

# Skeletal element abundances in archaeofaunal assemblages: economic utility, sample size, and assessment of carcass transport strategies

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## Abstract

Economic utility indices provide a means of interpreting butchery and transport decisions reflected in the relative abundance of skeletal elements. Because of destructive taphonomic processes, interpreting skeletal element abundances in terms of carcass transport strategies requires that faunal analysts consider only those elements which accurately reflect their original abundances following human discard. In this study we use resampling techniques to examine the impact of sample size on correlations between high-survival skeletal element frequencies and economic utility in four simulated population assemblages reflecting distinct carcass transport strategies. Correlations alone do not accurately reflect the true relationship between bone abundance and economic utility as particular transport strategies have a tendency to generate high frequencies of Type II errors as sample size decreases. We show that the Shannon evenness index can be used as a quantitative means of distinguishing between bone assemblages characterized by subtle variations in skeletal element abundances. The evenness index can also be used to evaluate whether observed correlations reflect sampling error. Results from our simulations are applied to three published faunal assemblages to evaluate likely carcass transport strategies.

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## 1. Introduction

Zooarchaeologists commonly use skeletal element abundances in archaeofaunal assemblages to make inferences about human behavior. Relative frequencies of skeletal elements are used to examine carcass-acquisition strategies, butchery and transport decisions, site function, and the taphonomic history of bone assemblages [9,10,15,21,32,38,55,66,74,76–79]. The underlying rationale for the analysis of skeletal element abundances is based on observations that hunters constrained by

transport limitations often select a limited number of bones for transportation from the kill site to the consumption site [3,9,10,22,42,64,65]. It is presumed that butchery and transport decisions are mediated by some recognition of the nutritional value associated with different elements. With Binford's [9] development of utility indices, archaeologists have been able to evaluate carcass butchery and transport decisions in relation to clearly defined economic variables. Binford [9] proposed a family of hypothetical utility curves, representing a scatterplot comparison of skeletal element abundances against economic utility to illustrate three hypothetical transport strategies: (1) the bulk strategy, in which the quantity of all but the lowest utility elements is maximized; (2) the gourmet strategy, whereby the quality of elements transported is

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maximized; and (3) the unbiased strategy, in which skeletal elements are transported in direct proportion to their economic utility (Fig. 1). In interpreting transport strategies, analysts typically fit Binford's curves to their own data by eye [54].

Since the introduction of utility indices, it has become apparent that skeletal element abundances are highly sensitive to taphonomic processes and do not reflect their original patterns following human discard. These processes, which include sub-aerial weathering [7], carnivore modification [13,16,18,56,57], and post-depositional alteration [39,50], are known to overprint human behavioral patterns. Lyman [44–48] and Grayson [31,32] have shown that our ability to interpret skeletal part frequencies in relation to economic utility is severely compromised by density-mediated destruction of bone. Thus, faunal analysts are faced with a serious dilemma in evaluating economic considerations underlying butchery and transport decisions. One solution to this problem is to examine only those skeletal elements that survive destructive processes. Marean and Frey [54] have demonstrated that with the inclusion of high-density [40,41], high-survival [56,67], long-bone shaft fragments, it is possible to evaluate skeletal element frequencies with respect to economic utility, albeit with just the long-bone sample.

Restricting the analysis of skeletal element abundances to a sample of high-survival elements is analytically problematic because it limits the number of units available for study and can lead to sample size issues. As more studies follow Marean and Frey's [54] example (e.g., [28,52,53,55]), we feel that it is necessary to address two central questions that arise when studying select subsets of a faunal assemblage: (1) What is the impact of sample size on the relationship between skeletal element abundance and economic utility (i.e., the shape of the

utility curve)? (2) At various sample sizes, when is it possible to confidently distinguish between utility curves characteristic of different transport strategies (i.e., bulk, gourmet, unbiased)? Examining these issues in further detail is the focus of this paper.

Sample size is known to impact a variety of archaeological and ecological measurements [23,30,33,49,58,69]. In any quantitative zooarchaeological analysis, it is necessary to show that observed patterns are truly representative of the population being sampled rather than artifacts of sample size. An enhanced understanding of the effects of sample size on the patterning of skeletal element abundances is necessary if we are to effectively use utility indices to make inferences on behavioral patterns. In addition, we believe that evaluating transport strategies by "eye-balling" the shape of the utility curve is overly subjective. A quantitative approach for evaluating relative abundances of skeletal elements will enhance our ability to interpret butchery and transport decisions. In this study we investigate these issues by generating simulated sample assemblages drawn randomly from four hypothetical faunal assemblages and apply generalizations from the results to evaluate likely transport strategies for three sites based on published abundance data.

### 1.1. Skeletal element analysis: high- versus low-survival elements

The analytical consequence of density-mediated attrition requires that faunal analysts consider only those elements that accurately reflect their original abundances following human discard. Marean, Cleghorn, and colleagues have shown that skeletal elements can be divided into a high- and low-survival set [27,28,52–54]. Dense elements with thick cortical walls and medullary cavities, such as long bones and mandibles, are classified as high-survival elements. The cranium, due to the presence of teeth and the petrosal, is also classified as a high-survival element. The low-survival set includes elements with thin cortical walls and low-density, grease-rich cancellous portions, such as vertebra, ribs, pelvis, scapulae and long-bone ends. Phalanges and small compact bones are also considered low-survival elements since they are readily consumed by carnivores [50]. High-survival elements are the best candidates for analyzing the economic decisions behind butchery and transport decisions. In contrast, the abundances of low-survival elements are highly sensitive to taphonomic processes that have acted on an assemblage following human discard. While low-survival elements and portions can serve as useful indicators of the severity of attrition to a faunal assemblage (e.g., [71]), they should not be considered as directly indicative of human behavioral patterns in assemblages subjected to destructive processes.

