Bone density studies in zooarchaeology

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Abstract

Accurate bone density data are essential for assessing the influence of destructive processes in archaeological faunal assemblages. Unfortunately, the diversity of methods employed by different researchers to derive density values has resulted in recent confusion. Two recent publications in this journal [J Archaeol Sci 29 (2002) 883; J Archaeol Sci 29 (2002) 979] exemplify this state of misunderstanding. Both studies argued that the role of bone density in shaping archaeological faunal assemblages has been largely overrated, but both based their conclusions on density values that were inaccurately derived. The former employed a method of calculating bone density that has been largely discredited over the past decade [J Archaeol Sci 29 (2002) 883]. Within a larger discussion of zooarchaeological methodology, the latter provided an assessment of the current state of bone density research that inappropriately characterized the discrepancies between available sets of density data as a reflection of the differences between two technologies—photon densitometry and computed tomography [J Archaeol Sci 29 (2002) 979]. The actual dichotomy exists—irrespective of the technology employed—between studies that account for variation in the shape of bone cross-sections and those that do not. The different sets of density data currently available to zooarchaeologists vary tremendously in their accuracy. We review and evaluate the different techniques employed in the research of bone density patterns of mammalian fauna. Computed tomography produces the most accurate density data. For elements without medullary cavities, photon densitometry may provide density values of similar accuracy but only if a method of cross-sectional shape-adjustment is applied.
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1. Introduction

The analysis of the taphonomic history of an archaeological faunal assemblage requires the assessment of the influence of post-depositional bone attrition. Because such destruction affects the preservation and the subsequent quantification of faunal remains, it is of primary concern to zooarchaeologists attempting to interpret prehistoric human activities on the basis of skeletal element representation. Since Lyman's [13] pioneering publication of density values for the skeletal elements of deer, the standard analytical technique for assessing the influence of post-depositional destruction has been to compare the abundance of skeletal elements (and portions thereof) with their bone density. Post-depositional destruction is assumed to be density-mediated, and a significant positive correlation between the abundance of a skeletal element and its density in an archaeological assemblage is evidence of the influence of taphonomic processes, suggesting that caution be applied in the inference of human behavior [7,14,15].

To date, complete sets of density values have been derived for only a small number of mammalian taxa: deer, *Odocoileus* spp., sheep, *Ovis aries*, pronghorn antelope, *Antilocapra americana* [13,16,21]; marmot, *Marmota* spp. [17]; bison, *Bison bison* [10]; seal, *Phoca* spp. [16]; camelids, *Lama* spp. [6,24]; leporids—*Oryctolagus cuniculus*, *Sylvilagus floridanus*, and *Lepus*

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spp. [20]; wildebeest, *Connachaetes taurinus*, reindeer, *Rangifer tarandus*, equids, *Equus* spp. [12]; and baboon, *Papio cynocephalus* [21]. Density data have also been published for fish and bird species [4,5]. Zooarchaeologists interested in species other than the aforementioned have encountered the dilemma as to which set of density values to choose for their analyses. Some researchers continue to use Lyman's original data for deer, likely due to an inability to evaluate the quality of the more recently derived data sets. For example, one recent article advocated the use of the density values derived by Lyman, citing their "longer track record" [25, p. 987]. There exist criteria other than antiquity by which to judge density data, and these will be discussed in a later section.

2. Bone density studies in zooarchaeology

While the relationship between bone density and faunal preservation has long been recognized by pale-ontologists and archaeologists (see [16], for a review), early attempts to measure the bone density of sheep/goat by Brain [3] and Behrensmeyer [1] produced incompatible results due to the differences in their respective methodologies. Lyman attempted to address this problem by employing photon densitometry (hereafter "PD") in his bone density research [13]. This technology enabled him to take readings of bone mineral content along the very narrowly defined areas ("scan sites") of each skeletal element. In his study of deer bone density, Lyman [13] published density values for scan sites distributed throughout the mandible and the entire post-cranial skeleton, and these data became an essential component of many subsequent zooarchaeological analyses.

