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PAPER

ANTHROPOLOGY

Sheena M. Harris,[1] *M.A. and D. Troy Case,*[1] *Ph.D.*

Sexual Dimorphism in the Tarsal Bones: Implications for Sex Determination

ABSTRACT: An accurate determination of sex is essential in the identification of human remains in a forensic context. Measurements of some of the tarsals have been shown to be sexually dimorphic by previous researchers. The purpose of the present study is to determine which dimensions of the seven tarsals demonstrate the greatest sexual dimorphism and therefore have the most potential for accurate sex determination. Eighteen measurements of length, width, and height were obtained from the tarsals of 160 European-American males and females from the William M. Bass Donated Skeletal Collection. These measurements were made using a mini-osteometric board. Logistic regression analyses were performed to create equations for sex discrimination. All measurements showed significant sexual dimorphism, with the talus, cuboid, and cuneiform I producing allocation accuracies of between 88 and 92%. Combinations of measurements provided better accuracy (88.1–93.6%) than individual measurements (80.0–88.0%).

KEYWORDS: forensic science, calcaneus, talus, cuboid, navicular, cuneiform

The accurate determination of sex is often the first analytical task of physical anthropologists when studying human skeletal remains. Our ability to accomplish this goal is influenced by the degree of preservation of the remains under study and the relative sexual dimorphism exhibited by those areas of the skeleton that remain intact. When skeletons are fairly complete, mostly undamaged, and exhibit indicators of sex with low ambiguity, the morphological approach may be the most accurate and efficient means of sex determination. The morphological approach has been shown to accurately sex adult skeletons more than 95% of the time, both in studies using multiple characteristics of the pelvis and skull (1,2), as well as in studies involving more limited subsets of features on the pelvis (3,4). However, when skeletons are incomplete, heavily damaged, or exhibit trait scores that are conflicting or ambiguous, metric methods may provide better information on sex, provided that an appropriate reference collection of known-sex skeletons exists for creating discriminant functions or logistic regression equations.

The tarsal bones show great potential for use in metric methods of sex determination because they preserve well in forensic contexts. Tarsals generally have a dense, compact structure and relatively thick cortices that help them to resist taphonomic processes associated with burial better than many other bones of the skeleton. When a body decomposes above ground, the tarsals are often shielded from scavengers and other taphonomic forces because of the protection afforded by footwear (5,6). Thus, recovery of intact and measurable tarsal bones should be relatively common in a forensic setting.

The tarsals may also be good candidates for metric sexing because they are weight-bearing bones located at the very bottom of the body mass column. Modern Americans tend to show sexual dimorphism of about 18% in body mass versus only about 8% in stature (7). If the greater body mass of males has a significant impact on tarsal size, then it is hypothesized that the weight-bearing bones of the ankle will provide better discrimination between males and females than most bones not involved in weight-bearing. The talus and calcaneus in particular are hypothesized to exhibit greater dimorphism than other bones of the tarsus, because the calcaneus (along with the distal metatarsals) bears the brunt of the body mass when walking (8).

Steele (9) was the first to consider the potential of tarsals as sex indicators. He assessed the degree of sexual dimorphism in the calcaneus and talus among 60 males and 60 females from the Robert J. Terry Anatomical Collection. The sample included equal numbers of European- and African-Americans of each sex. Five measurements of the calcaneus were taken and five additional measurements from the talus, including a length, width, and height measure for each bone. The only individual measure to correctly classify at least 80% of the combined sample of European- and African-Americans was talus length. Steele (9) also computed discriminant functions for the combined sample. The best four functions included two or three measurements each and correctly classified between 83 and 89% of the sample. These functions all included talar length, and three of them also included talar maximum width. The only calcaneal dimension in these functions was body height, and it was included in the best function along with talar length and width. No similar work has been carried out on separate samples of European- or African-Americans, nor have any studies been conducted with more recently deceased modern Americans.

Because talar length produced the best correct classification results, Steele (9) also tested the discriminatory ability of talar length on two archeological samples, one from the Larson site ($n = 40$), representing Arikara Indians, and the other from two Puebloan sites in the Southwest ($n = 49$). Talar length was found to be a little better at distinguishing the sexes in the Arikara sample than among the modern Americans, and about equal to the modern Americans among a pooled sample from the two Puebloan sites.

[1]Department of Sociology and Anthropology, North Carolina State University, Campus Box 8107, Raleigh, NC 27695-8107.

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Steele's work suggests that the talus is more sexually dimorphic than the calcaneus and that talar length alone is the most dimorphic single measure in these two tarsals.

In recent years, several researchers have followed up on Steele's work by assessing sexual dimorphism of the tarsals among populations, both modern and prehistoric, from other parts of the world (Table 1). Some studies have focused exclusively on the calcaneus (6,10–13) or exclusively on the talus (14–17). A few studies have included both of these bones (18–20), and additional studies have included one or both bones along with the navicular (21–23), the cuboid (23), or the second cuneiform (21). These studies (6,10–23) have confirmed a high degree of sexual dimorphism in the talus and calcaneus and have tended to agree with Steele (9) that talar length is the most sexually dimorphic dimension in the two bones. They have also generally found calcaneal length to be the most sexually dimorphic among the length, breadth, and height measures in the calcaneus (6,10–13,18).

The purpose of this study is to examine sexual dimorphism in all of the tarsal bones from a single set of recently deceased European-Americans to determine which bones and measurements show the greatest sexual dimorphism and therefore the greatest potential for metric sex determination. This study will introduce a set of new measurements for the tarsal bones using a mini-osteometric board and provide formulae for metric sexing of modern European-Americans that can be used in a forensic context.

Materials and Methods

The sample used for this study consists of 82 males and 78 females of European-American ancestry from the William M. Bass Donated Skeletal Collection housed at the University of Tennessee, Knoxville. The collection is composed of individuals who have died since 1981 and is heavily weighted toward the decade from 2000–2009. The sample used in this study ranges in age from 30 to 76 years, with a mean age of 58 years for females and 48 years for males. Individual measurements could not be taken on some bones because of pathology or postmortem damage, reducing sample sizes.

A total of 18 measurements were obtained from both the left and right tarsals of each skeleton by the first author (SMH) using a mini-osteometric board available from Paleo-Tech Concepts (Crystal Lake, IL). Initially, 21 measurements designed to capture length, breadth, and height dimensions for each of the seven tarsal bones were devised by the second author (DTC). Shape variation in some of the tarsals caused difficulty with consistent placement of some bones while measuring with the mini-osteometric board, resulting in the elimination of three dimensions prior to the study: calcaneal height, calcaneal breadth, and navicular height. For descriptions of the 18 measurements that remain, see Table 2A and B, and Figs 1–3. All measurements were made to the nearest 0.01 mm. The naming convention for these measurements includes a three- or four-letter abbreviation for the bone name, followed by a two- or three-letter abbreviation for the measurement dimension. The abbreviations for the bone names are calcaneus (Calc), talus (Tal), navicular (Nav), cuboid (Cub), cuneiform I (CF1), cuneiform II (CF2), and cuneiform III (CF3). Abbreviations for the dimensions are length (Lg), breadth (Brd), and height (Ht). Side is indicated by appending an "L" or "R" in front of the abbreviation, followed by a dash. Thus, right calcaneal length would be abbreviated R-CalcLg, and left cuneiform II breadth would be abbreviated L-CF2Brd.

