A New Metric Procedure for the Estimation of Sex and Ancestry from the Human Innominate

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Introduction

The human innominate has been examined previously through numerous metric and non-metric methods and has been determined by many to be the most accurate bone for sex estimation (Stewart 1979). However, this belief has largely been based on non-metric analyses and personal bias. Spradley (2003) examined postcranial metric variation in modern Americans and concluded that the innominate was not especially valuable, but the measurements were limited to the four innominate measurements used in the Forensic Data Bank. Due to ease of use, the preferred method of sex estimation has been to merely evaluate a number of non-metric traits of the pelvis as male or female (Phenice 1969, Bass 2005). Metric studies of the innominate (Day and Pitcher-Wilmott 1975, Milne 1990, Patriquin *et al.* 2005) have failed to become widely accepted.

Most metric and non-metric methods fail to meet the Daubert requirements (*Daubert v. Merrell Dow Pharmaceuticals, Inc. 1993*) due to questionable reliability and validity. In non-metric methods, a simple majority rule or overall impression is the basis of estimation, and in many metric studies, the definitions of measurements and landmarks are too vague and make measurement replication, and therefore reliability, questionable. Additionally, many of the metric studies used landmarks that are difficult to locate (Hanna and Washburn 1953, Krogman and Iscan 1986, Day and Pitcher-Wilmott 1975, Dibennardo and Taylor 1983).

Phenice (1969) reported sexing classification accuracy of 95% using his non-metric method, though validation studies have not produced such high accuracies. Previous metric studies for sex determination report classification accuracies between 85 and 95% (Dibennardo and Taylor 1983, Murphy 2000). However, these accuracy rates were not cross-validated, calling their accuracy, and therefore validity, into question. Morphometric differences in the pelvis due to ancestry have been less extensively researched than differences due to sex. Several authors (Davivongs 1963, Stewart 1979) have discussed the utility of the innominate as an indicator of ancestry, but to our knowledge, no metric studies of the pelvis for ancestry estimation have been published in the last 25 years.

The aim of this proof of concept study is to derive more rigorous landmark definitions, and as a result, more reliable measurements, and to ascertain their validity in sex and ancestry estimation using discriminant function analysis (DFA).

Materials and Methods

In our review of previous landmark definitions, we recognized that our landmarks needed to be better defined so they could be easily replicated in the hopes that these landmarks would be accepted and utilized. Problems with previous studies of the innominate included obscure terminology, poor or non-existent illustrations, or ambiguous landmarks. Definitions from this study are clearer because these problems have been addressed by thorough descriptions and illustrations. The challenge of the innominate for landmarks and measurements is that there are no type 1 landmarks (located at intersections of sutures), following Bookstein's (1991) hierarchy. For this study most landmarks used were type 2 landmarks, which are maximal measurements and instrumentally determined. Examples of such landmarks are the ventral symphyseal face (VSF) and the dorsal symphyseal face (DSF), which are defined here as the maximum width points of the pubic symphyseal face measured perpendicular to the long axis of the symphyseal face.

Innominates were selected from the Hamann-Todd Human Osteological Collection (HTH), housed at the Cleveland Museum of Natural History, based on the following criteria: individuals were at least 19 years old at the time of death with a left innominate complete enough for most measurements to be taken and with no apparent pathological conditions affecting the bone. A sample of 77 innominates was measured using sliding calipers. The sample included innominates from 22 Black males, 20 White males, 19 Black females and 16 White females. Next, the sample was digitized using a Microscribe G2 digitizer and 3Skull software (written by SDO), as was an additional 59 innominates from the HTH collection. Twenty-three landmarks (Figures 1 and 2, Table 1) from a total of 136 left innominates (35 Black males, 36 White males, 33 Black females and 32 White females) were digitized. One morphological outlier (a black female with a short and anterio-posteriorly elongated innominate) was detected based on jackknifed Mahalanobis distances and typicality probabilities, and was removed from further analysis.

