To the Graduate Council:

I am submitting herewith a thesis written by Elizabeth Briana Reilly entitled "Discriminant Function Analysis of the Radius and Ulna as a Method of Sex Estimation." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Anthropology.

Murray K. Marks

Murray K. Marks, Major Professor

We have read this thesis and recommend its acceptance:

Lyle W. Konigsberg

Walter E. Klippel

Accepted for the Council:

C W Minkel

Associate Vice Chancellor and Dean of The Graduate School

Discriminant Function Analysis of the Radius and Ulna as a Method of Sex Estimation

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Abstract

Sex estimation has long been of interest to researchers in the fields of physical and forensic anthropology. Over time, sexing methods have evolved from a strict reliance on morphological traits to the emergence of metric and statistical analyses. After years of focusing exclusively on the cranium and pelvis for the sexing of human skeletal remains, anthropologists have recently begun basing their sex predictions on indicators seen in bones of the postcranial skeleton, such as the femur, sternum, and sternal ends of the ribs.

The goals of this study include: 1. examining of the relationship between sex and the dimensions of the forearm bones, 2. developing a method for estimating the sex of an unidentified case from measurements of the radius and ulna, and 3. statistically assessing the usefulness of these bones for sex estimation in a modern population.

Sex estimating ability of the forearm bones was investigated in a skeletal sample (N=165) of modern U.S. whites and blacks of known sex. The research involved the collection of various measurements from the left and right radii and ulnae of each skeleton. The metric data was then analyzed using the SAS program. Statistical analyses identified the greatest discriminating variables for each side and calculated the linear discriminant functions for sex estimation. A crossvalidation procedure was employed to test the accuracy of the functions for sex classification.

Results indicate that different measurements have stronger sex discriminating capacities for the left and right sides. This difference may be due to the effects of handedness on the population. Left handedness is seen in only a small percentage of the

world population (approximately 10%) and occurs more often in males. The role of handedness remains a point of interest for this study. However, the factors that determine handedness are far from understood. Although several theories have been proposed to explain handedness, none have been conclusively proven. Obviously, additional research is necessary to examine any definite correlation between handedness and the sexing potential of the upper limb bones.

Based on the statistically significant crossvalidation results, this research contends that this sexing method could be beneficial to physical and forensic anthropologists. The sexing function for each side shows a high degree of accuracy indicating usefulness for an investigator faced with the daunting task of identifying an unknown case's sex from only the left or right arm bones. A more accurate sex estimation can be obtained by applying a discriminant function for a particular side to a bone from the same side. In addition, the use of only the radius and ulna for this study shows that this method could be extremely significant for sex identification in fragmentary or dismembered skeletal remains, in which more traditional indicators (i.e. pelvis, cranium) are absent.

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Chapter 1

Introduction

Importance of Sex Estimation for Physical Anthropology

The purpose of this study is to develop a method of predicting the sex of an unknown individual from measurements of the forearm bones. The primary research objectives are to examine the relationship between sex and the dimensions of the arm bones, specifically the radius and ulna, and to statistically ascertain the usefulness of these bones for sex estimation in a modern population. A primary reason for studying skeletal materials is that they offer a wealth of biological information about the individuals and the population from which they were drawn. Techniques for estimating the sex of an individual from human skeletal elements are invaluable to physical and forensic anthropologists concerned with the identification of human remains. As many studies depend on sexing of the material being analyzed, physical anthropologists are continuously seeking and developing more accurate sexing techniques. Sex estimation is most often the first logical step taken in the analysis of archaeological populations and forensic (medico-legal) cases (Bronowski and Long 1952). Accurate sexing in anthropological research allows the investigator to assign a new find to a known group, while the inability to sex specimens impedes identification (Calcagno 1981; Stewart 1979). For forensic cases, determining the sex of human remains increases the likelihood of identification by eliminating approximately half of the population from further consideration on a missing persons list. Also, several of the other tests of identity, such as age and stature estimation, are sex-specific with males and females having different standards and regression formulae (France 1998).

A high degree of accuracy in the sexing of unknown material can be limited by several factors, including intrinsic variability and lack of real standards, the age of the individual represented by the remains, and the often isolated or fragmentary nature of materials (Berrizbeitia 1989; Holman and Bennett 1991; Kelley 1979). Human skeletal variability is rather large and there are no simple, exact criteria for positively estimating the sex, or for that matter the race, age, or stature, of an individual from skeletal remains (Krogman and Iscan 1986). It is widely acknowledged that the majority of sexing techniques, with the exception of Hunt and Gleiser's (1955) method, are only applicable to adult (postpubertal) specimens and cannot accurately estimate the sex of subadults (France 1998; Hunt and Gleiser 1955). Using modern techniques, physical anthropologists are currently able to estimate the sex of unidentified adult skeletal material with an accuracy approaching 100%, depending on the recovered parts of the skeleton (Bass 1995; Stewart 1948). Obviously, accuracy in sexing relies upon skeletal completeness. Therefore, a common problem encountered by physical and forensic anthropologists is the classification of sex for incomplete or fragmentary remains. If a complete skeleton is recovered, sex can most likely be determined from the pelvis or cranium (Steele and Bramblett 1988; White 2000). However, when these bones are absent the researcher must resort to isolated bones or parts of bones for sex assessment (Pons 1955). For sex, the margin of error in any estimation varies with the skeletal elements available for examination (Meindl et al. 1985).

Role of Sexual Dimorphism

As more physical anthropologists examine sexual dimorphism in their research, it has become increasingly important to recognize the potential sources of error in such studies (St. Hoyme and Iscan 1989). Contrasting with the other phenotypic features in which humans vary, sex is not a continuous variable but rather expressed in a clear bimodal distribution (Hamilton 1982). Sexual dimorphism shows that defined, genetically determined forms of the same species can co-exist in a single breeding population (Thieme and Schull 1957). Thieme and Schull note that

> The phenotype of sex, while it is an expression of a distinct genotype, is fundamentally different from other kinds of polymorphism ...it differs first as a consequence of its being determined by a special genetic reproductive mechanism which is at the chromosome level and thus involves many genes; and secondly as a consequence of this, sex differences are expressed in many aspects of the phenotype through widely varying levels of genetic influence (1957:242).

Therefore some features of the phenotype clearly indicate sex while others have little or no practical use (Shipman et al. 1985). There are three possible reasons for errors in the estimation of sexual dimorphism: 1. mistakes in sex assessment may under or over estimate sexual size differences in a skeletal series, 2. sampling errors from other sources (i.e. age) can affect the measured magnitude of size dimorphism, and 3. lack of control over variables which influence sexual dimorphism at the genotypic or phenotypic level (Hamilton 1982). In addition, it is necessary to recognize that although genetic factors are influential in the degree of sexual dimorphism in a population, several other factors, including nutrition, climate, and economic base, also contribute (St. Hoyme and Iscan 1989).

The estimation of the sex of an individual from unidentified skeletal remains is contingent on the expression of sexually dimorphic traits. In the human skeleton, differences in sex are observed primarily in the size and secondarily in the shape of bones (Hrdlicka 1939; Sacragi 1996; Stewart 1979). A greater level of sexual dimorphism can increase the ability to differentiate between the sexes, especially if the dimorphism is functionally significant (Thieme and Schull 1957). The variability for sex markers in the human skeleton becomes evident after the cessation of the undifferentiated prepubertal phase. In comparing the sexes, postpubertal males differ from their prepubertal forms mostly in gross size of the long bones while postpubertal females show specific effects of hormone mediated changes (Hamilton 1982). Hrdlicka (1939) stresses that aside from the genitalia, the characteristics of the two sexes, whether in the skeleton or soft tissues, are not completely distinct but overlap under even the most normal conditions. This point is emphasized by St. Hoyme and Iscan (1989) when they state that both sexes share about 95% of the total range of variation and that this range is further modified by the factors of health, diet, and environmental conditions

Therefore, researchers must expect that in a series of skeletons or isolated bones, a certain proportion of the specimens will provide extreme difficulty or even impossibility for a definite sex assessment. In addition, these conditions vary among the different racial groups so that sex identification of skeletal elements is more difficult in some groups than others (White 2000). As the magnitude of size differences between the sexes can vary from one human population to the next, physical anthropologists must keep in mind that the classification of a bone is possible with a reasonable degree of certainty only when it can be compared to a series of known sexual dimorphism (France

1998; Garn et al. 1972). Males generally have more robust skeletons than females, but males in one population may be shorter, lighter, and less muscled than the females of another population with a different lifestyle (Buikstra and Ubelaker 1994; White 2000). Failure to use a series of known sexual dimorphism for comparison can result in the erroneous classification of a female as a male if the bone is particularly robust, or vice versa if a male specimen is gracile (Pons 1955). The overall accuracy of classifying sex is improved by a thorough knowledge of the general population from which the skeletal remains are drawn. It is impossible to define precise morphological and metrical boundaries between males and females that are applicable to all series (Workshop of European Anthropologists 1980).

