 2007).

Since metabolic, congenital, and dental defects are heavily used to infer about nutritional insufficiencies (e. g. Ortner and Ericksen 1997; Stuart-Macadam 1992), degenerative joint alterations, and trauma indicators are on the other hand used as an evidence for inferring about habitual activities, subsistence strategy, warfare, division of labor, occupational hazards etc. (Judd and Roberts 1998; Kilgore et al. 1997; Novak 2001; Jurmain 1999).

Over the long history of human skeletal pathology studies, there were methodological and interpretative problems. However, these problems were mainly with linking specific skeletal conditions to certain diseases or other agents (e. g. some infectious diseases and trepanations in 19^{th} century) (Mann and Murphy 1990). Moreover, studies originating before the 1950' were heavily influenced by racial theory and typologies that were manifested in focusing on human skulls (Armelagos and Van Gerven 2003, Rose et al. 1996). With the change of paradigms (encouraged by Sherwood Washburn's "New Physical Anthropology", 1953), more attention have been devoted to population perspective and to the interaction between biology and environment (Armelagos and Van Gerven 2003).

This paradigmatic shift also had an impact on paleopathology and facilitated the transition from isolated case reports to more complex studies focused on the interpretation of population health status. As a consequence, paleoepidemiology as a discipline was born. Even if the first paleoepidemiological study had been done much earlier (in 1930') by Ernest A. Hooton on Pecos Pueblo skeletal population (Armelagos and Van Gerven 2003), discipline became truly established later in mid 1960' (Mann and Murphy 1990).

Paleoepidemiological approach brought new perspectives and was able to explain different set of questions about human life in the past. However, in my opinion, it also brought some problems inherent to its aims that make interpretations tentative and not always very convincing. Thus, I would like to review these problematic areas and even if they are not completely exclusive for paleoepidemiology, I would like to demonstrate them on bone fracture frequency interpretations in skeletal populations.

In this sense, I can see two main problem areas influencing final interpretation of fracture frequencies in paleopathological record: methodological and biological.

Methodological set of problems

Taphonomy

Basic prerequisite for any study of human skeletons is their preservation. The preservation is a factor that researchers can't influence at all (in the interval from burial to just prior the excavation). Obviously, the state of preservation during excavation and later, during handling and sorting in museums can be substantially influenced by people.

Behrensmeyer (1991) listed a comprehensive set of factors influencing the state of preservation of any skeletal sample. Even if her work is set within the frame of general vertebrate taphonomy, several factors can be used for inferring about preservation of prehistoric and historic human skeletal collections.

1) Body size, bone size and bone shape. Larger bodies tend to preserve better than smaller ones. It is caused in part by the fact that larger bodies have larger bony elements. It has been shown in taphonomy studies that as a general rule, small elements move more easily in geological strata (Dodson 1973; Korth 1979) and they are also more prone to be destroyed by the soil chemistry or weathering (if exposed to surface) simply because they have less bone tissue (Behrensmeyer 1991). This is in fact one of the most prevalent cause of non-adult skeleton under-representation in the fossil and burial record.
2) Skeletal articulation. The state of articulation depends on the strength of connective tissue in the skeleton (Behrensmeyer 1991). When applied to medieval burial context, differences can be expected between adult and non-adult individuals (especially neonates). The direction is apparent: adult individuals will preserve better than non-adults.
3) Bone modification. This relates directly to the problem of counting fractures in skeletal elements. If the individual has been buried with a broken bone, the inner part (e. g. medullary cavity in long bones) is exposed to destructive processes after the soft tissues decompose. The most affected parts are usually those just around the breakage and if they become destroyed, precise fracture identification may be disabled.
4) Bone density. Bone density is simply the ratio between bone mineral content and thickness of a bone. It varies within a single bone, within an individual and within a population. It is influenced by many factors but some of them are age, nutrition, health status etc. (Turner-Walker and Mays 2001). More dense bones tend to preserve better (Galloway et al. 1997; Waldron 1987; Willey et al. 1997).
5) Environmental factors (or outer factors since I will include human cultural practices). This is a set of factors that may heavily influence skeletal preservation and they directly relate to the previous four points since they always act together. They are: faunaturbation, floraturbation, weathering, abrasion, soil chemistry, soil physics, influence of microorganisms, and human cultural practices. These all can alter the bone in significant ways. For example, soil pH is a significant factor influencing bone preservation. As pH decreases to acidic levels, bone mineral is dissolving and preservation rapidly drops. The most suitable soil pH for bone preservation is neutral or slightly alkaline (Gordon and Buikstra 1981). The example of influence of human cultural practices to skeletal preservation may be the depth of burial pit. Stojanowski et al. (2002) showed that deeper burial pits result in better preservation, since skeletons buried close to the surface are exposed to much harsher chemical and physical conditions in upper soil layers (water, oxygen content, floraturbation etc.).

