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PAPER

ANTHROPOLOGY

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Can Handedness be Determined from Skeletal Remains? A Chronological Review of the Literature

ABSTRACT: Research indicates that considerable bilateral asymmetry exists in the skeletons of primates, including humans. The published literature suggests that although this asymmetry may be influenced by handedness, it reflects other factors as well. Although exact statistics of handedness in the modern population are not available because definitions of handedness vary greatly, it is known that we live in a predominantly right-handed world. This knowledge makes the determination of handedness in forensic cases not as paramount in importance as other determinations. Review of the published scientific evidence clearly reveals that observations and measurements of the human skeleton cannot determine handedness with the degree of confidence needed for forensic applications.

KEYWORDS: forensic science, forensic anthropology, handedness, human skeletal remains, skeletal morphology

In 1979, T.D. Stewart (1) described his testimony in a court case regarding identification of a decedent. He noted that the arm long bones were longer on the left than on the right. At the time, this suggested to Stewart that the individual "might have predisposed to left-handedness" (1, p. 240). Other testimony in the trial indeed indicated that the decedent was known to have been left handed during life. Although Stewart's (1) cautionary use of "might have" reflected the tenuous nature of this interpretation, the confirmation of actual hand dominance in the identified individual buoyed confidence. He continued in his discussion to mention a number of skeletal attributes in the human skeleton that in addition to size showed promise as handedness indicators. These included general asymmetry of the glenoid cavity of the scapula, beveling of the dorsal margin of the glenoid cavity, torsion of the proximal end of the humerus, and arthritic changes. Although these factors intuitively could be linked to handedness, Stewart (1) noted that no research yet had been reported on the skeletal remains of individuals of known handedness. Until such research was conducted, interpretations of handedness would remain tenuous.

In 2011, 32 years after Stewart's above-cited comments, a growing scientific literature has amassed regarding the skeletal evidence of handedness. This literature is highly varied, both in approaches to the central issue and in the use of the available scientific information. In forensic contexts, the central issue is "can the handedness of an individual be predicted reliably from recovered skeletal remains?" The following discussion and literature review address the scientific evidence relating to this issue.

With the exception of relatively recent studies of skeletal structures of individuals of known handedness, likely the most important publication on this topic emerged at the very beginning of the scientific record, a report in 1937 by Adolph Schultz. Working at Johns Hopkins University in Baltimore and a later professor of medical student T. Dale Stewart (2), Schultz had very broad research interests in comparative primate anatomy. In his 1937 Human Biology article, Schultz (3) reported detailed measurements and indices taken and calculated on large numbers of modern humans and other primates of both sexes. Focusing on bilateral asymmetry, he reported that the human pattern involved larger right arm bones but larger left leg bones. He observed this pattern in adult remains, as well as in his study of a fetal sample (4). Asymmetry was found in all primate skeletons, but with great variation in nonhuman primates in the upper extremity (3). In the lower extremity, the pattern in nonhuman primates was more similar to that of humans. Schultz' (3,4) comparative skeletal analysis suggested to him that the asymmetry he observed could not be explained by handedness. He noted that he had detected these differences in fetal remains that obviously had not yet employed side dominance (4). He also noted that the condition of left handedness was much less common than size asymmetry favoring left arm bones (3).

Although Stewart (1) had been correct that no studies of skeletal remains of individuals of known handedness had been published prior to 1979, a strong indication of the likely outcome of such research was provided by Van Dusen (5) in 1939. He reported anthropometric measurements taken on male and female children of known handedness. His measurements of the children suggested that age was a factor in the development of asymmetry in long bone size in the upper extremities. His very young sample of children ages 1–4 years presented a tendency toward longer "left arms, forearms, forearms and hands, and wider left palms…" (5, p. 283). In contrast, children between the ages of 5 and 8 years presented the opposite pattern. He not only suggested that this aging shift of growth pattern might reflect patterns of use, but also cited factors of heredity and the dynamics of the growth process. Van Dusen (5) also reported that in his sample of right-handed adults, left

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measurements were greater than those of the right in 35% of arms, 24% of forearms, 13% of radii-ulnae, and 18% of palm breadths.

