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Attribution of Hand Bones to Sex and Population Groups

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ABSTRACT: Forensic anthropologists assign sex and population group (race) to individuals on the basis of skeletal remains. While the most useful bones for these determinations are cranial and pelvic, these are not always available. The purpose of this paper is to provide models for classification using metacarpals and hand phalanges. Four samples of 40 individuals each (black and white males and females) form the dataset. Measurements include lengths and radioulnar and dorsopalmar widths of the 19 bones of each hand. The large number of total variables necessitated separate models for metacarpal and phalangeal categories; due to the considerable number of significant differences between corresponding right and left hand variables, separate models were created for right and left sides. A stepwise discriminant procedure was used to select variables, with some highly correlated ($r > 0.85$) variables subsequently removed. The model for left hand metacarpals has the greatest power of discrimination (89.4%); that for right hand middle phalanges, the least (71.7%). Metacarpals assign approximately 87–89%, proximal phalanges 76–79%, middle phalanges 72–79%, and distal phalanges 81–83% of individuals to their correct sex and population groups. Models exchanging variables selected from one side for corresponding variables on the other show discriminating power ranging from 72.3 to 85.6%. Thus roughly 70–90% of individuals are correctly classified by these models; more conservative "jackknife" estimates yield a success rate of approximately 67–82%. When these models are used for classification of sex alone, 89.9–94.4% ("jackknife" range, 88.7–94.4%) of cases are correctly classified; for race alone, 80.5–98.1% ("jackknife" range, 77.4–96.9%).

KEYWORDS: forensic science, forensic anthropology, physical anthropology, human identification, metacarpals, phalanges

Anthropologists are frequently consulted in forensic cases involving osteological evidence. They are confronted with the challenge of determining the sex and population affiliation, or race, of an individual based solely on skeletal remains. The most useful skeletal regions for these determinations are the skull and pelvis, but in many cases these are not present. Non-pelvic postcranial bones must then be used in such an effort. Several models are available for a variety of postcranial bones (see (1)).

While metacarpals have been used to estimate stature (2,3), few studies have attempted sex or race identification using hand bones. Scheuer and Elkington (4) created regression equations for the metacarpals and first proximal phalanx to be used in sex determination. The good accuracy of these equations when applied to a small test sample is encouraging, and suggests that further exploring the use of hand bones in identification is merited.

The purpose of this paper is to present a series of models derived from an analysis of the metacarpals and phalanges of the hand. These bones may be found in association with other bones from an individual, in which case the models developed here can provide additional supporting information leading to classification. In other cases, hand bones may be found in isolation or only with other relatively "non-diagnostic" bones. In this situation, the models developed here allow a forensic anthropologist to suggest the most probable sex and race of the individual in the absence of any additional information, providing the bones used in one of the models are present.

Materials and Methods

Samples

The Terry and Huntington osteological collections of the Smithsonian Museum of Natural History (USNM/NMNH) provided samples for these analyses. Forty individuals of each sex were collected for each of two racial designations, listed here as "white" and "black." Assigning individuals to these categories is imprecise and of questionable biological validity but nevertheless is common in forensic work, in which in practice anthropologists are constrained to use these social categories (see (5) for discussion).

Individuals with complete, or nearly complete, bones of the hands and feet were selected for inclusion in the sample to be measured. (Although analyses of foot bones are not presented here, the dataset was created to permit analyses involving them.) Sampling was not random. The skeletons in these collections are not a random sample of the wider U.S. population of their time; furthermore, individuals were reviewed for condition of the bones and presence of required elements, as is common for studies utilizing such collections.

The Terry Collection was sampled first. Adults between the ages of 26 and 40 years were eligible for initial review. The upper age limit was established to avoid degenerative bone changes, primarily osteoarthritis, that could detract from the examination of normal variation. The lower age limit ensured skeletal maturity. For all but the black male sample (age range 26–35), these limits were subsequently extended (black females: 21–40; white males: 27–50; white females: 27–50) in the interest of obtaining sufficient numbers of individuals. Any individual with pathology affecting the hands or feet that was noted in the case records or determined upon examination was omitted.

For the white females and males, the Terry Collection did not yield the total desired sample sizes. A second, less utilized, Smithsonian skeletal collection, the Huntington Collection, contributed

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13 white females (ages 22–50) and 2 white males (ages 32 and 48). Established by the New York City physician George Huntington, the collection consists mainly of immigrants to the U.S. at the turn of the century. Although an excellent resource, the collection has been infrequently used in the past, largely due to ease of access to Terry skeletons, stored as individuals, compared with Huntington skeletons, stored by bone element. In the course of this research, I reunited several individuals' hands and feet. The Smithsonian staff are working to make this collection more accessible for future researchers.

Measurements

A series of length, radioulnar width, and dorsopalmar width measurements were collected from each metacarpal and hand phalanx. For metacarpals (MC) 1 through 3, both interarticular and maximum lengths were measured. For MC 4 and 5, maximum length equals interarticular length; hence only one length was measured. Maximum radioulnar and dorsopalmar base widths were measured for each metacarpal. These widths should be taken approximately at the level of the basal articulations of these bones. Radioulnar and dorsopalmar midshaft widths were measured at the approximate middle of the shaft, using the palmar curvature of the metacarpals as a visual aid. Condyle measurements were taken across the articular condyles of the metacarpal heads at the point of maximum width. Radioulnar and dorsopalmar maximum widths of the heads themselves complete the metacarpal measurements.