The 253 interlandmark distances (ILDs) calculated from the 23 landmarks were analyzed using Fordisc 3 (Jantz and Ousley 2005). To limit the number of variables in DFA, we performed stepwise selection of variables, which finds the best combination of a smaller number of variables that produce the most accurate classifications. In addition, shape variables were also calculated and analyzed using stepwise selection. All DFA classification percentages were cross-validated, a more conservative estimate of classification accuracy when applied to new individuals. Geometric morphometric analyses (GMA) with DFA were conducted using MorphoJ (Klingenberg 2008). The landmark differences between males and females after GMA are compared in Figure 3.

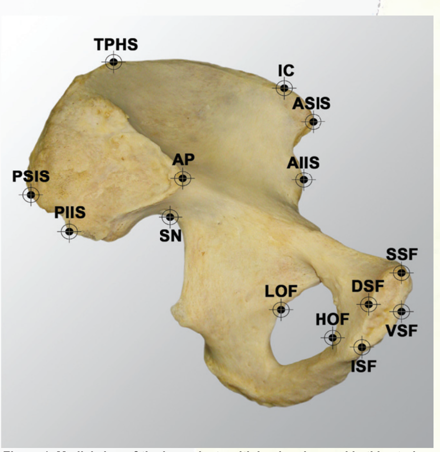

Figure 1. Medial view of the innominate with landmarks used in this study.

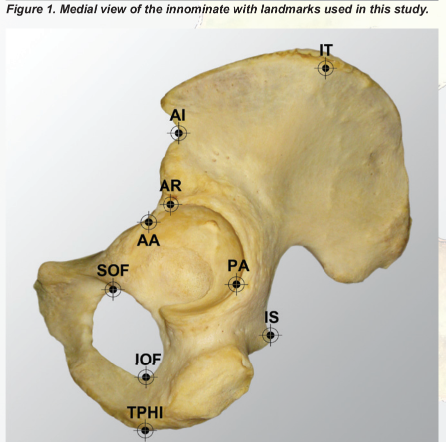

Figure 2. Lateral view of the innominate with landmarks used in this study.

Table 1. Alphabetized list of abbreviations for landmarks used in this study.

Abbreviation	Landmark Name
AA	Anterior Acetabulum
AI	Anterior Incurvature
AIIS	Anterior Inferior Iliac Spine
AP	Auricular Point
AR	Acetabular Rim
ASIS	Anterior Superior Iliac Spine
DSF	Dorsal Symphyseal Face
HOF	Horizontal Obturator Foramen
IC	Iliac Crest
IOF	Inferior Obturator Foramen
IS	Ischial Spine
ISF	Inferior Symphyseal Face
IT	Iliac Tubercle
LOF	Lateral Obturator Foramen
PA	Posterior Acetabulum
PIIS	Posterior Inferior Iliac Spine
PSIS	Posterior Superior Iliac Spine
SN	Sciatic Notch
SOF	Superior Obturator Foramen
SSF	Superior Symphyseal Face
TPHI	Total Pelvic Height Inferior Point
TPHS	Total Pelvic Height Superior Point
VSF	Ventral Symphyseal Face