Intra-observer error analysis was performed on each of the 18 measurements to assess their repeatability. Approximately every fifth skeleton was measured twice to verify accurate repeatability of each measure. These measurements were taken either later the same day, with many different measurements interposed between the repeated measurements, or on another day. When a particular fifth skeleton had a number of missing measurements, the next skeleton in the sequence was sometimes used. Intra-observer error was evaluated by considering the median absolute difference between repeated measures, the mean absolute difference between repeated measures, this same mean difference as a percentage of mean bone size, and the technical error of measurement (TEM). The "mean difference as a percentage of mean bone size" was calculated by dividing the mean absolute difference for all repeated measurements of a particular dimension by the grand mean size of all repeated measurements for that dimension. The TEM is a statistic often used in anthropometry to assess inter- and intra-observer precision. It provides an approximation of the standard deviation of the differences between paired measurements (24). The formula for TEM is

$$\mathrm{TEM} = \sqrt{\frac{\sum D^2}{2N}}$$

where D is the difference between two repeated measures and N represents the total number of subjects.

TABLE 1—*Previous studies of sexual dimorphism among the tarsals in various populations.*

Study	Bones	Largest *N*	Sample Date	Sample Type	Study Type	Best Overall Function (%)	Best Single Bone Function (%)	Most Dimorphic Measure
Steele (9)	C, T	120	19th Century	Mixed American	Skeletal	89	88	Talar length
Riepert et al. (10)	C	800	Modern	Central European	Radiographic	84	—	Calcaneal length
Hoover (21)	C, T, N, CF2	49	Prehistoric	Native American	Skeletal	—	94	—
Introna et al. (11)	C	80	Modern	Southern Italian	Skeletal	85	85	Calcaneal length
Wilbur (18)	C, T	282	Prehistoric	Native American	Skeletal	90	88	Talar length
Barrett et al. (14)	T	74	Prehistoric	Native American	Skeletal	93	93	Talar height
Gualdi-Russo (20)	C, T	118	19th Century	Italian	Skeletal	96	92	Talar length
Murphy (15)	T	51	Prehistoric	New Zealand	Skeletal	91	91	Talar length
Murphy (12)	C	48	Prehistoric	New Zealand	Skeletal	93	93	Calcaneal length
Murphy (19)	C, T	51	Prehistoric	New Zealand	Skeletal	92	N/A	—
Bidmos & Asala (13)	C	113	Modern	South African White	Skeletal	91	91	Dorsal Art. Fac. breadth
Bidmos & Dayal (16)	T	120	Modern	South African White	Skeletal	88	88	Talar length
Bidmos & Asala (6)	C	116	Modern	South African Black	Skeletal	85	85	Dorsal Art. Fac. length
Bidmos & Dayal (17)	T	120	Modern	South African Black	Skeletal	87	87	Talar head height
Ferrari et al. (22)	T, N, CF1	107	18th Century	British	Skeletal	86	86	Talar length

To maximize comparability of results among the various studies, stepwise discriminant function results are reported instead of direct discriminant results where available.

C, cuboid; CF1, cuneiform I; N, navicular; T, talus. N/A, not applicable; —, not reported.

TABLE 2—*Measurements of the (A) calcaneus, talus, cuboid, and navicular and (B) first, second, and third cuneiforms.*

Measurement	Description
(A)	
CalcLg	Place the calcaneus on its inferior surface with its long axis parallel to the long axis of the board. The posterior, middle, and anterior facets should be superiorly oriented. Measure the maximum length of the calcaneus from the most posterior point on the calcaneal tuberosity to the most anterior point on the calcaneal beak
TalLg	Place the talus on its inferior surface with its long axis parallel to the long axis of the board. Measure the maximum length from the most posterior point on the trigonal process to the most anterior point on the navicular facet
TalBrd	Place the talus with its inferior surface on the base of the board and the medial edge resting against the stationary upright, contacting the upright at two points. Measure to the most lateral point on the lateral process
TalHt	Place the talus on its medial side, with the inferior surface contacting the stationary upright at three points: a medial and lateral point on the posterior part of the inferior facet, and an anterior point beneath the head. Measure to the most superior point on the trochlea
CubLg	Place the cuboid on its medial side with the distal end resting against the stationary upright. The distal end should contact the stationary upright at two points. Measure to the most proximal point on the cuboid beak
CubBrd	Place the cuboid on its superior surface, with the medial side contacting the stationary upright at two points near the proximal and distal ends. The cuboid tuberosity should point upward. Measure to the most medial point on the medial side
CubHt	Place the cuboid on its lateral side with its long axis approximately perpendicular to the long axis of the board. The superior surface of the cuboid should contact the stationary upright at two points near the proximal and distal ends. Measure to the most inferior point on the beak
NavLg	Place the navicular with the proximal face against the stationary upright. It should contact the margins of the proximal facet at two points toward the medial and lateral ends. The medial tuberosity should contact the base of the board to the extent possible. Measure to the most distal point with the moveable upright
NavBrd	Place the navicular on its proximal surface with the long axis of the bone approximately parallel to the long axis of the board. The lateral edge of the bone should contact the board at two points toward the inferior and superior ends. Measure to the navicular tuberosity
(B)	
CF1Lg	Place cuneiform I on its medial surface with the distal end resting against the stationary upright at two points toward the inferior and superior ends. Measure to the inferior edge of the proximal end
CF1Brd	Place cuneiform I on its distal surface with the medial side of the bone resting against the stationary upright at two points toward the superior and inferior ends. Measure to the most lateral point on the lateral side
CF1Ht	Place cuneiform I on its medial surface with the inferior edge resting against the stationary upright at two points toward the proximal and distal ends. Measure to the superior end with the moveable upright
CF2Lg	Place cuneiform II on its lateral side with the proximal end contacting the stationary upright at two points toward the superior and inferior ends. Measure to the distal end with the moveable upright
CF2Brd	Place cuneiform II on its proximal end with the lateral edge contacting the stationary upright at two points toward the superior and inferior ends. Measure to the medial side with the moveable upright
CF2Ht	Place cuneiform II on its proximal end with the superior edge contacting the stationary upright at two points toward the medial and lateral sides of the bone. Measure to the inferior edge with the moveable upright
CF3Lg	Place cuneiform III on its medial side with the distal end contacting the stationary upright at two points toward the superior and inferior ends. Measure to the most proximal point on the proximal end
CF3Brd	Place cuneiform III on its distal end with the medial side contacting the stationary upright at two points toward the superior half of the bone. Measure to the most lateral point on the lateral side of the bone
CF3Ht	Place cuneiform III on its medial side with the superior end contacting the stationary upright at two points toward the proximal and distal ends. Measure to the inferior edge

To further assess the utility of these tarsal measures, the data distributions for each measure were tested for normality using a Kolmogorov–Smirnov normality test, and the male and female distributions for each measure were analyzed for equality of their variance–covariance matrices using Box's *M*-test. Both of these tests were conducted at a relatively conservative alpha level of 0.10. All statistical tests in this study were carried out using SPSS version 17.0 (SPSS Inc., Chicago, IL).

To confirm that the differences between the sexes were great enough to warrant use of these measurements for sex estimation, *t*-tests of each measure were performed between the male and female means on both the left and right sides. In addition, size asymmetry between the two sides of the body was examined by means of paired sample *t*-tests conducted separately by sex for each measure. Presence of significant side asymmetry would indicate that the measurements from the two sides are not interchangeable for sex estimation. All *t*-tests were performed at an alpha level of 0.05.

