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TECHNICAL NOTE

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An Evaluation of Determination of Handedness Using Standard Osteological Measurements*

ABSTRACT: Numerous studies have assessed side dominance assuming arm bones on the side of handedness will be larger, but concerns over sample size or replicability of measurements usually emerged. Attempting to improve upon these limitations, this investigation analyzes patterns of side difference for standard length and transverse dimensions of the scapula, clavicle, humerus, ulna, and radius for 137 individuals of known handedness. The results showed that with few exceptions, the right side of the skeleton was consistently larger in most individuals regardless of side dominance. Combinations of other measurements previously suggested to be indicative of handedness as well as the use of discriminant analysis also failed to provide reliable estimators. These findings are likely related to the fact that activities of modern individuals are generally not sufficiently unilateral in their stresses to cause asymmetrical development in the arm bones. Therefore, it is recommended that other means be developed to assess side dominance.

KEYWORDS: forensic science, forensic anthropology, handedness, osteometrics

Estimation of handedness, also called side dominance or hand dominance, has a relatively inconclusive history in forensic anthropology. While a variety of studies have been conducted in attempts to isolate skeletal markers of this individualizing trait (1), none thus far have proven to be reliable and/or standardized for use in forensic contexts. Despite this, the potential benefits that come with determining handedness have pushed researchers to continue exploring new avenues in evaluating effectiveness of potential markers, especially in light of the Daubert standards for court testimony (2).

Several traditional assessments of handedness have involved observation of anthroposcopic traits. Probably the most well regarded of these traits is the degree of beveling on the posterior edge of the glenoid fossa of the scapula as first described by Stewart (3–5). Schulter-Ellis (4) also noted that the development of the extensor facet near the glenoid fossa showed promise in evaluating side dominance. While these markers may indeed be quite useful, they have a serious drawback in that they are somewhat arbitrary in their evaluation, requiring an observer to have experience with a large variety of expressions in order to conduct an accurate assessment. In contrast, handedness estimators involving measurements are often perceived to be more accurate and easier to replicate. Furthermore, asymmetry in bone development related to handedness is a reasonable assumption based on Wolff's Law, which states that skeletal morphology is shaped by the stresses placed upon it (6). In other words, the habitual actions associated with side dominance would theoretically result in larger sized bones in one arm compared to the other. Several past populations have indeed shown notable asymmetry of the arm bones (e.g., 7,8) with unilateral physical activities such as use of the spear-thrower or archer's bow usually suggested as causes.

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Although evaluation of bone asymmetry seems quite applicable in the assessment of handedness, levels of success seen in various studies have been less than encouraging. Usually, problems with the sample or method appear evident. In one of the few investigations involving individuals of known handedness, Schulter-Ellis (4) identified two measurements as potential indicators, namely epicondylar breadth and the combined length of the humerus, radius, and ulna. Unfortunately, the number of individuals analyzed was only 10. Inglemark (9) observed that the combined length of the radius and humerus was longer in the side of handedness, but his sample consisted entirely of juveniles. Other studies have looked to bony markers that were reflective of muscle development. For instance, Kennedy (10) suggested that evaluation of the supinator crest in the ulna might reflect handedness, although he did not specifically test this premise. Blackburn and Knüsel (11) recently argued that asymmetry in epicondylar breadth was significantly associated with handedness, but their study found a correlation in only 68% of individuals in the modern sample. In an investigation of the distal radius, Holla et al. (12) identified two measurements on the distal radius that provided statistically significant differences in a sample of 125 modern individuals. This finding, however, is overshadowed by the use of random, unmatched sets of radii and measurements points that require extreme precision, yet are somewhat subjective. Furthermore, many of these muscle attachments are often projecting, which would increase the likelihood that they could be compromised through taphonomic processes. In an attempt to overcome some of the shortcomings of past studies, this project evaluates side domination by using a relatively large modern sample size of individuals of known handedness as well as standardized measurements that are commonly taken in forensic analysis of skeletons.