The distinction between high- and low-survival elements is primarily based on models of carnivore destruction of bone. While other destructive processes, such as trampling, sediment compaction, and chemical leaching, are considered to be density mediated [32,43–45,47], there has been little

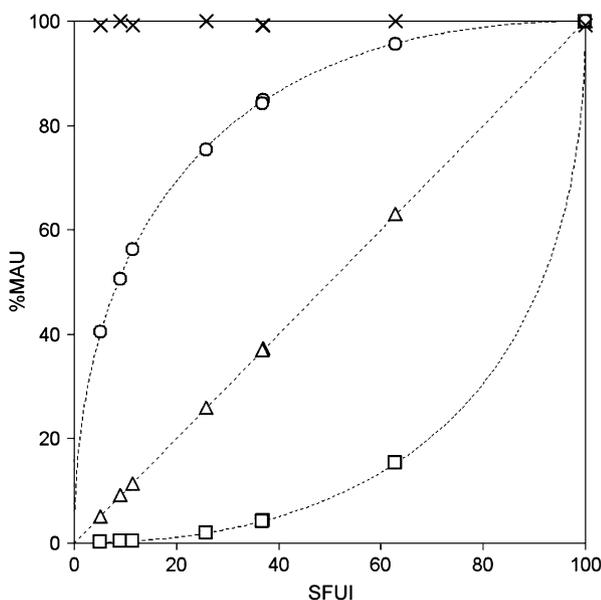


Fig. 1. Hypothetical utility curves for various transport strategies. Data points represent values from simulated populations conforming to four different transport strategies. Symbols: squares = gourmet strategy; triangles = unbiased strategy; open circles = bulk strategy; X's = unconstrained strategy.

experimental research to establish a direct link between bone density and destruction. Carnivore modification, however, has been well documented as a density-mediated process [19,40,56,57] and has been observed to impact modern faunal assemblages in a broad range of geographic and environmental contexts [2,4,9,14,16,25,26,29,36,37,56,57,73,80]. Numerous archaeofaunal assemblages also bear evidence of carnivore destruction (e.g., [1,17,34,52,55,61–63,68]). Beyond carnivore destruction, we note that density-mediated attrition is widespread in published faunal assemblages (e.g., [27,43,46]) and that several assemblages show a clear separation between the frequencies of high- and low-survival elements with respect to economic utility [52–55]. Thus, we believe the distinction between high- and low-survival elements provides the most accurate assessment of those elements that survive attritional processes and reflect human transport and butchery decisions. We caution that this division does not preclude a consideration of the effects of attrition on skeletal part frequencies in a faunal assemblage, particularly if taphonomic processes other than carnivore destruction have acted on an assemblage (e.g., fluvial transport [6,8,75]). In the following analysis, we include only those elements in the high-survival set: the cranium, mandible, femur, tibia, metatarsal, humerus, radius, and metacarpal.

### 1.2. Quantitative evaluations of transport strategies

Economic utility indices provide a set of expectations about how butchery and transport decisions are reflected in the abundance of skeletal elements in archaeofaunal assemblages [60]. Variation in the abundance of high-utility elements relative to other elements should reflect situational transport constraints, including transport distance, transport mode, number of carriers, and the number and size of animals transported, among other factors. Binford [9] discusses these relationships in terms of the bulk, gourmet, and unbiased strategy (Fig. 1). For the purposes of this study we propose the “unconstrained strategy,” in which skeletal elements are transported at equal frequencies, in relation to their abundances in a complete animal and irrespective of economic utility. The unconstrained strategy models scenarios where differential transport has not occurred, as in the transport of complete carcasses of small

prey types. The primary difference between assemblages characterized by these strategies is in the evenness of the distribution of specimens across classes of elements. For example, the unconstrained strategy is characterized by a perfectly even distribution of skeletal elements (standardized by their frequencies in the vertebrate body), whereas the gourmet strategy is characterized by an uneven distribution. Thus, we argue that different transport strategies can be quantified and evaluated using the Shannon evenness index, where  $evenness = -\sum p_i \ln p_i / \ln S$ , and  $S$  is the number of types (e.g., humerus, femur) of elements and  $p_i$  is the standardized proportion of specimens of the  $i$ -th element (see Magurran [49] and Grayson and Delpech [33,35]). In measuring the evenness of skeletal element abundances, it is important that bone frequencies be standardized by their actual frequencies in the vertebrate body. We standardize skeletal element frequencies using MAU (Minimal Animal Units) after Binford [11]. In this paper we will test the efficacy of applying this method to distinguish transport strategies.

## 2. Methods

We use randomization procedures to generate large numbers of ungulate sample assemblages drawn randomly from four simulated population assemblages reflecting the bulk, gourmet, unbiased, and unconstrained transport strategies (Table 1, Fig. 1). These sample assemblages will be used to evaluate the impact of sample size on evenness and the correlation between skeletal element abundance and economic utility.