A sexual dimorphism index was also calculated for each measure following the approach used by Hamilton (25): [(male mean − female mean)/female mean] × 100. This index indicates how much larger the male sample is compared with the female sample, in the form of a percentage. Presumably, larger percentage differences between males and females would correspond with greater ability to distinguish the sexes, so long as the data are normally distributed. Index values for each dimension were averaged between the two sides to allow comparison of relative sexual dimorphism for each of the 18 measurements, irrespective of the effects of asymmetry. The index values were also averaged across all measures oriented along a particular axis of the body (e.g., length, width, and height) to assess whether any particular axis showed greater sexual dimorphism.

Logistic regression analysis was then performed on the tarsal measurements to determine which individual measures, and which combinations of measures, show the greatest ability to correctly classify males and females. Discriminant analysis could not be used in this case because, although the data for each measure were found to be normally distributed, the assumption of equal variance–covariance matrices was violated for 4/18 measurements on the left side, and 6/18 measurements on the right, based on Box's *M*-test. Although logistic regression is less commonly used to determine sex from measurements than discriminant analysis, it has recently gained in popularity (26–29). Logistic regression can be used in place of discriminant analysis when the predictor variables do not have equal variance–covariance matrices (30), and it has the added benefit of being less sensitive to high correlations among the

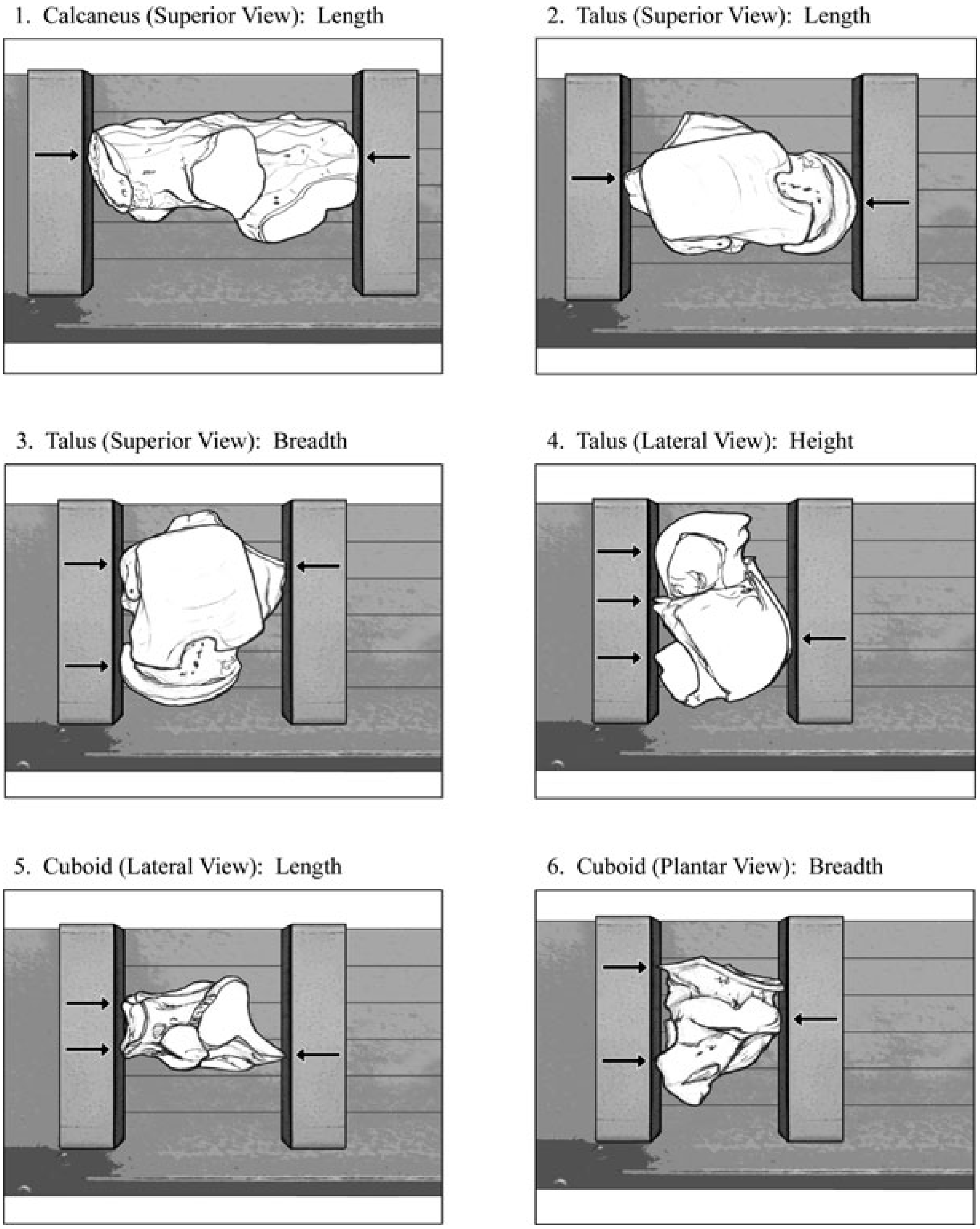

FIG. 1—*Illustration of the following six measurements: (1) CalcLg, (2) TalLg, (3) TalBrd, (4) TalHt, (5) CubLg, and (6) CubBrd. Arrows indicate typical contact points between each bone and the mini-osteometric board. (Drawings by Daniel Mehltretter.)*

predictor variables (31), and more tolerant of outliers (32). Simulations have shown that the difference in results between logistic regression and discriminant analysis is negligible when sample sizes are over 50 (31), as is the case in the present study, and therefore the results of this study should still be comparable to those produced by others using discriminant analysis. Logistic regression also has the advantage of relatively simple calculation of the probability of belonging to one sex or the other.

Logistic regression analyses were performed first on a subset of individuals with no missing data in a given foot. A sample of 109 individuals with all 18 measurements was present for the left foot, and a sample of 110 individuals was present for the right foot. These samples were created to assess the relative allocation accuracy of each dimension when tested on an identical sample of individuals. Equations for determining sex from each dimension were then calculated using the complete sample of 160 individuals, to maximize the information available and to create formulae based on the best possible model.

