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I am submitting herewith a thesis written by Tom Edward Bodkin entitled "Morphometric Discriminant Function Sexing of the Adult Human Greater Sciatic Notch." 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.

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MORPHOMETRIC DISCRIMINANT FUNCTION SEXING  
OF THE ADULT HUMAN GREATER  
SCIATIC NOTCH

A Thesis

Presented for the

Master of Arts

Degree

The University of Tennessee, Knoxville

Tom Edward Bodkin

December 1995

## **DEDICATION**

This Masters thesis is dedicated to my late father, Edward B. Bodkin. Every person that ever knew him said he was “the nicest person they’d ever met.” As a land surveyor he used to say, “God created this beautiful earth, I simply measure it with his help.” As a father he used to always say, “A day in which you don’t learn something is a day wasted.”

## ACKNOWLEDGMENTS

The completion of this thesis and my graduate training could not have been possible without my wife, Amy Bodkin. I thank her above and before all others. This personal thanks is also extended to my mother, my immediate and extended family, and my friends for supporting me during this quest- even during the neurotic times.

Professional thanks first go to the chair of my thesis committee, Dr. Lyle Konigsberg, for his patience, understanding, and help. Without him I would still be searching for a Skeletal Biology project. My other committee members, serving no less than the chair, were Dr. William Bass and Dr. Andrew Kramer. I would like to recognize Dr. Bass as the person responsible for transforming me from a graduate student to a professional. His patience should have been exhausted a long time ago yet he persisted with me. I am grateful to Dr. Bass for giving me a graduate assistantship, which gave me invaluable experience as well as financial help. I thank Dr. Kramer for his encouragement and advice, both of which improved my academic growth and my softball game. I could not have chosen a better committee.

Since the thesis is the culmination of one's Masters degree program, thanks must also be given to those along the way who have helped me get to this point. Moving down the hallway, thanks first go to Pam Poe, Charlene Weaver, Cheryl Shope, and Donna Patton. These are the people who really keep the department running, and have provided me with advice, information, and directions on more than one occasion. Thanks to Dr. Richard Jantz for compiling the Terry Collection database into a checklist for me, and Lee Meadows-Jantz for giving me advice, a ride here and there, and for being a friend over the years. Thanks to Dr. Walter Klippel for directly aiding in my other research ventures. Thanks to Dr. Benita Howell for being nice. Thanks to Dr. Sue Frankenberg for letting me earn some spending money. I would also like to thank all my fellow

graduate students for their humor, wit, help, spare change, and most of all their friendship. Some of them helped me with this thesis directly and others provided moral support. I have made a list of friends, both in the Anthropology Department and outside, too long to put here, and to each of you I say, "thank you." I feel fortunate to know each and every one of you.

Outside the department I would like to thank Dr. Bruce Latimer for allowing me to use the Hamann-Todd Collection as part of my sample, and Lyman Jellema, who made sure my every need was taken care of at the Cleveland Museum of Natural History. At the Smithsonian I thank Drs. Ubelaker and Owsley for granting me access to the Terry Collection, and Dr. Dave Hunt for attending to my logistical needs there. Thanks to Mr. and Mrs. Yost of the Cleveland Housing Registry for housing me while in Cleveland; and to my brother and his wife, John and Mary Bodkin, for housing me in D.C. Thanks also to Dr. Jim Schmidhammer in the Statistics Department for reviewing an embarrassingly rough draft of my Methods and Materials chapter, and for statistical advice; and to Dr. Mike Elam for statistical encouragement. I also thank Dr. Nick Honerkamp, Director of the Jeffery L. Brown Institute of Archaeology at UT Chattanooga, who although technically was my undergraduate advisor, has still been an advisor and friend to me through my graduate school experience. Thanks to Mr. And Mrs. Robert Espy for a financial contribution and being a great uncle and aunt. Thanks also must go to Craig Lahren and Dr. Frank King, two good friends who have been supportive of me all these years and gave me the opportunity to get some very valuable experience at the Hamilton County Forensic Center.

Two and half years has been a long time, and in that time I have met many, many people who in some way or another helped me get here. Because time and graduate school have taken their toll on my memory please forgive me for not mentioning your names, you deserve just as much thanks.

## ABSTRACT

Morphometry is a subfield of biometry that combines biology, geometry, and statistics for the purpose of describing biological shape and shape change to facilitate explanations of ontological and phylogenetic development. Recently morphometry has become a tool in human osteological studies to describe skeletal shapes, both in physical anthropology and in the broader areas of biomedicine. This thesis is an application of two-dimensional morphometric methods and discriminant function analysis to determine the sex of skeletal remains using the greater sciatic notch, a structure on the posterior border of the os coxa (hip bone). The sample in this study consists of 254 known sex and age os coxae from the Bass, Hamann-Todd, and Terry Collections. A black-and-white photograph was made of each sciatic notch from the ventral aspect. These photographs were scanned into the computer and digitized. The polygonal edge-approximation algorithm (Batchelor, 1980) was used to construct three homologous landmarks over the continuous form of the notch by fitting a convex hull to each digitized image. The landmarks are then scaled to the Cartesian grid, which allows the maximum width and maximum depth of the notch to be quantified. The sexual dimorphism is observed by holding two landmarks constant while allowing the other landmark to vary. The  $x$ - and  $y$ -coordinate data, or shape coordinates, are used to calculate two shape variable ratios. These variables were subjected to both linear and quadratic discriminant function analysis. The resulting linear discriminant function correctly classified 75.2% of the males, 87.2% of the females, and 81.1% of the total sample. The quadratic discriminant function correctly classified 72.9% of the males, 88.8% of the females, and 80.7% overall. These percentages illustrate that both shape variables exhibit sexual dimorphism when examined together. The male means for both shape variables are greater than in females. Males tend to have a greater length of the anterior segment of the maximum

width line, and they tend to have a greater maximum depth, and these differences are reflected in the ratios produced by these shape variables. The results (percent correctly classified by the discriminant function) are compared to traditional caliper-based studies of the sciatic notch and to other discriminant function analyses elsewhere on the skeleton. The comparison revealed that morphometric methods outperformed traditional methods in sexing the notch. Because the notch is a highly variable structure, however, the current methods did not perform as well as discriminant analyses using other less variable structures. Despite these results the sciatic notch has been an excellent proving ground for the use of morphometric methods in human osteology.

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## CHAPTER 1

### Introduction and Literature Review

This thesis will utilize the relatively new methodology of morphometrics in an attempt to determine the sex of adult human skeletal remains. There are several techniques to do so and no human osteologist would rely on any one single indicator. Several bones or groups of bones in the human skeleton are fairly reliable indicators of sex, such as the long bones or the skull, but the best indicators are those bones that are directly involved in the basic biological difference between the sexes- childbirth. These are the bones of the pelvic girdle: the innominates (also referred to as the os coxae, singular os coxa, or the hip bones) and the sacrum. This work will examine the sexual dimorphism of the innominates, specifically the dimorphism of a structure called the greater sciatic notch.

Why is it important to study sexual dimorphism in this structure? Very often anthropologists find themselves working with only fragmented material, particularly in the prehistoric context. According to White (1991) sciatic notch cortical bone is among the densest in the innominate, rendering it one of the most archaeologically survivable structures in the entire skeleton. The greater sciatic notch, then, would be one of the most sexually diagnostic fragments to recover in a badly damaged or poorly preserved skeleton.

The sciatic notch may be referred to by any one of several names: the greater sciatic notch, the ilio-sciatic notch, the great sacro-sciatic notch (Gray, 1974), or, less commonly, incisura ischiadica major (Letterman, 1941). The structure lies on the posterior border of the innominate, and is formed mostly by the iliac portion but also by the ischial portion. These two portions, along with the pubic portion, achieve complete

fusion as late as 17 years of age in white American males (McKern and Stewart, 1957). The notch functions as a passageway for, "The Pyriformis muscle, the gluteal vessels, and superior and inferior gluteal nerves; the sciatic vessels, the greater and lesser sciatic nerves, the internal pudic vessels and nerve, and the nerves to the Obturator internus and Quadratus femoris" (Gray, 1974:175). Concerning growth and development of the posterior pelvis region and the obstetrical significance of the pelvic outlet, Cave (1937), Morton (1942), and St. Hoyme (1984) provide good reviews. There exists a plethora of literature in osteology and related fields on sexing the innominates, and in most cases the sciatic notch was only one of several structures examined. Thus, a thorough treatment of the literature on this subject would not be complete if one were to include only those contributions that dealt solely with the sciatic notch. To provide a more complete historical framework this literature review will include studies where the sciatic notch was the focus of the study, a part of the overall study, or otherwise significant in the researcher's results.

*The history of sexing pelvis in human osteology can be accurately described as a history of changing methodology.* According to the literature (Day and Pitcher-Wilmott, 1975) the earliest mention of sexual dimorphism in the human pelvis comes from Matthaeus Realdus Columbus (1559). Some assert that the determinative consideration of sciatic notch sexual dimorphism came from Verneau (1875), who reported that this structure was narrower and more shallow in males than in females (Jovanovic and Zivanovic, 1965; Day and Pitcher-Wilmott, 1975; Singh and Potturi, 1978). This observation forms the basis of the subjective assessment of sex from the notch. St. Hoyme (1957) reports the first attempt to use measurements and indices to assess gender from the pelvis came from Matthew and Billings (1891). The reason quantitative studies of the pelvis appeared so late, St. Hoyme explains, was because nineteenth century anthropologists were more concerned with racial differences than sex differences; thus,

the skull received most of the metric attention. One early twentieth century study, Derry (1923), was indicative of this more objective, quantitative trend.

Derry (1923) examined sexual differences in the human ilium using 275 adult skeletons from the Whitechapel plague pits in England, Vth-XIIth Egyptian Dynasties (2500-2000 B.C.), the Predynastic era of Egypt, and from Kerma in the Sudan. Derry observed sexual dimorphism in the sciatic notch by way of the Chilotic line (Figure 1). This is an imaginary line extending from the pubo-iliac point (junction of the three portions of the innominate) to the auricular point (the point closest to the pubo-iliac point on the rim of the auricular surface). The apex is defined as the point in the sciatic notch nearest to the Chilotic line, which corresponded to the deepest point in the notch. A line drawn from the apex to the Chilotic line at 90° divides the Chilotic line into anterior (Pelvic) and posterior (Sacral) segments. He observed in females a longer absolute Pelvic Chilotic line and a larger Pelvic/Sacral index (Chorematic Index). In effect Derry was measuring the relative placement of the notch maximum depth along a fixed line. This idea is still prevalent today although the maximum width of the notch has replaced the Chilotic line because the latter is too difficult to locate from one observer to the next. Straus (1927) expresses his inability to replicate Derry's method. Both researchers, however, did concur with the "narrower versus wider" observations handed down by Verneau.

Derry's (1923) study can also be criticized because his sample consisted of individuals of unknown sex, in fact, in his introduction, he admits one of the problems during the early part of the twentieth century was the lack of availability of large collections of known skeletal material on which to perform skeletal studies. According to Letterman (1941:100), Greulich and Thoms (1938, 1940) overcame this barrier "by means of a rather ingenious method of x-ray pelvimetry." Thoms and Greulich (1940:62), in a roentgenological study of 69 adult white male students, qualitatively

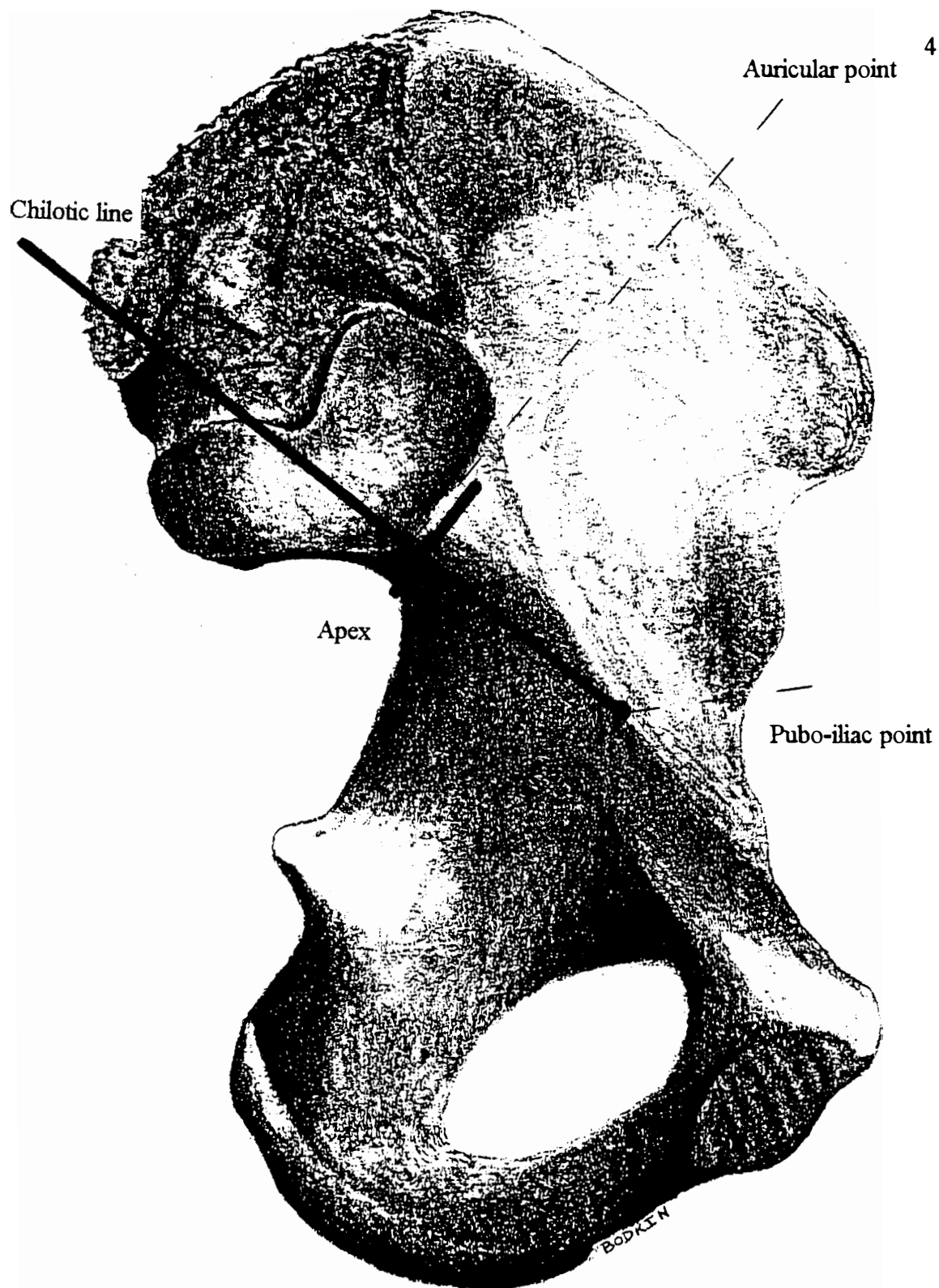


Figure 1. Derry's (1923) measurements (Chilotic and apex lines shown heavier for emphasis, left bone depicted).

observed the "characteristically male" sciatic notch (the Verneau characteristics). The use of x-ray studies opened up not only a new means of examining pelvic structures but also a new *known* living population from which to sample these structures (i.e., Morton, 1942). Caldwell and Moloy (1932), also using roentgenological techniques, explored the relationship of the sciatic notch, pelvic capacity, and the detrimental effects of a narrow cavity on childbirth.