Assemblage size was set at 1000 high-survival elements for each of the four population assemblages. High-survival skeletal element frequencies are listed in Table 1, as MNE and %MAU (Percent Minimal Animal Units) after Binford [11], and plotted against Metcalfe and Jones' [60] whole bone Standardized Food Utility Index (SFUI) in Fig. 1. We use Metcalfe and Jones' whole bone SFUI as a measure of economic utility since many hunter-gatherers transport skeletal elements as complete bones rather than as portions of bone [2,22,64,65]. For the unconstrained transport strategy, elements were distributed evenly to maximize evenness without regard to economic utility. Following Binford [9], our unbiased strategy

Table 1  
High-survival skeletal element abundances in Minimum Number of Elements (MNE) and Percent Minimal Animal Units (%MAU) for the four population assemblages of 1000 elements

Element	SFUI	Gourmet		Unbiased		Bulk		Unconstrained	
		MNE	%MAU	MNE	%MAU	MNE	%MAU	MNE	%MAU
Femur	100.0	792	100.0	352	100.0	178	100.0	133	99.3
Tibia	62.8	121	15.3	222	63.1	170	95.5	134	100.0
Metatarsal	37.0	34	4.3	131	37.2	151	84.8	133	99.3
Humerus	36.8	33	4.2	130	36.9	150	84.3	133	99.3
Radius	25.8	15	1.9	91	25.9	134	75.3	134	100.0
Mandible	11.5	3	0.4	40	11.4	100	56.2	133	99.3
Skull	9.1	1	0.3	16	9.1	45	50.6	67	100.0
Metacarpal	5.2	1	0.1	18	5.1	72	40.4	133	99.3

reflects the abundance of skeletal elements in direct proportion to their economic utility. Skeletal part frequencies for the gourmet and bulk population assemblages were fit to parabolic curves rotated 45° such that they both intersect SFUI = 0, %MAU = 0 and SFUI = 100, %MAU = 100, and have vertices at SFUI = 75, %MAU = 25, and SFUI = 25, %MAU = 75, respectively.

To evaluate the effects of sample size, we generated sample assemblages of 250, 150, 100, and 50 elements. For each of the four sample sizes, 5000 sample assemblages were drawn, without replacement, from each of the four population assemblages. The evenness (*E*) of the distribution of skeletal elements and Spearman’s rank-order correlation coefficient (*r<sub>s</sub>*) between the abundance of skeletal elements and the SFUI were calculated for each sample assemblage. Correlations between economic utility and skeletal element frequency are examined here because they are the most common means by which archaeologists quantitatively evaluate utility curves (e.g., [1,32,47,48,52,53,60]). Given the argument that skeletal element abundances and economic utility should be treated as ordinal-scale measures [30,47], we take a conservative approach and use Spearman’s rho in which correlation is dependent on rank-order values. In evaluating the impact of sample size on the correlations in the simulated assemblages, we determine the frequency of Type II errors, in which no correlation is found in a simulated assemblage despite the presence of a correlation in the population assemblage, and the frequency of Type I errors, in which significant correlations are found in a simulated assemblage when no such correlation exists in the population assemblage. Mean values and ranges of values for Spearman’s correlation coefficient and the Shannon evenness index were determined for sample sets of each transport strategy (gourmet, unbiased, bulk, and unconstrained) at each sample size (250, 150, 100, 50).

### 3. Results

#### 3.1. Sample-size effects on correlation

In Table 2 we present the correlations and evenness measures for the four population assemblages. With the exception of the unconstrained strategy, skeletal element abundances in all population assemblages are characterized by highly significant, perfect positive correlations with economic utility. For sample assemblages drawn from both the gourmet and unbiased populations, Type II errors for rank correlations between

Table 2  
Shannon evenness index and Spearman’s rho for the four population assemblages

Transport strategy	Evenness	Spearman’s rho	
	<i>E</i>	<i>r<sub>s</sub></i>	<i>p</i>
Gourmet	0.369	1.000	<0.001
Unbiased	0.842	1.000	<0.001
Bulk	0.980	1.000	<0.001
Unconstrained	1.000	−0.056	0.894

skeletal element abundance and economic utility are below 5% at all sample sizes (Table 3). For sampled bulk assemblages, however, Type II errors rapidly increase as sample size decreases from an error rate of 1.94% at MNE = 250–48.7% at MNE = 50. It is apparent that correlations do not reliably identify the relationship between element abundance and economic utility in assemblages characterized by a bulk transport strategy. For all three populations, a strong sample-size effect on correlation is evident with larger Type II error rates in smaller samples (Table 3, Fig. 2). The unconstrained population assemblage is not correlated with economic utility so here we consider those instances where Type I errors occur. Simulated assemblages drawn from the unconstrained population assemblage show Type I error rates between 10.9% and 11.7%. The rate of Type I errors shows no apparent relation to sample size (Table 3, Fig. 2).

A similar pattern is evident when mean values and the middle 95% range of observed correlations of the simulated data are considered. For samples drawn from the gourmet, unbiased, and bulk populations, mean rank correlations decrease and the ranges of the middle 95% of observed correlation coefficients increase as sample sizes decrease, indicating the lower likelihood of identifying the correct correlation for these populations at lower sample sizes (Table 4). In comparison, means and ranges of the middle 95% of correlations remain relatively stable but inaccurate across all sample sizes for the unconstrained population.