From the above mentioned points we can postulate that there will probably be differences in preservation regarding age and sex of buried individuals and regarding the environmental conditions. But these predictions need not to work perfectly. For example Walker et al. (1988) found significant relationship between the age of individual and its preservation but Stojanowski et al. (2002) did not. Regarding fracture frequencies, conclusions and interpretations must be made in consideration of possible bias due to preservation. Not only researchers may face biases in age and sex structure but also representation of certain skeletal elements (especially smaller ones).

Number of specimens and minimum number of individuals

From paleoepidemiological point of view, these two estimates are crucial for final interpretations of population's health status. Number of specimens here means the total number of bones observed. This number is used in fracture frequency studies for reporting fracture rates within given population. But how these studies deal with fragmentary nature of many bones in the assemblages? And how they count the total number of bones? For example Judd and Roberts (1999) state: The long bones (clavicle, humerus, radius, ulna, femur, tibia, and fibula) of each individual were identified as present (90%+ bone present), incomplete (50-90% bone present), fragmentary (50% bone present), or absent. Each bone was examined for evidence of antemortem or perimortem fracture. **Incomplete bones with fractures and all complete bones formed the "observable corpus."** (emphasis added).

It is obvious that some bias is introduced here since the fracture frequency is counted as the number of fractured bones/total number of bones observed multiplied by 100 and incomplete bones without fractures are not included. Moreover, some authors do not mention how they counted total number of bones (Djuric et al. 2006; Grauer and Roberts 1996) and some others used only intact bones omitting all incomplete skeletal elements (Lovejoy and Heiple 1981).

Another problem can be seen in estimating the number of individuals represented in skeletal assemblage. Most of the fracture frequency studies use, besides the fracture frequency rate, the number of individuals affected by fractures (Lovejoy and Heiple 1981; Djuric et al. 2006; Grauer and Roberts 1996). It is important to stress that this type of inference can be reliably done only on the skeletal sample coming from well defined burials in which we can assume that single burial represents single individual. But many graveyards do not fit to this scheme. Specifically, some medieval church cemeteries experienced burial crowding with frequent interventions and level structure. Some studies overcame this problem by simply counting only those burials that reliably represented single individual (Nakai et al. 1999). When counting fracture rates per individual, Lovejoy and Heiple (1981) assumed that all missing bones have been fractured at the same rate as bones actually observed. This is obviously another source of bias.

In extreme situations, we can deal with mass or other highly commingled burials. In these situations, estimating the number of individuals represented by skeletal assemblage is necessary. Three primary methods were developed. MNI (minimum number of individuals), Lincoln/Petersen index and MLNI (maximum likely number of individuals) (reviewed in Adams and Konigsberg 2004). Even if these methods are said to differ in validity and reliability, they are still estimates of original population and as such represent another source of bias if they are used.

Recognition, identification, diagnosis

If researchers are lucky enough and overcome problems with bone preservation, there is a challenge to identify the fracture. The diagnosis in skeletal populations usually proceeds by two primary methods. Macroscopic visual inspection is used as a first sorting method and than in equivocal cases, imaging methods can be used (mainly radiography) (Grauer and Roberts 1996).

Paleopathologists need to develop unitary system of trauma description in order to be able to compare data from skeletal samples from different times and environments. This effort was pushed forward by the raising voices of American native people for repatriation their ancestor's skeletal remains. Three primary descriptive methods were developed. That of Buikstra and Ubelaker (1994) (in relation to NAGPRA) and two others are from Grauer and Roberts (1996) and for cranial fractures from Filer (1992).

However, any method of fracture description will recognize two main sources of interpretation confusion: the variation in appearance expressed by fractures caused by the same mechanism of injury, as well as the similarities in appearance displayed by fractures caused by different mechanisms of injury (Lowell 1997). Even if the standards were developed to avoid these sources of confusion, variability in biological reaction to certain type of trauma may still confuse interpretation.