Although roentgenographic techniques proved to be a landmark in health related research, they simply could not replace hands-on experience with real skeletal material. This provided impetus for anatomists such as Robert J. Terry, Carl A. Hamann, and T. Wingate Todd to begin amassing large, well-documented skeletal collections. Letterman (1941), benefiting from one such collection, specifically addressed the sciatic notch using 426 adult innominate bones of known sex and age. His sample was from the Washington University anatomical collection, which was begun in 1920 by Robert J. Terry, and is now housed at the Smithsonian Institution, Washington, D.C. Letterman's study is relevant because the three measurements he used and identified as demonstrating sexual dimorphism are similar to the measurements in Derry (1923), save the notch maximum width replaces the Chiotic line. These measurements are 1) the greatest width of the sciatic notch (AB<sup>1</sup>), 2) the greatest height of the sciatic notch (CD), and 3) the distance from the posterior inferior iliac spine to the intersection of the maximum width and depth lines (AD; see Figure 2). Point C is Derry's (1923) apex. Letterman concluded that the mean of AB is larger in females than in males, the mean of CD larger in males than in females, and the mean of AD shorter in males than in females. Although there are other earlier studies (Genoves, 1921; Lazorthes and Lhez, 1939), this study was the first empirically sound work in English on sexing the sciatic notch.

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<sup>1</sup> The letter designations for all landmarks are used here as the authors use them in their respective articles.



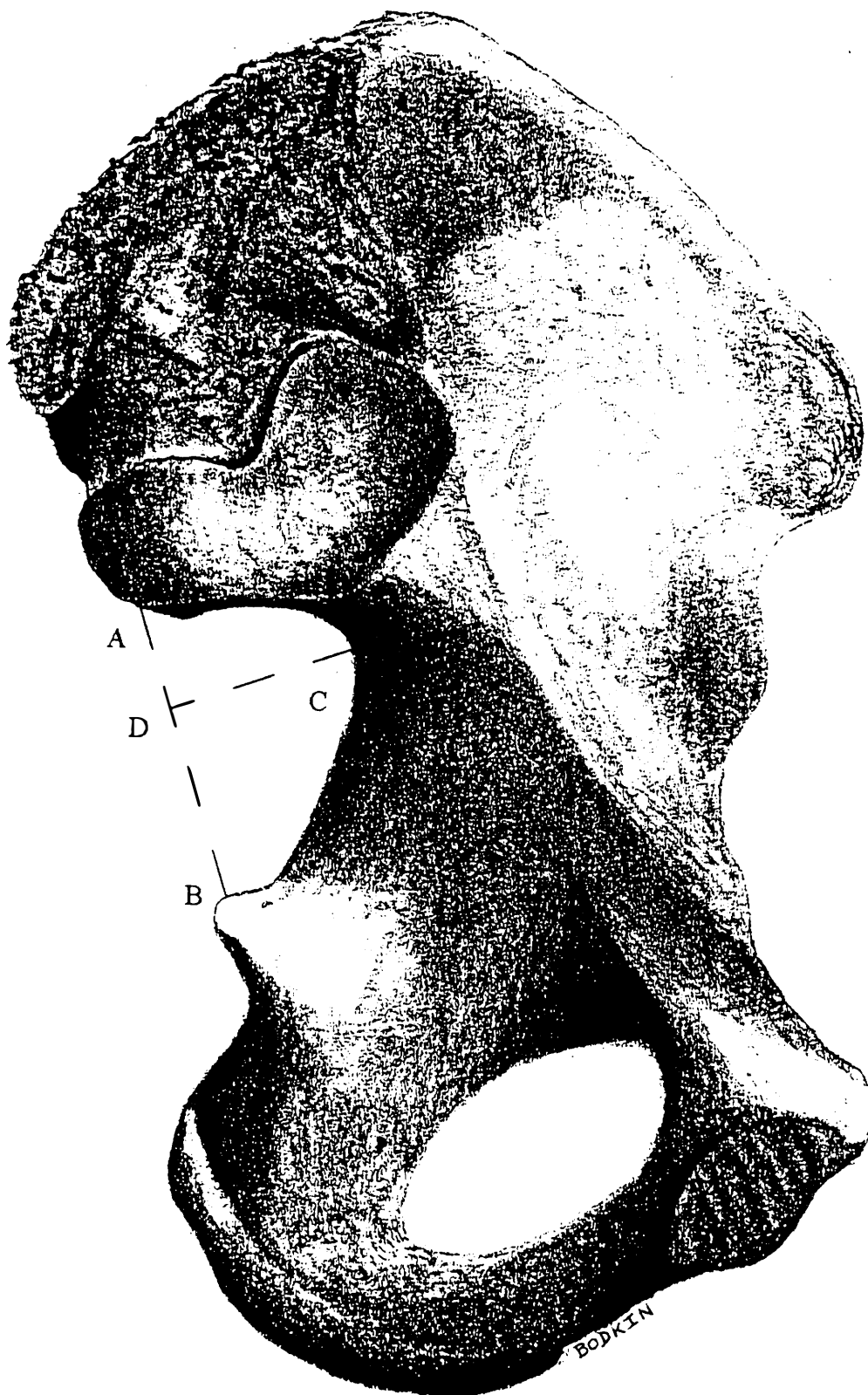


Figure 2. Letterman's (1941) measurements (left bone depicted).

In a short article adapted from his D.Sc. thesis (1945), Heyns (1947) examined the sexual differences in Bantu pelves. Among the 12 structures identified as being significantly dimorphic were the pubic arch and the sciatic notch, but, according to Heyns, the notch was a less reliable indicator of sex. The pubic arch is formed by the convergence of the ischial rami and os pubis portions of the articulated pelvis, and was later incorporated by Phenice (1969) in his visual sexing method. In his "Note of the greater sciatic notch," Heyns (1947:19) tested the claim that the iliac portion of the iliopectineal line is proportional to the width of the sciatic notch. The iliopectineal line is the crest of bone on the ventral surface of the os coxa, beginning at the ventral margin of the auricular surface and extending ventrally toward the ascending ramus of os pubis (Gray, 1974:174). Using a sample of 50 female and 40 male Bantu (Zulu) pelves he could not substantiate the hypothesis. As an alternative Heyns suggests that: 1) the greater width of the notch in females allows greater length of the superior limb of the notch; 2) in females the angle formed by the superior and inferior limbs (sides) of the sciatic notch is closer to 90 degrees than in males; and 3) ischial spine development will affect the anterior limb of the notch- the more massive the spine, the less wide the notch. In short, iliopectineal line development does not influence the width of the sciatic notch. Heyns makes no reference in this article as to whether or not his sample consisted of known or unknown material, nor of where the sample was housed. It might be assumed that the Bantu skeletons are from the University of Witwatersrand, South Africa, (Heyns' earlier D.Sc. granting institution), and that they were of known sex, because Washburn (1949) used this same collection as a known sex sample.

Washburn (1949) explored the applicability of pelvic sexing techniques across ethnic boundaries. In the main his article was a test of the ischium-pubis index devised by Schultz (1930) and tested earlier by Washburn (1948). In all of these works, after applying the index, the sciatic notch was consulted in order to assess gender in some of

the "doubtful cases." Washburn's (1949) study, however, did consider the notch as a separate character. Using 152 Bantu skeletons of known sex and 55 Bushman skeletons of unknown sex from several South African institutions (mainly the University of Witwatersrand), Washburn (1949) took only one measurement from the notch, its width. He found the female notch width averaged 1 centimeter (cm) wider than in the males, with a coefficient of variation of over 15. He suggested that the ischium-pubis index, with a coefficient of variation less than 5, was a more reliable indicator than the notch width. Nevertheless, Washburn (1949) concluded that while the majority of the skeletons could be sexed using the ischium-pubis index, the index combined with the notch could sex over 98% of the material.

In 1952 (and 1955) Sauter and Privat introduced the cotylosciatic index. Published in French, English researchers can find mention of this index in Jovanovic et al. (1973) and Krogman and Iscan (1986), however, there is a discrepancy between these two accounts. Jovanovic et al. (1973:63-65) report the index as  $\text{height of the sciatic notch} \times 100 / \text{cotylosciatic diameter}$ , while Krogman and Iscan (1986:211-212) write just the opposite,  $\text{cotylosciatic diameter} \times 100 / \text{height of the sciatic notch}$ . Regardless of which has reprinted the original formula, both agree on the measurements needed to compute the index. The cotylosciatic diameter is measured from the posterior border of the acetabulum to the middle of the anterior arm of the sciatic notch. The sciatic height is from the middle of the anterior arm of the sciatic notch to the lowest point on the posterior inferior iliac spine. One should note that Sauter and Privat's sciatic height differs from Letterman's (1941) sciatic height. In general, the cotylosciatic diameter should be larger in males than in females, and the sciatic height larger in females than in males. Although other methods have achieved higher percentages of correct classification, the Sauter and Privat method utilized new measurements and a new index to reveal the sexually dimorphic properties of the sciatic notch region.

Also using a new way of quantifying the sciatic notch, Hanna and Washburn (1953) tested the ischium-pubis index (Schultz, 1930) on an Eskimo population, and like Washburn (1949), the sciatic notch played a secondary role. Their sample consisted of 224 skeletons of unknown sex from the United States National Museum of Natural History, Smithsonian Institution. Instead of using the notch width, the angle of the notch was quantified. The innominate was placed anterior side up on a piece of paper and, with light from a distant source, the outline of the sciatic notch as it appeared on the paper was traced by hand. Straight lines tangent to the sides of the notch were drawn, and the angle between the lines was measured. The authors report that in no case did an ischium-pubis index of one sex combine with a sciatic notch angle of the other sex. Their results do seem to be significant but the replicability of computing the sciatic angle seems low at best from their published methods.

Davivongs (1963) reported on sex differences in an hitherto unexamined population, the Australian Aborigine. Among the several characters he quantified in the pelvic girdle was the sciatic notch. His sample consisted of 100 adults of unknown sex and age, 50 sexed as females and 50 as males, from the South Australian Museum and the University of Adelaide. On the notch he measured the greatest width (AB), the greatest depth (OC), and the posterior segment of the width line (OB), and calculated two indices:  $\text{Index I} = (\text{OC}/\text{AB}) \times 100$ , and  $\text{Index II} = (\text{OB}/\text{AB}) \times 100$  (see Figure 3). He cites Olivier (1960) as the source of Index I. Davivongs (1963) reports both conflicting and substantiating results from Derry (1923) and Letterman (1941). These latter researchers found that males tend on average to have deeper sciatic notches than females, but the Australian material demonstrates a greater depth in females than in males. Davivongs (1963:452) justifies this as being due to different measurement techniques, excluding Derry (1923) since he did not measure the notch depth *per se*. Davivongs concludes by

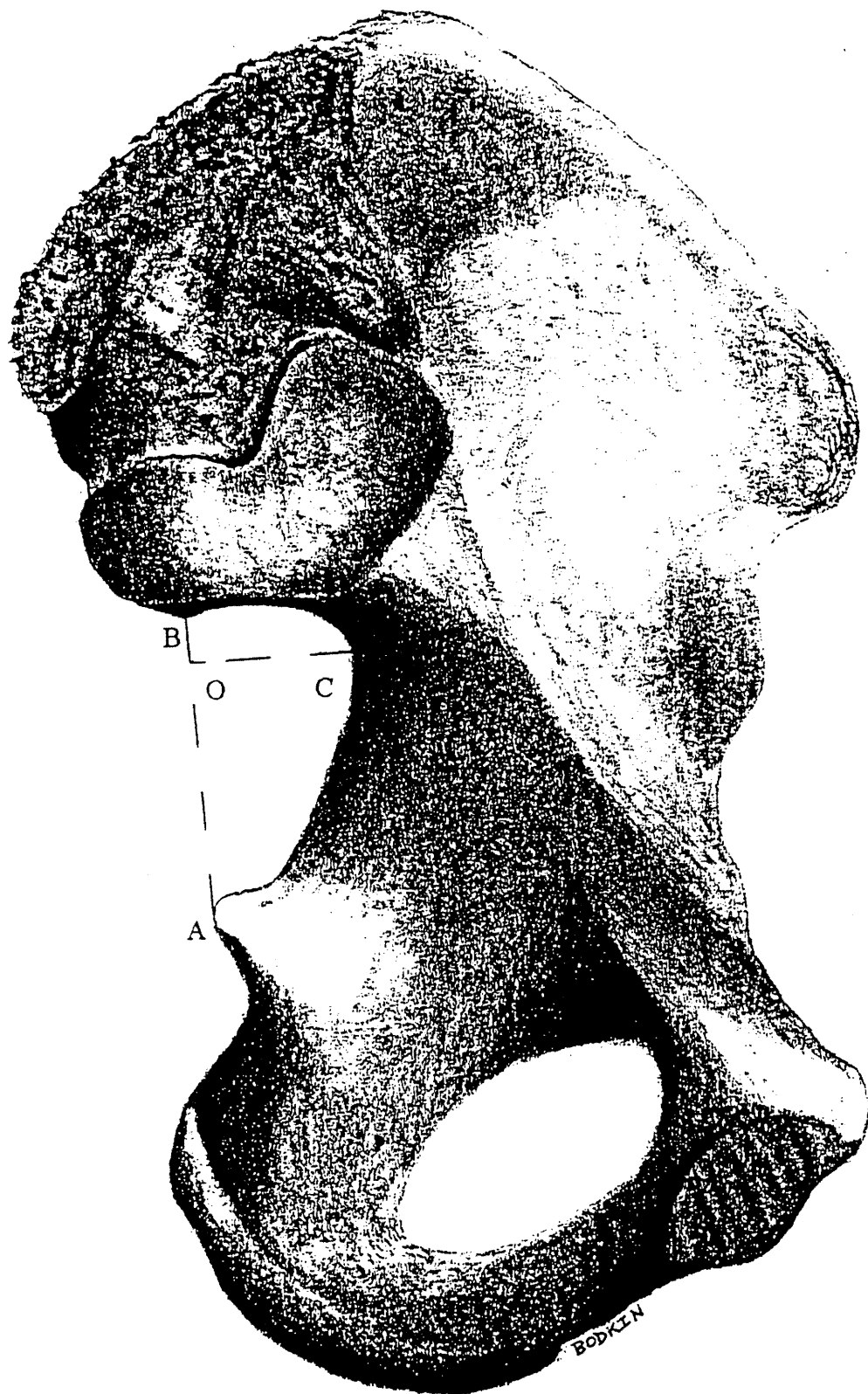


Figure 3. Davivongs' (1963) measurements (left bone depicted).

saying that the most useful determinants of sex concerning the sciatic notch are the length of OB and Index II. The OB measurement agrees with Letterman's (1941) line AD.