#### 3.2. Sample-size effects on evenness

The Shannon evenness index for each of the population assemblages is reported in Table 2. The bulk and unconstrained population assemblages have similar evenness values given the even distribution of specimens across classes of high-survival elements. The unbiased population assemblage is intermediate in evenness, although its value is closest to that of the bulk

Table 3  
Error rates at different sample sizes

Transport strategy	Sample assemblage size			
	250	150	100	50
<i>Gourmet</i>				
No error	4999	4977	4941	4828
Type II error	1	23	59	172
% Type II errors	0.02	0.46	1.18	3.44
<i>Unbiased</i>				
No error	5000	5000	4995	4882
Type II error	0	0	5	118
% Type II errors	0.00	0.00	0.10	2.36
<i>Bulk</i>				
No error	4903	4505	3859	2563
Type II error	97	495	1141	2437
% Type II errors	1.94	9.90	22.82	48.74
<i>Unconstrained</i>				
No error	4457	4421	4415	4439
Type I error	543	579	585	561
% Type I errors	10.86	11.58	11.70	11.22

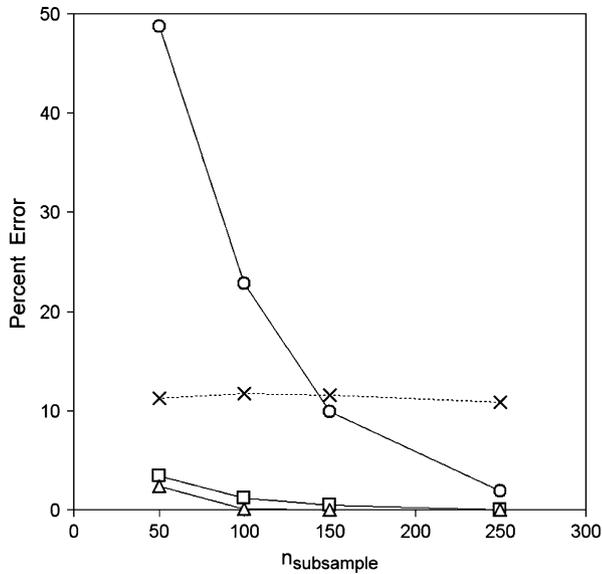


Fig. 2. Rates of Type I and Type II errors as a function of sample size. Symbols follow Fig. 1. Note that Type II errors (represented by open symbols) tend to decrease with increasing sample size, while Type I errors (represented by X's) do not show a relationship with sample size.

assemblage. With a dominance of high-utility femora, the gourmet population assemblage is the most uneven assemblage.

The effect of sample size on evenness is reported in Table 4 and shown graphically in Fig. 3. We present the mean and the upper and lower boundaries containing 95% of the simulated evenness values. At a sample size of 250, the Shannon evenness index discriminates well between the four assemblages and there is only minimal overlap in the middle 95% intervals

for the unconstrained and bulk populations. At 150 elements, the overlap in the evenness values of the unconstrained and bulk strategies is greater, but the gourmet and unbiased sample assemblages remain distinct from the other strategies. This pattern holds at a sample size of 100 elements. When sample size drops to 50 elements, the Shannon evenness index no longer effectively discriminates between the unbiased, bulk, and unconstrained strategies. The gourmet strategy, however, still remains distinct from the others when quantified using the evenness index.

### 3.3. Relationship between evenness and Spearman's rho

Upon inspection of the error rates reported in Table 3 and the evenness values reported in Table 4, it is apparent that there is a link between the frequency of Type II errors and the evenness of the population assemblage. Relatively even assemblages, particularly the bulk population assemblage, are more susceptible to Type II errors. In contrast, the less even gourmet and unbiased population assemblages, which have high frequencies of high-utility elements, show fewer Type II errors, although Type II error rates tend to increase with evenness within these two strategies (Fig. 4). The Type II error rates for all strategies and sample sizes are strongly correlated with evenness ( $r_s = 0.564$ ,  $p = 0.056$ ). This result is primarily driven by the high error rates present in the set of bulk sample assemblages. Thus, the accuracy of the correlation analysis is related to the evenness of the distribution of elements in the population assemblage. Such a pattern, however, is not apparent with the Type I error rates of the unconstrained sample assemblages (Table 3, Fig. 4).

Table 4  
Mean values and middle 95% range of sampled evenness values and correlations at MNE = 250, 150, 100, and 50