Proximal phalangeal (PP) measurements include maximum length, interarticular length, maximum radioulnar and dorsopalmar base widths, radioulnar and dorsopalmar midshaft widths (taken at the level of the approximate middle of the shaft), and maximum radioulnar and dorsopalmar head widths. For PP 2–5, the radioulnar articulation of the head of the bone is a separate measurement, taken at the approximate center of the articular surface, from one side to the other, across the articulation.

Middle phalangeal (MP) measurements include interarticular and maximum lengths, maximum radioulnar and dorsopalmar base widths, radioulnar and dorsopalmar midshaft widths (measured in the narrow region of the midshaft), and maximum radioulnar and dorsopalmar head widths. Distal phalangeal (DP) measurements include interarticular and maximum lengths, maximum radioulnar and dorsopalmar base widths, radioulnar and dorsopalmar midshaft widths, and maximum radioulnar and dorsopalmar tuft widths. On DP 2–5, the maximum dorsopalmar base width may include the *flexor digitorum profundus* insertion. The midshaft widths should be taken in the narrow region of the shaft between the base and tuft; the dorsopalmar measurement of this width on DP1 may include its *flexor pollicis longus* insertion.

Since complete or nearly complete sets of hands were measured, with right and left hands stored separately, problems of identification of side and ray number were minimized. With practice it is possible to determine the side and ray placement of most hand bones. Distinguishing right and left sides for middle and distal phalanges, and ray placement for middle and distal phalanges 3 and 4, is most difficult. DP 2 and 5 can be difficult to place as well, if less complete hand bone material is available. Sources useful for aid in identifying hand bones include Bass (6), Steele and Bramblett (7), and White and Folkens (8). Susman (9) provides comparative descriptions of hominoid metacarpals and phalanges that are also helpful.

Statistical Analyses

Both right and left hand bones were measured for each individual. Due to the large number of significant differences discovered between sides in exploratory t-tests, models were created separately for right and left hands. Stepwise discriminant analysis (SPSS/PC+, version 3.0) using the Mahalanobis' distance criterion for variable selection was employed to select the most useful variables for distinguishing sex and racial groups. The large number of measurement variables (159) relative to the number of cases ($40 \times 4 = 160$) necessitated creating models that used only a subset of available variables. The models presented here have been created using the major subdivisions of bones (that is, MC, PP, MP and DP).

The discriminant analysis procedure omits cases with missing data for any employed variable. A review of such cases was therefore undertaken to minimize the lowering of sample size that would otherwise occur. No alterations were necessary for the black male sample. In four black female cases, the values for from one to four missing variables were substituted from the opposite side in order to retain these cases in the analyses. Due to the greater difficulty of obtaining ideal material for the white samples, more cases have missing data for which values from the opposite side need to be substituted. Some of these cases have bones missing. In some instances, although the case as a whole was not omitted as pathological, there were areas of "lipping" or exostoses that were clearly better avoided. Two white female cases have an omitted brachydactylous bone (one MP5 and one DP1). For white males, 14 cases required some substitution (1 variable only for 7 cases; 4–9 variables for 6 cases; 16 variables for one case). For white females, two cases were allowed to drop from some analyses due to excessive missing data; 15 others required substitutions (1–2 variables for 4 cases; 4–9 variables for 9 cases; 16 and 18 variables for 2 cases).

To simplify the final models, three steps were taken. First, to reduce the number of variables, the minimum probability of F-to-enter and the maximum probability of F a variable is allowed to have before removal were both set at $P = 0.05$. By default, F-to-enter and F-to-remove are both 1.0, a fixed value. There are no default values for the probabilities of F-to-enter and F-to-remove (10). Specifying fixed significance levels of $P = 0.05$ for variable entry and removal results in fewer variables "making it" into the model produced at the end of the stepwise procedure. For example, for the left hand metacarpal model, the addition of these significance levels reduced the number of variables from 30 to 15.

Second, all models were limited to two functions. The default number of functions for these analyses would be 3 (the number of groups minus 1). However, the relative amount of variation explained by the third function is less than 5% in each case (8 models). When the third function is removed, the resulting average loss of discriminatory power in classification is not great, and limiting the models to two functions likely helps to remove minor differences specific to these particular samples, thus improving the models for purposes of classifying unknown cases. It has the additional benefit of simplifying the calculations that need to be made when classifying cases.

Third, choices among highly correlated variables ($r > 0.85$; $N = 158$ cases) were made, with some of these variables being eliminated from the final models. The rationale was to remove somewhat redundant information, while simplifying the process of classification of unknown cases by reducing the number of measurements.

As a test of the final 8 models, I applied them "in reverse." That is, models developed from right hand bone measurements were used to classify bones from the left hand, and vice versa. Although means for many variables may statistically differ significantly by side, a model generated with variables from one side should be capable of discriminating well on the other side. Although based on the same individuals, and recognizing that in some cases values from one side have been substituted with those from the other, the models used "in reverse" give some indication of how well the models' variables discriminate among the groups beyond finding minor statistical fluctuations in one set of data.