Jovanovic and Zivanovic (1965) wanted to make sexing the sciatic notch more replicable between observers, and to make the assessment of sex dependent only upon the notch. Using 102 known sex adult pelves from the Department of Anatomy in Lyon, France, they measured both the width and the depth of notch, the posterior segment of the width line (AC, Figure 4), and calculated an index. The width was taken to be from the posterior superior iliac spine to the most medial point on the inside ridge of the ischial (schiatric) tubercle (AB, Figure 4). Depth was measured from the line formed by the width measurement to the deepest point in the notch (CD, Figure 4). It should be noted that the width and depth lines do not correspond exactly to the depth measurement of previous researchers (e.g., Letterman, 1941). Jovanovic and Zivanovic (1965:102) state that although their width measurement is not the "correct [measure] of the notch," as prescribed by Verneau (1875) and Martin and Saller (1957), they are, "solid and permanent morphological points which can be found easily on every pelvic bone including damaged ones." The index used is  $AC \times 100/CD$ . Ironically, one weakness in their work is the unusual length of the width measurement: long measurements tend not to be as practical in skeletal studies because of the bone's low archaeological survivability.

These same authors tested the use of their technique in determining sex from the sciatic notch in pathologically deformed pelves, including asymmetrical abnormalities (Jovanovic et al., 1968). Using 75 adult pelves from the Lyon collection, they found it to be a reliable indicator of sex in deformed pelves, particularly the upper part of the notch, as measured from the junction of the depth and width lines to the posterior superior iliac spine. Again, caution should be taken when comparing Jovanovic and Zivanovic (1965) methods to other sciatic notch studies because of the different width measurement.



Figure 4. Jovanovic and Zivanovic's (1965) measurements (left bone depicted).

Jovanovic et al. (1973) tested the Sauter and Privat method on the same pathologically deformed collection but found that it was not a reliable indicator of sex in such circumstances.

Up to this point the majority of skeletal sexing studies had been done using univariate statistics, a methodology which tends to obscure complex shape information instead of revealing it. Univariate studies use single measurements to describe an individual. In reality an individual (or individual bone) is composed of a profile of measurements- or a vector- and univariate studies "dismember" the individual's measurement vector into a number that is no longer truly descriptive of the individual (Howells, 1969:312). In 1926 the emergence of the Pearson Coefficient of Racial Likeness (CRL) signaled a shift from correlation and variation studies to population comparisons (Pearson, 1926). Although the CRL was later discredited, the limitations of univariate studies became apparent. Howells (1969) recounts that to overcome the univariate shortcomings researchers began a major effort to use ratios and indices (see St. Hoyme, 1957), but the answer to making meaningful population comparisons came with multivariate statistical analysis. One such multivariate technique is the discriminant function, developed mainly through the work of Fisher (1936, 1938, 1940) and others (chiefly the separate works of Mahalanobis, Hotelling, and Rao). According to Day and Pitcher-Wilmott (1975), Howells (1964) was the first to use discriminant function analysis in the sexing of innominate bones. Kimura (1982) claims Hanihara and Kimura (1959) were first. Despite these boasts the recognition must go to Thieme and Schull (1957) for including the ischium length and pubis length in their discriminant analysis. The development of the CRL, claims Giles (1970; paraphrasing M.A. Girshick, originally in Hodges, 1955), represents the first stage in the development of multivariate discriminatory analysis, or the Pearsonian stage, while the discriminant function analysis currently in use represents the second, or Fisherian stage.



An important article in the development of sexing skeletons came from Weiss (1972). Weiss speculates that, in general, the examined skeletal series contained about 10-15%, or an average of 12%, too many males. Researchers should expect any given series to contain 50% males. The reason such systematic biasing exists could be the propensity of researchers to assign male to an indeterminate skeleton, cultural rules affecting burial practices that we do not know about, or that censused living pre-industrial peoples do not provide an accurate analog of expected sex ratios. Weiss maintains that systematic biasing can be avoided by being aware of the biases inherent in sexing techniques. Only when there is a complete lack of other information should a blanket correction factor be employed. Weiss's article is further evidence that more objective and accurate methods for sexing individual skeletons are needed (for more recent work on biasing in sex estimations, see Meindl et al., 1985).

Day and Pitcher-Wilmott (1975) attempted to satisfy this need. They performed a multivariate analysis on a series of 59 known sex skeletons from the St. Bride's Church in London. They used seventeen measurements and seven indices (a total of 24 variables), all measured with automated calipers feeding the information into a computer. The authors say they selected the variables because of their ability to discriminate sexually, either in their opinion or in the opinion of previous workers. Most of the variables originated in Genoves (1956). Two variables utilized measurements involving the sciatic notch: the width of the notch (I, Figure 5), and an index using the height of the acetabulum/width of the notch. The researchers define the height of the acetabulum as, "The maximum vertical diameter following the general axis of the body of the ischium and perpendicular to the superior pubic ramus" (Day and Pitcher-Wilmott, 1975:145). Of these two variables the index was more accurate than the width of the notch.

Another work addressing the greater sciatic notch appeared in 1978 from Singh and Potturi. They examined 200 skeletons of known sex from the Banaras Hindu



Figure 5. Day and Pitcher-Wilmott's (1975) measurements (left bone depicted).

University's Department of Anatomy, Varanasi, India. Using triflanged stainless steel calipers they measured the width (AB), depth (OC), posterior segment of the width line (OB), and calculated two indices and two angles: Index I =  $OC \times 100 / AB$ , Index II =  $OB \times 100 / AB$ , the total angle ( $\angle ACB$ ; constructed on paper), and the posterior angle ( $\angle BCO$ ; see Figure 6). Singh and Potturi (1978:623-624) conclude that AB and OC were useless criteria for sexing and the posterior angle ( $\angle BCO$ ) was the best parameter. The length of the posterior segment (OB) and Index II were also considered to be accurate. These authors cite Davivongs (1963) and Jovanovic and Zivanovic (1965) as the source for their indices. They make no mention, however, of Jovanovic and Zivanovic's (1965) different measuring technique.

Kelley (1979) was prompted to examine the sciatic notch in a slightly different manner because a) the notch width alone, as one has seen, tends not to be a reliable indicator, and b) even though the structure as a whole is more likely to survive in the archaeological context, the ischial spine tends to be damaged, precluding accurate measurement of the notch width. To overcome these problems Kelley used the sciatic notch/ acetabular index because both structures yield a better determination of sex when combined than either used alone. This index was originally introduced by Genoves (1956) and tested by Day and Pitcher-Wilmott (1975). He overcomes the damaged ischial spine problem by measuring sciatic notch width from the base of the spine, instead of its tip, to the pyramidal process (AB, Figure 7). The index is  $[\text{notch width in millimeters (mm)} / \text{acetabular diameter (mm)}] \times 100$ , which differs somewhat from the index given in Day and Pitcher-Wilmott (1975). Kelley was able to correctly sex at least 90% of his material. His sample consisted of 400 pelves of known sex from the Hamann-Todd Collection at the Cleveland Museum of Natural History and 200 archaeological specimens from the University of California, Berkeley.

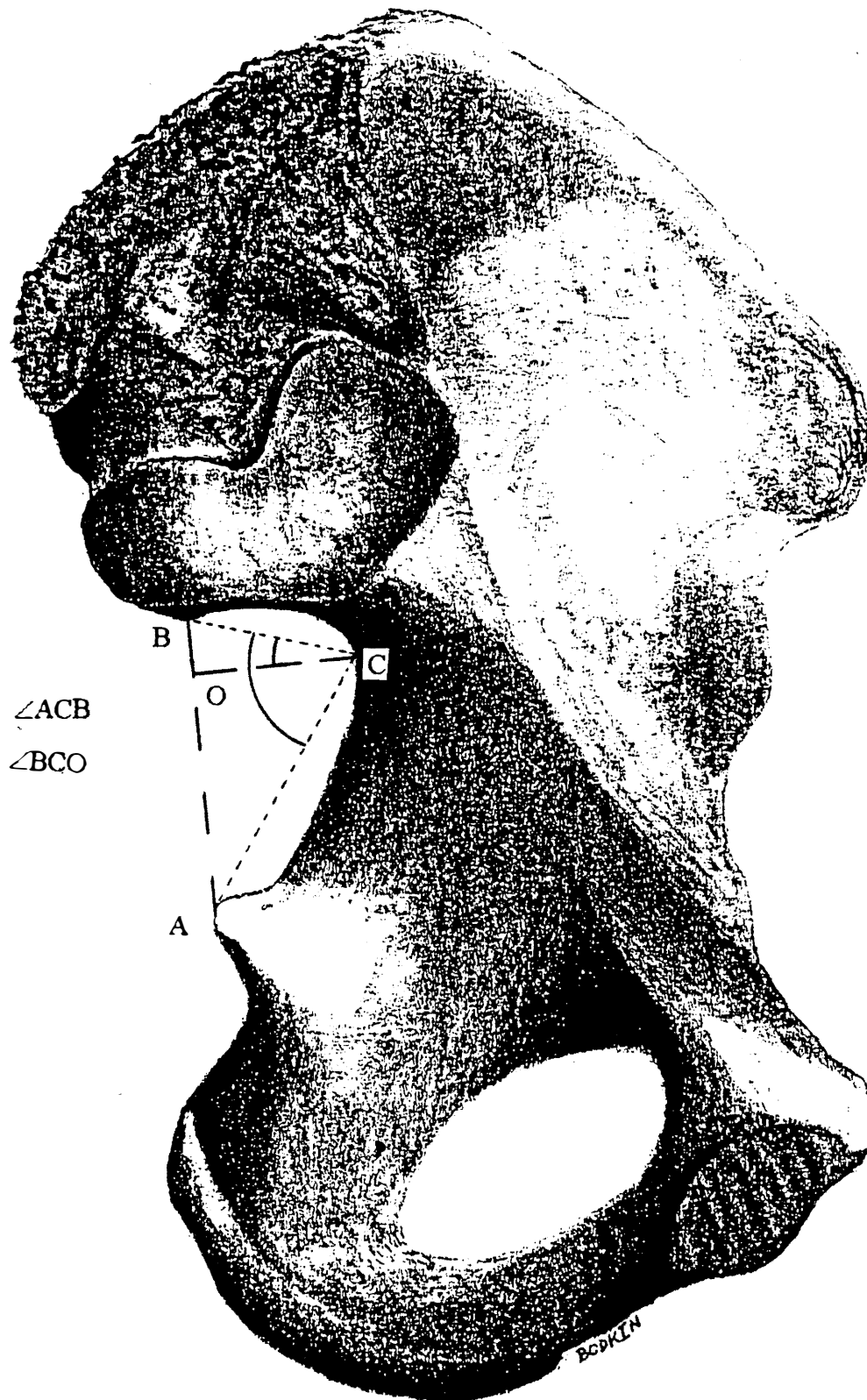


Figure 6. Singh and Potturi's (1978) measurements (left bone depicted).



Figure 7. Kelley's (1979) measurements (left bone depicted).

Segebarth-Orban (1980) examined the sciatic notch in a novel way. His sample consisted of 99 innominate bones and 59 mounted pelves of known sex dating from nineteenth century France and Belgium. He defined three points around the border of the notch: ECH as the deepest point in the notch, ES as the tip of the ischial spine, and EPI at the tip of the posterior inferior iliac spine. He then computed the triangle ES-ECH-EPI and found it to be more isosceles among women than among men (Figure 8). In essence Segebarth-Orban was measuring the “shifting” around of point ECH while attempting to hold the EPI-ES baseline constant. This is very similar to the morphometric characterization of the notch discussed in the next chapter. One criticism of this article is that the reader is not clearly informed of the percent correctly classified by the procedure.

Using discriminant function analysis, Taylor and DiBennardo (1984) modified Kelley's (1979) "simple linear approach" using a base sample of 260 known innominates from the Terry Collection, Smithsonian Institution. First, these authors added another variable to Kelley's notch width and acetabular height, that of notch position (distance from the tip of the ischial spine to the intersection of the notch height; BC in Figure 9). Secondly, these authors used discriminant function analysis instead of an index to discriminate sex when race is known. Taylor and DiBennardo were critical of Kelley's choice of landmarks, saying the base of the spine was too difficult to locate.

Another test of the Kelley (1979) “rule of thumb” came from MacLaughlin and Bruce (1986). Without modifications to the procedure, such as Taylor and DiBennardo (1984), these authors tested the index on two samples: 131 documented adults from the St. Brides Church in London, and 140 documented adults from a dissecting room cadaver collection housed at the University of Leiden, The Netherlands. The authors cite poor landmark definition and difficulty in orienting the innominate to measure acetabular height as reasons for their weak results.