Sample size	Evenness ( $E$ )			Spearman's correlation ( $r_s$ )		
	Mean	2.5% Boundary	97.5% Boundary	Mean	2.5% Boundary	97.5% Boundary
<i>MNE = 250</i>						
Gourmet	0.423	0.353	0.502	0.953	0.829	1.000
Unbiased	0.837	0.795	0.875	0.971	0.905	1.000
Bulk	0.975	0.956	0.989	0.867	0.623	0.994
Unconstrained	0.995	0.987	0.999	0.003	-0.719	0.719
<i>MNE = 150</i>						
Gourmet	0.438	0.345	0.530	0.928	0.700	1.000
Unbiased	0.838	0.783	0.890	0.957	0.880	1.000
Bulk	0.970	0.941	0.989	0.796	0.452	0.976
Unconstrained	0.990	0.976	0.998	0.002	-0.737	0.735
<i>MNE = 100</i>						
Gourmet	0.451	0.340	0.569	0.904	0.667	1.000
Unbiased	0.842	0.776	0.905	0.941	0.826	1.000
Bulk	0.964	0.927	0.989	0.726	0.275	0.964
Unconstrained	0.983	0.961	0.996	0.007	-0.732	0.743
<i>MNE = 50</i>						
Gourmet	0.483	0.327	0.641	0.893	0.577	1.000
Unbiased	0.859	0.767	0.937	0.883	0.631	1.000
Bulk	0.950	0.899	0.987	0.576	-0.048	0.934
Unconstrained	0.967	0.925	0.992	0.008	-0.710	0.741

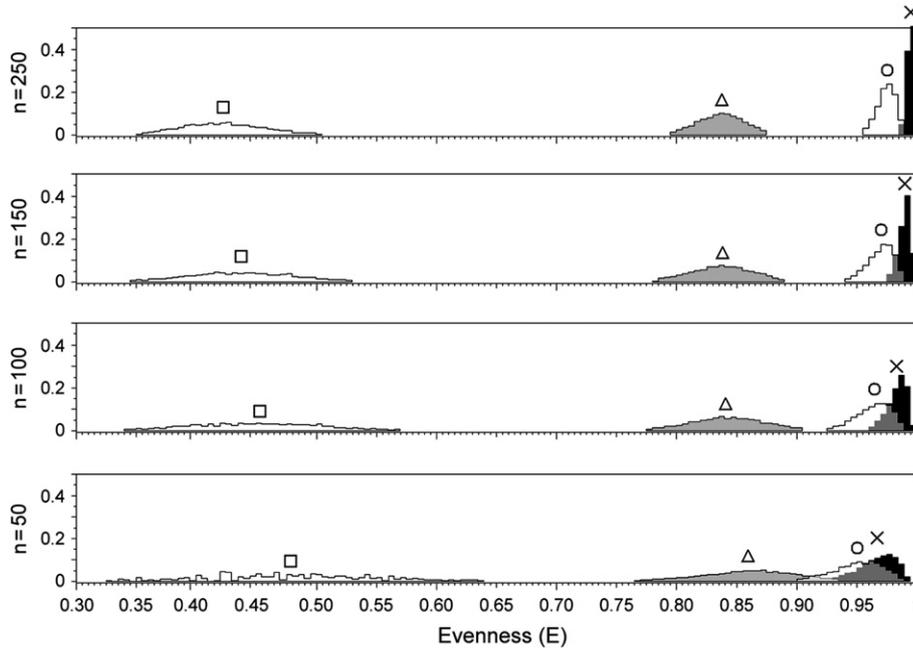


Fig. 3. Histograms showing middle 95% of sampled evenness values for sample sizes of 250, 150, 100, and 50 elements. Y-axis is relative frequency. Population type (gourmet, unbiased, bulk, or unconstrained) is denoted by the symbol placed over the distribution means. Symbols follow Fig. 1.

**4. Discussion**

Correlation analyses in conjunction with bivariate scatter-plots of skeletal element abundances relative to utility are used to determine whether or not differential frequencies of skeletal elements in archaeofaunal assemblages can be explained in terms of the nutritional value, or economic utility, of the respective elements. At sample sizes at or beyond 250 high-survival elements, this approach will suffice. However, based on our simulations, when sample sizes drop to 150 elements or below, the correlation approach is highly sensitive to how different butchery and transport strategies (e.g., gourmet, bulk) have affected the distribution of skeletal elements, and will not always provide an accurate evaluation of the relationship between body part frequency and economic utility. Our experimental simulations indicate that when evaluating the correlation between skeletal element abundance and economic utility, one must take into account both sample size and the impact of butchery and transport decisions on the evenness of the distribution of skeletal elements.

The near-significant positive correlation between the Type II error rates and evenness indicates that when interpreting the correlations between element abundance and economic utility, one must take into account the distribution of specimens across classes of elements. When there is an uneven distribution of skeletal elements dominated by high-utility bones, as in our unbiased and gourmet population assemblages, a significant correlation is more likely to be found at all sample sizes. This is due to the exaggerated leverage of the high-abundance, high-utility femora on the correlation. We see with our bulk-strategy population assemblage, however, that the even distribution of skeletal elements is associated with

an increased frequency of Type II errors. Our simulations suggest that when samples from population characteristic of a bulk-strategy drop to 100 or 50 elements, Type II errors severely hinder our ability to interpret bone frequencies with respect to economic utility. In cases where differential transport has not taken place, as in the unconstrained transport strategy, we noted a moderate likelihood (10.86–11.70%) of generating a correlation between bone frequency and utility, when there is