Logistic regression analysis produces regression coefficients for each measurement included in a model, as well as a constant. To use this information to assess the sex of an individual, a log-odd or logit must first be calculated using the following formula: $L = \text{Constant} + B_1X_1 + B_2X_2 + \cdots + B_nX_n$, where L is the logit, B_1 is the first coefficient, X_1 is the first measurement, and so on (26). A negative logit indicates a female skeleton, and a positive logit indicates a male skeleton. The logit value can also be used to calculate the probability of male sex (p_m) using the function: $p_m = 1/(1 + e^{-L})$. The probability of female sex is simply $p_f = 1 - p_m$. In practice, if $p_m > 0.5$, then the most likely sex is male, and if $p_m < 0.5$, the most likely sex is female. The closer the value of p_m is to 1, the greater the probability that the individual is male, and the closer the value of p_m is to 0, the greater the probability that

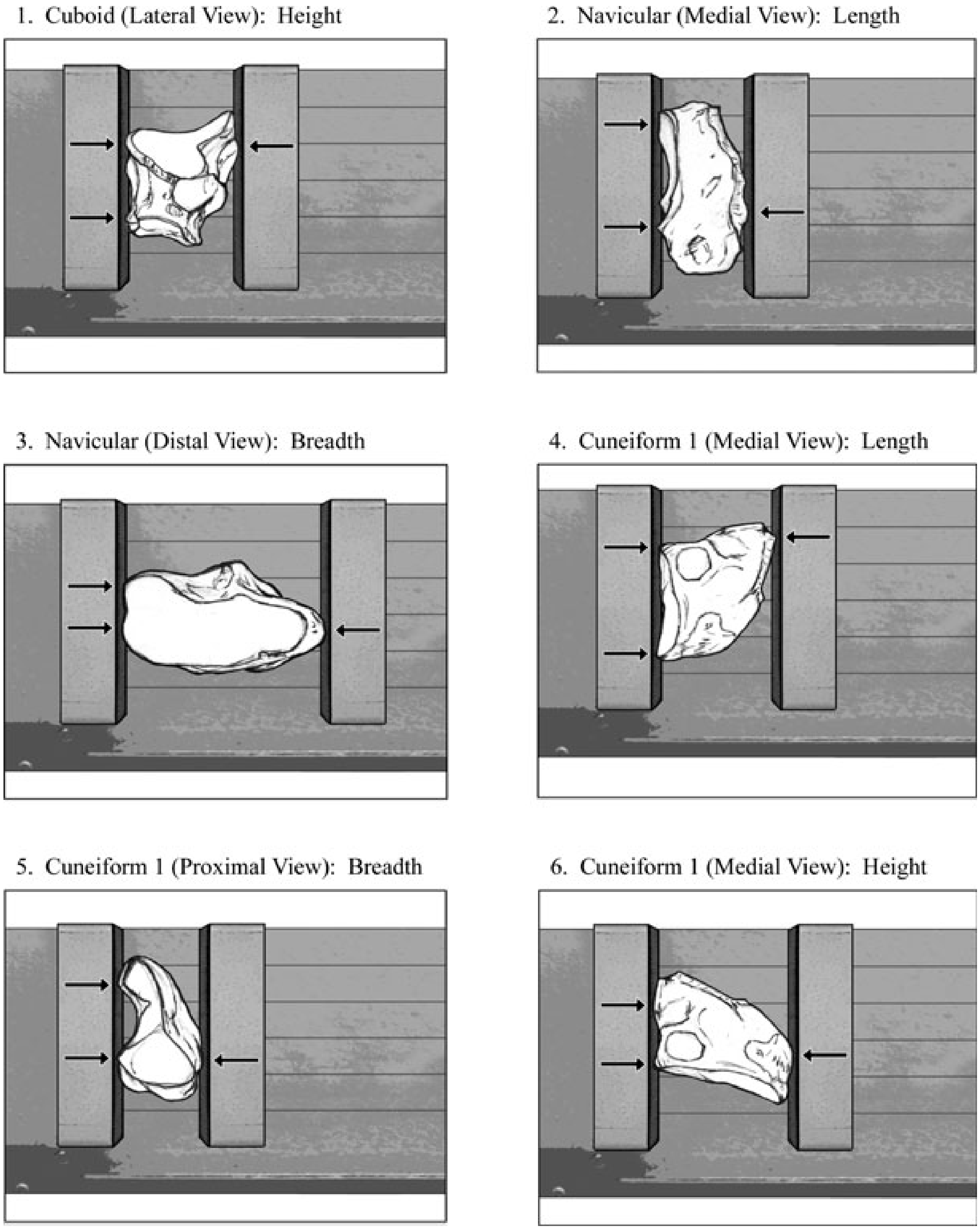

FIG. 2—*Illustration of the following six measurements: (1) CubHt, (2) NavLg, (3) NavBrd, (4) CF1Lg, (5) CF1Brd, and (6) CF1Ht. Arrows indicate typical contact points between each bone and the mini-osteometric board. (Drawings by Daniel Mehltretter.)*

the individual is female. To calculate these values in an excel spreadsheet, use the EXP function in place of "e" in the equation above.

Results

Results from the intra-observer error analysis are provided in Table 3. Measurement error was reasonably low for all 18 measurements taken. Median differences between repeated measures were 0.05 mm or lower for all measurements. Mean absolute differences were 0.10 mm or less, except for CubHt and CF3Ht that were only slightly higher. All TEM values were 0.16 mm or less, suggesting that the vast majority of measurements should fall within about 0.2 mm of each other, even for the most difficult dimension. When differences were considered as a percentage of bone size, 11/18 measurements showed differences between repeated measurements of <0.25% of bone size, and all but one were lower than 0.5% of bone size. The exception was CF2Brd at 0.60%. These results suggest quite good repeatability of these tarsal measures and more than sufficient repeatability for the purposes of this study.

Summary statistics for all 18 dimensions on both the left and right sides are reported in Table 4A and B. Not surprisingly, mean length, width, and height dimensions for each tarsal were all found to be significantly larger in males than in females ($p < 0.001$), suggesting that all of these measurements have potential as sex indicators. Significant bilateral asymmetry was found for 3/18 measurements in females and for 8/18 measurements in males (Table 5). Significant asymmetry was present in both sexes for CalcLg, TalLg, and CF2Ht. In addition, males showed significant side asymmetry in TalBrd, CubLg, CubBrd, CF2Brd, and CF3Ht. Generally, the dimensions that showed significant side asymmetry in the paired sample *t*-test were also those that exhibited the