It was almost a decade before bone density values became available for other species of mammal. In a 1989 study, Grayson [7] used Lyman's data for deer to assess the survivorship of marmot bones at archaeological sites. Speculating that significant differences in bone density patterns may exist between taxa, Lyman et al. [17] subsequently derived a set of density data for marmot, and Kreutzer [10] presented new data for bison. Both of these later studies also employed PD, and both also documented density patterns distinct from that of deer. However, these two studies also adopted methods of calculating density—described in the following section—that were slightly different from that of Lyman's [13] study. Lyman later published data for sheep, pronghorn antelope, and seal derived in the same manner as his original study [16]. Elkin [6] employed PD using Lyman's [13] method in a study of camelid bones. She also derived an independent set of density values using water displacement. Pavao and Stahl [20] and Stahl [24] used PD to derive density values for leporids and camelids, respectively. Each of these last two studies

produced two sets of values—one generated by simulating Lyman's methodology, the other by incorporating a number of modifications designed to increase the accuracy of the density measurements. In a recent study, Pickering and Carlson [21] employed Lyman's original methodology to derive density data for baboon and goat without adopting any of the technical improvements developed by earlier researchers. Lam et al. [12] produced density values for a sample of bovid, cervid, and equid species using a different technology, computed tomography (CT).

3. Different methods of calculating bone mineral density

Most zooarchaeological studies of bone density have employed a technology known as photon densitometry or absorptiometry. Photon densitometers do not provide a direct measure of bone density. They measure bone mineral content across a scanned section of bone. The volume of this scan site must be determined by the researcher before density may be calculated. Because scan length (i.e., the thickness of the scan "slice"; Fig. 1) is set by the densitometer, the researcher need only be concerned with determining the cross-sectional area of the bone at each scan site. Lyman [13] estimated the cross-sectional area of all of his scan sites as a product of the maximum bone width and maximum bone thickness (Fig. 1). Every scan site, regardless of its shape or the presence of any cavities, was in effect treated as a rectangle in the calculation of density (Fig. 1c). The primary shortcomings of this technique are not only that it underestimates the bone mineral density for any scan site that does not have a rectangular shape, but also that it underestimates density to a different degree for each scan site. This issue is discussed in detail by Kreutzer [10], Lam et al. [11] and Stahl [24].

Virtually every zooarchaeological study of bone density conducted since Lyman's [13] pioneering research has improved upon his original methodology [6,10–12,17,20,24]. Lyman et al. [17] adopted an "average", rather than a maximum, measurement of bone thickness—a modification that may be construed as a tacit admission of the shortcomings of his previous methodology. In her study of bison, Kreutzer [10] made a number of different measurements at each scan site to produce a geometric estimate of its cross-section. Pavao and Stahl [20], working with small leporid elements, produced similar estimates by categorizing scan sites as various geometric shapes. Stahl [24] employed a detailed technique of shape-adjustment, using a carpenter's molding tool to accurately recreate cross-sectional shapes.

Despite such efforts to estimate external shape, PD studies cannot distinguish internal heterogeneity in bone structure (Fig. 1a, b), a variable that is significant in any element that possesses a medullary cavity. To document
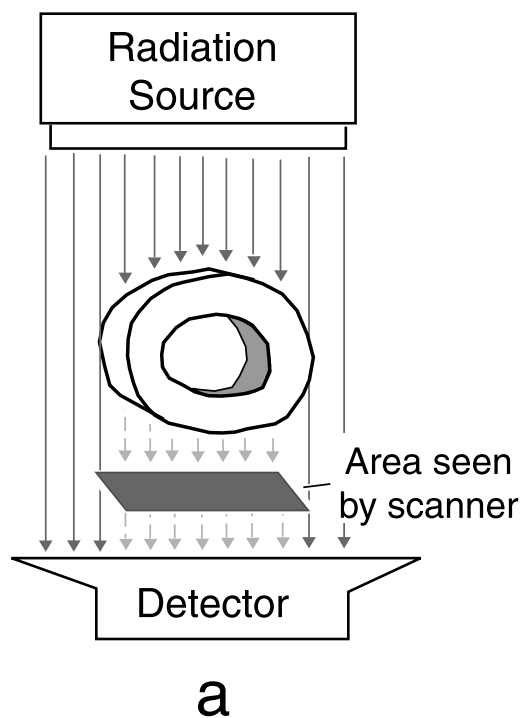
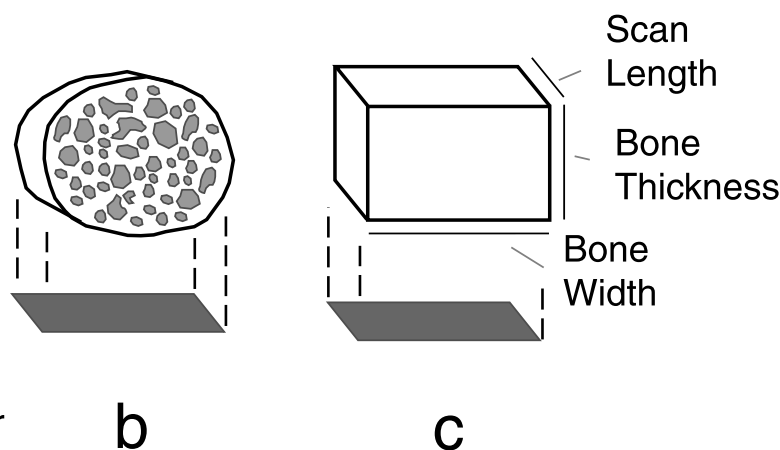## DENSITOMETER   RESULTS