Materials and Methods

The sample is comprised of 137 individuals from the Forensic Anthropology Data Bank and the William Bass Donated Skeletal Collection at the University of Tennessee–Knoxville for whom

TABLE 1—*Distribution of sample by handedness, sex, race, and mean age-at-death.*

	Left Dominant	Right Dominant
N	22	115
% male/female	64/36	61/39
% White/non-White*	95/5	93/7
Mean age at death	55.4	57.7

*Includes Black, American-Indian, Hispanic, and Asian racial designations.

handedness was recorded. The former database contains the results of standardized measurements from recent forensic cases submitted by a variety of researchers. The latter database consists of skeletal data from individuals who have donated their bodies to the research facility. Measurements were recorded to the nearest 1.0 mm, and are described in Moore-Jansen et al. (13). The handedness assignment for the individual cases was taken as reported in the files; 16% of the final sample was left-side dominant, which is fairly close to the incidence in most populations (14). When the left- and right-handed groups were compared, the two subsamples showed no statistically significant differences in their distributions by sex ($X^2 = 2.86$, df = 1, $p = 0.24$), ancestry (Fischer's Exact Test = 0.684), and age (Mann-Whitney $U = 802$, $p = 0.54$) (Table 1). All statistical analyses were carried out using SPSS-PC (Version 13.0).

Listed in Table 2, the measurements analyzed included all those described for the clavicle, scapula, humerus, radius, and ulna in Buikstra and Ubelaker (15) with the addition of the diameter of the radial head. If an individual did not have both right and left values for a particular dimension, then the case was not included in the evaluation of that dimension. Using these data, the measure of asymmetry was calculated as:

$$\frac{(R - L)1000}{(R + L)/2}$$

where R is the right-side value for a particular measurement and L is the left-side value (8). This calculation reflects both the direction and the magnitude of any asymmetry present.

TABLE 2—*Measurements taken on shoulder girdle and arm long bones.**

Clavicle
Maximum length
Anterior–posterior diameter
Superior–inferior diameter
Scapula
Height
Breadth
Humerus
Maximum length
Maximum head breadth
Maximum breadth at midshaft
Minimum breadth at midshaft
Epicondylar breadth
Radius
Maximum length
Maximum head diameter
Anterior–posterior diameter
Medial–lateral diameter
Ulna
Maximum length
Physiological length
Anterior–posterior diameter
Medial–lateral diameter
Minimum circumference

*Following Moore-Jansen et al. (1994).

We also tested handedness determination using two types of multivariate analysis under the assumption that the combined interaction of several measurements and/or their differences between side counterparts might be a more powerful indicator of handedness than that of a single measurement. The first type involved testing sets of variables that had previously been suggested to be reliable in previous studies. One of these was the combined lengths of the humerus, radius, and ulna as described by Schulter-Ellis (4). The second measure, noted by Inglemark (9), used the combined length of only the radius and humerus. The third measure was development of the deltoid tuberosity (16), which was improvised by subtracting humeral midshaft minimum from midshaft maximum. The second type of multivariate testing incorporated discriminant function analysis using all of the measurements as well as various subgroups of measurements (e.g., only those from the arm) since at times, certain dimensions may not be available for an individual under consideration because of bone elements being missing or damaged. The independent variables were entered together with the prior possibilities based upon group sizes. Following Safont et al. (17), those functions for which the Eigenvalue exceeded 1.5 and the value of Wilk's lambda was below .400 were considered to be most statistically valid.

Results and Discussion

The descriptive statistics for left- and right-handers separately are presented in Table 3*a*. As may be seen, the pattern of asymmetry between both groups was remarkably similar both in terms of direction and magnitude, as also revealed in the asymmetry values given in Figs. 1 and 2. Left- and right-handers had larger values in both length and transverse dimensions on the right side for nearly every measurement, a finding seen in other studies of past and present populations as well (5,18–20). The notable exceptions, clavicle length and scapular breadth, showed greater bone development on the *opposite* side of handedness; this pattern has also been previously observed. Mays et al. (21) have argued that this may be related to lateral compression stresses placed on the skeletal element.