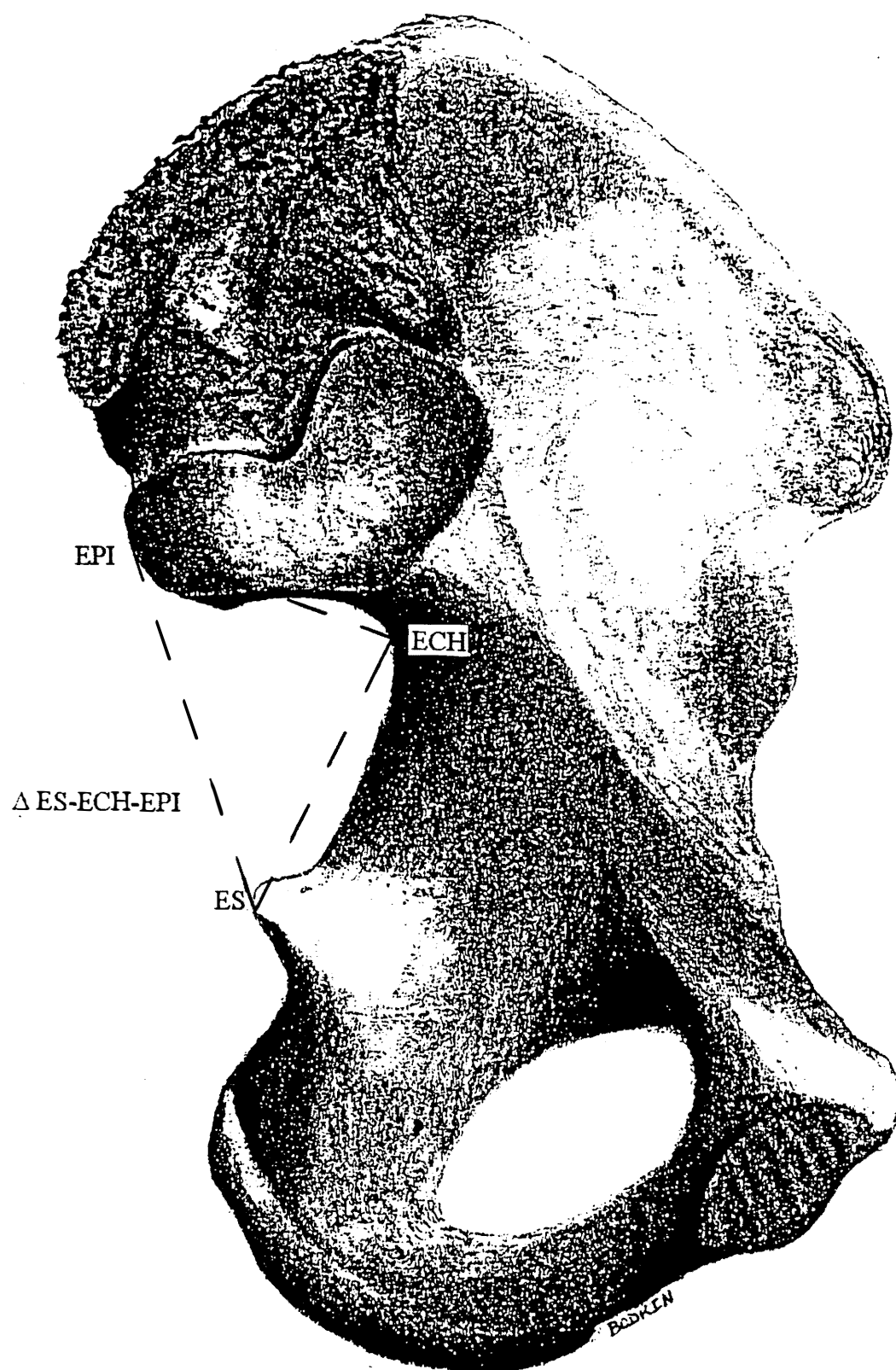


Figure 8. Segebarth-Orban's (1980) measurements (left bone depicted).

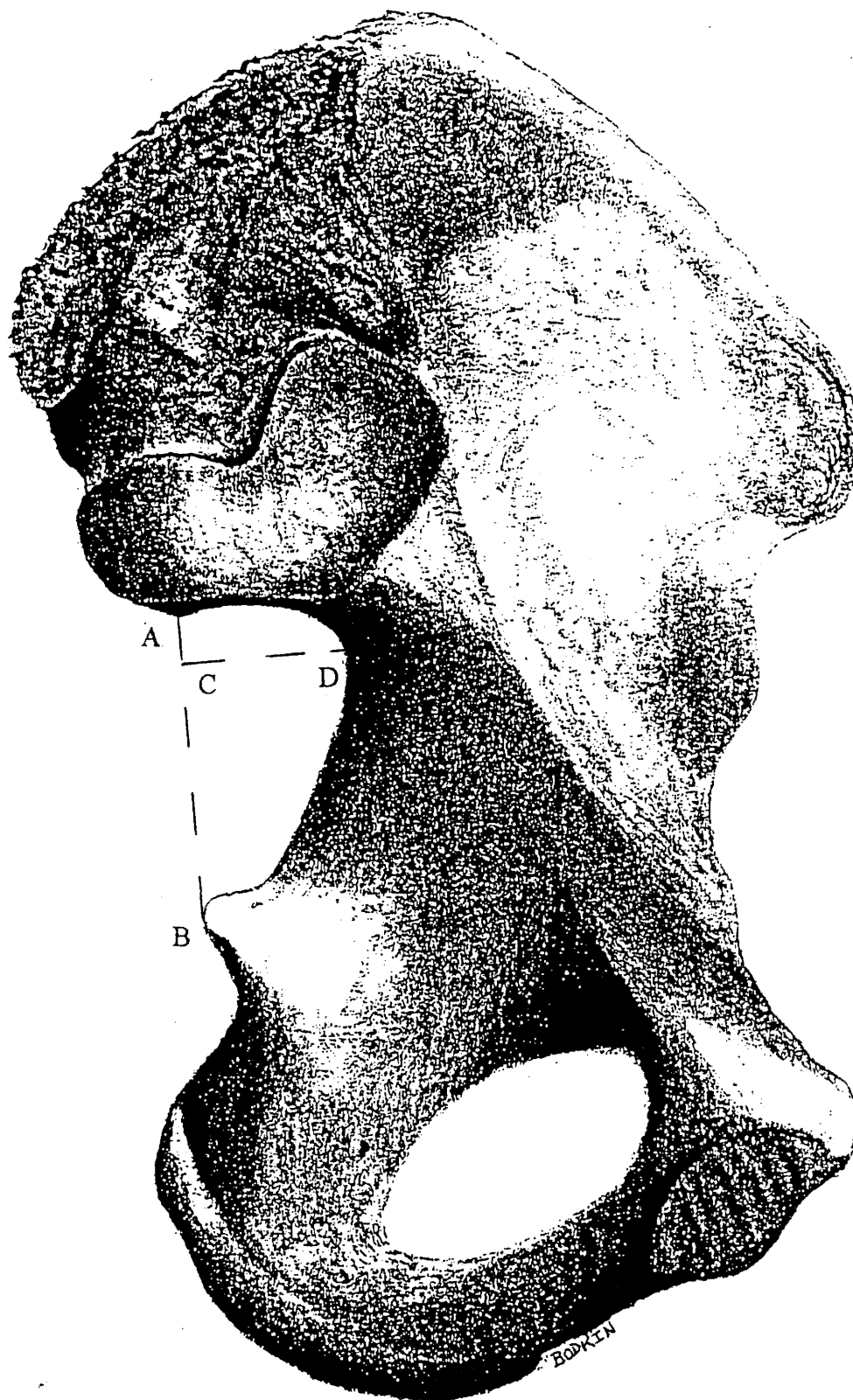


Figure 9. Taylor and DiBennardo's (1984) measurements (left bone depicted).



As is evident from this historical review there have been a variety of ways to examine and measure the greater sciatic notch, each with varying success. The earliest attempts to determine sex from the notch were subjective determinations, claiming the structure wide and shallow in females, narrow and deep in males (the Verneau characteristics). While these are valid dimorphic properties of the notch they create an objective void in forensic court cases. Metric analyses of the skeleton, to determine such things as sex, fill that void by rendering assessments about an individual replicable from one observer to the next. Objective assessments make interpretation less dependent upon the evaluator's experience and more dependent upon the physical evidence. But the need for objectivity extends beyond the courtroom to the analysis of archaeological samples. One of the first steps in attempting to reconstruct the lifeways of prehistoric peoples is to determine who exactly is represented in the sample. Sex ratios that depart from what one might expect warrant explanation, and we could feel more confident in our explanations if we know that observed sex ratio differences are due to cultural or preservational factors rather than our misdiagnosis.

The present thesis is an attempt to apply the methodology of morphometrics to the sciatic notch to effect a more objective assessment of sex in unknown individuals. Sophisticated morphometric analysis has only come to the foreground since the late 1970's and early 1980's, although its seeds were planted by D'Arcy Thompson (1961). Technological advances in computers and software, such as the SigmaScan software package used herein to describe shape, have undoubtedly advanced the field. The statistical procedures employed in this thesis have been in use somewhat longer, but it is geometry that enjoys the title of the oldest contributing member to morphometrics, owing its beginnings to the Egyptians around 1600-1850 B.C. and the Greeks around 640-546 B.C.

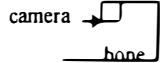
## CHAPTER 2

### METHODS AND MATERIALS

Sciatic notch shape in this thesis is analyzed within the theoretical and methodological framework of morphometrics, a subfield of biometry (Bookstein, 1978, 1982, 1986, 1991). Morphometry is the marriage of biology, geometry, and statistics united for the purpose of describing shape and shape change to facilitate explanations of ontological and phylogenetic developments. Its applications extend beyond physical anthropology into the broader areas of biomathematics and biomedicine. Here morphometric methods are used to quantify sciatic notch shape differences. Central to the morphometric analysis of biological structures are the concepts of homology and landmarks. The concept of homology can best be understood by reference to its sibling concept in biology. There, homology is a correspondence between structures in different organisms. For instance, the bony forearm of humans, consisting of the radius and ulna, is homologous to the forearm of the bat, even though the structures function in different ways. Morphometric homology is the correspondence of points, or landmarks, between organisms. Morphometry is concerned with the relationship between forms (between organisms) and not the single form itself. In order to operationalize hypotheses about this relationship forms need to be described in some empirical fashion. This consists of identifying discrete landmarks over the form that are biologically homologous from organism to organism. A landmark in two dimensions is referenced by a pair of numbers representing the  $x$ - and  $y$ -coordinates. Once the structure as a whole is located by grid coordinates, analysis of the form proceeds as the geometry of shapes. Forms could be referenced by multiple landmarks and analyzed using the geometry of a variety of shapes, but as will become evident, this thesis is only concerned with three shape coordinates and

the geometry of triangles. The methodology using morphometrics to determine sex from the sciatic notch was advanced by Holcomb and Konigsberg (1995), albeit this effort attempted sex discrimination in a fetal sample.

The sample used in this study consists of 254 adult human innominates of known age and sex from three well-documented collections in the United States. The sample is presented in Table 1. The specimens in this sample range in age from 20 to 98. There are a male and female per age year with a few exceptions (i.e., no complete specimen available). In all cases the left innominate was used. Only specimens with complete sciatic notches were selected- complete being defined as an intact ischial spine, notch, and posterior inferior iliac spine. Innominates exhibiting pathological conditions were not included.

Once selected a black-and-white photograph was made of the ventral surface of each bone (Figure 10). A camera stand was used to standardize the photographs, with the camera at a 90° angle  to the base of the stand. Each bone was placed on its dorsal side directly below the camera and allowed to lay naturally on the camera stand base. The photos were then scanned into the computer using a model 256 Logitech Scanman hand-held scanner at 300 dots per inch (dpi). The images were calibrated on the computer screen with a 5 centimeter (cm) scale following the calibration procedures in the SigmaScan software manual (Fox and Ulrich, 1995). Calibration ensures that every image is consistently measured by the computer in the same way. The sciatic notch outline was digitized (traced directly on the computer monitor) using a mouse and the SigmaScan software.

To transform the digitized image of the sciatic notch into a data matrix that will avail itself to multivariate statistical analysis, one needs homologous landmarks, size variables, and most importantly, shape variables. The simplest size variable in morphometry is the distance between two landmarks. Shape variables in morphometric

Table 1. Skeletal collection sources of the sample used in this study

| <b>Collection, Location</b>                                                      | <b>Males</b> | <b>Females</b> | <b>Total</b> |
|----------------------------------------------------------------------------------|--------------|----------------|--------------|
| William M. Bass,<br>University of Tennessee                                      | 14           | 10             | 24           |
| Carl A. Hamann and<br>T. Wingate Todd,<br>Cleveland Museum of<br>Natural History | 56           | 56             | 112          |
| Robert J. Terry,<br>Smithsonian Institution                                      | 59           | 59             | 118          |
| <b>Total</b>                                                                     | 129          | 125            | 254          |

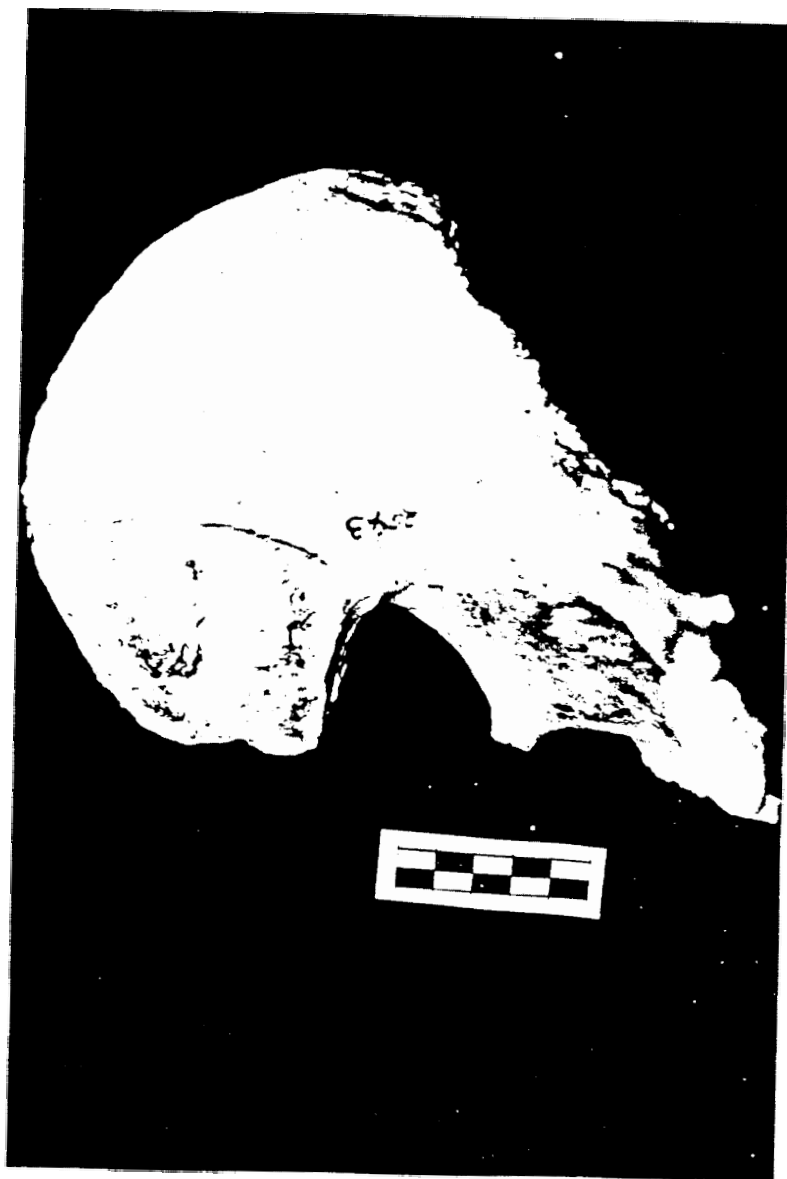


Figure 10. Black-and-white photograph of the ventral surface of the os coxa (left bone depicted).

analysis are considered to be, "The ratio of two size variables, and size variables are combinations of distances between constructed landmarks" (Bookstein, 1991:139). To get the shape variables we begin by identifying the landmarks on the sciatic notch.