Fig. 1. A schematic diagram of how density is measured by a photon densitometer (after [10]). PD does not detect the cross-sectional area of a scan site; this must be measured independently by the researcher. Most researchers have attempted to measure the external shape of the scan site, but even so PD can not distinguish between a hollow cylinder of thick cortical bone, A, and a tube of spongy bone, B. Some researchers [13,21] have chosen to treat the cross-sectional area of scan sites as a rectangle (C) with sides of maximum bone width and maximum bone thickness.

accurate cross-sectional areas, Lam et al. [11,12] employed CT, which produces a clear radiographic image of the bone cross-section that may be digitized. This technique allows the medullary cavity to be excluded from the calculation of bone density.

CT has been used for almost three decades to measure bone mineral density, and its advantages over PD in this task have been documented from the onset [22,23]. After years of improvements to both technologies, clinical researchers continue to prefer CT for the collection of density data [8,9]. The primary drawback of CT is that it involves much higher doses of radiation than PD [19], a consideration that is irrelevant to the type of study addressed here.

While we have been advocates of the use of CT in bone density studies, we readily acknowledge that PD can produce similarly accurate density values when researchers compensate for its technological limitations [11]. For scan sites without internal cavities, cross-sectional area can be accurately determined in the manner devised by Stahl [24]. For those with medullary cavities, obtaining an accurate assessment of the cross-sectional area is more problematic, requiring that the element be either physically sectioned or X-rayed at the

point of interest. To date, *no PD studies have excluded the volume of internal cavities from their calculation of bone density*. Therefore, PD values for scan sites with internal cavities significantly underestimate density.

The various methods of calculating cross-sectional area (and, by extension, bone density) are categorized and illustrated in Fig. 2. The terms "volume density" (VD) and "bone mineral density" (BMD) should be equivalent measures, but because of the variety of ways in which both are calculated, they are not. Group A consists of studies that do not employ any type of shape-estimation [13,21]. These studies treat each scan site as if its cross-section were a rectangle based on its maximum dimensions, resulting in underestimates of the density of all sites. The degree of underestimation is not systematic, varying according to the cross-sectional shape of each scan site, and is especially large in bones with large medullary cavities. The accuracy of density values produced by Group A studies is low.

Group B includes studies that approximate the cross-sectional area of a scan site as a (non-rectangular) geometric shape or as a geometric outline. These produce density data that are much more accurate than those in Group A but slightly less than those in Group

GROUP	Estimated cross-sectional area of scan site (without medullary cavity) FE 6	Estimated cross-sectional area of scan site (with medullary cavity) FE 4	Terminology	Reference
A. no shape adjustment			VD bulk BMD $VD_{LD/BT}$	Lyman [13,16] Elkin [6] Pickering & Carlson [21] Pavao & Stahl [20] Stahl [24]
B. shape estimated (external)			VD VD_{SA}	Kreutzer [10] Lyman et al. [17] Pavao & Stahl [20]
C. shape adjusted (external)			VD_{SA} BMD_1	Stahl [24] Lam et al. [12]
D. shape adjusted (external & internal)			BMD_2	Lam et al. [11] Lam et al. [12] Elkin [6]