Analyses of Skeletal Collections without Information on Known Handedness

A variety of published studies provide additional detail and perspective to the foundational research reported by Schultz (3) in 1937. Grube (6) reported bilateral asymmetry in the length and thickness of the humerus and femur and asymmetries on the occipital bone, but did not find a correlation between the two. Working in India, Singh (7) reported bilateral asymmetry in the torsion seen in human metacarpals in two women and 13 men. Dogra and Singh (8) reported weights of human bones from the lower extremity, finding variation similar to that found in the upper limbs. Longia et al. (9) studied 126 right and 74 left clavicles (sex unknown) from modern human populations, documenting that those on the right tended to be longer and broader.

In 1986, Glassman and Bass (10) studied bilateral asymmetry of long arm bones and the jugular foramen at the base of the cranium. They examined the skeletal remains of 125 adult men and 57 adult women for long bone and jugular foramen asymmetry. Frequency of asymmetry with jugular foramen size larger on the left side was low for both sexes. Symmetry in the size of the jugular foramen was found in 34% of the men and 32% of the women. Approximately 50% of the women exhibited right-side dominance compared to 29% of men. In addition, Glassman and Bass (10) found that slightly fewer than 20% of the men and women showed long bone dominance of the left side, *c.* 15% of the observations for each long bone indicated symmetry, and the remaining *c.* 65% exhibited right-side dominance. They concluded that neither bilateral asymmetry of the arm long bones nor that of the jugular foramen is related to handedness to "a degree appropriate for forensic science identification from skeletal remains" (10, p. 595).

Macho (11) found considerable femoral asymmetry in a southern African human sample (161 men and 122 women), noting that most size attributes were greater on the left side. Macho suggested that most people use their left leg for weight-bearing, regardless of their handedness status.

Kušec et al. (12) examined the asymmetry of measurements of the second, third, and fourth metacarpals in 419 men and 549 women from the former Yugoslavia. Finding significant asymmetry, they suggested physical activity as a key formative factor.

Vettivel et al. (13,14) documented asymmetry in their study of 200 adult humeri from India and suggested (but did not prove) that handedness was a key factor. Lazenby (15) also suggested that handedness was a factor in producing side differences in the size of the human second metacarpal that affect sex estimation from that bone.

In 1996, Holla et al. (16) examined robustness and related features at the distal end of the radius in an Indian sample of 61 left and 64 right bones. They found that most of the features examined were more greatly expressed on the right side and discussed possible relationships with handedness. In contrast, Plochocki (17) found that three size-related variables of the sacrum were greater on the left side in both sexes.

In 2003, Synstelien and Hamilton (18) called attention to the possible correlation of handedness with laterality of the spinous processes in vertebrae of men and women. They noted that such an association had been suggested previously in the chiropractic and clinical literature.

Similar research has also been conducted relating to nonhuman primates. Dhall and Singh (19) documented side differences in muscle and bone weights of the Rhesus monkey. Helmkamp and Falk (20) discussed how age- and sex-related factors may be involved in the production of asymmetry in forelimb bones of the Rhesus Macaque. Sarringhaus et al. (21) added to the growing scientific record by documenting bilateral asymmetry in limb bones of the chimpanzee.

Assessment in Human Samples Recovered from Archeological Contexts

Although Schultz (3) and others had noted the complex factors, including genetics, involved in producing asymmetry, anthropologists emphasized the biomechanical aspects in their studies of archeologically derived samples. Ortner (22) argued that "local stress" was a key factor in hypertrophic bone production at the distal joint surface of the humerus, with handedness and activity patterns differentiating skeletons of Eskimos from those of others.

Ruff and Jones (23) cited age and sex factors in explaining bilateral asymmetry in cortical bone of the humerus and tibia in samples from California. They also found less asymmetry in bone length measurements than in the breadth or cross-sectional measurements of the same bones. This publication paved the way for many others focusing on attributes within bone structure rather than just on measurement of external bone dimensions.

Bermúdez de Castro et al. (24) examined handedness issues in fossil hominids from Atapuerca/Ibeas, Spain. They argued that tool use led to scratching of the anterior teeth and that the pattern of the buccal striations presented evidence of handedness in the middle and early upper Pleistocene. The striations were oriented in a slanted pattern, predominantly "from the mesial cervical corner to the distal occlusal corner" of the right upper and lower incisors and "from the distal cervical corner to the mesial occlusal corner" of the left upper and lower incisors (24, p. 405). Their work also discussed various aspects of cranial asymmetry that might be related to handedness.