The landmarks were mathematically constructed using a FORTRAN program, written by Lyle Konigsberg and based on the polygonal edge-approximation algorithm (PEA) described by Batchelor (1980), which fits a convex hull to the digitized sciatic outline. A convex hull is a kind of convex set. A convex set, "is one with the property that the line segment joining any two points of [the set] lies entirely within the set" (Green, 1981:3). If the vertices are finite, the convex hull will be a closed convex polygon. Green (1981) discusses the use of convex hulls in bivariate data analysis, but here, fitting a convex hull to the sciatic notch outline will enable me to construct landmarks. Each of the digitized points on the outline becomes vertices of the convex hull, except for points that lie within a concavity. A concavity was identified whenever the PEA located two convex hull vertices not adjacent to one another. The PEA was used to identify the largest concavity, which in this case was the sciatic notch. The maximum width of the notch was plotted between the two vertices on either side of the notch, corresponding to the ischial spine and the posterior inferior iliac spine (A and B respectively, Figure 11). These two vertices become the maximum width landmarks. The maximum depth line had to be constructed, unlike the maximum width line, which was a line segment on the convex hull. The maximum depth line created one more landmark: point C is the farthest point on a perpendicular from the maximum width line, or the apex of the notch (Figure 11). Point O indicates the distance along the baseline of the triangle at which this perpendicular falls. Stated otherwise, the PEA has identified two convex hull vertices as morphometric landmarks (points A and B in Figure 12) and one size variable (line AB), from which one landmark (point C, Figure 12) and one size variable (line OC) were constructed. The size variable line AB can be further broken

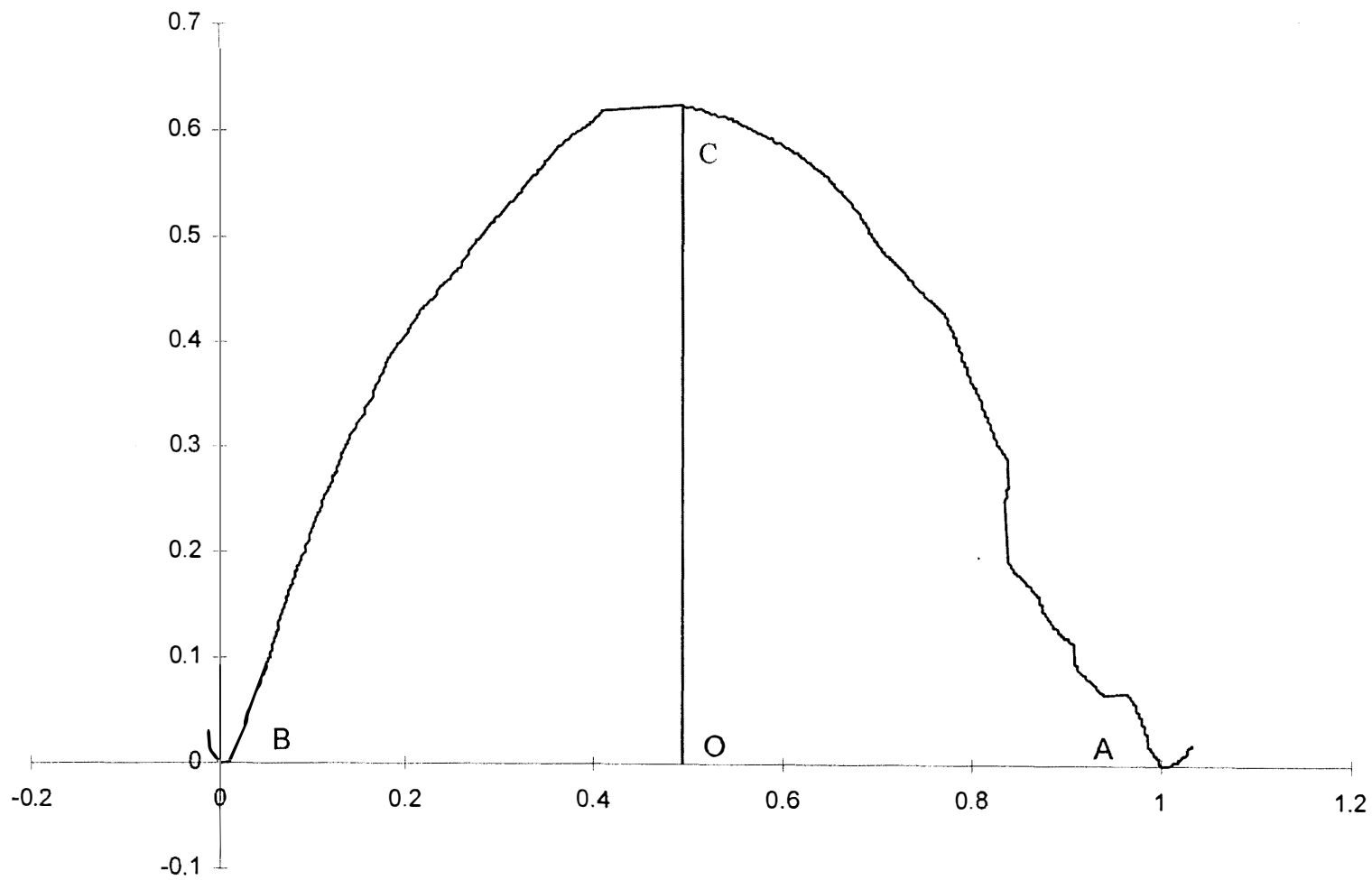


Figure 11. Digitized convex hull on Cartesian grid.

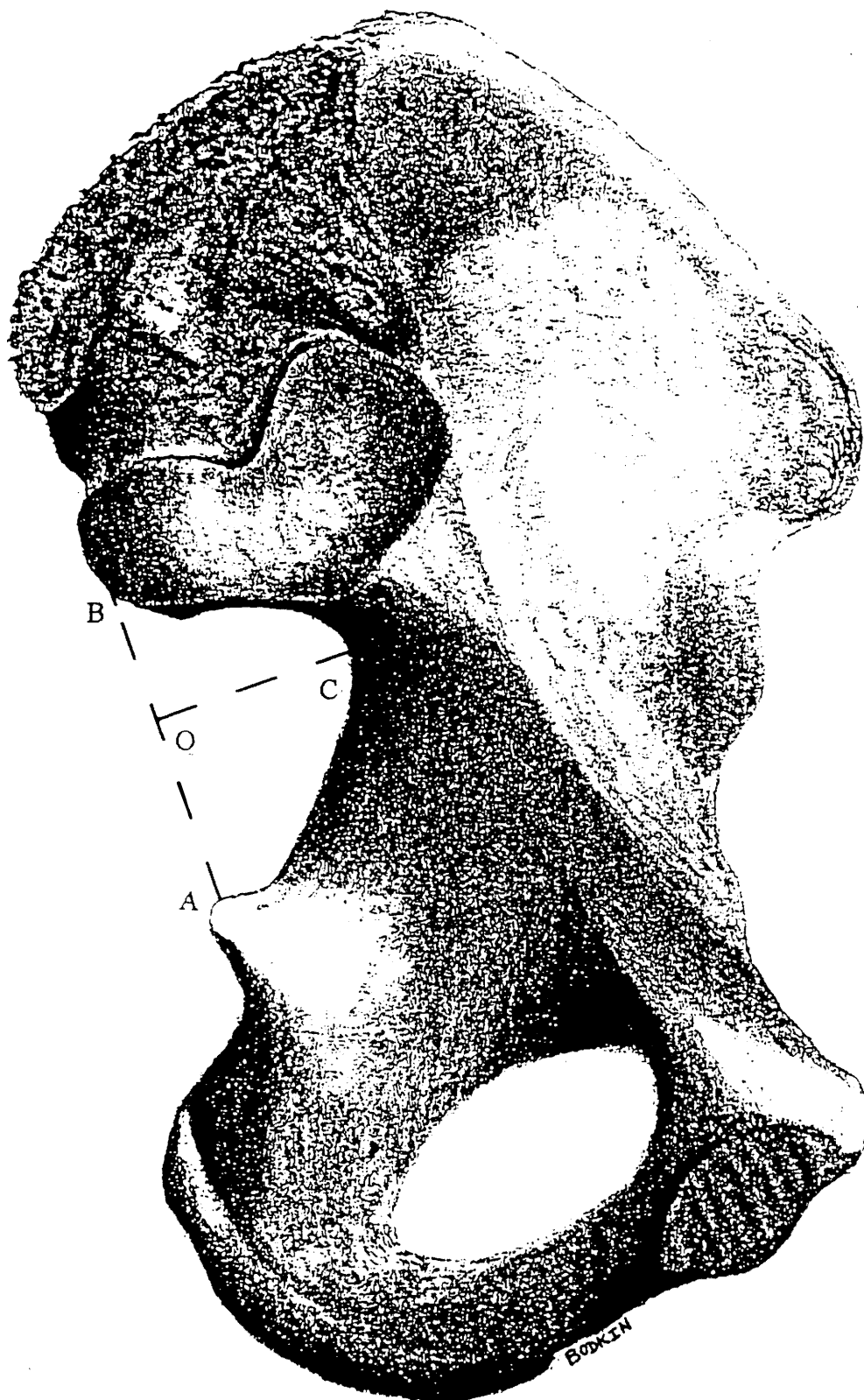


Figure 12. Measurements in this study (left bone depicted).



down into two size variables: line OA, and line OB. Lines OA and OB are the posterior segment of the maximum width line and the anterior segment of the maximum width line, respectively.

Since how the convex hull measures the notch is dependent upon how the outline is digitized, further detail should be given to this process. The notch was digitized (right to left) beginning at the *inferior portion* of the posterior inferior iliac spine, along the notch outline, and ending at the *posterior margin* of the ischial spine. Care was taken not to include in the digitization any of the degenerative lipping formations frequently observed at the posterior inferior iliac spine, nor to include any of the variations in ischial spine tip form. The resulting digitized outline could be characterized as the "essential" sciatic notch. To include the tip of the ischial spine would be to include ischial spine variation in a study of sciatic notch sexual dimorphism. The same reasoning applies to the piriform tubercle (or pyramidal projection), which is also a very variable structure (as Kelley did, 1979). Therefore, the convex hull program plotted the maximum width of the sciatic notch from a convex hull vertex at the *inferior portion* of the posterior inferior iliac spine to a vertex at the *posterior margin* of the ischial spine (AB, Figure 12).

With the landmarks established the digitized image was scaled to the Cartesian grid so that the posterior point (A) was located at the origin (0,0), and the anterior point (B) was rotated to (1,0). In this orientation point C and the notch itself lay within Quadrant I of the grid (Figure 11). Point O is lying on the x-axis. The x-coordinate for point C then becomes a measure of the anterior to posterior (A/P) placement of the maximum depth line along the maximum width line. The y-coordinate becomes a measure of the maximum depth. In effect, landmarks A and B, along with the size variable line AB, are being held constant so that the only landmark that is allowed to vary is C. Point O will vary too with point C. The Cartesian coordinates of point C are known as Bookstein shape coordinates. What is ultimately needed here is two shape variables to

analyze sexual dimorphism, and since a shape variable is the ratio of two size variables, shape 1 is defined as a ratio of AO/AB, and shape 2 is a ratio of OC/AB (Figure 11). These shapes are the predictor variables under investigation and are hypothesized to contain the information about sexual discrimination in the sciatic notch.

After translation, rotation, and scaling of the images, the shape variables are in data matrix form for each sex. Among several appropriate tests for determining bivariate normality with variables that are continuously distributed is Mardia's multivariate measures of skewness and kurtosis (Mardia, 1970, 1983, 1985; Sugiura, 1993). The null hypothesis being tested by this method is that the data are normally distributed. If the null hypothesis is not rejected the study may proceed under parametric assumptions. Mardia's test is conducted according to the procedure laid out in Sugiura (1993) which has three parts: the computation of a single value representing both skewness and kurtosis for each shape variable for each sex, checking the accuracy of these values against computer generated Monte Carlo iterations, and then checking the probabilities computed by the iterations by asymptotic approximation. The dimensionality ( $p$ ) of this study is two. Skewness, in this technique, is based on Mahalanobis distances and written as:

$$b_{1,p} = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n \{[x_i - \bar{x}]S^{-1}[x_j - \bar{x}]\}^3$$

Kurtosis, also based on Mahalanobis distances, is written as:

$$b_{2,p} = \frac{1}{n^2} \sum_{i=1}^n \{(\mathbf{x}_i - \bar{\mathbf{x}}) \mathbf{S}^{-1} (\mathbf{x}_i - \bar{\mathbf{x}})'\}^2$$

In these equations  $\mathbf{x}_i = (x_{1i}, \dots, x_{pi})$ ,  $i = 1, \dots, n$  is  $n$  independent observations on the  $p$ -variate random variable  $\mathbf{x}$ ,  $\bar{\mathbf{x}}$  is the sample mean vector, and  $\mathbf{S}$  is the sample variance-covariance matrix (Mardia, 1983; Mardia and Foster, 1983; Sugiura, 1993). Then a single value representing  $b_{1,p}$  and  $b_{2,p}$  is derived in an omnibus test of normality using the standardized quadratic form:

$$\mathbf{q} = (\mathbf{b}_{1,p}^{1/3}, \mathbf{b}_{2,p}) \mathbf{S}^{-1} (\mathbf{b}_{1,p}^{1/3}, \mathbf{b}_{2,p})'$$

The omnibus test is employed because occasionally the measures of skewness and kurtosis *alone* do not reflect a departure from normality (Mardia and Foster, 1983:210). Prior to quadratic combination, however, skewness ( $b_{1,p}$ ) was transformed using the Wilson-Hilferty transformation (Wilson and Hilferty, 1931; see also Mardia and Foster, 1983; Sugiura, 1993). This is done because the two terms ( $b_{1,p}$  and  $b_{2,p}$ ) do not agree in distribution. The term  $b_{1,p}$  has an asymptotically chi-square distribution with 2 degrees of freedom, and  $b_{2,p}$  is distributed asymptotically normal. After the transformation both terms ( $b_{1,p}$  and  $b_{2,p}$ ) agree in asymptotic normality. A Monte Carlo procedure was then used to produce 4999 iterations of the variance-covariance matrix for each sex, an iteration being a randomized artificial sample using the actual data. A 5000th observation

was the actual observed matrices of the sample groups. The Monte Carlo procedure computes the p-value under the null hypothesis. The p-value is the probability of getting a skewness/kurtosis test statistic value at least as extreme as the observed value (in the direction of the alternative hypothesis, which is that the data are not normal). The level of significance in this technique was 0.05, so p-values greater than 0.05 fail to reject the null hypothesis. The asymptotic approximation (Mardia, 1974; Sugiyura, 1993) is used to determine the reliability of the Monte Carlo iterations. The resulting values of the approximation should be close to the values derived by the Monte Carlo simulations.