Fig. 2. Summary of methods of estimating cross-sectional area in density studies employing photon densitometry and computed tomography. The scan sites used in this example are FE6 (distal epiphysis of femur) and FE4 (middle shaft of femur). Accuracy increases from Group A to Group D. Several studies [6,12,20,24] derive density using more than one method; data from the less accurate method is used for comparison with earlier studies. Kreutzer's [10] method of shape estimation was more elaborate than illustrated here, while that of Lyman et al. [17] was not clearly described (see text). Abbreviations (see original references for descriptions): VD (volume density), LD (linear density), BT (bone thickness), SA (shape-adjusted), BMD (bone mineral density).

C. Group C categorizes studies that involve an accurate reconstruction of external cross-sectional shape, using CT or other means. These produce correspondingly accurate density values for scan sites that do not contain an internal cavity. Group D consists of studies that exclude the marrow cavity from calculations of density. These employ CT or methods such as water displacement and produce accurate density values both for scan sites with internal cavities and those without.

Fig. 2 notes that a number of studies employ more than one method of density calculation. This is evidence of the pervasive influence of Lyman's pioneering work—several of these studies used Lyman's [13] methodology to derive a second data set of less accuracy for comparative purposes. Pavao and Stahl [20] calculated two separate sets of data for leporids based on PD measurements. One set was not shape-adjusted ($VD_{LD/BT}$) and was used for comparison with the data derived for marmot by Lyman et al. [17]; the other was shape-adjusted (VD_{SA}) and thus more accurate. Similarly, in his study of camelid density patterns, Stahl [24] presented one set of data that was shape-adjusted (VD_{SA}) and another that was not ($VD_{LD/BT}$) for comparison with Lyman's [13] values for deer. Elkin [6] derived density values for camelids using both Lyman's method and water displacement. Lam et al. [12] presented two sets of data for their sample of bovid, cervid, and equid species. One excluded the medullary cavity to produce an accurate calculation of bone density (BMD_2, in Group D), the other incorporated the cavity space to provide a data set comparable to those of photon-densitometry studies that employed a shape-adjusted method of density calculation (BMD_1, in Group C).

Kreutzer [10] speculated that some of the discrepancies between her density data for bison and Lyman's [13] data for deer reflected differences in their respective methodology rather than intertaxonomic differences between the skeletal morphology of deer and bison. Lam
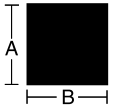
Scan Site	A PD density (Pickering & Carlson [21])	B Shape adjustment	C Shape-adjusted density	D CT density (Lam et al. [11])
FE4	 Area = A•B	 Area = (0.497)•A•B		
Density	**0.694**	**(0.694) / (0.497)**	**1.369**	**1.327**
FE6	 Area = a•b	 Area = (0.687)•a•b		
Density	**0.348**	**(0.348) / (0.687)**	**0.507**	**0.497**

Fig. 3. The effect of shape-adjustment on PD values. FE4—middle shaft of femur; FE6—distal epiphysis of femur. Column A lists Pickering and Carlson's [21] values for sheep bone density. If they had conducted shape-adjustment of the cross-sectional area of the scan site (Columns B to C), their values would have been similar to those derived for goat bones using CT (Column D).

et al. [12] confirmed this speculation, attributing most—if not all—of the differences between the two data sets to the lack of any shape-adjustment in Lyman's study. In a comparison of density data for different species, Lam et al. [12] found that the highest correlations occurred between data sets derived using the same methodology, regardless of any expected genetic or morphological similarity. For example, density values for reindeer, derived using CT, were much more highly correlated with CT data for equids than they were with PD data for deer from Lyman's [13] study. It is of interest to note that Lyman's [12] values for deer are more highly correlated to those of marmot (r_s=0.55, P<0.0001 [17]) than those of bison (r_s=0.525, P<0.001; [10]). This must reflect methodological differences between the two studies by Lyman and that of Kreutzer, who employed shape-estimation in her calculations; otherwise, we would have to infer that marmot and deer are more similar in skeletal structure than deer and bison. Differences in methodology clearly obscure the intertaxonomic differences in bone density patterns that researchers have been trying to document.