Albert and Greene (25) cited environmental stress as the likely cause of asymmetry in epiphyseal fusion. Similar environmental stress and biomechanical factors were used to explain asymmetry found in samples from ancient contexts from the Georgia coast of the United States (26,27), the Neolithic Jomon period of Japan (28), the medieval British sites of Norwich and Henry VIII's flagship, the Mary Rose (29), the medieval churchyard at Wharram Percy from Yorkshire, England (30), the 19th century Belleville, Ontario (31), the Upper Palaeolithic of Italy (32), Christ Church, Spitalfields, 18th/19th century London (33), the 18th century Quebec prisoners of war (34), 780 adults dating to the Holocene (35), Late Eneolithic and early Bronze Age Central Europe (36), medieval Nubia (37), both medieval and more recent populations of Central Europe (38), and hunter-gatherer populations from California and British Columbia (39). These studies, as well as research by May (40), indicate that considerable population differences exist in the expression of bilateral skeletal asymmetry.

General discussions and analysis of the complex genetic, biomechanical, adaptation, stress, age, sex, and evolutionary factors related to handedness and asymmetry are provided by Kennedy (41), Palmer (42), Anetzberger and Putz (43), Wilczak (44), Mays et al. (45), Steele (46,47), Lazenby (48), Ruff et al. (49), Cashmore et al. (50), Lazenby et al. (51), Uomini (52), and Cashmore (53). Steele (46,47) also discusses the complex factors involved in the assessment of handedness in living individuals. He notes that people declared to be right handed may have developed that preference in use rather than relying on their natural left-handed inclination. Documentation of handedness varies also from simple declaration to more comprehensive tests of hand and arm strength. Such variation calls for clear definition of handedness and related terminology (54).

Research Utilizing Living Humans

An important perspective on the central issue of the skeletal evidence for handedness originates from studies of patients and other living individuals with known handedness. Such studies can reveal information on skeletal features through radiography, anthropometric studies, and related procedures.

An early example of such research is Ingelmark's (55) 1946 study of 150 living individuals, 75 males and 75 females, 10 of each of age 6–20 years. Ingelmark used radiographic and anthropometric measurement in addition to the individual's demonstrated hand dominance to examine a correlation between asymmetry and handedness. He reported that for both right- and left-handed individuals in all age groups, the arm on the dominant side was longer when asymmetries occurred. In addition, Ingelmark (55) found that the asymmetry of the lower extremities inverted around the time of puberty so that in the older range of individuals, the left leg was longer for right-handed individuals and the right leg was longer for left-handed individuals.

Singh's (56) 1970 study of 94 students (66 men and 28 women) of known handedness found no correlation between handedness and dominance in the lower limbs. Acheson et al.'s (57) 1970 New Haven survey of joint disease examined the extent of osteoarthrosis in the hands of 1127 individuals of both sexes with evidence of both disease and known handedness. Although individual data are not presented, the summary statistics and discussion suggest that asymmetrical expressions of osteoarthrosis cannot reliably predict handedness. They note that minor repeated trauma likely contributes to the disease, but that in general it represents multiple complex factors.

In their study of 227 chronic renal patients, Garn et al. (58) examined bone size and mass in metacarpal midshafts. They found that the measurements were greater in the right side in a majority of patients, independent of handedness status (right handed, left handed, or ambidextrous).

Meals (59) examined the laterality of fractures and dislocations in consideration of known handedness. Working with a sample of 2716 reported skeletal injuries in individuals from Los Angeles, California, 89% were found in right-handed people and only 11% in left-handed individuals. Fractures involving right-handed people had a tendency to occur proximal to the wrist on the left side (although dislocations at the shoulder were more common on the right) and distal to the wrist on the right side. For the left-handed patients, all upper limb fractures were more common on the dominant side.

Plato et al. (60) studied bone measurements of the second metacarpals of 235 men in a Baltimore longitudinal study. Using grip strength to classify handedness, they examined width, length, total area, and cortical area of the second metacarpal. They found a tendency for right measurements to be greater than those on the left, regardless of hand preference. To them, the study suggested that hand dominance will influence but not determine the nature of bilateral asymmetry.

Also in 1980, Owsianik et al. (61) examined the extent of radiological articular involvement in rheumatoid arthritis patients of known handedness. They found such involvement to be significantly greater in the dominant hand. Individual data are not presented which would facilitate evaluation of articular alterations as indicators of handedness in forensic contexts.