Less biased estimates of classification can also be obtained through the use of a jackknife procedure. This procedure is not available as an option in the statistical package used. However, a macro is available from SPSS that will perform a procedure very similar to a jackknife (U-method, or leaving-one-out method), one which provides slightly more conservative estimates than a conventional jackknife. I used this macro (compatible with SPSS version 4.1, CMS) to obtain the "jackknife" figures presented here.

Box's M test was used to test for equality of group covariance matrices in the final 8 models. (One of the assumptions of linear discriminant analysis is that these matrices are equal.) For one of the 8 models, the groups had significantly different covariance matrices (left hand PP; $P = 0.04$). In addition, one other test was of borderline significance (right hand DP; $P = 0.05$). For models applied "in reverse," two tests showed significantly different covariance matrices (left hand MC applied to right, $P = 0.03$; right hand PP applied to left, $P < 0.01$). However, linear discriminant analysis is fairly robust even when this assumption is violated, and the good classification results are a positive sign that the violation is not detrimental (see (11)).

TABLE 1—*Left hand metacarpals.*

		Eigenvalue	% Variance	Canonical Correlation
F1		2.68	55.10	0.85
F2		1.98	40.68	0.82
		Centroids		
	BM	BF	WM	WF
F1	2.45	−0.46	0.07	−2.06
F2	−0.12	−2.07	1.81	0.38
		Unstandardized Coefficients		
Variable		F1	F2	
LHMC1RUB		0.1686	−0.4028	
LHMC1DPB		0.3821	0.5788	
LHMC1DPM		−0.0676	−1.0332	
LHMC1DPH		0.1137	0.7068	
LHMC2RUB		0.3899	0.4173	
LHMC2DPB		−0.4319	0.2312	
LHMC2DPH		−0.3987	1.0319	
LHMC3IAL		0.0783	−0.1447	
LHMC3RUB		−0.1162	−0.0946	
LHMC3RUM		0.5819	0.3696	
LHMC3DPM		0.6242	−0.1981	
LHMC4DPH		0.7254	−0.8780	
LHMC5CON		−0.7665	0.1020	
Constant		−17.5417	−9.0132	

89.38% Correctly Classified; $N = 160$
(88.75%, 3 functions; 81.88%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; LHMC = left hand metacarpal; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; CON = condyles.

Results

Eight models are presented here (for four bone categories for both hands; Tables 1–8) with accompanying all-groups scatterplots for the left hand models (Figs. 1–4). The simplest expectation would be that the first function (plotted along the x axis) would separate males from females and the second function (plotted along the y axis) would separate black from white samples. However, there is considerable overlap between territories; and the groups appear to separate along diagonals in several cases, indicating that both functions contribute to some degree to both sex and race separation. For example, for left hand metacarpals (Fig. 1), function 1 produces the most separation for black males and white females, and function 2 best helps to differentiate white males from black females. The plot for left hand middle phalanges (Fig. 3), however, does show that function 1 largely separates the male from the female groups, while function 2, with less distance between the centroids, separates the black and white groups.

The classification percentages for models applied "in reverse" are as follows: 1) Left Hand MC model used on Right Hand MC—83.65%; 2) Right Hand MC model used on Left Hand MC—85.63%; 3) Left Hand PP model used on Right Hand PP—76.73%; 4) Right Hand PP model used on Left Hand PP—78.13%; 5) Left Hand MP model used on Right Hand MP—72.33%; 6) Right Hand MP model used on Left Hand MP—73.13%; 7) Left Hand DP model used on Right Hand DP—81.01%; 8) Right Hand DP model used on Left Hand DP—81.25%.

Tables 1–8 provide the percentages of correctly classified cases based on two functions. In parentheses, 3-function and "jackknife" percentages are given; the 3-function percentages are shown since

TABLE 2—*Right hand metacarpals.*

		Eigenvalue	% Variance	Canonical Correlation
F1		3.71	71.08	0.89
F2		1.38	26.46	0.76
		Centroids		
	BM	BF	WM	WF
F1	2.46	1.09	−1.18	−2.43
F2	0.69	−1.49	1.47	−0.70
		Unstandardized Coefficients		
Variable		F1	F2	
RHMC1RUH		0.7788	0.1936	
RHMC1DPH		−0.2963	0.4974	
RHMC2DPB		−0.3649	0.0165	
RHMC2DPH		−1.3583	0.7706	
RHMC3IAL		0.1684	−0.0967	
RHMC3RUB		0.6143	0.2831	
RHMC4DPM		0.9875	−0.3456	
RHMC4CON		−0.4674	0.1401	
RHMC4DPH		1.0383	−0.3840	
RHMC5RUB		−0.5532	0.2575	
RHMC5DPB		−0.4578	0.0968	
RHMC5RUM		0.5219	−0.0692	
Constant		−6.9747	−16.6806	

86.79% Correctly Classified; $N = 159$
(87.42%, 3 functions; 81.76%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; RHMC = right hand metacarpal; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; CON = condyles.