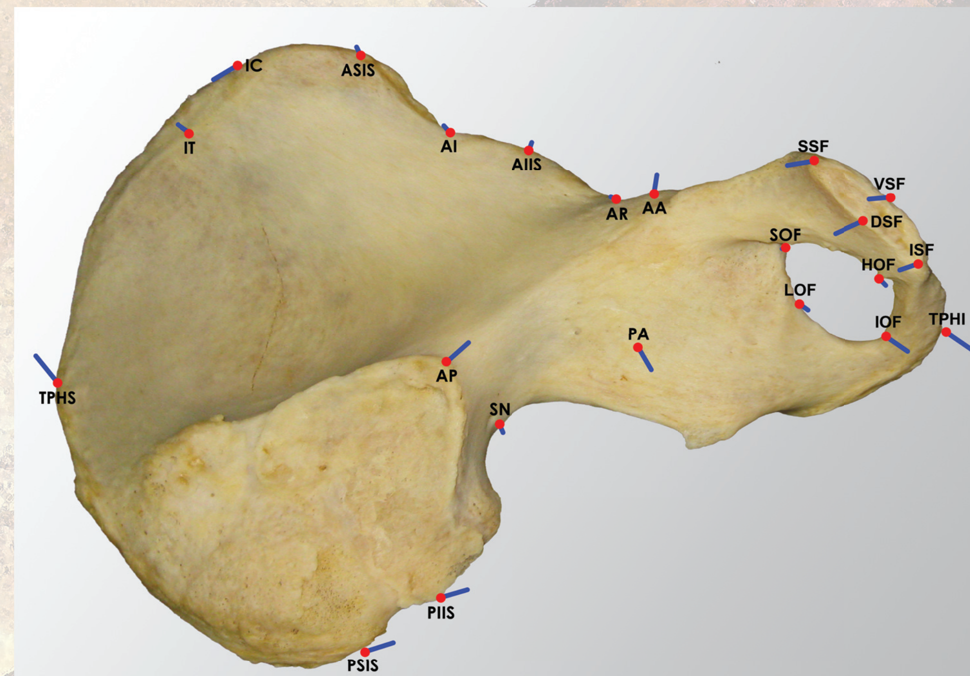

Figure 3. Mean landmark points for males and females after GMA. The red points represent females.

Results

In a comparison of comparable ILDs from the digitizer and caliper measurements, the mean difference between measurements was 1.1 mm with a standard deviation of 1.4 mm. One particular measurement, LOF-MOF, showed a mean difference of 5 mm, but this is likely due to landmarks incorrectly recorded for two individuals while digitizing. No ILDs important for sex or ancestry estimation showed mean differences over 1 mm.

A forward, stepwise DFA for sex produced five variables (AA-PA, AP-SSF, DSF-IT, IOF-ISF, IT-TPHI) that separated males from females with 99% accuracy. These ILDs emphasize the fact that females have relatively larger pubis lengths and smaller ischial heights, as is frequently emphasized in non-metric approaches. Also, in using different stepwise options in Fordisc, five other variables (AR-TPHI, ASIS-HOF, DSF-PSIS, ISF-LOF, TPHI-TPHS) were discovered that produced 100% accurate classifications (Figure 4). The differences between the sexes were apparent using shape variables as well, with five variables (AR-TPHI, ASIS-SOF, DFS-TPHS, DSF-IOF, LOF-TPHS) producing 100% accuracy (Figure 5). Using GMA, females and males were correctly classified 94% and 97% of the time, respectively.

Differences in the innominate due to ancestry, with sexes pooled, were smaller than differences due to sex but were still highly significant. Three variables (AC-PSIS, DSF-HOF, HOF-VSF) were derived using stepwise selection that classified individuals by ancestry 80% correctly (Figure 6). Using GMA, blacks and whites were correctly classified 78% and 84% correctly, respectively. In general, whites tended to have larger pelves, especially in total pelvic height from the superior ilium to the symphyseal face, as illustrated by DSF-TPHS, TPHS-VSF, SSF-TPHS and ISF-TPHS. Whites also tend to have longer iliac blades as seen in IT-PSIS and IC-PSIS.

In a four-way DFA for sex and ancestry (Figure 7), stepwise selection produced seven variables (AA-PA, AR-TPHI, ASIS-HOF, DSF-PSIS, IOF-ISF, IOF-TPHS, and SF-TPHS) that classified the groups with 83% accuracy (Table 2). Using shape variables, virtually the same accuracy was achieved. Using GMA, differences due to sex were larger than differences due to ancestry, but four-way classifications are not performed by MorphoJ. The classification accuracy using GMA would appear to be similar to those from ILDs based on pairwise classifications performed by MorphoJ.

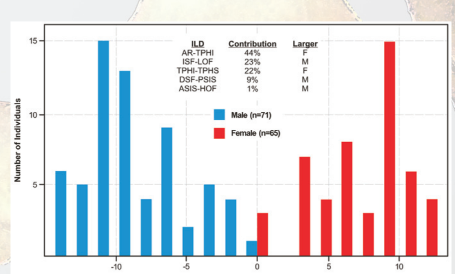

Figure 4. Two-way DFA results for sex using five stepwise selected variables.