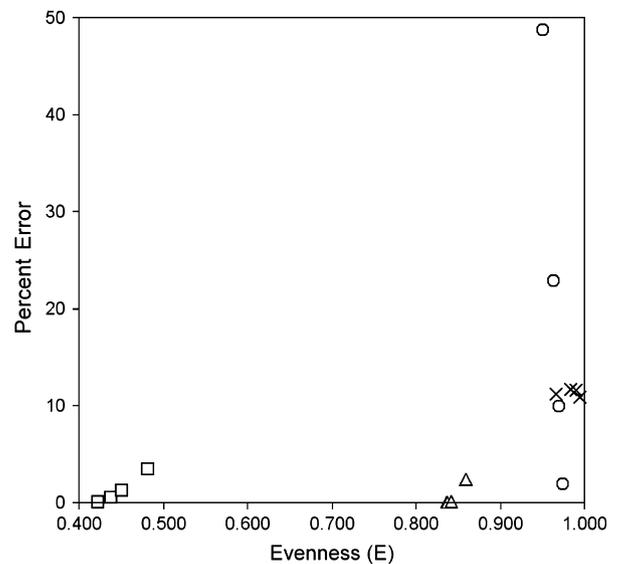


Fig. 4. Rates of Type I and Type II errors as a function of mean evenness value. See also Tables 3 and 4. Symbols follow Fig. 1. Note that Type II errors (represented by open symbols) tend to increase with evenness, while Type I errors (represented by X's) do not show a relationship with evenness.

none. In highly even assemblages, one must consider that an observed significant correlation may be due to a sampling effect. To avoid these pitfalls, one must determine whether skeletal element abundances are consistent with a transport strategy that tends to result in erroneous (Type I/II) correlations.

Correlation strength and significance are dependent on how well data points follow a linear relationship. By electing to use Spearman's rank correlation rather than Pearson's correlation, utility curve shape (e.g., curved versus linear) is less important than it would be otherwise because rank correlations will be equal to +1 for all monotonic increases regardless of shape, as shown by the Spearman correlation coefficient for the gourmet, unbiased, and bulk populations (Table 2, Fig. 1). However, utility curve shape plays an important role when smaller samples are drawn from these populations, because different curves influence the probability that rankings among the data points will change. For example, visual inspection of the gourmet and unbiased curves in Fig. 1 shows that it is unlikely that smaller samples would change %MAU values such that any element other than the femur, at an SFUI of 100, would also have the largest %MAU. However, sampling from the bulk population could easily produce assemblages in which other elements of considerably lower SFUI values had the highest %MAU values, decreasing the rank correlation and increasing the probability of a Type II error. These problems would be even more manifest if Pearson's correlation were used instead of rank correlation because any non-linear curve (such as those produced by gourmet or bulk transport strategies) would increase the variance from a linear relationship and decrease the likelihood of finding a significant positive relationship between the SFUI and %MAU. As for Type I errors, any sampling from the unconstrained population that by chance produces assemblages with slightly higher relative abundances at one end or the other of the SFUI distribution can produce a misleading significant correlation quite readily, regardless of sample size. The combination of the empirical evidence from the simulation and this consideration of correlation in the context of utility curves suggest that correlation alone should not be used in the investigation of transport strategies.

In addition to the complicating factors outlined above, other researchers have voiced problems concerning the statistical validity and interpretive power of the correlation approach as a means of examining bone frequencies relative to economic utility [5,70,72]. For example, Rogers [70] notes that non-parametric correlations assume that bone frequencies are independent of one another. This assumption is violated as unwanted skeletal elements may be transported simply because they are attached to elements that were desired [9, p. 64]. Alternatives to the correlation approach have been proposed and include examining mean utility [20,24], and ABCML (analysis of bone counts by maximum likelihood) [70], a statistical procedure designed to estimate the original number of elements, levels of attrition, and the proportionate contribution of different depositional agents. While calculations of mean utility allow for comparison of transport

strategies between sites and through time, results can be confounded by attritional processes. In response to this issue, ABCML has been proposed as a means of distinguishing selective transport from destruction [72]. However, effective use of ABCML relies on a broad range of models of bone deposition and attritional processes that are currently unavailable. Despite the alternatives, the use of correlations still remains the most common tool for relating bone frequencies to economic utility. Putting issues of statistical validity aside, this approach is limited in that it does not readily lend itself to a comparison of transport strategies across assemblages [5,70]. However, a quantitative means of distinguishing between various carcass transport strategies, in tandem with the correlation approach, can remedy this problem.

We propose that the Shannon evenness index can serve as a suitable method for distinguishing between different transport strategies. Variation in the evenness of the distribution of high-survival skeletal elements should reflect the degree to which foragers were selective in transporting carcass remains. This can be informative of transport strategies even when carcasses are transported in a way that is inconsistent with economic utility (e.g., [4]). Our simulation results demonstrate that at sufficient sample sizes, the Shannon evenness index effectively separates simulated assemblages drawn from population assemblages characterized by four hypothetical transport strategies. We are limited in the ability to distinguish between the bulk and unconstrained transport strategies, as they have very similar evenness values. At this point it is important to recognize that the hypothetical bulk and gourmet populations devised for our simulation study are arbitrary, in that there is no theoretical reason to suppose that these transport strategies should follow the particular curves that we selected, only that gourmet utility curves should arc below unbiased curves and bulk utility curves should arc above unbiased curves (Fig. 1). However, our unconstrained population is not arbitrary, in that unconstrained strategies require only that all elements are equally represented, regardless of economic utility. Similarly, our unbiased curve is not arbitrary in that element relative abundances are required to take %MAU values equal to their utility indices. That said, the particular values taken by relative abundances in an unbiased transport strategy depend on the particular index selected to represent economic utility.