TABLE 3—*Left hand proximal phalanges.*

	Eigenvalue	% Variance	Canonical Correlation
F1	2.84	77.28	0.86
F2	0.71	19.25	0.64

Centroids

	BM	BF	WM	WF
F1	2.34	−1.19	0.76	−1.91
F2	−0.62	−0.90	1.22	0.29

Unstandardized Coefficients

Variable	F1	F2
LHPP1RUM	−0.3419	1.0427
LHPP1DPM	−0.0264	−1.5117
LHPP1RUH	1.4319	−0.3696
LHPP2DPB	0.2049	0.2037
LHPP2DPM	0.4919	0.0285
LHPP2RUH	−0.9851	0.1543
LHPP2RUA	−0.1679	1.3295
LHPP4DPH	0.8575	0.2881
LHPP5MXL	0.0043	−0.2980
LHPP5RUM	0.5170	−0.0511
Constant	−18.5277	−3.7880

76.25% Correctly Classified; $N = 160$
(78.75%, 3 functions; 73.13%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; LHPP = left hand proximal phalanx; MXL = maximum length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; A = articular surface.

TABLE 4—*Right hand proximal phalanges.*

	Eigenvalue	% Variance	Canonical Correlation
F1	2.48	78.74	0.84
F2	0.59	18.73	0.61

Centroids

	BM	BF	WM	WF
F1	2.21	−0.79	0.51	−1.98
F2	−0.39	−0.93	1.10	0.23

Unstandardized Coefficients

Variable	F1	F2
RHPP1RUH	1.1886	0.1635
RHPP2DPB	0.3376	0.0615
RHPP2RUH	−0.9374	0.2221
RHPP2RUA	−0.7244	0.6755
RHPP3RUM	0.6645	−0.3572
RHPP3RUA	0.0105	1.2360
RHPP5MXL	0.0482	−0.2558
RHPP5RUH	0.9596	−0.7068
Constant	−18.5363	−5.1393

78.62% Correctly Classified; $N = 159$
(80.50%, 3 functions; 73.58%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; RHPP = right hand proximal phalanx; MXL = maximum length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; A = articular surface.

TABLE 5—*Left hand middle phalanges.*

	Eigenvalue	% Variance	Canonical Correlation
F1	2.59	73.02	0.85
F2	0.83	23.47	0.67

Centroids

	BM	BF	WM	WF
F1	1.94	−1.27	1.16	−1.83
F2	0.77	0.98	−1.16	−0.59

Unstandardized Coefficients

Variable	F1	F2
LHMP2RUM	0.8038	0.1862
LHMP2DPH	−1.7292	0.1804
LHMP3DPB	−0.2612	0.1025
LHMP3RUH	1.1279	0.2866
LHMP4RUB	−0.4374	0.4040
LHMP4RUM	−0.2585	−1.3300
LHMP4DPM	1.8448	1.5700
LHMP5IAL	−0.0757	0.3835
LHMP5DPB	1.3554	−0.7233
LHMP5DPM	−1.3465	1.1255
LHMP5DPH	1.4360	−3.1518
Constant	−17.3254	−0.0403

79.38% Correctly Classified; $N = 160$
(80.00%, 3 functions; 71.25%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; LHMP = left hand middle phalanx; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head.

TABLE 6—*Right hand middle phalanges.*

	Eigenvalue	% Variance	Canonical Correlation
F1	2.30	80.41	0.83
F2	0.55	19.27	0.60

Centroids

	BM	BF	WM	WF
F1	1.79	−0.91	1.04	−1.97
F2	0.55	0.84	−0.98	−0.41

Unstandardized Coefficients

Variable	F1	F2
RHMP2DPM	−1.1345	−0.5751
RHMP3DPM	2.0228	0.2558
RHMP4IAL	−0.0270	0.3041
RHMP5DPM	−0.1545	2.2369
RHMP5RUH	1.5864	−0.4166
RHMP5DPH	−0.2762	−3.0069
Constant	−16.3195	1.9879

71.70% Correctly Classified; $N = 159$
(71.07%, 3 functions; 66.67%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; RHMP = right hand middle phalanx; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; M = middle; H = head.

TABLE 7—*Left hand distal phalanges.*

		Eigenvalue	% Variance	Canonical Correlation
F1		2.53	68.94	0.85
F2		1.03	27.93	0.71
		Centroids		
	BM	BF	WM	WF
F1	2.30	−0.31	0.12	−2.12
F2	−0.16	−1.38	1.44	0.11
		Unstandardized Coefficients		
Variable		F1	F2	
LHDP1MXL		0.3450	−0.4672	
LHDP1DPB		0.9284	0.6259	
LHDP1DPM		−0.8457	1.1245	
LHDP3IAL		0.5426	−0.6787	
LHDP4DPB		0.1078	0.0512	
LHDP5MXL		−0.5380	0.8490	
LHDP5RUB		−0.0108	1.2683	
LHDP5DPB		0.3820	−1.0101	
LHDP5DPM		1.3529	−1.0567	
Constant		−19.5334	−4.8023	

80.63% Correctly Classified; *N* = 160
(83.75%, 3 functions; 78.75%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; LHDP = left hand distal phalanx; MXL = maximum length; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle.