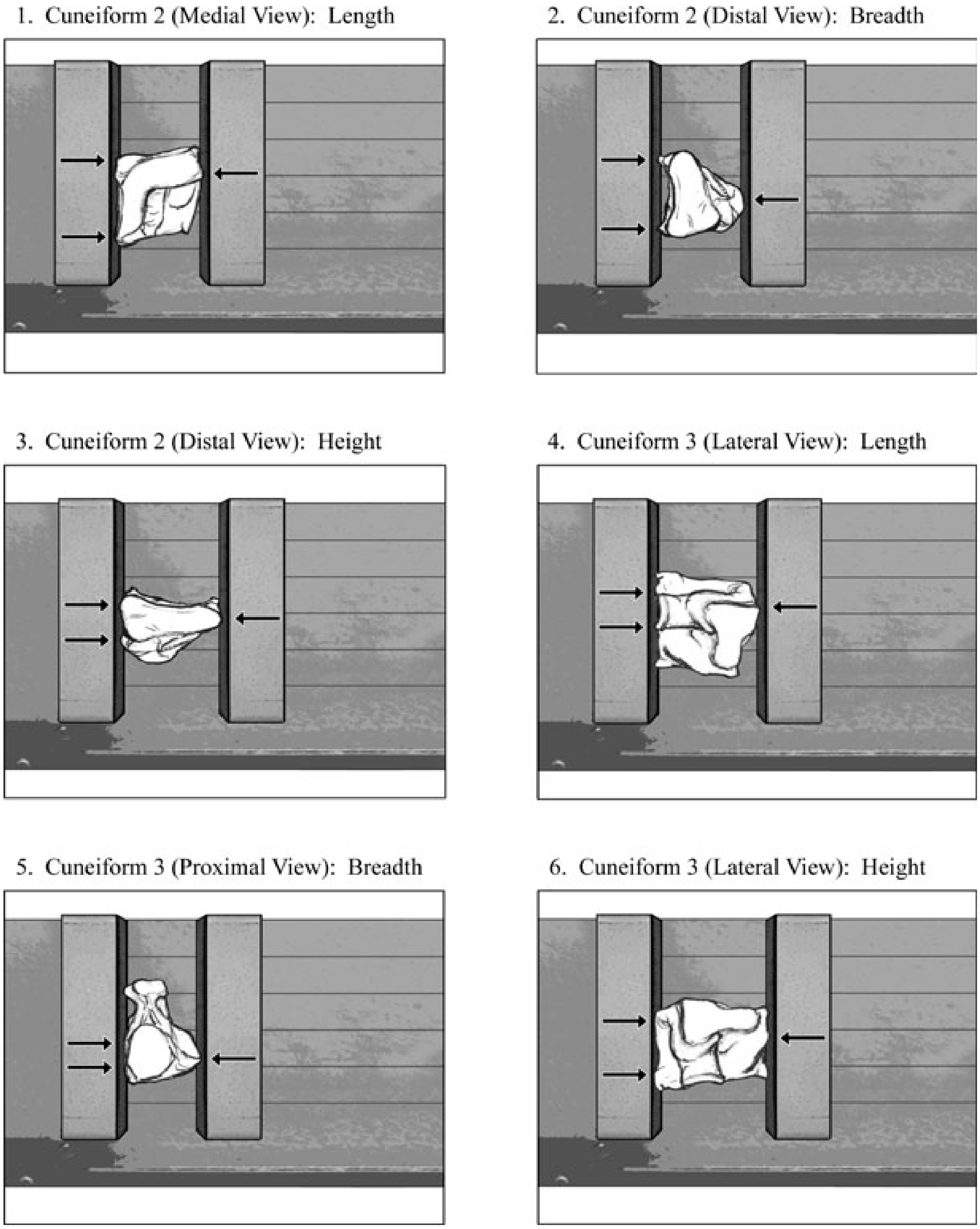

FIG. 3—*Illustration of the following six measurements: (1) CF2Lg, (2) CF2Brd, (3) CF2Ht, (4) CF3Lg, (5) CF3Brd, and (6) CF3Ht. Arrows indicate typical contact points between each bone and the mini-osteometric board. (Drawings by Daniel Mehltretter.)*

greatest absolute percentage difference in mean size between the sides in the whole sample. However, an exception to this rule was found for both the males and females. Among the females, CalcLg showed a significant difference between the sides in the paired sample *t*-test, but had a lower absolute mean percentage difference between the two sides than did CF2Brd, CF2Lg, or CF3Ht, which were not significant in the paired samples *t*-test. Likewise, the males showed a significant difference between the sides in the paired sample *t*-test for CF3Ht, but the mean difference between the sides for the sample as a group was only 0.04%, suggesting that directional asymmetry is probably not the reason for the significant difference in the paired sample test. Regardless of the type of asymmetry, the presence of significant side asymmetry in nearly half of the male measurements argues for separate treatment of the left and right sides when developing equations for metric sexing from the tarsals.

Sexual Dimorphism Index

Sexual dimorphism was relatively high among the tarsals. Dimorphism index values for all 18 measurements, when averaged between the two sides, ranged from 9.8 to 14.0% (Table 4A and B). The greatest sexual dimorphism was found for TalHt (14%), followed by TalLg (13.1%), and then by CubBr, CF2Br, and TalBr (12.8–12.9%). The lowest sexual dimorphism was found in CF3Lg (9.8%), CalcLg (9.9%), and then in CF1Ht, CF2Lg, CubHt, and CubLg (10.2–10.5%).

As a group, length measures exhibited the lowest mean dimorphism at 10.8%. Height measures were intermediate at 11.5%, and breadth measures were highest at 12.2%. Sexual dimorphism was higher on the right side for all length measures except CF3, and for all height measures except CF2. Sexual dimorphism among the breadth measures was evenly split between the left and right sides.

TABLE 3—*Intra-observer error statistics for tarsal measurements (left side).*

Measure	*N*	Median Abs Difference (mm)	Mean Abs Difference (mm)	Technical Error of Measurement (mm)	Mean Difference as Percent of Mean Size (%)
CalcLg	28	0.04	0.07	0.08	0.08
TalLg	30	0.03	0.06	0.08	0.10
CubLg	30	0.02	0.04	0.06	0.11
NavLg	29	0.02	0.09	0.14	0.44
CF1Lg	29	0.02	0.04	0.04	0.15
CF2Lg	27	0.03	0.06	0.08	0.33
CF3Lg	29	0.03	0.05	0.05	0.20
TalBrd	30	0.03	0.05	0.06	0.12
CubBrd	30	0.04	0.06	0.06	0.22
NavBrd	29	0.05	0.09	0.09	0.22
CF1Brd	29	0.01	0.02	0.02	0.11
CF2Brd	27	0.03	0.10	0.13	0.60
CF3Brd	29	0.02	0.08	0.14	0.48
TalHt	30	0.02	0.03	0.05	0.09
CubHt	30	0.04	0.12	0.16	0.49
CF1Ht	29	0.01	0.02	0.02	0.06
CF2Ht	27	0.04	0.08	0.10	0.36
CF3Ht	29	0.03	0.11	0.16	0.46

TABLE 4—*Descriptive statistics for male and female (A) length measures and (B) breadth and height measures.*