Among the individual measurements evaluated, only clavicular length seemed to show some promise as a dominant side indicator in that 90% of left-handers had the right side larger. However, nearly one-quarter of right-handers had the right side larger as well, which represents an overwhelming majority in the general

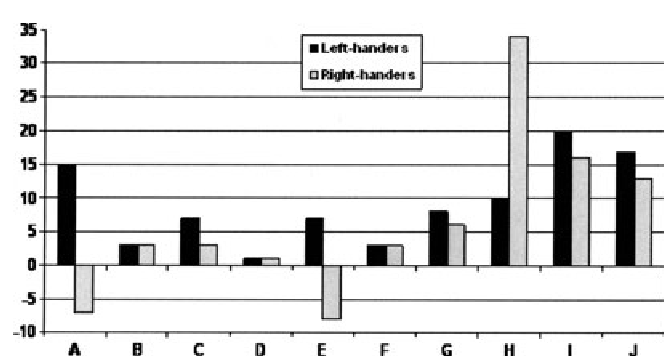

FIG. 1—*Degree of asymmetry for clavicular, scapular, and humeral measurements. (A) Clavicle: maximum length. (B) Clavicle: anterior–posterior diameter. (C) Clavicle: superior–inferior diameter. (D) Scapula: height. (E) Scapula: breadth. (F) Humerus: maximum length. (G) Humerus: diameter of head. (H) Humerus: maximum diameter at midshaft. (I) Humerus: minimum diameter at midshaft. (J) Humerus: epicondylar breadth.*

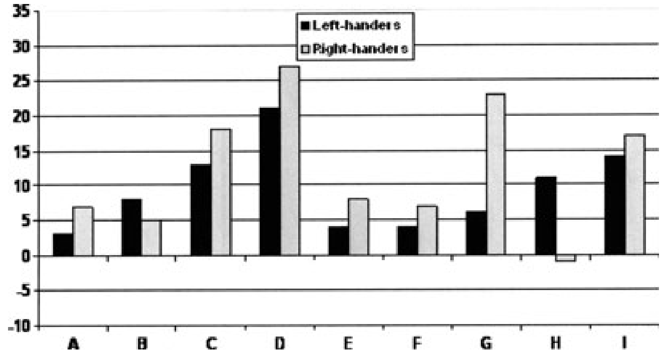

FIG. 2—*Degree of asymmetry for radial and ulnar measurements. (A) Radius: maximum length. (B) Radius: maximum head diameter. (C) Radius: anterior–posterior diameter at midshaft. (D) Radius: medial–lateral diameter at midshaft. (E) Ulna: maximum length. (F) Ulna: physiological length. (G) Ulna: anterior–posterior diameter. (H) Ulna: medial–lateral diameter. (I) Ulna: minimum circumference.*

population. Thus, there would seem to be too large of a margin of error for clavicular length to be reliably used. Two other measurements, epicondylar breadth and radius midshaft width, both of which have been suggested to be useful handedness indicators in previous studies (4,11,22), also failed to distinguish side of dominance (Table 3*a*). In fact, left-handers were more likely to have larger dimensions on the right side for both measurements than were right-handers. We also analyzed the data to see whether there might be some sort of threshold in the distribution of values for a measurement difference that, when exceeded, would correlate with handedness. One cause for this threshold might be that smaller asymmetry values might simply be the result of "noise," such as from interobserver differences in measurement technique whereas larger values would result from handedness. Although several options for the threshold were considered, including differences between sides exceeding 2% of the dimension or an arbitrarily chosen value of 3 mm, again virtually no consistent pattern correlated with side dominance was apparent.

Similarly, evaluation of certain multivariate indicators also previously suggested by other researchers did not provide encouraging results, as may be seen in Table 3*b*. Only one of the indicators, deltoid muscle development, showed promise in that asymmetry of measurement values were in opposite directions for each side of dominance and the magnitude was quite large. However, when the raw data were examined, only 47% of right-handers and 35% left-handers had larger humeral midshaft dimensions on the predicted side; over one-third of individuals had the same value on both sides. Since preliminary analysis in the present study suggested

TABLE 3—*Mean differences for (a) all measurements by side of handedness, (b) selected multivariate measures by side of handedness.*