Following the test for normality Box's test (1949) was conducted to determine whether the variance-covariance (or just covariance) matrices for males and females were equal, or heterogeneous. This statistical step actually has two parts: testing for matrix equality and determining which group has the more variance. Two matrices of the same dimensions are considered equal if each and every element in one matrix is the same as its complement element in the other matrix. This relationship can be expressed as  $A_{ij} = B_{ij}$ , where **A** and **B** are both matrices, *i* indexes the row, and *j* indexes the column. The covariance matrices are of the same dimensions (2x2 for each sex- unlike the data matrices which are not of the same dimensions, 2x125 for females, 2x129 for males). The test statistic resulting from Box's test has a chi-square distribution that is compared to a chi-square distribution table. Values higher than the table entry reject the null (that the matrices are equal), while values lower than the table entry fail to reject the null. The Box test is carried out in order to determine which test statistic will be used in the F test to follow. A determinant is a single number calculated from each matrix representing the variance of that group (see Appendix A in Tatsuoaka, 1971, for the rules on deriving determinants). The determinant for the male group is divided by the determinant for the female group to yield a determinant ratio, which was then transformed to its natural log.

This final value shows which group has the more variance (by whether it is negative or positive).

Next an F-test for equality of means between covariance matrices of each sex was performed. Because the Box test revealed covariance matrix heterogeneity, the means could not be tested using Hotelling's  $T^2$ , a standard test about means. Rather, Yao's (1965) multivariate generalization of Hotelling's  $T^2$  was used, which allows for matrix inequality (see Mardia et al., 1979 for more on this procedure). The null hypothesis here is that the mean male and female shape variables are equal. Differences between group means were tested using a one-factor multivariate analysis of variance (MANOVA) for both shape variables considered together (bivariate), and a one-factor analysis of variance (ANOVA) for each independent shape variable. MANOVA tests are employed when there is more than one criterion variable (both shape variables considered together). ANOVA tests are appropriate when there is one criterion variable (each shape variable considered separately). The "one-factor" refers to the number of predictor variables. There is one predictor variable in both the MANOVA and ANOVA- sex. (These should not be confused with the criterion and predictor variables that will be referred to in the discriminant function discussion.) The variance between samples divided by the variance within samples yields an F ratio. The numerator, or variance between samples, considers the difference in the means of both male and female. The denominator, or variance within samples, is a pooled mean of the variances of both sexes. For this reason, excessively large F values (when compared to an F distribution table) represent unequal means, or a rejection of the null hypothesis. The F ratio approximate degrees of freedom ( $k_1, k_2$ ) in the present work was for the bivariate analysis (2,180), for the analysis of shape 1 (1,248), and the analysis of shape 2 (1,229). The degrees of freedom in the numerator is  $k_1$  while  $k_2$  is the degrees of freedom in the denominator.

There are two assumptions that must be satisfied prior to performing a discriminant analysis: 1) the discriminating variables must be normally distributed, and 2) the group covariance matrices must be equal (Klecka, 1980: see also Kachigan, 1986). These assumptions were checked using Mardia's test and Box's test, respectively. The F-test demonstrated the differences in group means. Discriminant analysis begins with the identification of criterion variables and predictor variables. Criterion variables are the groups into which a researcher is attempting to classify an object, and must assume a minimum of two values. Classification into criterion variables is based upon characteristics of the object, or predictor variables. Predictor variables can be numerous, but generally these variables should be restricted to variables known to have some relationship with the criterion variables. In this analysis the criterion variables are sex, male and female, and the predictor variables are shape 1 (the ratio of AO/AB) and shape 2 (the ratio of OC/AB). The generalized discriminant function for a bivariate analysis is as follows:

$$L = b_1x_1 + b_2x_2 ,$$

where  $x_1$  and  $x_2$  represent predictor variable values obtained from the object (i.e., measurements from the bone) and  $b_1$  and  $b_2$  represent constant values or weights associated with the particular predictor variable (these  $b$ 's are different from the  $b$ 's mentioned in the skewness and kurtosis discussion). The goal in constructing a discriminant function is derive the  $b$  coefficients and cutoff scores. The value of  $L$  represents an individual object's discriminant score, which becomes meaningful when compared to a cutoff score. Graphically the cutoff score is a straight line dividing the two

criterion variables. An object's affiliation with one or the other of the criterion variables depends upon which side of the line its discriminant score falls. An individual is classified into one sex with a score higher than the cutoff score, and into the other sex if their score is lower than the cutoff score. Both the  $b$  coefficients and the cutoff score are calculated so as to maximize the percentage of correct classifications.

When the assumptions mentioned earlier are satisfied the  $b$  coefficients and  $x$  values can be combined into a simple linear form, hence the name linear discriminant function. When covariance matrices are not homogenous, as demonstrated by the Box test, there is an alternative construction that might improve the percentage of objects correctly classified- the quadratic discriminant function. The quadratic discriminant function uses the covariance matrices of each sex, rather than combined as in the linear, to compute the  $b$  coefficients. Graphically the quadratic discriminant function appears as a curved line, rather than a straight line as in the linear function, and mathematically it is more complex. Concerning the violation of the matrix equality assumption, some authors (Lachenbruch, 1975; Klecka, 1980:61) feel that the discriminant analysis is robust enough to overcome some deviations with no major effects on its ability to separate objects into groups. In other words, if the violations are minor a linear discriminant function will suffice. This study has produced results for both the quadratic and linear discriminant functions.

Once a discriminant function has been constructed its efficacy must be tested. One method for judging precision and accuracy is the "leave-one-out" technique (Lachenbruch and Mickey, 1968). This estimate of error was used for both the linear and quadratic discriminant functions. This method estimates the error in classification by removing an individual from the sample, reconstructing a new discriminant function for the sample without the removed individual, and then classifying the "left out case." This technique, "Does not succumb to the circularity of classifying a case which has

participated in calculation of the discriminant function" (Holcomb and Konigsberg, 1995:120). The true test of a discriminant function, however, is to apply it to a random sample of significant size representing a different population than the one on which the discriminant function was calculated.



## CHAPTER 3

### RESULTS

Simple descriptive statistics were computed from the data matrices and are shown in Table 2 and 3. Ratios from the data matrices are presented in Figures 13-15. These figures are scatter plots of each individual with shape variable 1 scaled on the  $x$ -axis and shape variable 2 on the  $y$ -axis. Figure 13 is both sexes plotted together, Figures 14 and 15 plot each of the sexes independently (total  $n = 254$ , female  $n = 125$ , male  $n = 129$ ).

Mardia's test of skewness and kurtosis was employed to determine whether the data were distributed normally. The statistics of this test are presented in Table 4. The critical chi-square value for 2 degrees of freedom and a 0.05 level of significance is 5.991. The resulting values are lower than this critical value indicating that the null hypothesis could not be rejected. The Monte Carlo iterations computed  $p$ -values for each sex, which must be higher, or in the upper-tail, than the 0.05 significance level to not reject the hypothesis of normality. The resulting values show that the null hypothesis was far from being rejected. Moreover, the asymptotic approximation values are close to the Monte Carlo values, further lending support to the Monte Carlo findings.

Following the establishment of normality Box's (1949) test was employed to determine the equality of the covariance matrices for males and females. This test yielded a chi-square of 23.0323 with 1 degree of freedom ( $p < 0.001$ ). The critical chi-square value of 10.827 falls within the rejection region indicating the two matrices are not equal. The determinant ratio was calculated by dividing the male covariance matrix determinant by the female covariance matrix determinant, and then transformed to its natural log, 0.7657. This shows that males have a greater dispersion of shape coordinates than females. The dispersion is also evident in Figures 14 and 15.

Table 2. Descriptive statistics of shape variable 1 (A/P to width ratio).

| <b>Statistic</b>                                           | <b>Male</b>       | <b>Female</b>     |
|------------------------------------------------------------|-------------------|-------------------|
| <b>Mean</b>                                                | 0.628662          | 0.512299          |
| <b>95% Confidence interval<br/>for the population mean</b> | 0.61408 - 0.64325 | 0.49900 - 0.52560 |
| <b>Standard error of mean</b>                              | 0.007441          | 0.006786          |
| <b>Median</b>                                              | 0.619216          | 0.51182           |
| <b>Standard deviation</b>                                  | 0.084518          | 0.075875          |
| <b>Kurtosis</b>                                            | -0.34646          | 0.153254          |
| <b>Skewness</b>                                            | 0.117516          | 0.214846          |
| <b>Minimum</b>                                             | 0.418722          | 0.334773          |
| <b>Maximum</b>                                             | 0.807704          | 0.758319          |
| <b>Count</b>                                               | 129               | 125               |

Table 3. Descriptive statistics of shape variable 2 (depth to width ratio).

| <b>Statistic</b>                                           | <b>Male</b>       | <b>Female</b>     |
|------------------------------------------------------------|-------------------|-------------------|
| <b>Mean</b>                                                | 0.715715          | 0.609827          |
| <b>95% Confidence interval<br/>for the population mean</b> | 0.69831 - 0.73312 | 0.59745 - 0.62220 |
| <b>Standard error of mean</b>                              | 0.008878          | 0.006313          |
| <b>Median</b>                                              | 0.709097          | 0.600866          |
| <b>Standard deviation</b>                                  | 0.100837          | 0.070584          |
| <b>Kurtosis</b>                                            | -0.6779           | -0.17437          |
| <b>Skewness</b>                                            | 0.142071          | 0.127714          |
| <b>Minimum</b>                                             | 0.49669           | 0.438274          |
| <b>Maximum</b>                                             | 0.922922          | 0.788659          |
| <b>Count</b>                                               | 129               | 125               |

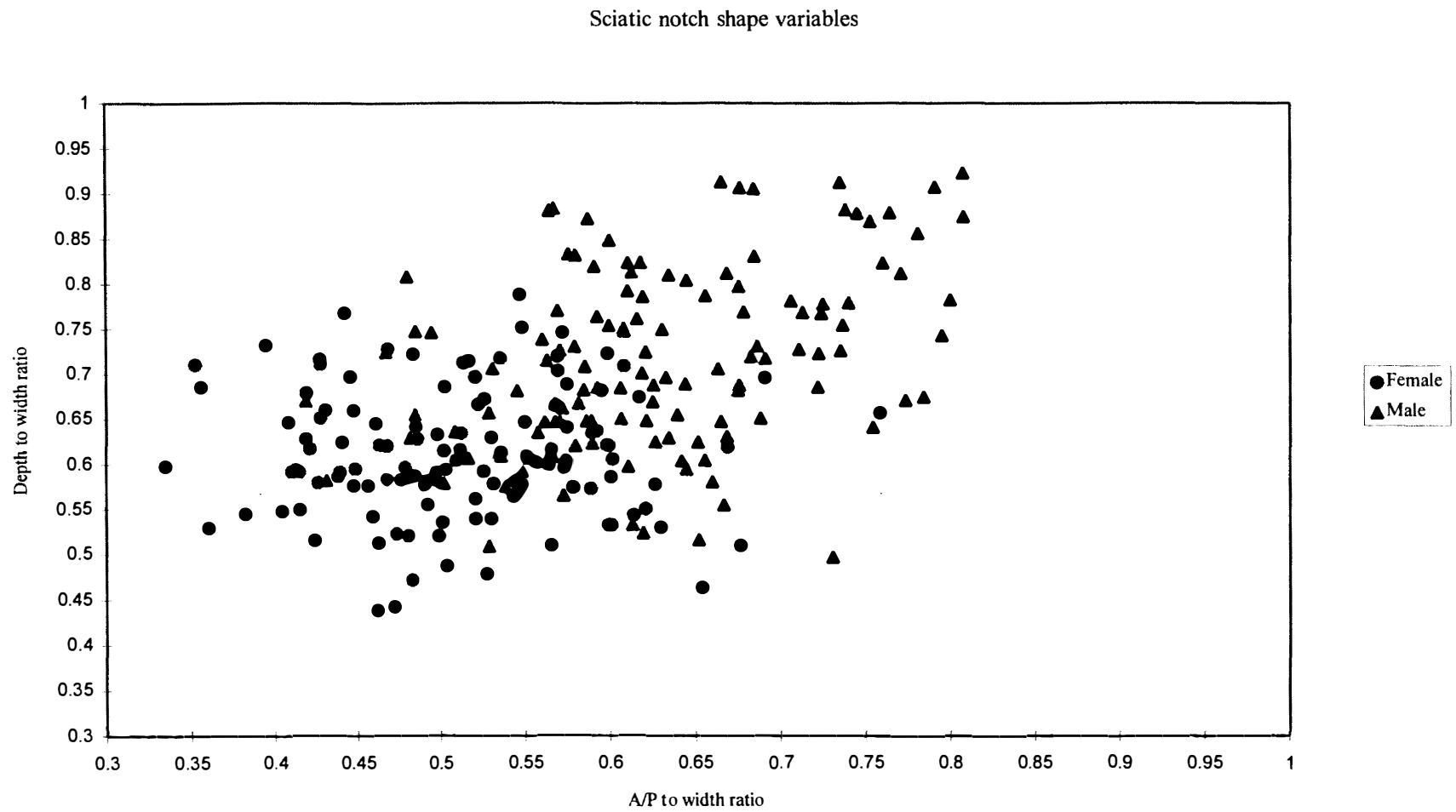


Figure 13. Scatter plot of the sciatic notch shape variables.