4. Assessing the accuracy of different methods

Notwithstanding the earlier discussion of different methodologies and technologies, the most appropriate manner of evaluating the relative quality of density data is by examining the density values themselves. The middle shaft portions of artiodactyl long bones consist primarily of cortical bone. Pickering and Carlson [21] noted that the mineral density of cortical bone should be approximately 1.17–1.30 g/cm^3. Only density values produced by CT and water displacement approach this expected range. In a CT study of goat bones, the mineral density of the middle shaft portions of the six long bones ranged between 1.06–1.33 g/cm^3 [11]. Elkin's [6] water displacement study of similar portions of camelid elements produced values ranging between 1.15–1.30 g/cm^3. In contrast, no PD study documents density values near this range. For example, Pickering and Carlson [21] produced a much lower range of values (0.55–0.75 g/cm^3) for the middle shaft portions of the one sheep skeleton that they measured. Lyman [13] and Kreutzer [10] produced similarly low values for the long bone mid-shafts of deer and bison, respectively. In contrast, shape-adjusted density values for the analogous scan sites in camelids fall above the expected range [24].

As noted above, the low values produced by Lyman [13] and Pickering and Carlson [21] simply reflect the fact that they treated the cross-section of every scan site as a rectangle. Fig. 3 contrasts the different shapes used to estimate the cross-section of the distal femur (scan site FE6) and the femoral middle shaft (scan site FE4). For their sheep skeleton, Pickering and Carlson [21] derived a value of 0.348 g/cm^3 for FE6 and 0.694 g/cm^3 for FE4 applying their rectangular estimate. The shape-adjusted cross-sectional outlines in Fig. 3 were derived for goat bones using CT. The CT outline of FE6 represents a

smaller area than the rectangular representation used by Pickering and Carlson [21], covering only 68.7% of its area. The CT outline of FE4 represents proportionally an even smaller fraction (49.7%) of its rectangular counterpart. If Pickering and Carlson had conducted a shape-adjustment for these two scan sites, they would have produced values of 0.507 g/cm³ for FE6 and 1.396 g/cm³ for FE4. These shape-adjusted values are remarkably similar to the values for these scan sites derived by CT—0.497 g/cm³ and 1.327 g/cm³, respectively [11].

It is important to note that, as illustrated in this example (Fig. 3), the method employed by Lyman [13] and Pickering and Carlson [21] underestimate density to varying degrees, depending on the shape of the bone. The density of middle shaft portions, because of the medullary cavity, will be underestimated far more than the density of epiphyses. At the same time, this example demonstrates that the data produced in such PD studies can be converted into accurate density values if shape-adjustment is applied.

5. The importance of using accurate density values

While acknowledging that CT produces more accurate density data, Pickering and Carlson [21] derived bone density values for baboons using PD and uncorrected volume measurements (Group A) in the same manner as Lyman [13]. To justify their decision not to conduct any kind of shape-adjustment, they argued that, because a significant positive correlation was observed between CT and PD values [12,16] for ovicaprid long bones, data derived using the latter method must possess diagnostic value. However, when the entire range of skeletal elements are compared, the strength of the correlation observed between CT data sets and Lyman's PD values decreases while remaining significant at $P<0.05$ ([12, Table 5]). The Spearman's correlation coefficients between Lyman's data for deer and the three CT data sets are very low ($r_s=0.421$ for equid, $r_s=0.404$ for wildebeest, $r_s=0.533$ for reindeer, $P<0.05$ for all comparisons [12]).

The occurrence of a statistically significant correlation (e.g., at $P<0.05$) between CT values and another set of unknown quality does not attest to the latter's accuracy. Two sets of density values that are significantly correlated may result in contradictory conclusions regarding the same faunal assemblage. For example, Kreutzer's [10] study found a significant correlation between her values for bison and Lyman's values for deer ($r_s=0.525$, $P<0.001$). However, when compared with the survivorship of bison bones at Glenrock Buffalo Jump, the bison values produced a significant correlation ($r_s=0.522$, $P<0.01$) but the cervid values did not ($r_s=0.188$, $P<0.20$). In a second example, Lyman et al. [17] derived density values for marmot that were significantly correlated with those of deer ($r_s=0.55$,

$P<0.0001$). When compared with the survivorship of marmot bones from archaeological sites in the White Mountains of California, Grayson [7] found a significant positive correlation using deer density values ($r_s=0.63$, $P<0.01$). Conducting a re-analysis using marmot bone density values, Lyman et al. [17] found no such significant correlation ($r_s=0.0008$, $P=0.95$). Pickering and Carlson [21] found a significant correlation between baboon and sheep bone density ($r_s=0.49$, $P=0.000$).