	Females					Males						
Measure	*N*	Min.	Max.	Mean	SD	*N*	Min.	Max.	Mean	SD	Dimorphism Index*	Mean L/R Dimorphism
(A)												
L-CalcLg	76	69.52	90.22	79.05	4.042	80	75.76	98.44	86.79	4.692	9.79	
R-CalcLg	76	69.90	89.30	79.46	3.797	81	75.70	96.30	87.37	4.404	9.95	9.9
L-TalLg	77	46.46	62.44	54.64	2.936	81	51.89	69.83	61.55	3.424	12.65	
R-TalLg	74	45.40	60.50	53.75	2.870	79	52.90	69.30	61.05	3.586	13.58	13.1
L-CubLg	71	30.76	40.18	35.20	2.041	81	30.50	44.28	38.74	2.757	10.06	
R-CubLg	72	30.90	40.96	35.26	2.163	79	29.88	47.30	39.11	2.842	10.92	10.5
L-NavLg	72	17.17	22.55	19.60	1.301	79	17.99	25.17	21.71	1.497	10.77	
R-NavLg	70	17.23	22.50	19.53	1.188	80	17.51	25.64	21.81	1.695	11.67	11.2
L-CF1Lg	70	21.95	29.38	25.43	1.499	77	23.28	31.50	28.11	1.786	10.52	
R-CF1Lg	72	21.97	29.32	25.42	1.344	78	22.85	32.55	28.18	1.868	10.86	10.7
L-CF2Lg	67	15.21	19.85	17.71	1.066	71	16.64	22.69	19.54	1.361	10.33	
R-CF2Lg	67	15.66	19.34	17.60	0.911	76	16.67	22.22	19.44	1.300	10.45	10.4
L-CF3Lg	72	20.96	26.56	23.71	1.099	73	21.98	29.36	26.07	1.563	9.95	
R-CF3Lg	71	21.49	26.10	23.82	1.028	72	21.85	29.52	26.11	1.377	9.61	9.8
(B)												
L-TalBrd	77	33.55	42.87	39.15	2.038	82	39.67	50.68	44.45	2.460	13.54	
R-TalBrd	77	34.08	43.38	39.29	2.021	80	38.69	52.18	44.01	2.443	12.01	12.8
L-CubBrd	71	22.48	29.92	26.25	1.530	81	25.48	33.92	29.57	1.807	12.65	
R-CubBrd	73	22.76	31.39	26.32	1.624	79	25.95	34.38	29.77	1.772	13.11	12.9
L-NavBrd	73	33.33	45.21	38.03	2.502	80	35.84	48.84	42.52	2.759	11.81	
R-NavBrd	71	33.32	43.48	38.17	2.304	80	35.54	48.30	42.28	2.684	10.77	11.3
L-CF1Brd	70	15.10	19.63	17.46	1.040	78	16.66	22.57	19.55	1.280	11.97	
R-CF1Brd	72	15.38	19.47	17.52	1.021	78	16.62	23.23	19.67	1.335	12.27	12.1
L-CF2Brd	67	13.01	18.68	15.68	1.049	71	13.61	21.75	17.57	1.505	12.05	
R-CF2Brd	68	13.27	17.77	15.57	1.036	75	13.73	21.09	17.69	1.464	13.62	12.8
L-CF3Brd	71	13.90	17.60	15.69	0.885	74	14.40	21.60	17.46	1.327	11.28	
R-CF3Brd	71	13.94	17.89	15.74	0.915	72	14.56	21.64	17.46	1.330	10.93	11.1
L-TalHt	77	27.65	34.67	30.48	1.563	82	29.34	38.79	34.69	1.986	13.81	
R-TalHt	77	27.57	34.30	30.50	1.632	81	28.86	39.36	34.81	1.978	14.12	14.0
L-CubHt	71	19.39	27.87	23.10	1.666	80	21.16	30.79	25.48	1.777	10.30	
R-CubHt	71	19.60	27.70	23.11	1.630	78	20.40	32.00	25.56	1.969	10.60	10.5
L-CF1Ht	70	25.77	34.44	31.35	1.656	78	28.90	40.28	34.49	2.042	10.02	
R-CF1Ht	72	26.13	36.70	31.36	1.704	78	29.10	39.84	34.59	2.037	10.30	10.2
L-CF2Ht	65	17.20	24.91	21.14	1.453	71	19.91	28.39	23.78	1.764	12.49	
R-CF2Ht	68	18.05	24.26	21.52	1.276	76	19.82	28.44	24.07	1.714	11.85	12.2
L-CF3Ht	69	19.13	25.94	22.99	1.406	73	22.04	30.94	25.35	1.643	10.27	
R-CF3Ht	68	19.90	26.10	22.85	1.428	71	21.40	29.90	25.36	1.619	10.98	10.6

*Calculated as [(male mean − female mean)/female mean] × 100 after Hamilton (25).

When considered by bone, the talus had the highest mean dimorphism at 13.3%. CF2 was next at 11.8%, followed closely by the cuboid and navicular at 11.3%. CF1 showed 11.0% dimorphism, followed by CF3 at 10.5% and the calcaneus at 9.9%. The low sexual dimorphism in the calcaneus probably results from only one dimension, length, being measured for this bone.

TABLE 5—t-*Tests of left/right side asymmetry and dimorphism index for each measurement.*

	Female		Male	
Measure	Mean Difference* (%)	*p*-Value	Mean Difference* (%)	*p*-Value
CalcLg	0.52	*0.001*	0.66	*0.005*
TalLg	−1.66	*<0.001*	−0.82	*0.021*
CubLg	0.17	0.498	0.94	*0.006*
NavLg	−0.36	0.437	0.46	0.203
CF1Lg	−0.04	0.753	0.26	0.374
CF2Lg	−0.62	0.073	−0.51	0.114
CF3Lg	0.46	0.067	0.15	0.192
TalBrd	0.36	0.131	−1.00	*0.001*
CubBrd	0.27	0.997	0.67	*0.031*
NavBrd	0.36	0.383	−0.57	0.109
CF1Brd	0.34	0.594	0.61	0.294
CF2Brd	−0.71	0.395	0.68	*0.015*
CF3Brd	0.32	0.254	0.00	0.470
TalHt	0.07	0.223	0.34	0.151
CubHt	0.04	0.107	0.31	0.329
CF1Ht	0.03	0.576	0.29	0.841
CF2Ht	1.77	*<0.001*	1.20	*0.003*
CF3Ht	−0.61	0.281	0.04[†]	*0.025*

*Mean Side Asymmetry = [(right mean − left mean)/right mean] × 100.
[†]Because the difference between left and right means is small, the asymmetry within males may not be directional.
p-Values less than 0.05 are italicized.

Logistic Regression (Reduced Sample)

Results of the logistic regression analysis on the reduced sample with no missing measurements suggest that individual measures of the right side tend to correctly distinguish the sexes better than those of the left side, based on allocation accuracy for the pooled sexes (Table 6). On the right side, the best individual measures for distinguishing the sexes were TalLg (90.0%), followed by TalHt (88.2%), CubBrd (86.4%), and CF3Lg (86.4%). All but three measures on the right side correctly classified the sexes at least 80% of the time. The exceptions were CubLg, NavLg, and CF2Lg. On the left side, the order of best allocation accuracy was slightly different: CF1Lg (86.2%), TalBrd (85.3%), TalHt (85.3%), and TalLg (84.4%), and only 9/18 measures exhibited >80.0% correct classification. In sum, the right side did a better job of accurately allocating individuals than the left for 13/18 dimensions. The exceptions were TalBrd, CubLg, CF1Lg, CF1Brd, and CF2Lg.

Logistic regression equations that include two or more measurements for an individual bone improve the allocation accuracy about half the time in the reduced sample, when compared to the best single measure from the same bone (Table 7). In general, all individual tarsal bones exceeded 80% allocation accuracy for both sides, and three bones on the right (cuboid, talus, cuneiform I) and one on the left (talus) exceeded 90%. Generally, the larger bones of the tarsus showed greatest improvement in allocation accuracy with inclusion of additional measurements. On the right, the talus, cuboid, and cuneiform I showed the greatest improvement in allocation accuracy with additional measurements, while the smaller bones showed either no improvement (navicular, cuneiform II) or a poorer result (cuneiform III) when multiple measures were used. One surprising finding on the right side is that, while the three talar measurements produced some of the best classification results individually, they came in second place collectively behind the cuboid (91.8%) and tied with cuneiform I (90.9%) when combined into a single equation. On the left side, the talus, cuboid, and navicular showed the greatest improvement in allocation accuracy with additional measurements. Unlike the case on the right side, on which cuneiform I showed the greatest improvement with the use of multiple measurements, this bone performed the worst (−3.1%) when multiple measures were used on the left side.