Three types of influences affect sex differences in the skeleton: 1. the reproductive function that is expressed predominantly as variability in pelvic morphology, 2. genetically influenced contrasts in gross bone size and proportions, and 3. differences in amount of body musculature as evidenced by attachment markings on bone (Hamilton 1982). Throughout history, anthropologists have observed that the main distinctions between the male and female skeleton are manifested discretely in the pelvis (Bass 1995). The modification of the pelvis for childbearing in women and the resulting differences in the bony structure of the male and female pelves have established and maintained the innominate bones as the best indicators of sex (Kelley 1979; Stewart 1979). However significant levels of sexual dimorphism are also evident in the skull and the remainder of the postcranial skeleton (Calcagno 1981; Holman and Bennett 1991; Richman et al. 1979). Historically, visual methods of sex classification based on qualitative morphological traits have been predominant in the area of human skeletal identification. Older studies of sex differences were mainly focused on describing morphological traits in the pelvis and cranium and subjectively assessing the degree of expression of particular features (Krogman and Iscan 1986). Recognition of other sex related characteristics of the skeleton has risen recently. In essence, physical anthropologists today are able to employ a variety of sex indicators to assist them in their identification efforts (Bass 1979).

After the pelvis and skull, the appendicular bones of the postcranial skeleton are the most reliable predictors of sex (Richman et al. 1979). In general, male skeletal elements are larger and more robust than female bones of the same population. In addition, male long bones have more pronounced muscle attachments, expressed as prominent ridges, crests, and tuberosities (Buikstra and Ubelaker1994; Steele and Bramblett 1988). However, the most significant sexual differences in the long bones are found in the articular surfaces and diameters, which in males are typically much larger (Dwight 1904). Estimating sex from long bones that have intermediate expression of muscular development should be approached with caution, as the diagnosis of sex in this case would be uncertain, especially without pelvic or cranial traits for corroboration. Weiss (1972:240) warns against such a case by pointing out the tendency for researchers to classify specimens with intermediate size or rugosity as male when assigning sex based on secondary sex characteristics.

Methods of Sex Estimation

The methods of sex estimation have not been perfected and efforts are constantly being made to improve them (Bass 1979). Anthropologists must choose between subjectivity and objectivity, description and measurement, and experience and statistical standardization (Stewart 1954). Some physical anthropologists continue to rely exclusively on observation of morphological traits for sex classification, citing obvious visual evidence matched with their previous experience (France 1998). However, sex estimation based on traditional nonmetric methods depends heavily on the researcher's ability and experience, factors that can seldom be evaluated objectively and accurately (Richman et al. 1979). Obviously, the subjective opinions of the investigator may influence his diagnosis of sex (Pons 1955). Several anthropologists that have become discontent with visual sexing methods advocate the use of quantitative techniques that would make sex identification more "scientific" and less "artistic" (Bronowski and Long 1952; White 2000). Physical examination can give a general idea but to be completely accurate in sex estimation, metric methods are indispensible. Newer studies focus more on morphometry, mainly because objective metric techniques are presumed to be repeatable, easier to teach to students, and reassuring to those who are less experienced in sex determination by observation (Meindl et al. 1985). In addition, metric methods that consider population variation are clearly superior to subjective morphological criteria in that they provide rigorously defined objective methods for identifying sex, resulting in fewer specimens being classified as "ambiguous" compared to morphological evaluation (Weiss 1972). Metric analysis has especially gained popularity in the field of forensic anthropology as forensic anthropologists are reporting their results in court and are asked to provide statistical weight to their opinions. Forensic anthropologists' positions as expert witnesses in court cases are strengthened if they can testify that the attribution of sex by metric procedures agrees with their subjective judgements (France 1998; Stewart 1979). Although proponents argue that the main appeal of metric analysis is that verifiable scientific methods are introduced to replace less satisfactory ones, several researchers, among them, Konigsberg and Hens (1998), have achieved better sexing results using only morphological traits. The introduction of precise measuring techniques does not preclude the need for an anthropologist's experience with visual sexing but rather adds variety to the methods and increases the certainty of the conclusions (Weiss 1972).

A discussion of metric analysis would not be complete without a brief description of the discipline of anthropometry (and its subdivision, osteometry) and the rapidly increasing use of discriminant functions in anthropological research. Hrdlicka (1939:3) defines anthropometry as the "systemized art of measuring and taking observations on man, his skeleton, his brain, or other organs, by the most reliable means and methods, for scientific purposes." The first appearance of anthropometry can be traced back to Old Egypt and Greece where artists used measurements to formulate various standards for the human body. In the nineteenth century, the anthropometric system of techniques became more refined as anthropologists began concentrating on studies of race, sex, and human growth. The development of anthropometry for anthropological purposes can be attributed to several American and European anthropologists, including Morton, Blumenbach, Broca, Topinard, and Virchow. These early anthropologists recognized the endless normal variability of human structure and turned to anthropometry as a means to evaluate the infinite range and variety seen in the human body. Anthropometry is based on several organic laws, the most important of which are the laws of heredity, variation, and correlation (Hrdlicka 1939:4). Every fixed feature that anthropometry deals with is essentially the expression of inheritance. These features show basic relations in the growth of the human body and also present a fairly definite range of normal variation about the mean in every human group. For physical anthropologists, anthropometry should ideally function to completely eliminate personal bias and provide absolutely correct data on the dimensions of the body and skeleton for any given human group (Hrdlicka 1939).

Emergence of Discriminant Function Analysis

The limitations of univariate analysis led to the development of multivariate approaches by Fisher, Mahalanobis, Hotelling, and Rao. Analysis of multivariate variables shows the essential differences in size and shape, information that cannot be reliably obtained through univariate methods (Howells 1969). First introduced by Fisher (1936), discriminant analysis, a type of multivariate statistics, was seen as a solution to problems in physical anthropology and biology. Although researchers have used discriminant analysis in a wide variety of applications, physical anthropologists have found it to be an effective quantitative approach to sex and race estimation (DiBennardo and Taylor 1983). Physical anthropologists often want to compare several groups and test hypotheses with regard to several specific features. Usually the features under investigation are compared between sexes, among ethnic or geographic groups, or among age cohorts (Bronowski and Long 1952) Discriminant analysis is a statistical technique that permits the researcher to examine the differences between two or more groups of objects with respect to several variables simultaneously (Klecka 1980; Klepinger and Giles 1998). A basic prerequisite is that the variables are measurable at the interval or ratio level (Klecka 1980). When utilizing discriminant analysis or other related statistical techniques, anthropologists should try to use an array of measurements that do not repeat information about sex differences (Klepinger and Giles 1998). In practice, an endless set of measurements on a specimen should not be taken. As more and more measurements are taken, each new measurement becomes correlated with some previous measurement, thereby rendering the additional information contributed negligible after a certain point (Bronowski and Long 1952).

The primary purpose of discriminant analysis is to reduce subjective judgement. Physical anthropologists come across statistical statements in two areas of their work: conducting research and interpreting research results (France 1998). Discriminant analysis is a broad term that refers to several closely related statistical techniques that can be divided into those employed for interpreting group differences and those used for classification of cases (Klecka 1980) A researcher is involved in interpretation when examining the ways in which groups differ. The researcher must question whether it is possible to discriminate between the groups on the basis of some set of characteristics, how well these features discriminate, and which are the most powerful discriminators (Bronowski and Long 1952). The other application, classification, consists of deriving mathematical equations called discriminant functions (Klecka 1980). Discriminant functions combine group characteristics to allow a researcher to identify the group that an unknown case most resembles (Klecka 1980; Richman et al. 1979; Workshop of European Anthropologists 1980) According to Giles and Elliot (1963), while discriminant function analysis can be a solution to the problem of assigning an individual to a group, it does not attempt to sort out heterogeneous material. Discriminant function analysis only assigns individuals to one group or another on the basis of available information (Giles and Elliot 1963).