Moreover, there are some practical problems. First of all, correct diagnosis heavily depends on the level of observer's experience. Not only those less experienced researchers will have higher rates of incorrectly identified fractures but there will be variation even among similarly experienced ones. Miller et al. (1996) examined interobserver error rates among similarly experienced paleopathologists. They found out that the accuracy was only 42.9 percent for recognizing general category of the disease and 28.6 for specific diseases within the general categories. In case of trauma, the results were even worse (only 27 percent for the general category and 18 percent for specific type of trauma).

Secondly, there is a problem of differentiating between perimortem and postmortem fractures. Perimortem fractures can be recognized on the basis of edge morphology (sharp and skewed) and radiating fractures from the point of breakage. Pieces usually don't fit together well due to plastic deformation just prior to breakage. Also the different coloration and angulation can help (Lowell 1997). On the other side, postmortem fractures tend to be irregular, cragged, and edgeless. Pieces usually fit together well. However, these descriptions are exactly those generalizations we have to be aware of, because postdepositional processes can affect bone in many ways and we have to hold in mind the information about other fractures in the sample and about the geological and cultural context in order to make distinction (Lowell 1997).

Finally, diagnosis can be made more difficult if we don't have intact bone from the other side of the body for comparison or if we can't verify macroscopic visual observations by using radiography.

Sex and Age

Estimating sex and age of individuals in a skeletal sample is necessary in order to be able to make inferences about differences in habitual activities between men and women, and to differentiate them with regard to age. In almost all fracture frequency studies this is as a part. But strong inconsistencies between studies were found in terms of methods used and their presentation.

Firstly, I can illustrate these inconsistencies in methods on an example of three studies. Djuric et al. (2006) present methodology of age and sex estimates and they use relatively modern estimating methods that are still widely used (Buikstra and Ubelaker 1994; Brooks and Suchey 1990) except of some older ones (Iscan et al. 1984, 1985). Grauer and Roberts (1996) use as many estimation methods as possible but some of those methods (McKern and Stuart 1957; Todd 1921a,b) are outdated and moreover, have been shown to be heavily biased in direction to mimic reference sample, or to overestimate or underestimate age in the youngest and the oldest age categories (Brooks and Suchey 1990; Bocquet-Appel and Masset 1982; Buckbarry and Chamberlain 2002; the same critique by Aykroyd et al. 1997, 1999 for some other age estimating methods). And in the third example, Judd and Roberts (1999) and Neves et al. (1999), do not mention age and sex estimation methods at all (Judd and Roberts

1999 only cite some unpublished report its results they followed).

Secondly, there is a paradox between the methods of estimation and skeletal preservation. The most reliable methods for sexing and aging skeletons (Bruzek 2002; Brooks and Suchey 1990; Buckbarry and Chamberlain 2002) are derived from pelvic traits. But in reality, pelvic bones are rarely preserved in the archeological record and as Waldron (1987) state, for example the preservation of the pubic region rarely goes over 30 %.

And finally, it seems that there are some differences in scholastic traditions regarding reliance on the precision of methodology. From problem oriented "western" tradition to methodologically oriented tradition in continental Europe. This can be illustrated on the same studies as with inconsistencies in methodology (Djuric et al. 2006 representing continental Europe and the other works representing "western" tradition).

On the basis of these notes, we have to be sensitive to interpretations based on methodologically disputable analyses and scholastic traditions have to be taken into account as well.

Time scale

Time scale is another central problem. Many archeological collections come from cemeteries used for decades and chronology often includes intervals of centuries. Special sites like plague pits, battle cemeteries or catastrophic burials resulting from natural disasters as in Pompeii and Herculaneum, are very rare (Mendonca de Souza et al. 2003). If skeletal samples cover such a long time periods, how can we make interpretations about fracture prevalence if we usually don't know how local conditions changed through time.

BIOLOGICAL FACTORS

Biological factors form the second large source of potential bias in fracture frequency studies. It is due to biological processes such as aging, healing and bone remodeling.

Aging

Aging is a natural process defined as any change in an organism through time. Many biological and also non-biological theories were proposed to explain causes of this process. However, in relation to skeletal trauma there are some relationships between specific life stages and specific fractures.

For example, in the immature bone, transverse fractures may be incomplete and are termed "greenstick", "bowing" or "torus" (Resnick et al. 1995 cited in Roberts and Manchester 2007) and its incompleteness may facilitate healing process (especially in young individuals) and subsequently make diagnosis more difficult.