	Left-Handers						Right-Handers					
		L > *R*			*L* < *R*			*L* > *R*			*L* < *R*	
	N	*X**	%†	*L* = *R*‡	*X**	%†	*N*	*X**	%†	*L* = *R*‡	*X**	%†
(a)												
Clavicle												
Maximum length	14	5.00	0.071	0.071	3.33	0.858	100	3.85	0.540	0.103	2.45	0.357
Anterior–posterior diameter	16	1.00	0.125	0.688	0.67	0.187	100	1.22	0.220	0.460	1.34	0.320
Superior–inferior diameter	16	1.00	0.063	0.625	1.00	0.312	100	1.00	0.130	0.640	1.22	0.230
Scapula												
Height	17	3.67	0.353	0.118	2.78	0.529	91	2.76	0.418	0.132	2.59	0.450
Breadth	17	1.00	0.235	0.235	1.89	0.530	95	2.37	0.516	0.274	1.75	0.210
Humerus												
Maximum length	17	2.00	0.235	0.235	2.78	0.530	99	2.83	0.303	0.152	3.21	0.545
Maximum midshaft diameter	17	1.00	0.118	0.588	1.20	0.294	104	1.00	0.067	0.337	1.47	0.595
Minimum midshaft diameter	15	1.00	0.067	0.600	1.40	0.333	95	1.19	0.170	0.436	1.22	0.390
Maximum head diameter	15	1.00	0.067	0.600	1.40	0.333	94	1.19	0.170	0.606	1.22	0.324
Epicondylar breadth	19	1.00	0.105	0.211	1.69	0.684	106	2.06	0.142	0.170	1.63	0.688
Radius												
Maximum length	15	1.75	0.533	0.000	3.86	0.467	98	1.79	0.143	0.143	2.64	0.714
Maximum head diameter	14	1.00	0.286	0.429	1.50	0.285	77	1.33	0.156	0.545	1.09	0.298
Anterior–posterior diameter	16	2.00	0.063	0.685	1.00	0.250	102	1.00	0.069	0.676	1.24	0.255
Medial–lateral diameter	16	1.00	0.125	0.563	1.20	0.312	101	1.11	0.178	0.366	1.20	0.456
Ulna												
Maximum length	14	2.40	0.357	0.143	5.29	0.500	96	2.78	0.094	0.115	3.13	0.791
Physiological length	14	3.50	0.143	0.286	2.50	0.571	97	1.73	0.155	0.175	3.12	0.670
Anterior–posterior diameter	16	1.00	0.125	0.688	1.00	0.187	105	1.06	0.171	0.486	1.36	0.343
Medial–lateral diameter	16	1.00	0.125	0.688	1.00	0.187	105	1.06	0.171	0.486	1.36	0.343
Minimum circumference	15	1.20	0.333	0.267	2.17	0.400	98	1.44	0.163	0.347	1.71	0.490
(b)												
Combined maximum length of humerus/radius/ulna	13	4.75	0.308	0.000	7.78	0.692	88	3.79	0.216	0.045	7.34	0.739
Combined maximum length of humerus/radius	17	3.33	0.231	0.154	5.63	0.615	104	2.91	0.250	0.080	5.38	0.667
Difference of humerus midshaft maximum and minimum	13	1.67	0.353	0.333	1.25	0.314	88	1.21	0.231	0.298	1.69	0.471
Combined ([difference of humerus midshaft maximum and minimum]§ −1), scapula breadth and clavicle maximum length	12	4.00	0.083	0.250	5.63	0.667	74	4.87	0.608	0.135	2.74	0.257

*Mean of the side excess.
†Percentage of the subsample in which the designated side was larger for the particular dimension.
‡Percentage of the subsample in which both sides had the same value for the dimension.
§Percentage of the subsample in which both sides had the same value for the dimension.