Discriminant function studies have proliferated and produced techniques that can be used on every major bone as well as fragmentary skeletal remains (Holman and Bennett 1991). Due to its extreme utility for assigning sex to individual specimens, the use of discriminant analysis in anthropological research has many advantages. Discriminant analysis leads to the selection of a linear function of measurements (variables), resulting in a simple formula for classifying the sex of any single specimen (Klepinger and Giles 1998). Accuracies for sex prediction using this method vary depending on the measurement set, but most fall within the middle to high 80th to low 90th percentile range (Calcagno 1981). Accuracy may increase if measurements from more than one skeletal element are included (Pons 1955). Although discriminant functions are often used to confirm a determination of sex based on traditional criteria, they can also determine the sex of a questionable bone (Weiss 1972). A significant application of discriminant function sexing in forensic anthropology occurs when the investigator is asked to examine the remains of a dismembered individual in which the pelvis and cranium are not present. The development of sexing functions on as many skeletal elements as possible is clearly desirable for such cases (France 1998). In general, statistical analyses are beneficial to the field of physical anthropology, as they allow the researcher to communicate their results to colleagues with a high level of confidence.

An extremely significant contribution to the field of forensic anthropology involving metric data collection and its application was the development of the Forensic Data Bank and FORDISC (Ousley and Jantz 1998). The Forensic Data Bank is a computer data base that stores collected forensic data that can be used to develop identification standards for modern skeletons. The data bank contains cranial and postcranial measurements for 1019 skeletons of known sex and race, in addition to information on medical history, cause of death, and preservation. The Forensic Data Bank is more useful for the identification of forensic materials because it is better represented by younger individuals compared to anatomical collections (i.e., Terry and Hamann-Todd collections) (Jantz and Moore-Jansen 1988). Metric and morphological standards derived from nineteenth century collections are inaccurate when applied to modern Americans. The Forensic Data Bank is a more appropriate source of information because it accounts for secular trends and illustrates the importance of using modern reference samples for modern forensic cases (Jantz and Moore-Jansen 1988; Ousley and Jantz 1998). FORDISC, an extension of the Forensic Data Bank, is a computer program that can classify an unidentified skull by utilizing any combination of cranial measurements. In addition to modern whites and blacks, FORDISC also has population reference samples for several other groups, including Amerindians, Hispanics, Chinese, and Vietnamese, which are not readily available to most researchers. FORDISC is especially useful for forensic anthropologists because it applies multivariate discriminant analyses to modern data to assess the sex and race of cranial materials and serves as a test of other methods of sex and race estimation (Ousley and Jantz 1998).

Along with its advantages, discriminant analysis has some limitations as well. Critics have identified and described numerous problems associated with this procedure. Because samples are not always large, perfectly representative, and normally distributed, anthropologists should adapt statistical techniques to the prevailing conditions and regard probabilities of error as guidelines rather than precise statements (Meindl et al. 1985). Important considerations include sample size and variable selection (Klepinger and Giles

1998). The primary basis for the controversy surrounding the applicability of discriminant analysis, however, concerns the population specific nature of the technique (Birkby 1966; DiBennardo and Taylor 1983) . To account for race-linked differences in sexual dimorphism, the use of discriminant functions is only appropriate when the unknown specimen belongs to the population upon which the discriminant function sexing formulaes are based (Meindl et al. 1985; Shipman et al. 1985). Although discriminant functions work with extreme accuracy on the population upon which they are based, their reliability markedly decreases when populations are sexed by functions based on unrelated populations (Pons 1955). Size variation between populations most likely accounts for the inapplicability of the functions (Calcagno 1981). Therefore, erroneous results are quite likely to be produced by applying sexing functions based on a non-representative sample to unknown individuals (Birkby 1966; Calcagno 1981). To prevent the unnecessary reporting of erroneous results, Giles (1966) recommends that discriminant sexing functions be subjected to controlled tests to ascertain their level of accuracy on a variety of populations before conclusions are drawn. Overall, anthropologists should understand that statistical methods can elevate their levels of objectivity and certainty if used properly, but can also confuse or mislead if carelessly or incorrectly applied.

Chapter 2

Literature Review

Few studies have been performed on the use of the upper limb bones, specifically those of the forearm, for sex estimation. Previous research that focuses on the radius and ulna as predictors of sex have shown mixed results, depending on the type of measurements and sample used. Following Dwight's (1894) assertion that the "carrying angle" (angle between the forearm and humerus) should be larger in females in order for their forearms to clear their wider hips, Atkinson and Elftman (1945) were among the first to attempt to correlate dimensions of the arm with sex. Their study consisted of measuring the angle formed between the humerus and extended and supinated forearm in a sample of 105 white males and 112 white females. They found that the average carrying angle in the female was only 1.8 degrees greater than the male, a difference they deemed too small to serve as a useful criterion for sex identification in individual cases. Furthermore, the extensive overlapping of the range of variation for both sexes also precluded the use of the angle as a secondary sex indicator (Atkinson and Elftman 1945).

A study of the radius (Singh, G. et al. 1974) and a similar study of the ulna (Singh, S. et al. 1974) both used the "demarking point" concept to determine the applicability of the forearm bones for sex classification. Using contemporary Indian samples consisting of 92 males and 39 females and 191 males and 54 females, respectively, G. Singh and coworkers and S. Singh and his colleagues measured the length, midshaft circumference, and distal width of each bone. Maximum and minimum limits of a given dimension were then found by taking three standard deviations around the mean. If a bone had a value outside these limits, correct identification of sex would be 99.75% that the bone was male (greater than the maximum limit) or female (less than the minimum limit) (Singh, G. et al. 1974; Singh, S. et al. 1974).

More recently, Berrizbeitia's (1989) research indicated that the radial head by itself could be an accurate predictor of sex. Berrizbeitia's simple radial head method of sex estimation consisted of measuring the minimum and maximum diameters of the radial head in a sample of 152 white males, 172 black males, 103 white females, and 140 black females taken from the Smithsonian Institution's Terry Collection. These measurements were then compared with test cutoff points. According to Berrizbeitia, the specimen was male when the maximum diameter (either left or right) was greater than or equal to 24 millimeters, and female when the maximum diameter was less than or equal to 21 millimeters. The cutoff points for the minimum head diameter were 23 millimeters or more for males and 20 millimeters or less for females. Crossvalidation with a sample of different specimens produced sexing accuracies of 92% for the left radius, 94% for the right radius, and 96% for both radii together (Berrizbeitia 1989)

Steel (1972) used measurements taken on an historic English church site sample consisting of 27 males and 33 females to establish three discriminant function formulae. The following measurements were utilized to calculate the functions· length, width of distal epiphysis, and vertical diameter of the head of the humerus; length, tuberosity diameter, and width of the distal epiphysis of the radius; and length, coronoid height, and width of the distal epiphysis of the ulna. The sexing accuracies obtained by Steel were not as high as those found by Singh, G. et al., Singh, S. et al., and Berrizbeitia, as they fell in the low 80th percentile range (Steel 1972).

Holman and Bennett's (1991) examination of U.S. whites and blacks in the Terry Collection is another example of a study using osteometric dimensions of the humerus, radius, and ulna for discriminant function analysis. In addition to looking at the maximum lengths of all three long arm bones, Holman and Bennett also included two measurements that reflect wrist breadth. Based on a sample of 76 white females, 76 white males, 75 black females, and 75 black males, their results indicated that seven of the 31 possible measurement combinations common to whites and blacks produced functions with sex estimation accuracies (85% or better) comparable to those obtained for other postcranial elements. However, they also found that whites were classified more accurately than blacks by these functions. Holman and Bennett (1991) determined that the distal end of the radius had the greatest sex discriminating power followed by the distal end of the ulna, while the long bone lengths were significantly less useful.