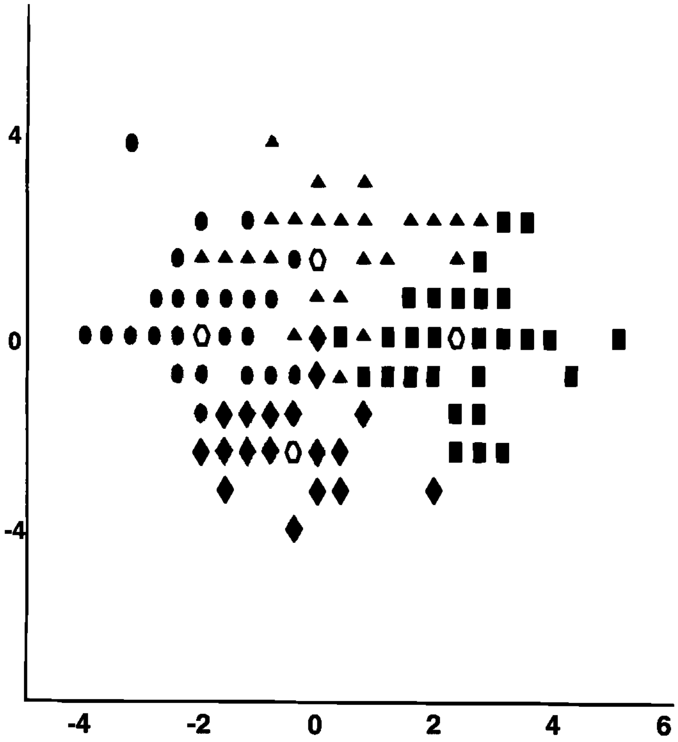

FIG. 1—*Left hand metacarpals. ■ = black males; ♦ = black females; ▲ = white males; ● = white females; O = group centroid.*

TABLE 8—*Right hand distal phalanges.*

		Eigenvalue	% Variance	Canonical Correlation
F1		2.51	69.31	0.85
F2		0.99	27.35	0.71
		Centroids		
	BM	BF	WM	WF
F1	2.33	−0.28	−0.05	−2.09
F2	−0.16	−1.28	1.47	−0.04
		Unstandardized Coefficients		
Variable		F1	F2	
RHDP1MXL		0.5157	−0.3456	
RHDP1DPM		−0.6973	1.1087	
RHDP3MXL		0.2345	−0.5693	
RHDP3RUB		0.5490	0.4586	
RHDP5MXL		−0.2308	0.6217	
RHDP5RUB		−0.0429	1.2756	
RHDP5DPB		0.4173	−1.0562	
RHDP5DPM		1.2824	−0.8602	
RHDP5RUT		−0.5169	0.3093	
Constant		−18.6211	−6.7616	

82.91% Correctly Classified; *N* = 158
(83.54%, 3 functions; 77.85%, "jackknife")

Abbreviations: F1 = function 1; F2 = function 2; BM = black males; BF = black females; WM = white males; WF = white females; RHDP = right hand distal phalanx; MXL = maximum length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; T = tuft.

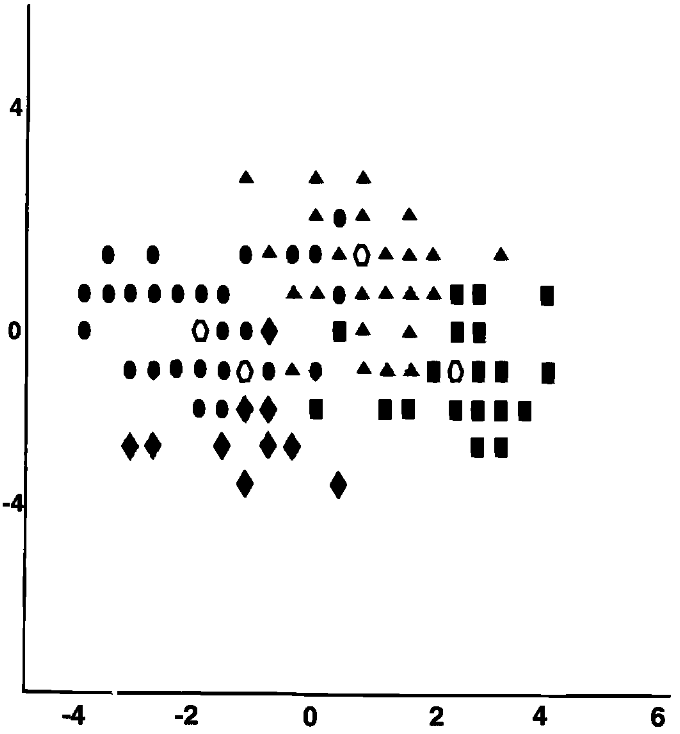

FIG. 2—*Left hand proximal phalanges. ■ = black males; ♦ = black females; ▲ = white males; ● = white females; O = group centroid.*