Clearly, the use of an inaccurate set of density values may result in the incorrect assessment of the influence of post-depositional destructive processes. Stiner [25] argued that the effect of density-mediated bone attrition has been greatly exaggerated for Pleistocene sites. She cited a weak relationship ($r_s=0.40$, $P=0.03$) between bone density and the log% MAU (Minimum Animal Units; for definition, see [2]) estimates for long bone portions in the Mousterian assemblage from Kobeh Cave studied by Marean and Kim [18]. This weak correlation resulted from the use of Lyman's [16] PD values for sheep in this analysis; CT data were not yet available at the time. When newly derived CT values were used in this analysis, the relationship between bone density and long bone survivorship at Kobeh became much more significant ($r_s=0.75$, $P<0.0001$) [11]. Density played a very important role in the preservation of faunal remains at this site.

6. Choosing the appropriate set of density data

When conducting an analysis of bone survivorship, zooarchaeologists tend to select density data for their species of interest, if available, or for a closely related species. Unfortunately, as we have demonstrated here, this may not be the most appropriate choice. We believe that some published density data are simply not of adequate accuracy to be useful in any type of analysis. Researchers should use density data based on shape-adjusted calculations, even if such data are only available for a distant relative of their species of interest. The patterns of bone density among bovids and cervids are very similar [12]; within these families, it is most important to use an accurate set of density data irrespective of species. In other words, shape-adjusted density data for a bovid species will provide a much more accurate estimate of deer bone density than Group A data for that species of deer.

One unfortunate result of the wide variety of methodologies employed in density studies is that it allows researchers to choose those data that most support their interpretations. Recently, there has been some disagreement among zooarchaeologists regarding the most appropriate method to calculate the abundance of long bones in faunal assemblages. Some researchers [11,18] have advocated a focus on the quantification of long bone shaft fragments due to their higher density;

others [25] have argued that long bone shafts are not more likely to be preserved than epiphyses. CT supports the former position, documenting large differences between the density of middle shaft portions and that of epiphyses. Proponents of the latter position [25] have preferred data derived by PD, which underestimates the density of middle shaft portions far more than the density of epiphyses, thus understating the differences between the two.

Shape-adjustment is much more readily and accurately conducted using CT. CT has produced mineral density values that correspond to those clinically documented for cortical bone; PD has not. In addition, CT can isolate specific cross-sectional features and therefore is more effective at examining bones of complex composition, such as the cranium. While it has been suggested that CT standards are relatively "incomplete" [25, p. 986], CT studies have provided density values for cranial bone (the petrous [12]), while PD studies have not. Density studies in zooarchaeology should endeavor to produce increasingly accurate measurements by means of methodological and technological advances, and zooarchaeologists should refrain from the persistent resurrection and endorsement of techniques whose shortcomings have been unequivocally demonstrated.

The selection of a density data set should no longer be a matter of personal preference. While archaeologists may not have the expertise to evaluate the relative advantages and shortcomings of photon densitometry and computed tomography, it should be clear that this is less an issue of technology than one of geometry. Shape-adjustment requires a considerable investment of time and effort whether CT or some other method is used, and density data derived in this manner are clearly superior to those that are not.

Acknowledgements

References

[1] A.K. Behrensmeyer, The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages east of Lake Rudolf, Kenya, Bulletin of the Museum of Comparative Zoology 146 (1975) 473–578.

[2] L.R. Binford, Nunamiut Ethnoarchaeology, Academic Press, New York, 1978.

[3] C.K. Brain, The contribution of Namib Desert Hottentots to an understanding of australopithecine bone accumulations, Scientific Papers of the Namib Desert Research Station 39 (1969) 13–22.