In his comparison between the sexes, Sacragi (1996) chose to include the radio-ulnar weight index, in addition to conventional parameters, to examine if the difference in body weight between males and females was also reflected in their bones. Using a modern sample of 20 Japanese males and 20 Japanese females, Sacragi weighed and measured each right forearm bone. His results showed that the mean values for all of the radial and ulnar measurements were significantly greater in males than in females. In contrast, the radio-ulnar weight index presented no clear sex difference. Sacragi obtained two discriminant functions, one that included the radio-ulnar weight index as a variable and one that did not. No difference was observed between the discriminating rates of the two functions. Both functions determined the bones as male with 90% accuracy and as female with 90% accuracy, therefore the radio-ulnar weight index failed to improve the sexing accuracy. Sacragi (1996) concluded that the radio-ulnar weight index should not be considered an accurate predictor of sex.

Allen et al. (1987) applied standard measurements (maximum length, midshaft diameter, and maximum transverse distal width) to roentgenograms of fleshed radii instead of using actual bone specimens. Roentgenograms of the radii from a sample of 63 males and 63 females taken from a Dutch dissecting room collection were measured and the midpoint between male and female mean values served as a sectioning point. Specimens with values greater than the sectioning point were classified as male, while specimens with values less than the sectioning point were classified as female. Of the variables, maximum transverse distal width had the highest discriminatory capacity (85% accuracy) followed by maximum length (75%) and midshaft diameter (65%) (Allen et al. 1987).

The majority of previous research concerning the radius and ulna as indicators of sex shows that reasonably high levels of accuracy can be obtained, especially if the investigator includes distal width as a parameter (Allen et al. 1987; Holman and Bennett 1991; Sacragi 1996; Singh, G. et al. 1974; Singh, S. et al. 1974). Maximum distal width is the most biologically significant measurement of sexual dimorphism in the forearm bones, an observation that is most likely directly related to differences between male and female forms (Hamilton 1982). The combined effects of increased body size and greater muscle power that differentiates males and females results in increased loading on joint surfaces that is reflected as larger articular surfaces in the long bones (Dwight 1904).

Chapter 3

Materials and Methods

Sample

As stated in Chapter 1, the purpose of this study is to develop a method of predicting the sex of an unknown individual from measurements of the forearm bones. All skeletons used in this study are curated in the William M. Bass donated human skeletal collection in the Forensic Anthropology Center at the University of Tennessee, Knoxville. The reference sample is composed of 165 skeletons of known sex and race, consisting of 107 white males, 32 white females, 23 black males, and 3 black females. Only adult specimens were included in the sample, as indicated by complete epiphyseal fusion. For cases in which the left or right bone was absent or damaged (through pathology, erosion, or postmortem breakage), only the measurements that could be accurately obtained were taken and recorded. None of the skeletons were rejected from the sample based on missing or incomplete skeletal elements or modifications.

Measuring Procedures

Ten measurements (6 radial and 4 ulnar) were taken on the left and right radii and ulnae of each skeleton in the sample (Figures 1 and 2). The specimens were examined and measured without prior knowledge of the individual's sex or race. The sex and race of each skeleton were concealed to avoid biasing the researcher. Each bone was measured as described below.

The maximum lengths of the radius and ulna were measured with an osteometric board according to Moore-Jansen et al. (1994) and approximated to the nearest 0.5

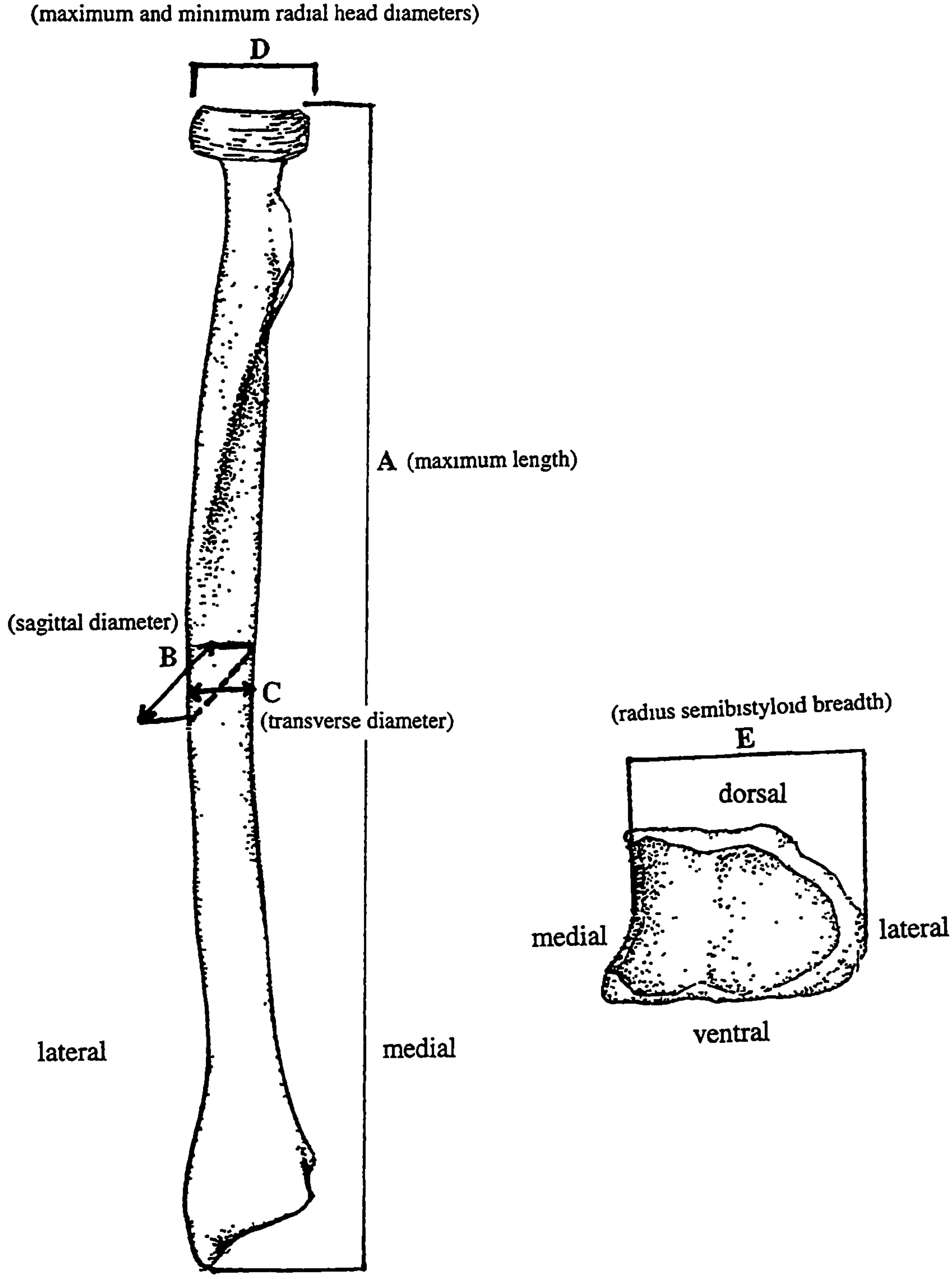

Figure 1. Anterior and distal views of a right radius showing the location of measurements.