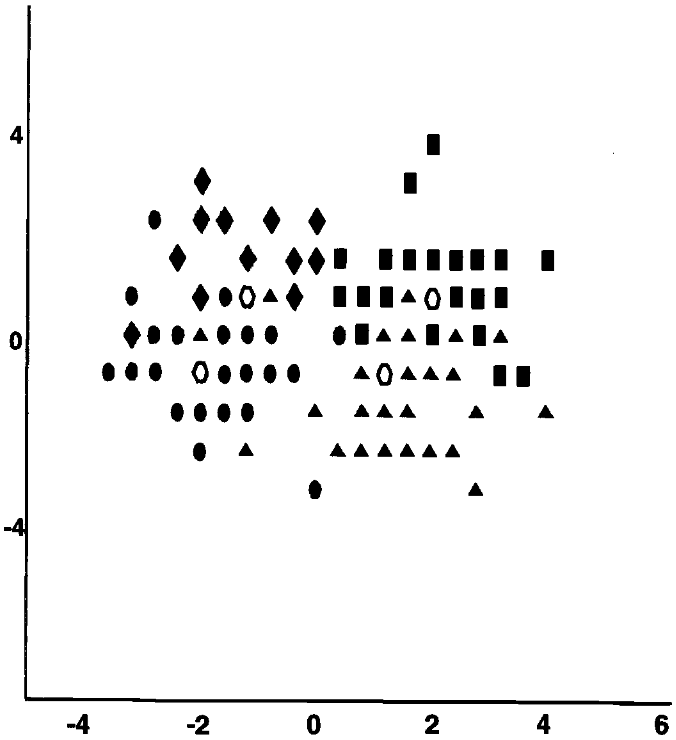

FIG. 3—*Left hand middle phalanges.* ■ = *black males;* ♦ = *black females;* ▲ = *white males;* ● = *white females;* O = *group centroid.*

the macro from SPSS is not easily modified from the default situation and therefore the better comparison between values is with these percentages.

To use Tables 1–8 to assign a sex and race to an unknown case (with "white" or "black" being the presumed choices for race), compute a score for both function 1 and function 2 by obtaining the sum of the value for each variable multiplied by its unstandardized coefficient, plus the constant. Using these scores, a Mahalanobis' distance (D^2) from each group centroid can then be calculated by obtaining the sum of the square of the differences between the function scores for the unknown case and the respective function scores of the centroids for each group. The case in question can then be assigned to the group from which it has the smallest D^2. It is in addition useful to know the posterior probability (the probability a case belongs to a group given its score or D^2) associated with membership in each group, because this provides a sense of how likely the group assignment is. (See (12) for a worked example including D^2 and posterior probability calculations.)

The variables employed in the models presented here were selected for the purpose of discriminating among four groups, considering both sex and race in group categorization. To achieve correct classification, a case must be assigned to both the correct sex and the correct race. Although variables were selected for their value in 4-group classification, using the same variables in 2-group discriminant analyses, with groups defined either by sex or by race alone, provides an indication of the power of these models to discriminate by sex and race separately. These functions are listed in Tables 9–16. It would be expected that performance would be better in the discriminant analyses by sex alone than in those

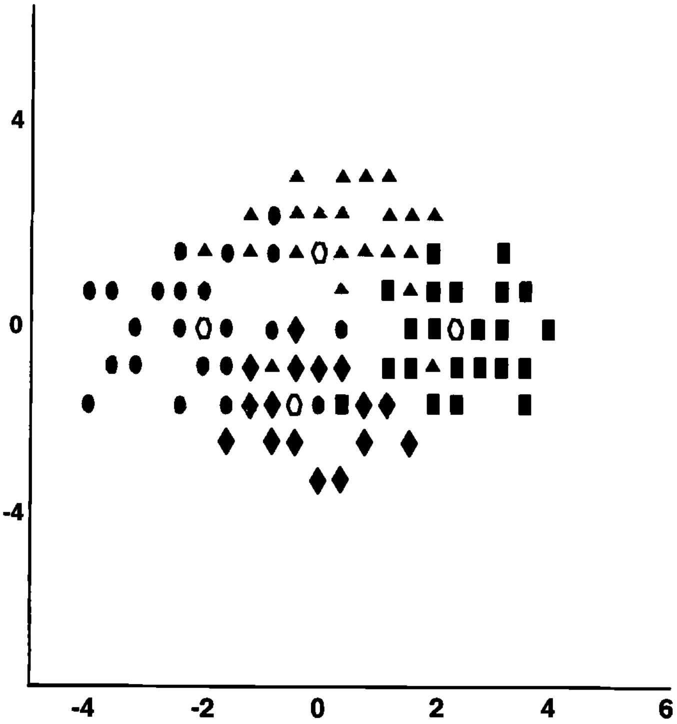

FIG. 4—*Left hand distal phalanges.* ■ = *black males;* ♦ = *black females;* ▲ = *white males;* ● = *white females;* O = *group centroid.*

TABLE 9—*Left hand metacarpals; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
2.24	0.83	2.21	0.83
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.49	−1.49	1.48	−1.48
	Unstandardized Coefficients		
Variable	Sex	Race	
LHMC1RUB	−0.0856	0.4257	
LHMC1DPB	0.5604	−0.2400	
LHMC1DPM	−0.6738	0.7954	
LHMC1DPH	0.5076	−0.5040	
LHMC2RUB	0.5239	−0.1054	
LHMC2DPB	−0.2015	−0.4437	
LHMC2DPH	0.3459	−1.0720	
LHMC3IAL	−0.0424	0.1638	
LHMC3RUB	−0.0139	0.0059	
LHMC3RUM	0.5666	0.0482	
LHMC3DPM	0.3252	0.5318	
LHMC4DPH	0.0767	1.1409	
LHMC5CON	−0.4278	−0.5393	
Constant	−19.3303	−3.1349	
	93.75% Correctly Classified; N = 160 (91.88%, "jackknife")	95.63% Correclty Classified; N = 160 (91.25%, "jackknife")	

Abbreviations: LHMC = left hand metacarpal; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; CON = condyles.