In 1985, Schell et al. (62) examined directional asymmetry of body dimensions among 135 White adolescents from suburban Philadelphia. They studied upper arm circumference, biepicondylar breadth, triceps and subscapular skin folds, bicondylar breadth of the femur, and calf circumference. Their research revealed that these measurements were significantly larger on the right among right-handed individuals, but with no significant differences among left-handed individuals.

Reichel et al. (63) examined the radii of 251 living individuals of both sexes and of known handedness for side differences in width and mineral content. They determined that the radius of the dominant arm shows a significantly larger width and more bone mineral content than that of the nondominant arm. Testing this method on a skeletal sample of medieval and Neolithic individuals proved to be too difficult to interpret because of the small sample size.

Mody et al. (64) studied the records of 256 patients with rheumatoid arthritis. They found greater radiological changes in the dominant hand. In a later study of 93 male and female patients with rheumatoid arthritis, Boonsaner et al. (65) documented more swelling and tenderness on the dominant side. However, Hasselkus et al. (66) in 1981 found no significant association of rheumatoid arthritis hand joint changes and handedness in either sex.

Neumann (67) contributed the observed asymmetries in the upper extremities of 221 male subjects, ranging in age from 3 to 44 years, to the fact that we live in a predominantly right-handed environment. This type of environment allows right-handed individuals to use their dominant hand mainly, whereas left-handed individuals often use their nondominant hand for tasks. This practice produces greater asymmetry in right-handed individuals.

Focusing on children (both sexes) between the ages of 8 and 16 years, Faulkner et al. (68) found that bone mineral content and density were generally significantly greater in the dominant limb. Individual data are not available for this study that would enable evaluation of the usefulness of these variables for prediction of handedness in forensic contexts.

In 1994, Roy et al. (69) examined hand dominance and bilateral asymmetry in structural attributes of the second metacarpal. Using a very large sample of 609 men and 383 women from the Baltimore longitudinal study, they examined cortical thickness, cortical bone area, periosteal area, medullary area, percent cortical area, and the second moment of area in the mediolateral plane. According to Roy et al. (69), the moment of area is "proportional to bending and torsional rigidity of a bone" (p. 205). Analysis revealed significant differences in favor of greater size on the dominant side.

An aspect of the Trinkaus et al. (70) study of humeral bilateral asymmetry and bone plasticity included data from modern professional tennis players. Their analysis suggests that load/activity features represent a component in diaphyseal robusticity.

Taaffe et al. (71) examined the correlation of upper limb bone mineral and soft tissue composition in 25 young and 35 elderly women in California. They found that handedness correlates positively with the variables examined.

Adding to the growing literature on the relationship of handedness with trauma and disease experiences, Borton et al. (72) examined fractures in 426 male and female children from Dublin, Ireland, with known handedness. They found a greater tendency to fracture the nondominant arm.

Blackburn and Knüsel (73) examined hand dominance and bilateral asymmetry in the measurement of epicondylar breadth of the humerus using a living sample of 50 individuals (27 women and 23 men) from Ontario. Of these, 42 (84%) were right handed and the remaining 8 (16%) were left handed. They found that bilateral asymmetry accurately reflected hand dominance in only 68% of the cases examined.

As noted by Chaisson et al. (74), patterns of osteoarthritis can be detected in bones of the hands of both sexes. Niu et al. (75) also noted that multiple hand joints are involved. However, in their study of 134 mature adults of known hand use, Lane et al. (76) found no correlation of osteoarthritis in the hand with handedness.

Özener (77,78) conducted research on asymmetry in young male laborers in Turkey. His interpretation was that asymmetry was influenced by biomechanical factors that could include handedness as a factor. Activity factors (habitual throwing and swimming) also were implicated in the study of Shaw and Stock (79) on upper limb diaphyseal strength and shape in 51 men.

Also in 2007, Shiri et al. (80) published their very comprehensive evaluation of the role of hand dominance in upper extremity musculoskeletal disorders. Working with a database derived from 6254 individuals from Finland, they found that such disorders were more common in the dominant extremity. They also noted that musculoskeletal disorders also frequently were greater expressed in the nondominant extremity.

Study of Skeletal Remains of Individuals of Known Handedness

As Stewart (1) pointed out back in 1979, the extent to which handedness can be determined from skeletal remains in forensic contexts can be clarified with study of the skeletons of individuals of known handedness. Since 1979, three studies have emerged that offer such clarification.