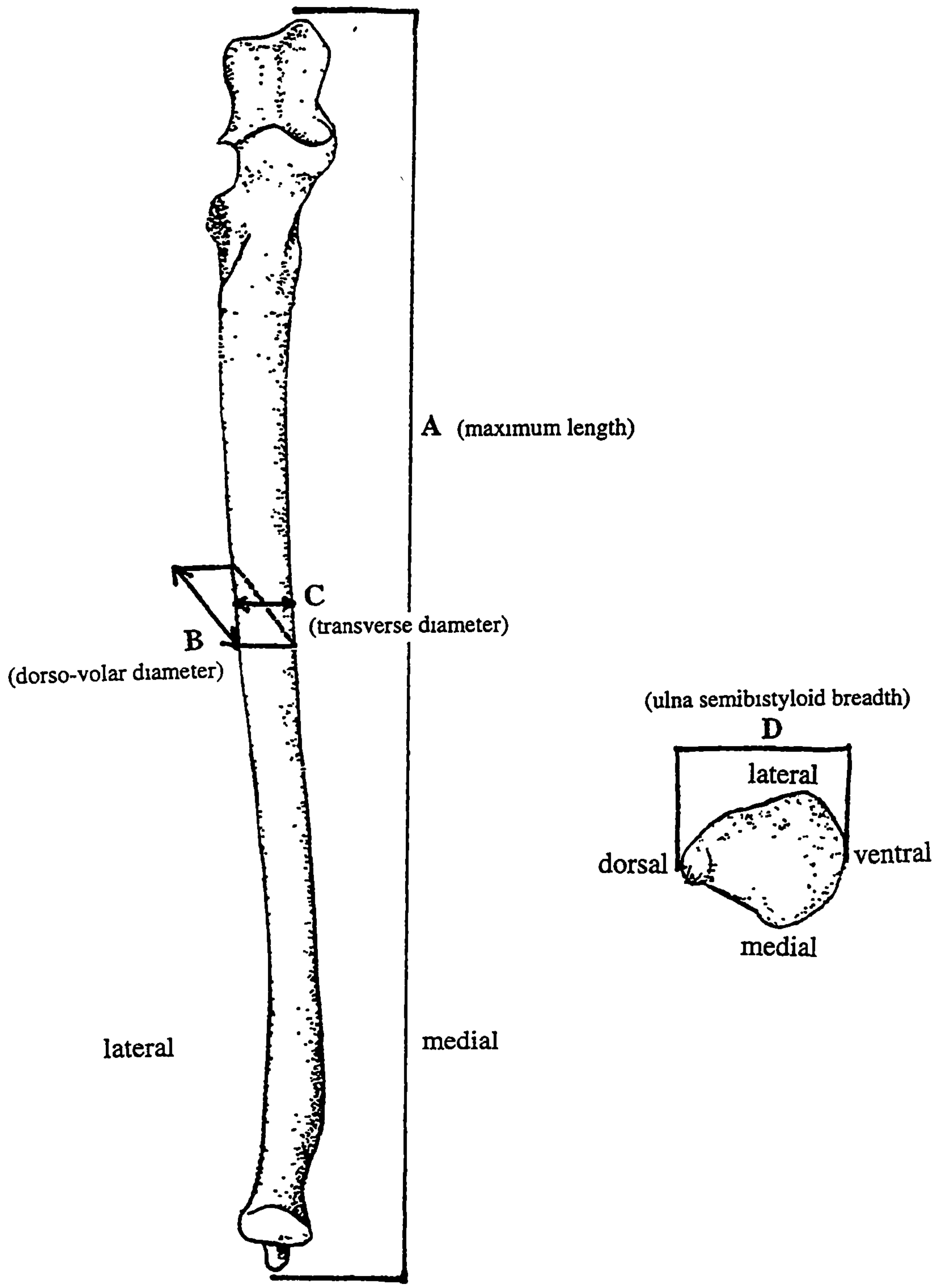

Figure 2. Anterior and distal views of a right ulna showing the location of measurements.

millimeter (Figure 1,"A"; Figure 2,"A"). The remaining measurements were taken with digital sliding calipers. The sagittal diameter of the radius was defined as the antero-posterior diameter at midshaft (Figure 1,"B"), while the transverse diameter of the radius measured the distance between the maximum medial and lateral bone surfaces at midshaft (Moore-Jansen et al. 1994) (Figure 1,"C"). Measuring the dorso-volar and transverse diameters of the ulna consisted of taking the maximum diameter of the shaft where the crest shows the greatest development and the diameter perpendicular to this at the same level of crest development, respectively (Moore-Jansen et al. 1994) (Figure 2,"B"; Figure 2,"C"). Following the measuring procedures of Berrizbeitia (1989), the maximum and minimum head diameters were obtained by rotating the ends of the caliper around the proximal end of the radius (Figure 1,"D"). The semibistyloid breadth (SBB) of the radius and ulna represent an approximation of wrist breadth and were measured as described by Holman and Bennett (1991). The SBB of the radius was taken from the most lateral point on the styloid process to the deepest point of the ulnar notch (Figure 1,"E"). The SBB of the ulna was taken from the most medial point on the head to the most lateral point on the styloid process (Figure 2,"D"). Both SBB measurements were taken at a right angle to the long axis of the bone (Holman and Bennett 1991).

Statistical Analyses

White males dominated the sample, hence the data for white males and females and black males and females were pooled before statistical analysis. The radius and ulna are not widely recognized as good indicators of race, therefore we must assume that separate discriminant functions for each racial group would be of little use to an investigator trying to identify an individual of unknown racial affiliation from only the radius and ulna. The investigator would not be able to apply a race-specific discriminant sexing function accurately. However, a pooled function could yield an accurate prediction of sex.

All statistical analyses were performed using SAS (SAS Institute 1999). The first step of the statistical methodology was to perform a two sample paired t-test to determine the degree of directional asymmetry in the arm bones. The researcher anticipated a high degree of asymmetry between the left and right bones due to handedness. For this reason, separate discriminant functions were calculated for the left and right measurements. Investigators that are examining a case with the radius and ulna from only one side present can use the discriminant function for that side instead of applying a right side function to left sided bones and vice versa.

The analysis for each side was carried out by SAS in four stages. First, the STEPDISC procedure was used to generate stepwise entry and determine which variables (measurements) had the greatest sex discriminating capacity. The STEPDISC function eliminates unnecessary variables by using a stepwise procedure to select the most useful discriminating variables. This procedure combines forward and backward selection, such that each step starts with a review of the variables previously selected and any variables that no longer sufficiently contribute to the discrimination are cast out. In this way, the stepwise procedure produces an optimal set of discriminating variables for each side. The strongest predictors of sex, or those showing the most sexual dimorphism, were the measurements included in the discriminant function. The DISCRIM procedure was used to obtain the unstandardized discriminant function coefficients for each side. These coefficients were the values used to calculate the linear discriminant function for sex prediction. The researcher then used the WCOV procedure to generate a variance-covariance matrix. The variance-covariance matrix is a way to measure the correlation (covariation) between two variables, because it indicates how well a large deviation on one variable corresponds to a large deviation on the other. The matrix is a summary of how much the data points are spread out around the total space defined by all the variables, also known as dispersion (Klecka 1980). The variance-covariance matrix is especially useful because it allows another researcher to calculate any discriminant function for these measurements. Instead of using a test sample, the CROSSVALIDATE procedure was employed to test the accuracy of each discriminant sexing function (left and right). The CROSSVALIDATE procedure takes each case in the data set and applies the discriminant function to it to see if it is classified correctly.

Chapter 4

Results

The summary statistics (Tables 1 and 2) reflect the properties of the variables in the sample For both the left and right sides, the female mean values for all measurements are significantly smaller than the male values at P<0.001.

To determine the degree of directional asymmetry, the two sample paired t-test (Table 3) tests the null hypothesis that the difference between the left and right side mean values for each measurement equals zero. The levels of asymmetry for each measurement differ for males and females. For the females, some measurements (radius length, sagittal diameter of the radius, ulna length, dorso-volar diameter of the ulna, and transverse diameter of the ulna) show a high degree of directional asymmetry. This is indicated by a Prob>t that is less than the cut-off value of 0.05, leading to rejection of the null hypothesis in favor of an alternative hypothesis (i.e. there is a difference in the mean left and right values of the measurement). Out of the 10 measurements, maximum and minimum radial head diameters, transverse diameter of the radius, dorso-volar diameter of the ulna, and ulna SBB show significant asymmetry for the males. The other measurements (for males and females) that have high probabilities most likely do not show directional asymmetry because they are small and not significant.