Logistic Regression (Complete Sample)

Regression coefficients and constants for use in sex determination were derived using all data available from the complete sample of 160 individuals (78 females, 82 males). Each analysis for individual measurements included 65–77 females and 71–82 males. A comparison of the results from the complete sample with those from the reduced sample indicates mild improvement in allocation accuracy with the complete sample on the left side (+0.74% on average) and mildly poorer allocation accuracy for the right side (−0.42% on average). Slight differences are also evident in the ranking of individual measurements based on allocation accuracy in the complete sample. Such differences are expected, because the

TABLE 6—*Sexing potential of individual measures based on reduced sample.*

Measure	Left Side Pooled (%)	Left Side Rank (High to Low)	Right Side Pooled (%)	Right Side Rank (High to Low)	Best Side*
CalcLg	78.9	10	81.8	12	R
TalLg	84.4	4	90.0	1	R
TalBrd	85.3	2	83.6	6	L
TalHt	85.3	3	88.2	2	R
CubLg	78.9	11	78.2	16	L
CubBrd	81.7	7	86.4	3	R
CubHt	72.5	18	80.0	15	R
NavLg	73.4	17	76.4	18	R
NavBrd	81.7	8	84.5	7	R
CF1Lg	86.2	1	83.6	5	L
CF1Brd	82.6	6	81.8	11	L
CF1Ht	78.0	12	81.8	13	R
CF2Lg	78.0	14	75.5	17	L
CF2Brd	75.2	16	83.6	9	R
CF2Ht	80.7	9	83.6	8	R
CF3Lg	82.6	5	86.4	4	R
CF3Brd	78.0	13	80.0	14	R
CF3Ht	77.1	15	82.7	10	R

*The best side is the one with the highest pooled accuracy.

TABLE 7—*Sexing potential of multiple measures from each tarsal bone (reduced sample).*

Bone	Side	Based On	Female (%)	Male (%)	Pooled (%)	% Improvement*
Talus	R	Length, height	91.7	90.3	90.9	+0.9
Cuboid	R	Breadth, height	91.7	91.9	91.8	+5.4
Navicular	R	Length, breadth	81.3	87.1	84.5	+0.0
Cuneiform I	R	Length, breadth, height	91.7	90.3	90.9	+7.3
Cuneiform II	R	Length, height	81.3	85.5	83.6	+0.0
Cuneiform III	R	Length, height	85.4	85.5	85.5	−0.9
Right side mean			87.2	88.4	87.9	+2.4
Talus	L	Breadth, height	94.8	90.1	92.4	+6.1
Cuboid	L	Breadth, height	84.3	85.0	84.7	+3.0
Navicular	L	Length, breadth	81.9	86.1	84.1	+2.4
Cuneiform I	L	Breadth, height	81.4	84.4	83.0	−3.1
Cuneiform II	L	Length, height	81.5	83.1	82.4	+1.5
Cuneiform III	L	Length, height	83.8	80.8	82.3	−0.3
Left side mean			84.6	84.9	84.8	+1.6

*Compared to best single measure from the same bone.

complete sample includes missing data for some measures, and thus each regression equation is based on a slightly different sample size and a slightly different collection of individuals.

Logistic regression coefficients and constants are reported for all measurements with 80% or better pooled allocation accuracy in Table 8A and B. In addition, coefficients and constants derived from a stepwise procedure using up to three measurements for each individual bone are reported in Table 9. Finally, logistic regression analysis was conducted on sets of measurements from multiple bones to identify any combinations of bones and measurements that would yield better results than those obtained for individual tarsals. These final analyses included a stepwise procedure for all 18 measurements on each side, for adjacent bones such as talus/calcaneus, cuboid/navicular, and cuneiforms I, II, and III, and finally for the four most proximal bones (calcaneus, talus, cuboid, and navicular) and the five most distal bones (cuboid, navicular, and cuneiforms I, II, and III). Coefficients and constants for the analyses that produced higher allocation accuracy than the best individual bone of a particular group are reported in Table 10.

Discussion and Conclusions

It is clear from the results of this study that the tarsals show sufficient sexual dimorphism in modern European-Americans for use in metric sex determination. The individual measurements of the tarsals exhibit a range of percent sexual dimorphism as a group (9.8–14.0%) that is higher than the range exhibited by long bone lengths in many other populations (e.g., humerus: 5.2–11.2%, femur: 3.3–10.7%), and that is comparable with other skeletal dimensions such as humeral head diameter (12.8–16.2%), femoral head diameter (10.5–14.0%), humeral epicondylar breadth (7.2–15.2%), and femoral condylar breadth (9.1–13.7%) in these same populations (25,33–37). Perhaps because of the high percent sexual dimorphism in the tarsals of our European-American sample, every

TABLE 8—*Logistic regression equations for measures with 80%+ allocation accuracy (A) left side and (B) right side.*

Measure	Logit Equation*	Standard Error	Female (%)	Male (%)	Pooled (%)
(A)					
CalcLg	$L = -34.571 + 0.419 \times \text{CalcLg}$	0.067	78.9	81.3	80.1
TalLg	$L = -35.061 + 0.606 \times \text{TalLg}$	0.088	87.0	86.4	86.7
TalBrd	$L = -54.163 + 1.302 \times \text{TalBrd}$	0.226	88.3	86.6	87.4
TalHt	$L = -35.879 + 1.107 \times \text{TalHt}$	0.165	84.4	89.0	86.8
CubBrd	$L = -34.975 + 1.263 \times \text{CubBrd}$	0.202	81.7	86.4	84.2
NavBrd	$L = -26.248 + 0.655 \times \text{NavBrd}$	0.105	80.8	83.8	82.4
CF1Lg	$L = -25.583 + 0.962 \times \text{CF1Lg}$	0.156	81.4	83.1	82.3
CF1Brd	$L = -31.512 + 1.715 \times \text{CF1Brd}$	0.28	82.9	82.1	82.4
CF3Lg	$L = -33.905 + 1.369 \times \text{CF3Lg}$	0.226	81.9	78.1	80.0
CF3Ht	$L = -27.573 + 1.146 \times \text{CF3Ht}$	0.194	78.3	82.2	80.3
(B)					
CalcLg	$L = -40.174 + 0.483 \times \text{CalcLg}$	0.076	81.6	80.2	80.9
TalLg	$L = -38.264 + 0.670 \times \text{TalLg}$	0.103	87.8	87.3	87.6
TalBrd	$L = -43.763 + 1.054 \times \text{TalBrd}$	0.170	85.7	88.8	87.3
TalHt	$L = -37.083 + 1.139 \times \text{TalHt}$	0.174	85.7	90.1	88.0
CubBrd	$L = -31.695 + 1.137 \times \text{CubBrd}$	0.176	84.9	84.8	84.9
NavBrd	$L = -27.737 + 0.694 \times \text{NavBrd}$	0.114	80.3	86.3	83.4
CF1Lg	$L = -27.523 + 1.035 \times \text{CF1Lg}$	0.164	86.1	82.1	84.0
CF1Brd	$L = -30.865 + 1.671 \times \text{CF1Brd}$	0.269	79.2	84.6	82.0
CF1Ht	$L = -28.793 + 0.878 \times \text{CF1Ht}$	0.137	79.2	82.1	80.7
CF2Brd	$L = -23.822 + 1.448 \times \text{CF2Brd}$	0.247	82.4	82.7	82.5
CF2Ht	$L = -23.467 + 1.037 \times \text{CF2Ht}$	0.165	79.4	81.6	80.6
CF3Lg	$L = -39.775 + 1.598 \times \text{CF3Lg}$	0.256	85.9	83.3	84.6
CF3Ht	$L = -26.468 + 1.102 \times \text{CF3Ht}$	0.181	82.4	81.7	82.0

*A negative logit indicates female, a positive logit indicates male.