In 1980, only 1 year after the publication of Stewart's discussion, Schulter-Ellis (81) reported on her acquisition of the humerus, radius, and ulna of 10 adult skeletons in the Maryland area with known handedness. Of these 10, one was left handed, one was naturally left handed but functionally right handed, one ambidextrous, and seven right handed. She reported finding a correlation with the dominant side in variables extensor facet, greater dorsal inclination of the glenoid fossa, greater total length of long bones, and greater bicondylar width. Of the eight individuals with clear left or right preference, four displayed congruence of the attributes examined with their dominant side but four did not (in at least one attribute). One right-handed woman showed no difference in deflection angle and larger total length on the left side. One right-handed man displayed a larger deflection angle on the left side, no difference in bicondylar width, and a larger total length on the left side. Another right-handed man displayed a larger bicondylar width on the left side. A third right-handed man presented a larger deflection angle on the left side. Although the sample size was small, it suggested complexity in the determination of handedness from the attributes examined.

In a 1992 study, Glassman and Dana (82) examined asymmetry in the jugular foramen of 54 subjects (40 men and 14 women) at autopsy. All were of known handedness, including 47 with right dominance and seven with left dominance. Of the 36 crania displaying asymmetry, 28 (78%) exhibited positive correlation with known handedness. Of course, this also indicates that eight (22%) did not correlate. Four of the seven left-handed individuals exhibited larger foramina on the right side. Glassman and Dana (82) concluded that for forensic purposes, "no significant association exists" (p. 145) between handedness and asymmetry of the jugular foramen. This research and other literature published at that time led Jurmain (83) to note the complex factors involved and Klepinger (84) to conclude that "skeletal indicators of popularly defined handedness are unreliable at the present time" (p. 93).

In 2008, Danforth and Thompson (85) reported on their study of 137 individuals (both sexes) of known handedness in the Bass donated collection at the University of Tennessee, Knoxville, and in the forensic databank also maintained by the University of Tennessee. Their sample included 115 right-handed individuals and 22 left-handed individuals. They found that standard measurements of arm bones tended to be larger on the right, regardless of known handedness. They also observed the general associations discussed in the literature, but found no attributes or combinations of attributes, including the use of discriminant function analysis, that were diagnostic for handedness. Similar results were reported by Danforth and Thompson in 2007 (86) and Driscoll in 2007 (87) and 2009 (88).

Discussion and Conclusions

Much of the literature discussed offers positive evidence for the relationship of certain skeletal asymmetries and handedness. Research conducted on skeletal samples without information regarding known handedness (7,8,10,15–18,21,24) and on living individuals (55,61,63,68,69,71) suggests that handedness contributes to bilateral asymmetries.

A larger part of the literature though presents evidence that argues against a diagnostic correlation between bilateral asymmetry found in the skeleton and handedness. Schultz (3,4) and Van Dusen (5) both presented early evidence suggesting that handedness could not be predicted reliably from skeletal asymmetry. Later, three key articles, Schulter-Ellis (81), Glassman and Dana (82), and Danforth and Thompson (85), offered clarification of the extent to which handedness can be assessed from skeletal remains in a forensic context. All three articles documented asymmetry in the skeleton but, citing the complex factors involved, could not sufficiently relate it to handedness to support diagnostic use in a forensic context.

The definition of handedness is as complex an issue as the determination of handedness from the skeleton. The criteria for handedness vary widely among studies, sometimes ranging from simple declarations of handedness to more comprehensive tests of hand and arm strength. Other issues include an individual's developed hand preference versus natural inclination (46,47) and handedness as a task-specific phenomenon (54). In consideration of the intricacies of handedness, current definitions of handedness are quite ambiguous. A clear definition of handedness is needed to facilitate any possible future forensic assessment (54).

The vague nature of current definitions of handedness prevents accurate statistics on handedness in the modern population. Despite the lack of a concrete count, it is evident that we live in a right-handed environment (67). This affects the importance of determinations of handedness in forensic applications because an assessment of handedness would only minimally aid in identification efforts.

Extensive research and many publications have provided considerable information and discussion on the relationship between human handedness and skeletal morphology. This research suggests that Stewart's (1) cautionary approach to handedness estimation in forensic contexts was fortuitous. The research also suggests that Schultz' (3) interpretations back in 1937 were very close to what has been learned and confirmed subsequently. At this time, the scientific data suggest that it is not possible to determine the handedness of an individual from skeletal morphology alone with the accuracy needed for forensic applications.

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