In this study, the researcher had several potential discriminating variables but was uncertain whether all of them were valuable and necessary. For such a situation, one or more of the variables (measurements) may be poor discriminators because the group means are not very different on those variables. The variables selected by SAS for the left

Table 1. Reference sample means and variances (in mm) for left side measurements with pooled race

Variable	Females mean	Females variance	Males mean	Males variance
N	35		130	
Radius length	220.31	172.93	254.93	164.19
Max. radial head diameter	20.42	0.84	24.28	1.94
Min. radial head diameter	19.23	0.81	23.05	1.82
Sagittal diameter of radius	10.45	0.56	13.02	1.51
Transverse diameter of radius	13.59	2.75	16.51	2.63
Radius semibistyloid breadth	28.80	2.78	33.95	3.46
Ulna length	237.20	141.06	273.76	184.73
Dorso-volar diameter of ulna	10.46	0.90	13.30	1.40
Transverse diameter of ulna	14.22	1.16	17.37	2.92
Ulna semibistyloid breadth	17.95	2.67	21.85	2.68

Table 2. Reference sample means and variances (in mm) for right side measurements with pooled race

Variable	Females		Males	
	mean	variance	mean	variance
N	35		130	
Radius length	222 64	160.24	256 05	169.38
Max radial head diameter	20 46	0.88	24.54	2.10
Min radial head diameter	19 25	0.91	23.30	2 04
Sagittal diameter of radius	10 56	0 51	13.21	1.59
Transverse diameter of radius	14 02	2 59	16.95	3.23
Radius semibistyloid breadth	29 14	2.21	34 12	3.43
Ulna length	240 31	136.35	275 03	184.84
Dorso-volar diameter of ulna	10 61	0.52	13.60	1.67
Transverse diameter of ulna	14.39	0 99	17.52	3.25
Ulna semibistyloid breadth	18 24	2 44	22 22	2.63

Table 3. Two sample paired t-test for means of measurements for females and males

Hypothesis Test	Females			Males		
Null hypothesis	t statistic	DF	Prob>t	t-statistic	DF	Prob>t
Mean of (L rad length-R rad length)=0	-3.130	30	0.0039	-1.147	116	0.2536
Mean of (L max head-R max head)=0	-0.964	19	0.3473	-2.338	88	0.0217
Mean of (L min head-R min head)=0	-0.370	19	0.7156	-2.311	88	0.0231
Mean of (L sag diam-R sag diam)=0	-2.171	30	0.0380	-1.481	118	0.1413
Mean of (L trans diam-R trans diam)=0	-2.558	30	0.0158	-3.352	117	0.0011
Mean of (L rad SBB-R rad SBB)=0	-1.724	31	0.0947	-0.904	119	0.3679
Mean of (L ulna length-R ulna length)=0	-2.485	27	0.0194	-1.257	107	0.2116
Mean of (L dv diam-R dv diam)=0	-3.155	28	0.0038	-2.537	116	0.0125
Mean of (L trans diam-R trans diam)=0	-2.289	28	0.0298	-1.177	116	0.2418
Mean of (L ulna SBB-R ulna SBB)=0	-1.681	29	0.1035	-2.325	114	0.0218

side are minimum radial head diameter, radius SBB, ulna length, dorso-volar diameter of the ulna, and ulna SBB, while the variables selected for the right side are the maximum radial head diameter, ulna length, dorso-volar diameter, and ulna SBB (Tables 4 and 5).

The DISCRIM procedure calculated the unstandardized coefficients for the linear discriminant sexing function for each side (Tables 6 and 7). These linear formulas indicate that the discriminant scores are computed by taking the original value for a case on each variable and multiplying it by the coefficient for that variable; then adding these products along with the constant term. Tables 6 and 7 also report the canonical correlation for the left and right side functions. The canonical correlation is a way to judge the substantive utility of the discriminant function because it is a measure of the association that summarizes the degree of relatedness between the groups and the function (Klecka 1980). High correlation coefficients, such as those found for the left and right functions in this study, indicate that a strong relationship exists between the groups and the discriminant function. The total structure coefficients are reported in Tables 8 and 9 to depict the similarity between a single variable and the discriminant function. The structure coefficients show how closely a variable and a function are related (Klecka 1980). If the magnitude of the coefficient is very large, as it is for all the left and right side variables, the function is carrying nearly the same information as the variable. The variance-covariance matrix for each side by sex is presented in Tables 10 through 13.

Table 4. Stepwise selection summary for left side measurements

Step	Entered	Removed	F Value	Pr>F	Wilks' Lambda
1	min head diam		162.90	<.0001	0.42008306
2	ulna length		22.10	<.0001	0.35334841
3	dorso-volar diam		10.08	0.0019	0.32509319
4	radius SBB		7.35	0.0077	0.30556069
5		min head diam	2.09	0.1510	0.31111444
6	ulna SBB		2.93	0.0898	0.30339141

Table 5. Stepwise selection summary for right side measurements

Step	Entered	Removed	F value	Pr>F	Wilks' Lambda
1	max head diam		201.67	<.0001	0.37693106
2	ulna length		22.51	<.0001	0.31781898
3	dorso-volar diam		12.62	0.0005	0.28758338
4	ulna SBB		4.38	0.0384	0.27736693

Table 6. Unstandardized discriminant function coefficients for the left side for U.S. Whites and Blacks*

Measurements	discriminant function 1
Min. radial head diam	0.68375
Radius SBB	0.63292
Ulna length	0.11556
Dorso-volar diam of ulna	1.26843
Ulna SBB	0.53198
Constant	-89.57498
Canonical correlation	0.837910

*Total discriminant scores less than 0 classify as female.

Table 7. Unstandardized discriminant function coefficients for the right side for U.S. Whites and Blacks*

Measurements	discriminant function 1
Max. radial head diam	1.1751
Ulna length	0.13188
Dorso-volar diam of ulna	1.20864
Ulna SBB	0.57074
Constant	-86.50441
Canonical Correlation	0.850495

*Total discriminant scores less than 0 classify as female.

Table 8. Total canonical structure coefficients for left side measurements

Measurements	Coefficients
Ulna length	0.895442
Dorso-volar diam	0.822055
Radius SBB	0.876256
Ulna SBB	0.833736
Min. radial head diam	0.908836

Table 9. Total canonical structure coefficients for right side measurements

Measurements	Coefficients
Max. radial head diam	0.926879
Ulna length	0.898612
Dorso-volar diam of ulna	0.832323
Ulna SBB	0.815873

Table 10. Within class covariance matrix for left side measurements

	Sex=F		DF=21		
Variable	ulnal	dv	rsbb	usbb	minh
ulnal	86.82467532	-0.85019481	5.53787879	3.14813853	2.06461039
dv	-0.85019481	1.07232835	-0.08159654	-0.05482641	0.32806861
rsbb	5.53787879	-0.08159654	3.49760173	1.39199870	0.78239740
usbb	3.14813853	-0.05482641	1.39199870	3.03348312	0.19449481
minh	2.06461039	0.32806861	0.78239740	0.19449481	0.82569199

Table 11. Within class covariance matrix for left side measurements

	Sex=M		DF=97		
Variable	ulnal	dv	rsbb	usbb	minh
ulnal	173.5400799	4.0728824	9.4769304	7.7268714	8.4748664
dv	4.0728824	1.2023639	0.3456666	0.5795005	0.5697617
rsbb	9.4769304	0.3456666	3.1144598	1.2223770	1.4453527
usbb	7.7268714	0.5795005	1.2223770	2.5225607	0.7964365
minh	8 4748664	0.5697617	1.4453527	0.7964365	1.7863626

Table 12. Within class covariance matrix for right side measurements

	Sex=F		DF=26	
Variable	maxh	ulnal	dv	usbb
maxh	0.91071538	1.49692308	0.23596154	0.05646538
ulnal	1.49692308	83.94301994	-1.00133903	3.58911681
dv	0.23596154	-1.00133903	0.71562507	-0.03887037
usbb	0.05646538	3.58911681	-0.03886037	2.48844900

Table 13. Within class covariance matrix for right side measurements

	Sex=M		DF=98	
Variable	maxh	ulnal	dv	usbb
maxh	1.9597187	8.3284838	0.6270016	1.0337924
ulnal	8.3284838	179.2110905	3.4979293	7.8345898
dv	0.6270016	3.4979293	1.6256042	0.4334557
usbb	1.0337924	7.8345898	0.4334557	2.8203320

The percentage accuracies of each discriminant function are presented in Tables 14 and 15. The left and right side functions both classify all the females correctly and have high accuracies for the males as well. The total error count estimate for the left side function is only 1.5% while that for right side function is slightly higher at 2.5%. Histograms (Figures 3 and 4) are used to illustrate the distribution of discriminant scores for males and females for each function and show the number of misclassified cases.