TABLE 10—*Right hand metacarpals; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
1.52	0.78	3.21	0.87
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.22	−1.23	1.77	−1.79

	Unstandardized Coefficients	
Variable	Sex	Race
RHMC1RUH	0.4048	0.6245
RHMC1DPH	0.3909	−0.4692
RHMC2DPB	−0.0893	−0.3405
RHMC2DPH	0.3482	−1.5460
RHMC3IAL	−0.0449	0.1908
RHMC3RUB	0.4461	0.4452
RHMC4DPM	−0.0474	1.0391
RHMC4CON	0.0030	−0.4757
RHMC4DPH	−0.0644	1.1123
RHMC5RUB	0.0864	−0.6107
RHMC5DPB	−0.0359	−0.4500
RHMC5RUM	0.0786	0.4928
Constant	−17.9304	0.3703
	91.19% Correctly Classified; $N = 159$ (89.94%, "jackknife")	98.11% Correctly Classified; $N = 159$ (96.86%, "jackknife")

Abbreviations: RHMC = right hand metacarpal; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; CON = condyles.

TABLE 11—*Left hand proximal phalanges; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
2.28	0.83	0.78	0.66
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.50	−1.50	0.88	−0.88

	Unstandardized Coefficients	
Variable	Sex	Race
LHPP1RUM	0.1331	−0.9361
LHPP1DPM	−0.5705	1.5590
LHPP1RUH	1.0943	0.6217
LHPP2DPB	0.2402	−0.2153
LHPP2DPM	0.3844	−0.1443
LHPP2RUH	−0.8164	−0.4367
LHPP2RUA	0.3954	−1.1660
LHPP4DPH	0.9022	0.1014
LHPP5MXL	−0.1127	0.2745
LHPP5RUM	0.4578	0.2743
Constant	−17.9953	−2.1818
	94.38% Correctly Classified; $N = 160$ (92.50%, "jackknife")	81.88% Correctly Classified; $N = 160$ (79.38%, "jackknife")

Abbreviations: LHPP = left hand proximal phalanx; MXL = maximum length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; A = articular surface.

TABLE 12—*Right hand proximal phalanges; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
1.75	0.80	0.78	0.66
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.31	−1.32	0.87	−0.88

	Unstandardized Coefficients	
Variable	Sex	Race
RHPP1RUH	1.0609	0.3002
RHPP2DPB	0.2918	−0.0427
RHPP2RUH	−0.6712	−0.5531
RHPP2RUA	−0.2782	−0.8610
RHPP3RUM	0.3945	0.6610
RHPP3RUA	0.6020	−1.0354
RHPP5MXL	−0.0821	0.2388
RHPP5RUH	0.4733	1.0826
Constant	−17.9002	−3.2820
	90.57% Correctly Classified; $N = 159$ (88.68%, "jackknife")	83.02% Correctly Classified; $N = 159$ (77.36%, "jackknife")

Abbreviations: RHPP = right hand proximal phalanx; MXL = maximum length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head; A = articular surface.

TABLE 13—*Left hand middle phalanges; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
2.43	0.84	0.86	0.68
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.55	−1.55	0.92	−0.92

	Unstandardized Coefficients	
Variable	Sex	Race
LHMP2RUM	0.7212	0.2192
LHMP2DPH	−1.7151	−0.1200
LHMP3DPB	−0.2592	0.2093
LHMP3RUH	1.0215	0.4665
LHMP4RUB	−0.5192	0.3199
LHMP4RUM	0.0850	−1.1884
LHMP4DPM	1.4094	1.8484
LHMP5IAL	−0.1649	0.3589
LHMP5DPB	1.4690	−0.5953
LHMP5DPM	−1.5716	0.8582
LHMP5DPH	2.1347	−2.8785
Constant	−16.8139	−3.6169
	94.38% Correctly Classified; $N = 160$ (94.38%, "jackknife")	81.88% Correctly Classified; $N = 160$ (79.38%, "jackknife")

Abbreviations: LHMP = left hand middle phalanx; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; H = head.

TABLE 14—*Right hand middle phalanges; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
1.96	0.81	0.62	0.62
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.38	−1.40	0.78	−0.79

Variable	Unstandardized Coefficients Sex	Unstandardized Coefficients Race
RHMP2DPM	−0.8422	−0.9006
RHMP3DPM	1.7713	0.8451
RHMP4IAL	−0.1107	0.2731
RHMP5DPM	−0.8319	2.0766
RHMP5RUH	1.6004	0.0575
RHMP5DPH	0.6591	−2.9199
Constant	−15.9453	−2.5921
	89.94% Correctly Classified; $N = 159$ (88.68%, "jackknife")	80.50% Correctly Classified; $N = 159$ (79.25%, "jackknife")

Abbreviations: RHMP = right hand middle phalanx; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; M = middle; H = head.

TABLE 15—*Left hand distal phalanges; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
1.71	0.79	1.44	0.77
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.30	−1.30	1.19	−1.19

Variable	Unstandardized Coefficients Sex	Unstandardized Coefficients Race
LHDP1MXL	−0.0645	0.5607
LHDP1DPB	1.0653	−0.0002
LHDP1DPM	0.1273	−1.3948
LHDP3IAL	−0.0446	0.8801
LHDP4DPB	0.1491	0.1035
LHDP5MXL	0.1698	−0.9923
LHDP5RUB	0.8514	−0.9682
LHDP5DPB	−0.4121	0.9794
LHDP5DPM	0.2553	1.5729
Constant	−17.3941	−7.7572
	91.88% Correctly Classified; $N = 160$ (91.88%, "jackknife")	86.88% Correctly Classified; $N = 160$ (84.38%, "jackknife")

Abbreviations: LHDP = left hand distal phalanx; MXL = maximum length; IAL = interarticular length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle.