Another confounding factor may be fractures caused secondary to other pathology (Lowell 1997). With aging, an organism is more susceptible to various diseases and fractures often occur secondarily to them. Systemic diseases such as metabolic disturbances and nutritional deficiencies leave bone vulnerable to spontaneous fracture or to the fracture from minor trauma (Lowell 1997). Examples are provided also in Lowell (1997): "neoplastic fractures are seen when the break is through or adjacent to a tumor that is in, or of, bone, and the collapse of vertebral bodies is not an uncommon consequence of tuberculosis in the spine (Pott's disease)".

"The big topic" in this context is the influence of osteoporosis on fracture prevalence. Osteoporosis is a weakening of a bone by reducing bone mineral density and disrupting bone microarchicture. Its causes are not well understood (Štěpán 1997). Currently, this is a big health problem in many western societies (Ruff et al. 2006). The potential bias resulting from osteoporosis is that the prevalence of fractures is expected to increase with age and with regard to sex (since postmenopausal women are the most affected).

Healing

Healing is a process of reuniting broken parts of the bone. It starts just after the fracture happens and lasts up to 6 months depending on the bone involved and, of course, on many other factors (nutrition, general health status etc.) (Lowell 1997).

The length of healing process is usually influenced by the specific nature of fracture and by potential complications (periostitis, osteomyelitis, bone necrosis, nerve injuries, post-traumatic haematoma ossification) (Lowell 1997).

Two key factors for successful healing are good sanitary conditions and health care standards. These two were not the same in various populations and through time. Especially the realization that broken bones must be fixed and stabilized was essential for successful healing. Such a realization first appeared probably in Paleolithic but was much more common in prehistoric Egypt (Koudela 2002).

The problem rises from the fact that only limited information is known about sanitary conditions and health care standards in the past. The problem is even deepened for the prehistoric periods where there is no help from written sources. Artistic depictions and direct archeological artifacts may help but, for example, as Grauer and Roberts (1996) pointed out, materials used for treatment were probably biodegradable and hence not preserved. Finally, as the variation in the level of health care and sanitary conditions between populations from different geographic areas and different time periods certainly existed, interpretations of fracture frequencies should take this into account (at least in cases where some information is available).

Remodeling

Remodeling of a bone is often presented as the third part of healing process (Lowell 1997; Pokorný et al. 2002). Remodeling is one part of broader processes of bone growth and modeling. Since bone growth and modeling in a strict sense last only about 20 years, process of bone remodeling is active throughout the whole life of an individual. This process is driven by many factors (genetic, hormonal, nutritional, traumatic etc.) but mechanical are one of the most important (Ruff 2000, but see Pearson and Lieberman 2004).

Mechanical nature of bone remodeling was first described by Julius Wolff in 1892 and became famous as a "Wolff's law" (Ruff et al. 2006). Even if this term was criticized (and recently suggested to be replaced by the term "bone functional adaptation"), the concept standing behind is still recognized to be one of the major bone shaping forces (Ruff et al. 2006). It simply states that the shape of long bones (this does not directly relate to cranial bones since they have different functional status) is formed according to major forces acting upon the bone. During remodeling, old bone is broken down by osteoclasts and new bone is deposited by osteoblasts in directions related to major strains. Remodeling is also responsible for repairing microfractures (Taylor and Lee 2003). As with many other biological features, variation exists between individuals and populations mainly because of multifactorial origin of this phenomenon.

From the above presented information, it is apparent that differences between individuals and populations in rates and degree of remodeling as a consequence of fracture will differ. The health status, nutritional status, life style and many other factors will play part and as a result, the interpretation of the fracture frequency may be seriously affected.

Conclusions

With the development of paleoepidemiology, new perspective has been brought to paleopathology. Researchers were able to focus on disease prevalence within and between populations. In this work, the limits of applying paleoepidemiological approach in studies of human diseases (specifically fractures) have been discussed. As Mendonca de Souza et al. (2003:26) state: "…most archaeological data is residual, scarce and incomplete and can not be reproduced by experimentation, and as a consequence very few data allow conclusive inference, and the limits and uncertainties have to be clearly defined and accepted. Statistical significance is not obtained for many results but cultural significance, which is not simply a matter of quantity, also must be clear."

It must be stressed that not only limits of data but also limits of methodologies may confound final interpretations. While the nature of archeological data is much more influenced by processes that can't be controlled (e. g. preservation, healing, bone remodeling), the analyses of data (in broader sense everything from diagnosis to interpretations) can, and therefore, there should be an inquiry to be certain that we did methodological maximum (which seems to me is not the case in all fracture frequency studies) before any interpretation is made. At the same time, there must be an effort to refine our methods. Otherwise, our interpretations will bear the same degree of uncertainty and will become useless.

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