Table 14. Cross-validation summary of linear discriminant function for left side

Number of Observations and Percent Classified into Sex

From sex	F	M	Total
F	22 100.00	0 0.00	22 100.00
M	3 3.06	95 96.94	98 100.00
Total	25 20.83	95 79.17	120 100.00

Error Count Estimates for Sex

	F	M	Total
Rate	0.0000	0.0306	0.0153

Table 15. Cross-validation summary of linear discriminant function for right side

Number of Observations and Percent Classified into Sex

From sex	F	M	Total
F	27 100.00	0 0.00	27 100.00
M	5 5.05	94 94.95	99 100.00
Total	32 24.40	94 74.60	126 100.00

Error Count Estimates for Sex

	F	M	Total
Rate	0.0000	0.0505	0.0253

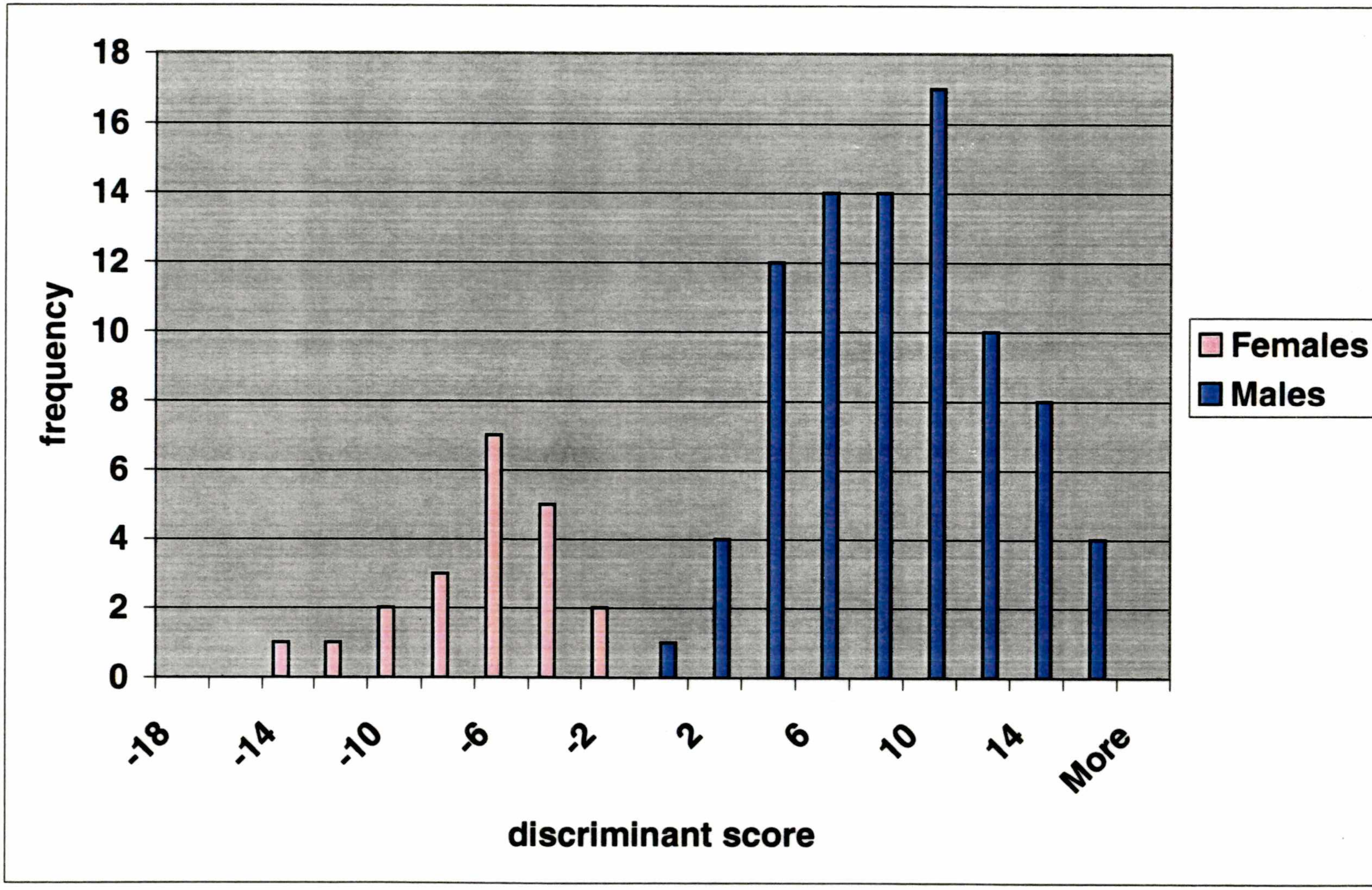

Figure 3. Distribution of males and females based on left side discriminant function.

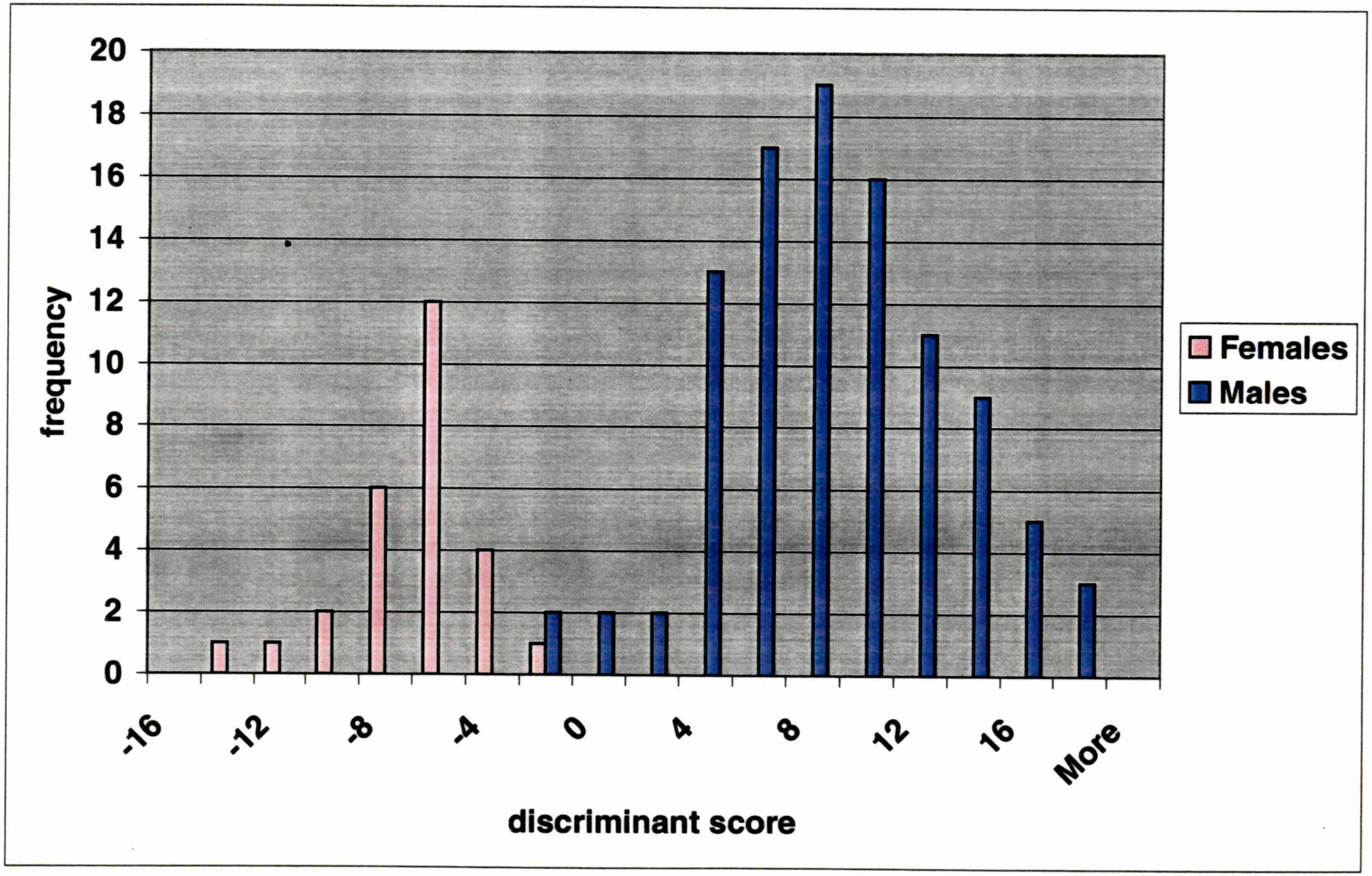

Figure 4. Distribution of males and females based on right side discriminant function.