TABLE 16—*Right hand distal phalanges; 2-group analyses.*

Sex		Race	
Eigenvalue	Canonical Correlation	Eigenvalue	Canonical Correlation
1.60	0.78	1.41	0.77
Male Centroid	Female Centroid	Black Centroid	White Centroid
1.24	−1.27	1.17	−1.20

Variable	Unstandardized Coefficients Sex	Unstandardized Coefficients Race
RHDP1MXL	0.1124	0.5714
RHDP1DPM	0.2973	−1.2862
RHDP3MXL	−0.2377	0.6394
RHDP3RUB	0.6987	−0.1155
RHDP5MXL	0.2769	−0.6857
RHDP5RUB	0.8636	−0.8744
RHDP5DPB	−0.4532	1.1608
RHDP5DPM	0.2792	1.2355
RHDP5RUT	−0.1387	−0.4906
Constant	−17.5316	−6.2597
	89.87% Correctly Classified; $N = 158$ (89.24%, "jackknife")	87.97% Correctly Classified; $N = 158$ (86.71%, "jackknife")

Abbreviations: RHDP = right hand distal phalanx; MXL = maximum length; RU = radioulnar; DP = dorsopalmar; B = base; M = middle; T = tuft.

by race alone. This is indeed the case except for metacarpals, where classification by race is highly effective for these samples (about 96–98%). "Jackknife" values show essentially equivalent rates for LHMC discrimination by sex alone and race alone, but for RHMC, correct classification by race alone still exceeds that for sex alone. As expected, in all cases the 2-group analyses achieve higher classification rates than the respective 4-group ones.

Discussion and Conclusions

The metacarpal models have the greatest power of discrimination, assigning about 87–89% ("jackknife," 82%) of individuals to their correct sex and population groups. Perhaps more surprising is the relatively good performance of the DP models, which assign approximately 81–83% ("jackknife," 78–79%) of individuals correctly. Proximal phalanges correctly assign 76–79% ("jackknife," 73–74%) of individuals. The greatest difference between left and right hand models occurs for middle phalanges. The left hand MP model, employing 11 variables, yields a correct placement in 79% ("jackknife," 71%) of cases; the right hand model, employing 6 variables, gives correct classification in 72% ("jackknife," 67%) of cases. For the other three pairs of models, number of variables entered differs by at most two, and the difference in classification success is only 2–3% ("jackknife" difference < 1%).

For models applied "in reverse," metacarpals assign 84–86%, distal phalanges 81%, proximal phalanges 77–78%, and middle phalanges 72–73% of individuals to their correct categories. Thus these models, when applied to bones of the opposite side from that on which they were developed, perform very similarly within bone subdivisions. In addition, there is not much difference in the average ability of models developed on bones of one side to discriminate among the groups using bones from that side as opposed to the opposite side. For metacarpals, this difference is 3.4%; for middle phalanges, 2.8%; for distal phalanges, < 1%; and for proximal phalanges, the average performance of original and "reverse" models is equal. Thus the combinations of variables used retain their power of discrimination when used on the opposite hand, suggesting that the models are detecting more than minor statistical fluctuations in one set of data. The "jackknife" figures, while giving somewhat lower rates of correct classification, nevertheless support this conclusion.

Given the required sets of bones from one hand, approximately 67–82% of individuals can be assigned to their correct sex and population groups, judging from the "jackknife" values. This result indicates that some models produce relatively good classification accuracy in the simultaneous assignment of individuals to sex and population ("racial") categories, at least for the dichotomous "racial" groups ("black" versus "white") tested here.

In many forensic cases, the entire set of bones from one model will not be present. In such cases classification will be more tenuous. Substitution of matching bones from the opposite side should not affect classification greatly in the majority of forensic cases. High correlations among some variables provide another avenue for possible substitution in the models presented here. The dataset from which these models were derived can be used to generate other models specific to the bones available in a given case.

Some caution is merited with archaeological or historical samples, or bones suspected to have derived from such a context. Lazenby (13) found bilateral asymmetry to affect the success rate of sex classification of skeletons from a 19th century cemetery when using Scheuer and Elkington's equation (4) for the second metacarpal. Furthermore, in his sample prediction accuracy for females was low, regardless of side used, presumably due to the greater skeletal robusticity of these females relative to 20th century women. Thus attention to context of recovered bones is, as always, wise. While the Terry and Huntington collections are recent by archaeological standards, it should be recognized that they are not from contemporary populations. The Huntington Collection dates from the late 1800s and early 1900s; the Terry Collection, from the 1920s through the 1960s. The Terry Collection individuals sampled here were born between the 1870s and the 1930s; judging from Huntington Collection dates, the individuals sampled would have been born between the 1850s and 1880s. Thus any secular changes in hand bone dimensions which have occurred recently would affect the applicability of these models.

In summary, in the absence of preferred cranial and pelvic material, sets of hand bones can provide a classification by sex and population group that offers a considerable improvement over prior probabilities.

Note added in proof:

Readers interested in determination of sex using metacarpals can also consult Falsetti, A. B., J. Forensic Sci. 1995;40:774–76.

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