TABLE 4—*Results of discriminant function analysis.*

Variables entered	*N*%	Correctly Classified as Left*	Correctly Classified as Right*	Eigen Value	Statistically Significant	Wilk's Lambda
All measurements	54	75.0	78.3	5.47	0.005	0.154
All scapula–clavicle measurements	85	8.3	94.5	0.27	0.047	0.789
All arm measurements	68	0.0	84.7	0.61	0.643	0.622
All arm length variables	93	0.0	97.5	0.07	0.463	0.938
All arm transverse measurements	78	0.0	86.2	0.25	0.683	0.803

*Side of handedness.

clavicle lengths, scapula breadths, and humeral midshaft differences to show the greatest differentiation by handedness, we also tested whether their efficacy could even be increased further if they were combined into a single variable. This was accomplished by adding the differences between clavicle lengths and scapula breadths to the opposite value of the differences between humeral midshaft dimensions. The latter step was necessary since the first two measurements had the larger dimension on the opposite side of handedness whereas the humeral differences were on the *same* side as handedness. When this indicator was calculated, only one left-hander (8.3%) had a negative value, but nearly one-quarter of right-handers did as well. Once again, the level of error seemed too high for reliable use.

The results of discriminant function analysis fared little better; they are given in Table 4. The function produced using all the measurements taken had the best success in classifying the cross-validated cases, and the Eigen- and Wilk's lambda values were in the desired ranges. Nevertheless, the resulting function is not likely to be of much practical use for several reasons. First, an accuracy rate of 75% in determining handedness would not be considered acceptable to most forensic anthropologists. Second, the requirement of including virtually all the measurements is prohibitive in many cases, as evidenced by the fact that the total sample size was cut in half because of missing measurement values. Third, calculation of the function for individual cases using all of the variables involved would be very tedious and present a large room for error. As combinations of fewer numbers of measurements were included in the analysis, the number of usable cases did increase, but the accuracy rate in classification generally decreased. Therefore, none of the discriminant functions generated can be recommended for determination of handedness either.

Certain aspects of the research design may have potentially contributed to the lack of differences by hand, but this seems unlikely. First, the measurements used in this study were collected by a large number of observers, making it possible for interobserver error to be having an effect. However, it seems unlikely that any error would have consistently been in a single direction. Furthermore, if a set of measurements is to be a successful indicator of handedness, the dimensions should be sufficiently asymmetrical to overcome slight differences in measuring technique. A second critique is that there was no consistent criterion, such as hand used for writing or throwing a ball, for *a priori* determination of side dominance. It is presumed, however, that the ones used to label the individuals in this study were the same ones that would be typically used by forensic scientists as they attempted to identify a victim. A final shortcoming of the research design, and arguably the most serious, is that the sample size of left-handers is less than ideal, although it is larger than that of any other known study of identified side dominance. Unfortunately, handedness is not typically recorded for victims in forensic cases nor, it appears, for those who donate their remains. This limitation is further compounded given the small minority of the population that is left-handed.

Several possible explanations do exist for the lack of reflectance of side dominance using bone size in the present investigation. Although our findings of greater right side development are somewhat in alignment with the argument of Annett (23) that there was a "genomic shift" in human evolution to favor right handedness, and perhaps bone size, it seems more likely that biomechanical factors in the environment are responsible for the findings in this study, a conclusion drawn by a number of other researchers as well (e.g., [5,24]; cf. [25] for growth and hormonal factors). For example, Steele and Mays (8) found greater bias favoring the right in adults compared to juveniles in an Anglo-Saxon population. Even more, Auerbach and Ruff (20) have argued that past groups will have more asymmetry compared to recent groups in that the former is more likely to have had routine activities that were strongly unilateral in the stresses they placed on muscle and bone. In addition, modern populations are much less physically active, which may mean any morphological changes to bone that result are very subtle. Finally, many have noted that handedness is probably viewed best as a continuous rather than a discrete value, especially for left-handers as they cope in a right-handed world. Given all of these considerations, it seems unlikely that the standard measurements used in forensic evaluation of the skeleton will be able to indicate handedness with any desirable degree of reliability in most cases.

Conclusions

- Analysis of bone measurements standard to forensic evaluations showed that the right side consistently is larger in most bones, regardless of handedness.
- Environmental factors most likely are responsible for shaping the size of the arm bones; these results suggest that the activities of modern populations are not sufficiently correlated with hand dominance to cause consistent differences in skeletal size by side.
- Based on the results of this study, determination of handedness using standard arm bone dimensions individually or in combination is not recommended.

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