[4] V.L. Butler, J.C. Chatters, The role of bone density in structuring prehistoric salmon bone assemblages, Journal of Archaeological Science 21 (1994) 413–424.

[5] F.J. Dirrigl, Bone mineral density of wild turkey (*Meleagris gallopavo*) skeletal elements and its effect of differential survivorship, Journal of Archaeological Science 28 (2001) 817–832.

[6] D.C. Elkin, Volume density of South American camelid skeletal parts, International Journal of Osteoarchaeology 5 (1995) 29–37.

[7] D.K. Grayson, Bone transport, bone destruction, and reverse utility curves, Journal of Archaeological Science 16 (1989) 643–652.

[8] H. Haapasalo, S. Kontulainen, H. Sievänen, P. Kannus, M. Järvinen, I. Vuori, Exercise-induced bone gain is due to enlargement in bone size without a change in volumetric bone density: a peripheral quantitative computed tomography study of the upper arms of male tennis players, Bone 27 (2000) 351–357.

[9] T.L.N. Jarvinen, P. Kannus, H. Sievänen, Have DXA-based exercise studies seriously underestimated the effects of mechanical loading on bone? Journal of Bone and Mineral Research 14 (1999) 1634–1635.

[10] L.A. Kreutzer, Bison and deer bone mineral densities: comparisons and implications for the interpretation of archaeological faunas, Journal of Archaeological Science 19 (1992) 271–294.

[11] Y.M. Lam, X. Chen, C.W. Marean, C. Frey, Bone density and long bone representation in archaeological faunas: comparing results from CT and photon densitometry, Journal of Archaeological Science 25 (1998) 559–570.

[12] Y.M. Lam, X. Chen, O.M. Pearson, Intertaxonomic variability in patterns of bone density and the differential representation of bovid, cervid, and equid elements in the archaeological record, American Antiquity 64 (1999) 343–362.

[13] R.L. Lyman, Bone density and differential survivorship of fossil classes, Journal of Anthropological Archaeology 3 (1984) 259–299.

[14] R.L. Lyman, Bone frequencies: Differential transport, *in situ* destruction, and the MGUI, Journal of Archaeological Science 12 (1985) 221–236.

[15] R.L. Lyman, Anatomical considerations of utility curves in zooarchaeology, Journal of Archaeological Science 19 (1992) 7–22.

[16] R.L. Lyman, Vertebrate Taphonomy, Cambridge University Press, Cambridge, 1994.

[17] R.L. Lyman, L.E. Houghton, A.L. Chambers, The effect of structural density on marmot skeletal part representation in archaeological sites, Journal of Archaeological Science 19 (1992) 557–573.

[18] C.W. Marean, S.Y. Kim, Mousterian large mammal remains from Kobeh Cave (Zagros Mountains, Iran): Behavioral implications for Neanderthals and early modern humans, Current Anthropology 39 (1998) S79–S113.

[19] R.B. Martin, D.B. Burr, N.A. Sharkey, Skeletal Tissue Mechanics, Springer-Verlag, New York, 1998.

[20] B. Pavao, P.W. Stahl, Structural density assays of leporid skeletal elements with implications for taphonomic, actualistic and archaeological research, Journal of Archaeological Science 26 (1999) 53–66.

[21] T.R. Pickering, K.J. Carlson, Baboon bone mineral densities: Implications for the taphonomy of primate skeletons in South African cave sites, Journal of Archaeological Science 29 (2002) 883–896.

[22] I. Posner, H.J. Griffiths, Comparison of CT scanning with photon absorptiometric measurement of bone mineral content in the appendicular skeleton, Investigative Radiology 12 (1976) 542–544.

[23] N.E. Reich, F.E. Seidelmann, R.R. Tubbs, W.J. MacIntyre, T.F. Meaney, R.J. Alfidi, R.G. Pepe, Determination of bone mineral content using CT scanning, American Journal of Roentgenology 127 (1976) 593–594.

[24] P.W. Stahl, Structural density of domesticated South American camelid skeletal elements and the archaeological investigation of prehistoric Andean ch'arki, Journal of Archaeological Science 26 (1999) 1347–1368.

[25] M.C. Stiner, On in situ attrition and vertebrate body part profiles, Journal of Archaeological Science 29 (2002) 979–991.