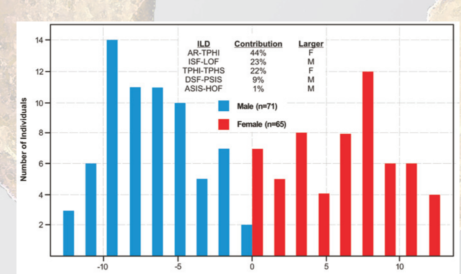

Figure 5. Two-way DFA results for sex using five stepwise selected shape variables.

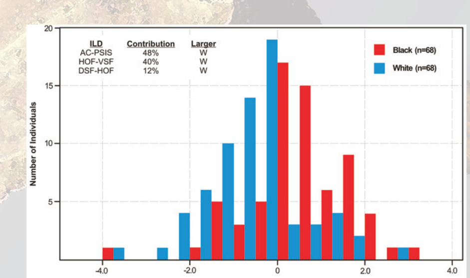

Figure 6. Two-way DFA results for ancestry using three stepwise selected variables.

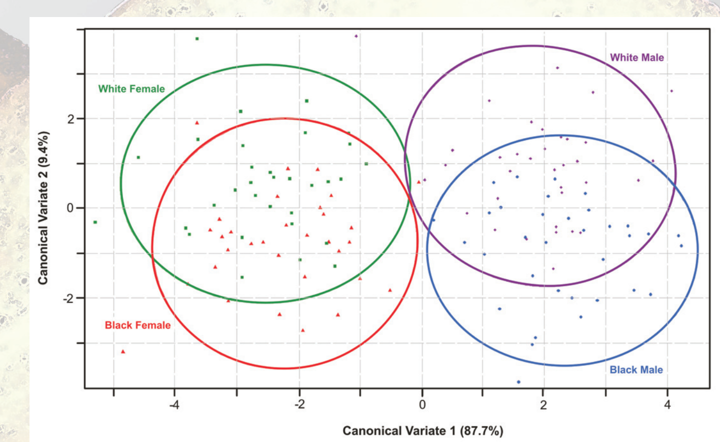

Figure 7. Four-way DFA results for ancestry and sex using seven stepwise selected variables.

Table 2. ILDs used in four-way DFA for sex and ancestry (83% cross validated).

Interlandmark Distance	Largest
IOF–TPHS	WM
ISF–TPHS	WM
AA–PA	WM
DSF–PSIS	BF
AR–TPHI	WM
IOF–ISF	WF
ASIS–HOF	WM

Discussion and Conclusions

This proof of concept study has shown the utility of the statistical approach to estimating sex and ancestry using measurements in a 20th century population and shows promise for modern populations. We discovered new measurements for accurately estimating sex and ancestry with better results than previously published studies. Using the Microscribe G2 digitizer to collect three-dimensional coordinates of landmarks eliminated data entry errors, allowed faster and more efficient data collection, and also allowed the calculation of numerous interlandmark distances that can be analyzed for their validity in estimating sex and ancestry. For example, two independent sets of five ILDs were discovered that produced sex classification accuracies of 99 and 100%. Also, stepwise selection of 253 variables yielded seven variables that classified our groups in a four-way DFA with 83% accuracy, which is equivalent to DFA using craniometrics.

ILDs provide great potential for finding differences between groups. ILDs bring out features that have been visually appreciated (e.g. the shape of the pubis) as well as previously unrecognized variation. Using stepwise-selected ILDs often produced classification accuracies better than using geometric morphometric methods, likely due to the use of fewer variables with less morphological "noise", i.e., morphometric variation that does not differ between groups. Additional research by the authors will include testing this method on modern groups for the estimation of sex and ancestry.

Our definitions showed small differences between measurements calculated from digitizing and measurements from calipers. Although the use of the Microscribe digitizer is more efficient, this study has shown that calipers can also be used to record dimensions useful for discrimination. With well written and well illustrated definitions, a small number of measurements can be specified and used to accurately discriminate between the sexes and often between American blacks and whites.

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