With the caveat that our results only apply to studies using the SFUI insofar as unbiased utility curves are concerned, the following observations may be made. At larger sample sizes, sample assemblages from unbiased transport strategies are discernible from those of unconstrained strategies on the basis of evenness 95% of the time or more. At all sample sizes, bulk strategies have mean evenness values between those of unbiased and unconstrained strategies, and gourmet strategies have mean evenness values below those of unbiased strategies (Table 4, Fig. 3). Furthermore, although bulk and unconstrained strategies are the most likely to be mistaken for each other on the basis of similar evenness, they produce very different Spearman's correlation coefficients, with high positive values for bulk utility curves and a range of negative

and positive values centering around zero for unconstrained utility curves. Thus, the results of our simulation can be used as a comparison to identify the most likely transport strategy responsible for producing observed utility curves in zooarchaeological assemblages on the basis of evenness, rank correlation, and sample size.

**5. Application**

Below we illustrate how correlation analyses can be used in conjunction with the Shannon evenness index to enhance our ability to interpret patterns in the archaeological record. We have selected three previously reported zooarchaeological assemblages where the abundances of high-survival elements have been accurately estimated (i.e., high-survival shaft fragments are included in measures of long-bone abundance).

*5.1. Example 1: Porc-Epic Cave*

In this first archaeological assemblage, we consider the Middle Stone Age size 2 [19] archaeofauna recovered from Porc-Epic Cave in southeastern Ethiopia and reported by Assefa [1]. Based on taphonomic analyses and comparisons with actualistic data, Assefa concludes that the human occupants of Porc-Epic Cave were the primary accumulators of the faunal assemblage. Assefa also shows that the skeletal element abundances are significantly correlated with the SFUI. We now ask, what kind of transport strategy best describes the relationship between bone frequency and utility?

High-survival skeletal elements of size 2 mammals from Porc-Epic Cave are plotted against the SFUI in Fig. 5. We

list the sample size, Spearman’s rho, and the evenness in Table 5. Based on our simulations, the large sample size at Porc-Epic (MNE = 287) suggests a low potential for sample-size effects on the correlation and evenness index. A significant, positive correlation between economic utility and high-survival element abundance is apparent. The evenness index of 0.817 is consistent with the unbiased transport strategy as it falls within the simulated 95% confidence limits at 250 elements (Table 4). However, the strength of the correlation, although significantly positive, is slightly lower than would be expected for the unbiased strategy (Table 4). In all likelihood, this reflects variation in how the human occupants of Porc-Epic transported carcass remain relative to the Metcalfe and Jones’ [60] SFUI, and suggests a further caution against a reliance on correlation alone. Utility indices are designed to aid in the prediction of which elements are to be transported relative to transport constraints; deviations in observed patterns are to be expected. Regardless of this error, the skeletal element frequencies of size 2 mammals at Porc-Epic are most consistent with a transport strategy in which skeletal elements were transported to the cave in direct proportion to their economic utility.

*5.2. Example 2: Die Kelders Cave*

Here we explore Marean et al.’s [52] study of the Middle Stone Age fauna excavated from Die Kelders Cave on the southwest coast of South Africa. We focus on the size classes 3 and 4 [19] ungulates recovered from Layers 10 and 11. Marean and colleagues’ analysis indicates that the Die Kelders humans were the primary accumulators of these bones. The evenness index and correlation between skeletal element abundance and the SFUI for the Die Kelders fauna (Table 5) are fully consistent with our model of the bulk transport strategy at a sample size of 100 elements, to the exclusion of the other strategies (see evenness ranges in Table 4). Our simulations suggest that the moderate sample size of 79 elements at Die Kelders Cave is associated with increased risk for Type II errors under the bulk strategy. However, the correlation between high-survival element abundance and economic utility is positive and significant (Table 5, Fig. 5). This is in agreement with previously documented results [51,52]. The results of our analysis allow us to suggest that the butchery and transport decisions made by the inhabitants of Die Kelders Cave follow a bulk model in which the quantity of elements transported is maximized. High-utility femora, tibiae, humeri, and radii

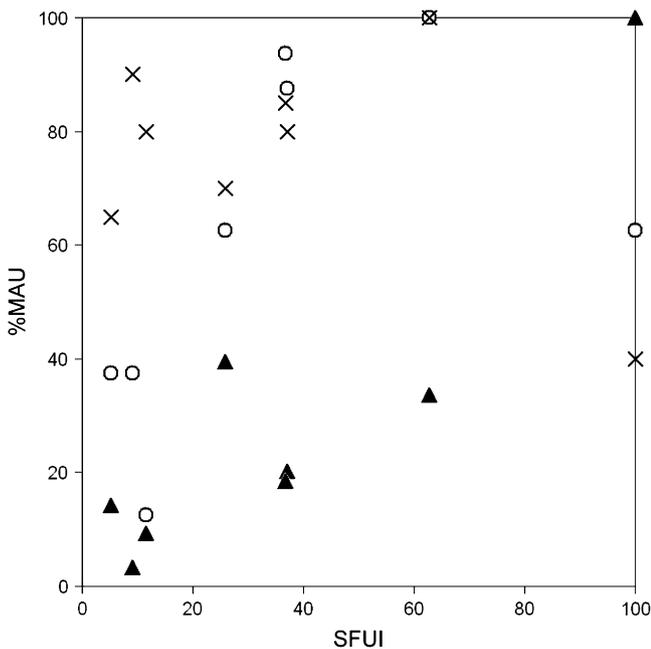


Fig. 5. The relationship between high-survival skeletal element abundances (%MAU) and the SFUI for three zooarchaeological assemblages. Symbols: filled triangles = Porc-Epic cave [1]; open circles = Die Kelders cave [52]; X's = FLKN levels 1–2 [21].