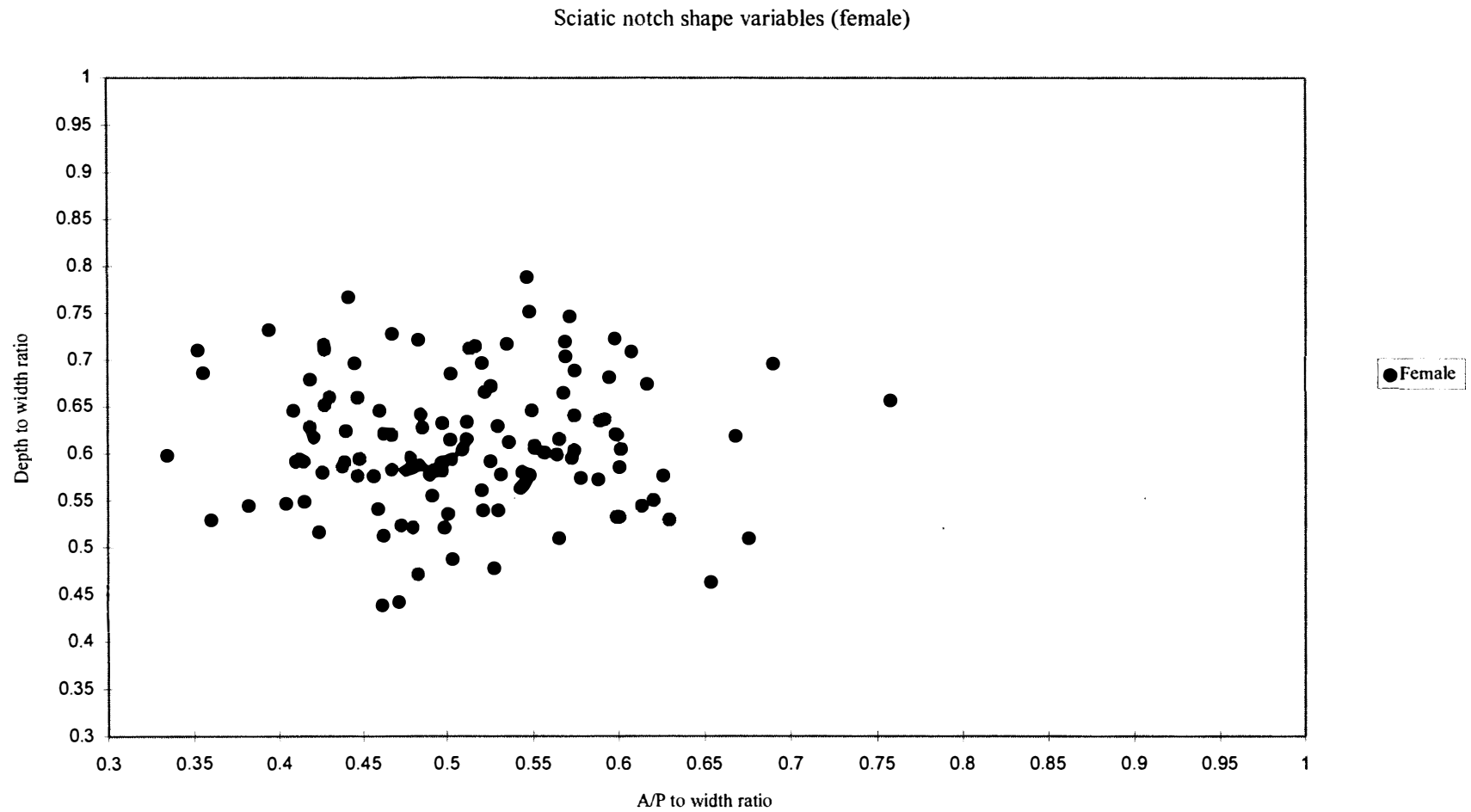


Figure 14. Scatter plot of the sciatic notch shape variables (females).

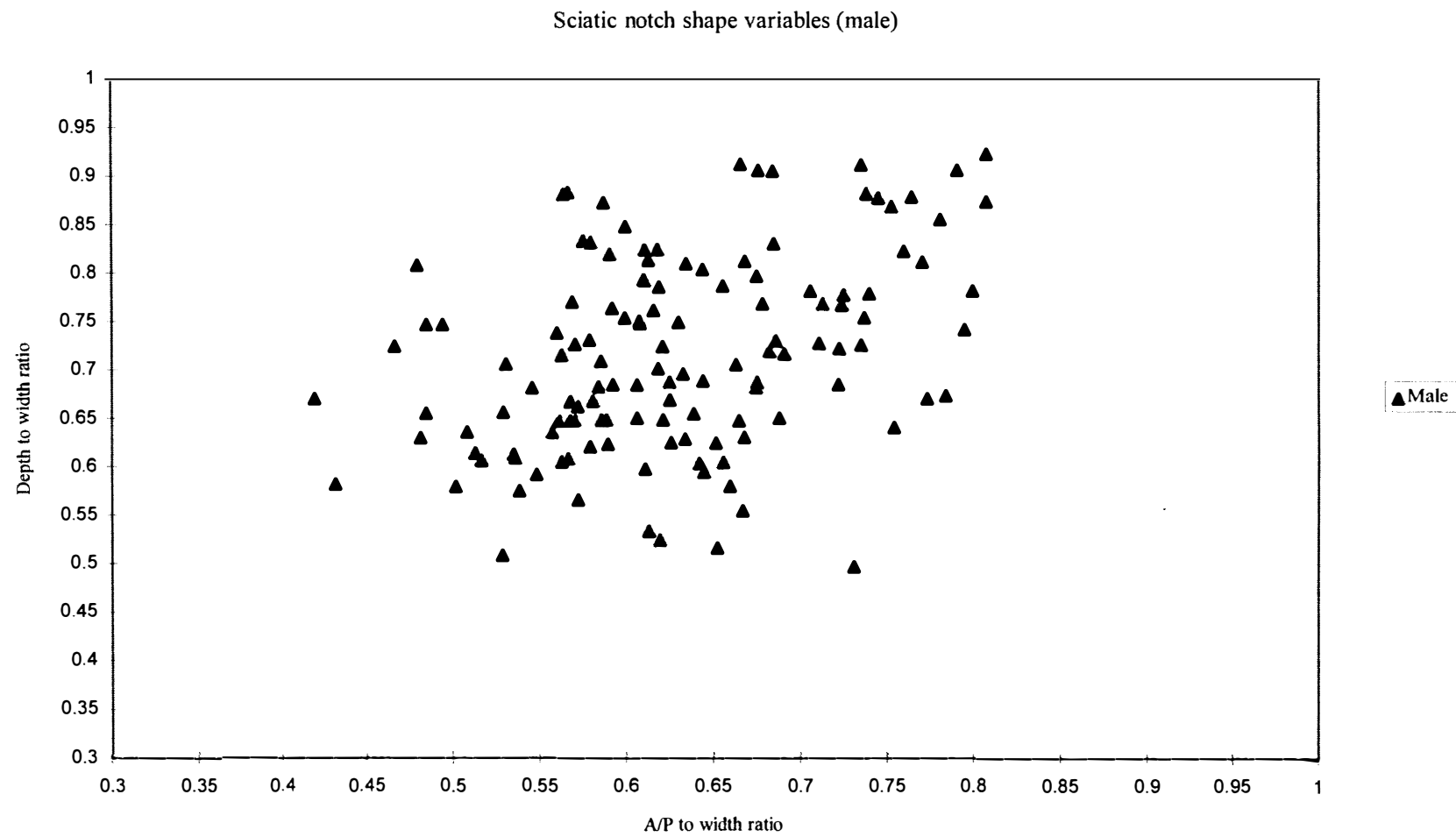


Figure 15. Scatter plot of the sciatic notch shape variables (males).

Table 4. Test of bivariate normality for the shape coefficients within females and males.

|                          |            | <b>Probability</b> |                   |
|--------------------------|------------|--------------------|-------------------|
| <b>Sample</b>            | $\chi^2_2$ | <b>Monte Carlo</b> | <b>Asymptotic</b> |
| <b>Females (n = 125)</b> | 0.9047     | 0.643              | 0.636             |
| <b>Males (n = 129)</b>   | 1.3150     | 0.495              | 0.518             |

Yao's (1965) multivariate generalization of Hotelling's  $T^2$  provides a test of the means when covariance matrices are heterogeneous. First, both shape variables were tested together in the MANOVA, then each one separately in an ANOVA. The resulting F values greatly exceeded the tabled F distribution values when considered with their approximate degrees of freedom. This indicates that there is a significant difference between the means of males and females. Table 5 reports the results of this F-test.

Both linear and quadratic discriminant functions were constructed. Despite the violation of the covariance matrix equality assumption, the linear discriminant function performed better in the overall classification and in classifying males. The quadratic function performed better in classifying females. Table 6 contains the results of both discriminant functions (the columns give the absolute numbers and percents for correct classifications).

The linear discriminant equation derived from the sample was:

$$L = (15.2759 * \text{shape 1}) + (10.5426 * \text{shape 2}).$$

The male mean discriminant was 17.1489, and the mean discriminant for the female was 14.2550. The cutoff score is 15.7019. The correlation of shape 1 with the discriminant score was 0.9052, while for shape 2 the correlation was 0.8010.

The shape variables exhibit sexual dimorphism when examined together. Males have a greater mean than females in both shape variables. In general this is because the anterior segment of the maximum width line and the maximum width line itself both are shorter in males than in females. Males also tend to have longer line OC size variable distances than females.



Table 5. F-tests based on the generalized Hotelling's  $T^2$  for males versus females.

| <b>Variables</b>  | <b>F</b> | <b>Approximate<br/>d.f.</b> | <b>Probability</b> | <b>Randomization<br/>probability</b> |
|-------------------|----------|-----------------------------|--------------------|--------------------------------------|
| <b>Bivariates</b> | 46.5283  | 2,180                       | <0.0001            | 0.001                                |
| <b>Shape 1</b>    | 32.5007  | 1,248                       | <0.0001            | 0.001                                |
| <b>Shape 2</b>    | 32.3613  | 1,229                       | <0.0001            | 0.001                                |

Table 6. Classification by linear (LDF) and quadratic (QDF) discriminant function analysis.

| <b>Type analysis</b> | <b>Males (n = 129)</b> | <b>Females (n = 125)</b> | <b>Total (254)</b> |
|----------------------|------------------------|--------------------------|--------------------|
| LDF                  | 97 (75.2%)             | 109 (87.2%)              | 206 (81.1%)        |
| QDF                  | 94 (72.9%)             | 111 (88.8%)              | 205 (80.7%)        |
| LDF (leave one out)  | 96 (74.4%)             | 108 (86.4%)              | 204 (80.3%)        |
| QDF (leave one out)  | 92 (71.3%)             | 111 (88.8%)              | 203 (79.9%)        |

It was mentioned that the methodology used here was introduced by Holcomb and Konigsberg (1995). There are a few differences, however, such as this study examines adult humans and the other a fetal population. In addition, the landmarks constructed on the fetal sciatic notch were different than those constructed here because the ischium has not yet fused to the ilium, and therefore the ischial spine cannot be used as a landmark.

## CHAPTER 4

### DISCUSSION

One indicator of the effectiveness of a discriminant function, or any sexing technique, is its percent correctly classified. In this chapter I will compare the results of this study to the previous sciatic notch studies, to discriminant analyses performed elsewhere on the skeleton, and discuss the concept of landmarks in more depth.

#### Comparison of this Study to Previous Sciatic Notch Studies

Derry (1923) did not publish his results in the form of percent correctly classified so we must examine a test of his technique by Hausermann (1925). Kimura (1982) claims Hausermann correctly diagnosed 83.4% males and 45.6% females in his German sample. Hausermann's poor performance could have been a product of the ambiguous landmarks, particularly the pubo-iliac point. Using the notch alone Washburn (1948) could sex a minimum of 75% of his Hamann-Todd sample, but through combining the ischium-pubis index and the sciatic notch, Washburn (1949) could sex 98% of the Bantu and Bushman skeletons. Hanna and Washburn (1953) report 95% separation of Eskimo pelves using the same techniques. The increase in percentages in these latter two studies reflects the incorporation of the ischium-pubis index as opposed to the notch alone. Jovanovic and Zivanovic (1965) could sex approximately 75% of the innominates in the Lyon sample, with accuracy depending upon which side was analyzed. This low percentage might be due to the use of the longer width measurement. In the Australian

sample Davivongs (1963) reports 75.5% correct classification using the posterior segment of the maximum width line and 72.5% using Index II. Using both indices and absolute measurements, Day and Pitcher-Wilmott (1975) sexed 97% of the St. Bride's sample in a discriminant function analysis. This high percentage takes all 24 of their variables into account with no report on the notch as a single indicator. Singh and Potturi (1978) found the posterior angle to be the best indicator, identifying 75-88% male innominates and 92-100% of the females (the different percentages are left-right sides). At first glance their technique appears to be promising, particularly the posterior angle indicator which they are credited for introducing, however, they were able to achieve such success by using "demarking points" (Jit and Singh, 1966). In short, demarking points are maximum and minimum values for each measurement set at 3 standard deviations from the mean. This is how they were able to achieve 100% correct classification of right female pelvises. No percentages at 1 standard deviation were reported. Singh and Potturi's (1978) line OB showed less promise with correct classifications of 52% in male rights, 42% in male lefts, 97% in female rights, and 95% in female lefts; and again these percentages are based on fiducial limits of 3 standard deviations away from the mean. All things considered, Singh and Potturi's techniques are worthy of further investigation. Kelley (1979) could sex at least 90% of his Hamann-Todd sample. Although these findings appear high he combined the acetabulum height in the "rule of thumb" index with the sciatic notch, and since the head of the femur is a fairly secure sexually dimorphic structure (Stewart, 1979), its inclusion in the index could be causing the higher percentages. The assumption here being that the sexual dimorphism in the femoral head is mirrored in the acetabulum. It is felt that the findings of MacLaughlin and Bruce (1986) are more indicative of this technique's worth. These authors, using the "rule of thumb," correctly sexed 90.5% (Dutch) to 95.8% (English) of the males, but only 46.7% (English) to 57.6% (Dutch) of the females. These authors cite populational differences and ambiguous landmarks as the

reasons for the poor performance of Kelley's methods. Segebarth-Orban (1980) reports his findings in Student's  $t$  values but not how many of his 158 pelves were classified correctly or incorrectly. He compares his Student's  $t$  value of 1.56 for the maximum width measurement to a Student's  $t$  value of 12.74 derived from Washburn (1949), to which I could add Day and Pitcher-Wilmott's (1975) Student's  $t$  value of 0.36 for the same measurement. Segebarth-Orban's value was not significant, Washburn's was significant at the 1% level, and Day and Pitcher-Wilmott's significant at 0.5. One important parameter of the Student's  $t$  is the degrees of freedom, which was only reported by Day and Pitcher-Wilmott (1975) at 37. The Student's  $t$  distribution provides a way to estimate the population standard deviation when it is unknown and when the population is normally distributed. And finally, using discriminant function analysis, Taylor and DiBennardo (1984) classified 93.8-95.4% of whites (females-males) and 90.8% of blacks (both sexes) in their base sample, and 90.0-88.0% white (females-males) and 90.0-92.0% blacks (females-males) in their test sample. Like Kelley's study, Taylor and DiBennardo include the height of the acetabulum, which could account for the higher percentages. This is one of the few studies dealing with purported ethnic differences in the sciatic notch. These studies are summarized in Table 7 with the results from this study as the final table entry.