TABLE 9—*Logistic regression equations for whole bones.*

Bone	Logit Equation*	Female (%)	Male (%)	Pooled (%)
Left side				
Talus	$L = -60.771 + 1.008(\text{TalBrd}) + 0.584(\text{TalHt})$	94.8	90.1	92.4
Cuboid	$L = -38.732 + 1.052(\text{CubBrd}) + 0.399(\text{CubHt})$	84.3	85.0	84.7
Navicular	$L = -28.365 + 0.421(\text{NavLg}) + 0.492(\text{NavBrd})$	81.9	86.1	84.1
Cuneiform I	$L = -38.884 + 1.219(\text{CF1Brd}) + 0.504(\text{CF1Ht})$	81.4	84.4	83.0
Cuneiform II	$L = -36.046 + 1.018(\text{CF2Lg}) + 0.772(\text{CF2Ht})$	81.5	83.1	82.4
Cuneiform III	$L = -40.826 + 0.968(\text{CF3Lg}) + 0.702(\text{CF3Ht})$	83.8	80.8	82.3
Right side				
Talus	$L = -48.890 + 0.617(\text{TalBrd}) + 0.716(\text{TalHt})$	92.2	91.3	91.7
Cuboid	$L = -36.676 + 1.006(\text{CubBrd}) + 0.362(\text{CubHt})$	88.6	88.5	88.5
Navicular	$L = -28.313 + 0.710(\text{NavBrd})$	81.2	86.3	83.9
Cuneiform I	$L = -38.600 + 0.623(\text{CF1Lg}) + 1.191(\text{CF1Brd})$	87.3	89.7	88.6
Cuneiform II	$L = -45.695 + 1.082(\text{CF2Lg}) + 0.623(\text{CF2Brd}) + 0.694(\text{CF2Ht})$	85.1	88.0	86.6
Cuneiform III	$L = -44.965 + 1.171(\text{CF3Lg}) + 0.660(\text{CF3Ht})$	86.8	84.5	85.6

*A negative logit indicates female, a positive logit indicates male.

TABLE 10—*Logistic regression equations for multiple bones.*

Bones Considered	Logit Equation*	Female (%)	Male (%)	Pooled (%)
Left side				
Cuboid, Navicular	$L = -41.727 + 0.911(\text{CubBrd}) + 0.413(\text{NavBrd})$	89.4	87.0	88.1
Cuneiforms I, II, III	$L = -54.895 + 1.326(\text{CF1Brd}) + 1.229(\text{CF3Lg})$	89.7	87.3	88.4
Cub, Nav, CF I, II, III	$L = -56.962 + 0.946(\text{CubBrd}) + 1.245(\text{CF3Lg})$	88.2	90.2	89.3
Right side				
All	$L = -64.948 + 0.958(\text{TalHt}) + 1.369(\text{CF3Lg})$	93.8	93.5	93.6
Cuboid, Navicular	$L = -43.356 + 0.880(\text{CubBrd}) + 0.473(\text{NavBrd})$	85.9	93.4	90.0
Cuneiforms I, II, III	$L = -60.561 + 1.137(\text{CF1Brd}) + 0.520(\text{CF2Ht}) + 1.118(\text{CF3Lg})$	91.4	89.2	90.2
Cub, Nav, CF I, II, III	$L = -67.375 + 0.690(\text{CubBrd}) + 0.413(\text{NavBrd}) + 1.274(\text{CF3Lg})$	92.0	90.5	91.2

*A negative logit indicates female, a positive logit indicates male.

tarsal has at least one dimension that produces 80% or better allocation accuracy for the pooled sexes, except for cuneiform II on the left side. These results are much better than those reported by Steele (9) on Americans from the Terry Collection and may in part reflect a gain in allocation accuracy from not combining two different populations (African- and European-Americans).

As in many of the studies that have considered at least the talus and calcaneus (Table 1), it seems clear from this study that the three talar measurements are by far the best set of dimensions for distinguishing males and females from a single bone. Based on the sexual dimorphism index, TalHt is the most dimorphic measure of the three (averaging 14.0%), followed by TalLg and TalBrd (Table 4A and B). TalBrd is the least dimorphic of the three (12.8%), but the only other measurement with a higher percent dimorphism is CubBrd (12.9%). CF2Brd is tied with TalBrd at 12.8%.

This trend toward greater sexual dimorphism in TalHt is generally confirmed in the logistic analysis of the left talus, although on the right side, TalLg rather than TalHt clearly produces the best allocation accuracy, as well as the best result for a single measure on either of the two sides. This finding accords well with the results of previous studies on other populations, which have tended to find TalLg, and occasionally TalHt to be the most dimorphic measures when considering the talus, calcaneus, and cuneiform I (Table 1).

The better results for TalLg on the right side may be the result of high bilateral asymmetry (Table 5). TalLg tends to be greater on the right side in both sexes, but the difference between the sides is almost twice as high for males as for females. When considering the pooled results from the complete sample, the allocation accuracies for TalLg, TalBrd, and TalHt are within 0.7% of one another on both sides, and the two sides differ in allocation accuracy by an average of <1% (Table 8A and B). TalBrd performs slightly better (+0.7%) than TalLg on the left side in the complete sample, and TalHt performs slightly better (+0.4%) on the right side. However, differences in allocation accuracy of <1% should be treated as negligible because they probably indicate a misallocation of a single individual in the study sample.

The allocation accuracies for whole tarsal bones, as opposed to individual measurements, are quite impressive. Three of the seven tarsals performed particularly well when all available measures were used. Allocation accuracies above 90% were achieved for the talus, cuboid, and cuneiform I on the right side when tested using the reduced sample that had no missing data ($n = 110$). The cuboid performed slightly better than the talus and cuneiform in this test, with nearly identical correct allocation percentages for both sexes (Table 7). Using the complete sample, the talus rather than the cuboid performed best on both sides, but this may be due to a larger sample size for the talus ($n = 158$) compared with the cuboid ($n = 151$) and cuneiform I ($n = 150$). The overall results suggest that any of these three bones would be good choices for sex determination in a forensic context. In addition, the calcaneus, which only had one measurement, produced allocation accuracies for the pooled sexes of >80% on both sides.

Finally, when dimensions from multiple bones were considered, several additional combinations of variables with allocation accuracies above 88% were identified (Table 10). On the left side, none of these new combinations produced better allocation accuracy than the 92.4% obtained from the two talar measurements alone. However, on the right side, four new combinations of no more than three variables were identified with allocation accuracies of 90.0% or better. The best of these combinations involved TalHt and CF3Lg and correctly allocated the sexes 93.6% of the time, with very little difference in allocation accuracy between the males and females.

In summary, the best allocation results for modern European-Americans can be achieved by combining TalHt and CF3Lg on the right side. If those dimensions are not available, accuracies between 88 and 92% can be obtained using the talus, cuboid, or cuneiform I from the right side or the talus from the left side. In addition, any single complete bone from either side can be used with allocation accuracy of at least 82%. Even when most of the tarsals are damaged, every bone except cuneiform II on the left side has at least one dimension that can allocate the bone to the correct sex >80% of the time.

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Additional information and reprint requests:
D. Troy Case, Ph.D.
Department of Sociology & Anthropology
North Carolina State University
Campus Box 8107
Raleigh, NC 27695-8107
E-mail: dtcase@ncsu.edu