Table 5

Minimum Number of Elements (MNE), evenness, Spearman’s rank-order correlation, and transport strategy interpretation for Porc-Epic cave [1], Die Kelders cave [52], and FLKN levels 1–2 [21]

	MNE	Evenness	Correlation		Interpretation
		<i>E</i>	<i>r<sub>s</sub></i>	<i>p</i>	
Porc-Epic cave	284	0.817	0.786	0.021	Unbiased
Die Kelders cave	79	0.939	0.711	0.048	Bulk
FLKN levels 1–2	113	0.987	0.228	0.587	Unconstrained

were transported most often and to the exclusion of lower utility metapodials, crania, and mandibles.

### 5.3. Example 3: FLKN levels 1–2

In this final example we turn to the small mammal (size groups 1–2 [21]) remains from the Plio-Pleistocene assemblage from FLKN levels 1–2 in Olduvai Gorge, Tanzania. We use Bunn's [21] data because he includes long-bone shafts in his calculation of long-bone abundances. With an MNE of 113 high-survival elements, there is potential for an increased frequency of Type II errors, particularly if skeletal element frequencies are consistent with a bulk transport strategy (Table 3). The relationship between high-survival element abundances and the SFUI is slightly negative, although we see a positive but insignificant rank-order correlation (Table 5, Fig. 5). The evenness index of 0.987 falls within the range of both the bulk and unconstrained transport strategy at a sample size of 100 elements, although that value is only just within the range of values for the bulk strategy (0.927–0.989) (Table 3). The Spearman's correlation coefficient matches only the range of values generated by our simulated sampling of the unconstrained transport strategy. Taken in combination, these results suggest an assemblage most likely produced by an unconstrained transport strategy. We note in Fig. 5 a low abundance of high-utility femora; some have argued that the paucity of high-utility elements reflects foraging strategies in which hominins had secondary access to carcasses after high-utility elements had been removed or defleshed by primary carnivores [12,15,59]. However, given the low correlation and even distribution of high-survival elements at FLKN levels 1–2, the abundance of femora can be accounted for by random sampling error.

Bunn [21] emphasizes that vertebrae, ribs, and pelves are poorly represented at FLKN levels 1–2 and concludes that meaty appendicular elements were selectively transported to the site by the Plio-Pleistocene hominins. However, this pattern in which appendicular elements are present at higher frequencies than axial elements is consistent with documented patterns of carnivore destruction [14,15,18,29,37,57]. This highlights the need to consider only those high-survival elements that accurately reflect their original abundances when interpreting behavioral patterns. Our analysis of the high-survival small mammal remains recovered from FLKN levels 1–2 suggests that entire carcasses may have been originally deposited at the site. This is a feasible transport strategy for smaller sized mammals, particularly if predation risks imposed by large carnivores limited the amount of time to process carcasses at butchery or kill sites.

## 6. Conclusions

Since Binford's [9] derivation of the MGUI, economic utility indices have been widely implemented by zooarchaeologists as a means of interpreting skeletal element abundances in terms of carcass transport strategies. Well-founded inferences about how skeletal element abundances reflect human

behavioral patterns require recognition of (1) the taphonomic processes that differentially alter skeletal part frequencies and (2) the impact of random sampling effects on observed patterns. The purpose of this paper was to explore sampling patterns in light of our current understanding of how destructive processes impact bone assemblages.

A broad range of actualistic studies and taphonomic analyses has shown that only a subset of elements in the vertebrate body will survive destructive processes and accurately reflect their original abundances; Marean and colleagues refer to these elements as high-survival elements [27,52–54]. In light of this distinction, we focused our analysis on the abundances of high-survival elements. The results of our simulated assemblages lead us to several conclusions. First, our data indicate that correlation analyses, the most common statistical means by which archaeologists evaluate utility curves, are highly sensitive to the interaction between sample size and the evenness of the distribution of skeletal elements. Transport strategies resulting in relatively even distributions of skeletal elements, such as the bulk strategy, are more likely to provide erroneous non-significant correlations. Second, we have shown that the Shannon evenness index can be successfully applied as a quantitative means of distinguishing between assemblages reflecting distinctive transport strategies. Such an approach allows one to discern subtle variations in skeletal element abundances that cannot be distinguished with qualitative observations. Finally, given the demonstrated link between evenness, sample size, and the results of correlation analyses, we suggest that both evenness and sample size should be considered when interpreting correlations between relative abundance and economic utility. Non-significant correlations may reflect sample-size artifacts associated with even distributions of skeletal elements.

Our ability to interpret skeletal element abundances is only as sound as our ability to factor out sampling errors from actual patterns reflecting past behaviors. Improved understanding of the effects of sampling bias on zooarchaeological measures will further enhance future interpretations of past human activities.

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