### Other Discriminant Function Analyses

To place these results into a wider perspective I compare them to other discriminant analyses, regardless of which bone was the focus of the study. What is

Table 7. Correct classification percentages of other sciatic notch studies.

| Study                          | Percent correctly classified             |
|--------------------------------|------------------------------------------|
| Hausermann (1925)              | 83.4% males                              |
| (using Derry, 1923)            | 45.6% females                            |
| Washburn (1948)                | 75% overall                              |
| Washburn (1949)                | >98% overall                             |
| Hanna and Washburn (1953)      | 95% overall                              |
| Davivongs (1963)               | 75.5% (OB measurement)                   |
|                                | 72.5% (Index II)                         |
| Jovanovic and Zivanovic (1965) | 75% overall                              |
| Day and Pitcher-Wilmott (1975) | 97% overall                              |
| Singh and Potturi (1978)       | 75% right males, posterior angle only    |
|                                | 88% left males, posterior angle only     |
|                                | 92% right females, posterior angle, only |
|                                | 100% left females, posterior angle, only |

Table 7 (continued)

| Study                        | Percent correctly classified     |
|------------------------------|----------------------------------|
| Kelley (1979)                | >90% overall                     |
| Taylor and DiBennardo (1984) | 90.0% white females, test sample |
|                              | 88.0% white males, test sample   |
|                              | 90.0% black females, test sample |
|                              | 92.0% black males, test sample   |
| MacLaughlin and Bruce (1986) | 90.5% Dutch males                |
|                              | 95.8% English males              |
|                              | 46.7% English females            |
|                              | 57.6% Dutch females              |
| This study                   | 75.2% males, LDF                 |
|                              | 87.2% females, LDF               |
|                              | 81.1% total sample, LDF          |



being compared is the ability of the discriminant function to separate skeletal material into male and female using a variety of predictor variables.

Kimura (1982) reports that Hanihara and Kimura (1959), using three measurements and the ischium-pubis index, achieved an 88.9% accuracy in a Japanese sample. Giles (1964) reports between 83.8% and 84.9% for three discriminant functions of three predictor variables each from the mandible. Giles (1970) also published a collection of various discriminant functions. Two of these functions involved the sciatic notch height (or maximum depth), one achieved 93.1% correct classification, the other 96.5%. Using Thieme and Schull's (1957) methodology, Richman and colleagues (1979) correctly sexed 88% of their Terry Collection sample and 96% of the Howard University sample. Their predictor variables included femur length, femur head diameter, humerus length, epicondylar width of the humerus, clavicle length, ischium length, and pubis length. These authors state that they could not achieve the 98.5% accuracy claimed by Thieme and Schull. Calcagno (1981) achieved 91.7-98.6% correct classification using only mandibular measurements, but found the accuracy decreased when applying the functions to populations other than the base sample. Kimura (1982) using pubic length, ischial length, and iliac width in a discriminant analysis was able to classify 94.29-96.71% in three samples, and a worst case of 77.22-79.11% using only the pubic length and iliac width. Iscan and Miller-Shaivitz (1984) performed a discriminant analysis on 159 specimens of mixed ethnicity from the Terry Collection using measurements on the tibia (totals only): the circumference (77.2-80.0%), length (65.8-81.3%), length and circumference (78.5-82.5%), circumference and anteroposterior diameter (77.2-81.3%), and length, anteroposterior, and circumference combined (78.5-83.8%). At the 1992 American Academy of Forensic Sciences meeting, Ousley and Jantz (1992) presented the discriminant functions for a variety of bones from the University of Tennessee Forensic Data Bank. Their sample consisted of approximately 1000 modern individuals of mixed

ethnicity. Functions with two predictor variables included: the scapula (94%), radius (99% female, 86% male), ulna (91%), tibia (86%), and the calcaneus (84%). Functions with three predictor variables: clavicle (96% female, 88% male) and humerus (96%). Functions with four predictor variables: femur (91%). These studies are summarized in Table 8.

Tables 7 and 8 represent only a casual survey of literature, some dealing with discriminant analysis, some not. Of the 22 percentages in Table 7 the mean correct classification rate is 82.39% with a standard deviation of 15.65, yielding a 1 standard deviation range of 66.74-98.04%. Of the 17 percentages in Table 8 (counting both values separately when given a range) the mean percent correct classification is 88.32% with a sample standard deviation of 8.92, yielding a 1 standard deviation range of 79.39%-97.24%. By comparison, the total percent correctly classified in this study was 81.1%. Relative to other sciatic notch studies the methodology presented here separated the sexes better than most, but compared to discriminant analysis elsewhere on the skeleton it is evident that other structures are more amenable to such an analysis than is the sciatic notch.

### More on Landmarks

The timeless problem of sciatic notch studies has been which landmarks to use in measuring the notch, especially the width. Letterman (1941), as in this study, measured from the posterior margin of the ischial spine and the posterior inferior iliac spine. He defends his choice of landmarks claiming, "There is, indeed, great variation in the shape of both the posterior inferior iliac spine and the ischial spine. . . . It was, therefore,

Table 8. Correct classification percentages of other discriminant function analyses.

| Study                            | Percent correctly classified           |
|----------------------------------|----------------------------------------|
| Hanihara and Kimura (1959)       | 88.9%, innominate                      |
| Giles (1964)                     | 83.8-84.9%, mandible                   |
| Giles (1970)                     | 93.1-96.5%, includes the sciatic notch |
| Richman et al. (1979)            |                                        |
| (using Thieme and Schull, 1957)  | 88-96%, multiple bones                 |
| Calcagno (1981)                  | 91.7-98.6%, mandible                   |
| Kimura (1982)                    | 94.29-96.71%, innominate, best scores  |
|                                  | 77.22-79.11%, innominate, worst scores |
| Iscan and Miller-Shaivitz (1984) | 65.8-83.8%, tibia                      |
| Ousley and Jantz (1992)          | 84-99%, multiple bones                 |
| This study                       | 75.2% males, LDF                       |
|                                  | 87.2% females, LDF                     |
|                                  | 81.1% total sample, LDF                |

essential that certain other more specific and constant features be selected as the cardinal points of the measurement" (Letterman, 1941:103-104). Day and Pitcher-Wilmott (1975) also used the posterior margin of the ischial spine, but used the piriform tubercle instead of the

posterior inferior iliac spine. Davivongs (1963), Singh and Potturi (1978), and Taylor and DiBennardo (1984) all measured from the piriform tubercle to the tip of the ischial spine. Segebarth-Orban (1980) used the top of the posterior inferior iliac spine and the top (tip) of the ischial spine. Kelley (1979) measured from the piriform tubercle to the base of the ischial spine, however, he was criticized by MacLaughlin and Bruce (1986) citing his "base" of the spine too ambiguous to locate. A few studies have attempted to document "typological" variation in ischial spine form (Caldwell, et al., 1934; Greulich and Thoms, 1939; see also the "Discussion" in MacLaughlin and Bruce, 1986). It is clear that there are many opinions on how the sciatic notch should be measured.

Given this confusion a description of morphometric landmarks is necessitated. Bookstein has identified three principle types of points with examples of each (1991:63-72). Type 1 is a discrete juxtaposition of tissues. This is a point where three tissues meet, for example the cranial landmarks *lambda*, *bregma*, and *nasion*, and the lingual contact of the alveolar ridge and the maxillary and mandibular incisors (see Bass, 1987 for definitions of osteological terms and *italicized* landmark names). At these locations an osteologist can place the tip of a measuring instrument, like sliding calipers, directly on the landmark. Type 1 landmarks can be observed in the same place from specimen to specimen (landmarks subjected to relative shifting or relocation due to infrequent features such as ossicles are another matter).

Type 2 landmarks are maxima of curvature or other local morphogenetic processes. These include tips of processes, crests, spines, or tubercles and the lowest point in a groove. Type 2 landmarks may be where biomechanical forces are the

strongest, such as muscle attachments or occlusal surfaces of teeth. Some examples Bookstein lists of Type 2 landmarks on the cranium are the tip of the anterior nasal spine, tip of the lower or upper incisor, roots of the incisors, *opisthion*, *basion*, and the posterior nasal spine.

Type 3 landmarks are extremal points. According to Bookstein (1991:65) these are the most common landmarks in multivariate morphometrics and include, "Endpoints of diameters, centroids, intersections of interlandmark segments, points farthest from such segments, constructions involving perpendiculars or evenly spaced radial intercepts, and the like." Even though these points may not physically lie on the tissue in question, but somewhere in space adjacent to the tissue, they can be just as meaningful and rich in information because they can be located by coordinate reference on the Cartesian plane.

The landmarks in this thesis can be classified according to this scheme (refer to Figures 11 and 12). Points A and B are essentially Type 2 landmarks because they are tips of spines. There is some modification here because of the decision to not include the morphological variation in these regions. A true Type 2 point A landmark would require that the digitization outline extend around and encompass the entire posterior inferior iliac spine/auricular surface projection. The convex hull vertex defining point A would thus vary with age-related changes in this region. A true Type 2 landmark of point B would require digitizing over and past the tip of the ischial spine so the convex hull vertex would be located at the tip of the spine. This vertex would also vary with age-related changes such as osteophytosis (ossification of ligamentous tissue; see Ortner and Putschar, 1985). Point C is a Type 3 extremal landmark because it is defined geometrically as a point farthest from a segment. I shall allow <sup>BOOKSTEIN</sup> (1991:61) to conclude this discussion by defining landmarks as, "The points at which one's explanations of biological processes are grounded."

## CHAPTER 5

### CONCLUSION

Concomitant with the introduction of a new methodology into a scientific discipline is skepticism. Skepticism is vitally important to scientific growth. It fosters refinements that lead to new developments and is therefore welcomed in healthy doses. It is to be hoped that this study will instill skepticism in future researchers who will refine the methods presented here. Replicative studies need to be performed using both convex hull and caliper measurements.

To use the current discriminant function with caliper measurements, measure the notch maximum width and depth *with triflanged steel calipers*, combine the measurements into the shape variable ratios, and insert the ratio values in the discriminant function:

$$L = (15.2759 * \text{shape 1}) + (10.5426 * \text{shape 2})$$

Individuals with an L value higher than the cutoff score (15.7019) are considered to be male, and individuals with a lower L value are female. Care should be taken to measure the notch width as outlined in chapter 2 and illustrated in Figure 12.

Can the discriminant function be used if the ischial spine is damaged, as is the case with most archaeologically derived samples? The sample in this study consisted of complete innominates only. It is not known what effect measuring the sciatic notch without a complete ischial spine would have on the ability of the function to assign a sex.

A study to this effect would certainly either strengthen or weaken the function's utility. The computerized measurement technique used in this study should also be tested, not only on the sciatic notch (both with and without ischial spines), but also on other bones to determine its overall effectiveness.

Several questions were not addressed in this study. Some authors (Letterman, 1941; Washburn, 1948, 1949; Davivongs, 1963; Taylor and DiBennardo, 1984) have alluded to ethnic differences in this structure, however, no attempt in this study was made to quantify such differences. The sample in this study consists of individuals drawn mainly from the African and European concentrations of the ethnic continuum. Also not examined in this study was secular trend, or change in notch shape from generation to generation. Similarly, there was no investigation of change in shape throughout an individual's life. Accurate information concerning this type of change would be impossible without a longitudinal roentgenological study, making cross-sectional studies, which limit us in our generalizations, the more feasible alternative. After reviewing the literature and observing the sample there does not seem to be any reason to suspect that age directly affects sciatic notch shape. Age does, however, seem to affect the position of landmarks- which are used to characterize notch shape- not the shape itself. This is an interesting point.

MacLaughlin and Bruce (1986) speculate that a decreasing width of the notch could be related to age. They draw this conclusion because they used Kelley's (1979) measurements, which includes the piriform tubercle. Since this is one of the origination sites of the piriformis muscle (also pyriformis), they cite ossification of the connective tissue as effecting the decreasing notch width. They also report a negative correlation with age in their English sample, though the level of association was not significant. It is felt that a thorough analysis of the age related changes of all the structures in the sciatic notch region needs to be carried out; "all" meaning that anatomical structures do not exist

in isolation, rather they are constantly influencing and being influenced by nearby structures and associated biomechanical forces. Such a study would show which areas in the region tend to change less with age. These constant areas, then, would make ideal standard landmarks or as Letterman (1941:104) called them, "cardinal points of measurement."

This study has been an application of morphometry and discriminant function analysis to assess the sex of human skeletal material based on the greater sciatic notch. The results of this thesis show that the sciatic notch exhibits significant sexual dimorphism when both shape variables are considered together. As mentioned in chapter 1, the history of sexing skeletal material has been a history of changing methodologies. The morphometric techniques used here to quantify notch shape offers itself as the most recent attempt at developing an objective, replicable method. When compared to previous studies of the sciatic notch this method was more successful, but compared to other discriminant analyses it did not perform so well. This is because the sciatic notch contains a wide range of variation in forms that tends to obscure its sexually dimorphic properties. On the other hand the notch has been an excellent proving ground for the use of morphometry in physical anthropology. Morphometric methods- through further refinement, application, and testing- could quite possibly become the caliper of the next century in human osteology.



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## VITA

Thomas (Tom) Edward Bodkin was born on October 20, 1968, in Chattanooga, Tennessee. He grew up in a stable home in a middle class suburb, the last of three sons to a land surveyor and caring mother. Tom was baptized and raised Presbyterian yet attended both Lutheran and Catholic schools. He was active in the school sports of baseball, soccer, and cross-country, and was the co-editor of his high school yearbook. In 1986, Tom graduated from Notre Dame High School. All things considered he had a fairly normal childhood and adolescence free from traumatic experiences. Having spent way too many years in private schools, at 17 he joined the United States Army as an engineer; an obligation that would culminate with an honorable discharge in 1994. From 1986 to 1989, while the Iron Curtain was still tightly drawn, he served three years of active duty in Karlsruhe, Germany. His experiences there were valuable, not only in terms of military responsibilities, but also interacting closely with European peoples and traveling the continent. This was a very impressionable time in his life. After developing his self-confidence and earning enough G.I. Bill money, he chose to leave the military to start an academic career. In 1989, Tom started the University of Tennessee at Chattanooga, where he majored in anthropology and minored in biology. While in college he was inducted into four honor societies, was given two outstanding student awards, and graduated magna cum laude with a Bachelor of Arts in 1992. It was during this same year he married his college *liebchen*, Amy. Knowing that an undergraduate degree in anthropology alone would not realize gainful employment, Tom applied and was accepted into the Masters program in anthropology at the University of Tennessee at Knoxville in 1993. He became the first person in his immediate family to pursue post-baccalaureate education. Tom was inducted into two more honor societies, but the highlight of his Masters training was managing Dr. Bass's Anthropological Research

Facility as a graduate assistant. Tom developed many intellectual outgrowths from this close association with Dr. Bass. Like the army, graduate school was a time of great learning, new experiences, and happy memories. In the fall of 1995, Tom graduated UT with a Master of Arts degree. With his wife Tom enjoys backpacking, camping, playing chess and scrabble, eating out, throwing darts, listening to all types of music, and tending to their cats.

“In order to find yourself, you must first lose yourself.” -Author