Chapter 5

Discussion

From the forensic standpoint, the usefulness of this study lies ultimately with the posterior probabilities of the discriminant function for each side. In this context, the posterior probability tells the likelihood of an unknown individual's sex. Assuming equal priors of 0.5 for each group (males and females), the posterior probability is expressed as π male • exp (discriminant score)/π female + π male • exp (discriminant score). Using posterior probabilities helps us avoid the trap of the sectioning point. For example, if the calculated discriminant score is zero (also the value of the sectioning point) the posterior probability would be 0.5, which tells us that the individual is equally likely to be either sex. A posterior probability of 0.5 indicates that the likelihood that an individual is male is 50% (also 50% for female), therefore a discriminant score of zero is essentially uninformative in regard to sex estimation. In another example, a discriminant score of 2 yields a posterior probability of 0.8808, indicating that the likelihood of an individual with this score is male is around 88%.

The fact that long bone lengths and especially radial head diameters and wrist breadth measurements were selected as the most discriminating variables is not surprising. Obviously, these measurements show more sexual dimorphism than the others. Males and females do show a large amount of variation in arm length. More significant, however, is that head and wrist breadth dimensions both represent articular surfaces. The selection of these variables most likely reflects the increased loading on joint surfaces due to larger body size and muscle mass typically seen in males compared to females (Dwight 1904/1905; Hamilton 1982).

The researcher is still unsure why different variables were chosen for the left and right side functions, but considers the effects of handedness on the sample as a possible explanation. In this context, handedness is defined as limb dominance for any manipulation performed by the upper extremities (Corballis 1983). The phenomenon of handedness is itself poorly understood despite centuries of observation and speculation. A primary source of confusion is that handedness is apparent in function rather than in structure and therefore, one cannot easily determine a person's handedness by simply inspecting the hands (Coren 1992). Handedness, however, appears to be a uniquely human trait, at least in the sense that the majority of our species are right handed, while other species do not seem to show this consistent bias (Corballis 1983). In fact, estimates of the percentage of left handers in the human population range from only 8% (McManus 1991) to 12% (Bryden et al. 1996; Corballis 1983; Coren 1992). The actual cause of the variation among people has not been determined, and it is not known which factors account for the strong shift toward right lateral dominance in man. Several theories have been proposed that suggest that variations in handedness may arise from three sources: 1. genetic transmission, 2. factors operating accidentally in the course of development, and 3. cultural transmission (Annett 1972; Bishop 1990; McManus 1991). In addition, empirical data shows that males are 25% more likely to be left handed than females (Corballis 1983; Coren 1992; McManus 1991). This observed sex difference is often explained as a difference between men and women in the association between handedness and cerebral organization (McManus 1991). One of the more interesting explanations proposed by Annett (1972) concerns the well-established difference between the sexes for the efficiency of certain language functions especially during early development. According to Annett (1972), the higher occurrence of right handedness among females together with their advantage in the development of vocabulary and reading skills suggest that right laterality and language development may depend on a common factor. Obviously, the most significant point raised by the handedness research, at least for this study, is the greater frequency of left handedness in males compared to females. However, the effect an individual's handedness may have on the discriminant function's sexing ability, if any, is not clear at this time.

Clearly, many aspects of skeletal morphology have changed since the nineteenth century (Eveleth et al.1979; Fogel 1986; Jantz 1996). The skeletal biology of Americans is constantly changing due to new migrations and improvements in nutrition, medicine, and hygiene, which results in different patterns of growth, development, morbidity, and mortality (Jantz and Owsley 1984; Prince 1995). For this reason, historic anatomical collections are rendered less appropriate for the development of discriminant sexing functions for application in modern situations (Ousley and Jantz 1998). Accuracy in sex prediction is improved considerably with discriminant functions developed from measurements taken from modern skeletons, as shown by this study.

In conclusion, while both the radius and ulna can be of value for estimating the sex of the human skeleton, the dimensions of the ulna have more sex discriminating capacity. This method could be extremely useful for assessing the sex of unknown individuals, particularly in a forensic setting where dismemberment and disarticulation are not uncommon. Discriminant function analysis of the radius and ulna provides anthropologists with an alternative sexing technique that would be especially important for cases of scavenged or fragmentary remains in which other indicators (i.e. pelvis, cranium) cannot be used. However, this method is not without fault and like with all methods, caution should be exercised when relying solely on the radius and ulna for sex estimation. If possible, investigators should examine all the indicators present to obtain the most accurate sex prediction for an unidentified case.

Chapter 6

Conclusion

A study of sex estimation was conducted on 165 white and black skeletons of known sex from the William M. Bass donated human skeletal collection in the Forensic Anthropology Center at the University of Tennessee, Knoxville. A series of measurements were taken on the paired radii and ulnae of each skeleton and recorded on data sheets prior to analysis by the SAS statistical program. The outcome of the statistical analysis was as follows:

• the selection of certain discriminating variables particular to each side (left: minimum radial head diameter, radius semibistyloid breadth, ulna length, dorso-volar diameter of the ulna, ulna semibistyloid breadth; right: maximum radial head diameter, ulna length, dorso-volar diameter of the ulna, ulna semibistyloid breadth).

• the calculation of separate discriminant functions for each side for estimating the sex of an unknown individual.

left side function:
discriminant score=0.68375(min head)+0.63292(radius SBB)+0.11556(ulna length)
+1.26843(d-v diameter)+0.53198(ulna SBB)+ -89.57498

right side function:
discriminant score=1.1751(max head)+0.13188(ulna length)+1.20864(d-v diameter)
+0.57074(ulna SBB)+ -86.50441

*discriminant scores less than 0 classify as female for both sides

• high degrees of accuracy for both sexing functions as shown by crossvalidation within the sample.

It was found that although the left and right functions used slightly different combinations of measurements, primarily measurements of the ulna were the most diagnostic for sexing. This outcome is in direct contrast to results obtained by previous researchers, such as Berrizbeitia (1989) and Holman and Bennett (1991), who suggested the radius as a better predictor of sex. Despite the reported success of the functions for sex estimation, females were classified more accurately than males by both functions, perhaps due in part to the relatively small amount of females in the sample.

An interesting point raised by this research is the possibility of a link between handedness and sex, and what effect this may have on methods of sex estimation. Future research should explore the role of the sex differential in handedness and its impact on an anthropologist's ability to diagnose skeletal material. One avenue of research could investigate whether cases misclassified by one function (left or right) could be accurately assessed by the function for the other side. Perhaps the question should be raised whether sex estimations based on dimensions of the upper extremities would become more accurate if the individual's hand preference was known. For this reason, it may be beneficial to the field of forensic anthropology if databases for skeletal material began providing handedness information.

In summary, this thesis has examined the relationship between sex and dimensions of the forearm bones, in particular the radius and ulna, in an attempt to devise a method of sex estimation. As they are based on a modern sample, the resulting discriminant functions are more applicable for use in modern forensic cases compared to historic anatomical collections. The sexing functions obtained through this research can yield more satisfactory sex estimations because they are less susceptible to the effects of secular change. In addition, since a significantly high degree of accuracy is reported for each function, this method may prove especially useful in dismembered, fragmented, or scavenged cases where other reliable indicators of sex are not present.

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Vita

Elizabeth Briana Reilly was born in Ft. Lauderdale, Florida on August 22, 1976. In May of 1994, she graduated from Palm Beach Lakes Community High School. She attended the University of Florida, majored in Anthropology, and received a Bachelor of Arts degree with honors in May of 1998. In the fall of 1998, Elizabeth began her graduate studies at the University of Tennessee, Knoxville and was awarded the Master of Arts degree in the field of Anthropology in May of 2000.