Sex Estimation from the Navicular Bone in a Thai Population

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ABSTRACT

Foot bones are of interest for forensic sexing because of high reported accuracy in recent studies and often good preservation. This study investigated 202 pairs of navicular bones (104 males, 98 females) obtained from the Chiang Mai University Skeletal Collection. Metric measurements of eight dimensions of the navicular bone were taken with a digital caliper and analysed statistically to determine mean differences between the sexes and to calculate discriminant functions. Discriminant functions obtained from a combination of all variables had a pooled accuracy of 91.1% for the left navicular and 92.1% for the right. Using a stepwise method, discriminant functions showed 89.6% and 92.1% accuracy for left and right bones, respectively. In addition, the functions from stepwise method from either left or right side can be applied to the opposite side with similar obtained accuracy. Variables from the articular facets of the navicular bone had a high effect size and were included in all of our derived discriminant functions. We suggest that detailed measurement of articular facets could be useful for skeletal sexing.

Keywords: Forensic anthropology, navicular bone, sex estimation, metric measurement, discriminant analysis

Siriraj Med J 2014;66:210-218
E-journal: http://www.sirirajmedj.com

INTRODUCTION

The most important step in the identification of skeletonized remains, both from archaeological and forensic contexts, is the construction of biological profiles. Estimation of sex is commonly the first step of skeletal identification, and many bones have been shown to be useful for sexing. By visual assessment, the ventral arc of the pubic bone is efficiently capable of sex determination with 96% accuracy.[1] The skull is usually the second area of choice in morphological sex assessment, since cranial features are found to be useful for sex estimation with up to 90.1% accuracy in American samples.[2] However, morphological evaluation of the pelvis or skull is not possible in all situations, since these are large-sized bones that are easily subjected to post-mortem destruction or loss, and high sexing reliability may require several features to be preserved.

Bones of the foot have recently gained interest as subjects of study for sex estimation using osteometric analysis.[3] The foot and ankle are weight-bearing parts of the body and therefore have a tendency to exhibit large size differences between males and females. Fessler and coworkers[4] found that, in individuals of similar body height, males tend to have a longer foot than females. Several anthropological studies suggest the use of the calcaneus, talus and metatarsal bones in sex identification of American and European

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Received 17 March 2014
Revised 22 April 2014
Accepted 29 April 2014

skeletons, all of which have reasonably high accuracy using discriminant analysis.[5-7] Furthermore, a comparative study in a mass grave context suggested that tarsal bones are usually contained within footwear, which not only protects them from natural taphonomic environments, but also helps keep the tarsal bones intact.[8] Thus, tarsal bones are good candidates for osteometric sexing.

Among the tarsal bones, the calcaneus and talus have been the most thoroughly studied in different ethnic groups. A study by Steele[9] was the first to show the value of the talus and calcaneus in sex estimation of European- and African-American populations. More recent studies have confirmed the reliability of these two bones for sexing of Italians[6], South Africans[10,11] and Koreans[12]. However, there is comparatively little data on measurements of the navicular bone, which is another essential bone in weight-bearing and in maintenance of the medial longitudinal arch of the foot. One study by Harris and Case[13] showed that the navicular is another bone that has satisfactory sexual dimorphism in a European-American population, and detailed analyses by Kidd and Oxnard[14] revealed that the navicular bone shows differences, both in terms of sexual dimorphism and ethnicity among people from Britain, China, and South Africa. So far, though, there appear to have been no morphometric analyses of the sexing capacity of the navicular bone, except in European-Americans. Our purposes in this study are to investigate the utility of dimensional parameters of the navicular bone for sex estimation and to develop discriminant function equations for sexing of Thai skeletons.

MATERIALS AND METHODS

Navicular bones used in this study represented a modern Thai population in the northern region, and were obtained from the Chiang Mai University Skeletal Collection of the Faculty of Medicine, Chiang Mai University. A total of 404 navicular bones were obtained from 202 skeletons (104 males and 98 females), which were collected between 2005 and 2010 from donated cadavers with documented sex and age at death. Both left and right navicular bones were subjected to osteometric measurement. Age at death in the male sample ranged from 29 to 86 with a median age of 65 years old, whereas in the female sample it ranged from 15 to 90 with a median age of 70 years old. Only one female individual was under the age of 20 years. Pathological and damaged specimens were excluded from our study. The method of study was approved by the Institutional Ethical Review Board and informed consent was waived.

Eight navicular dimensions were measured and had been previously defined in other studies.[13,14] Definitions of each measured dimension have been provided in Table 1 and Fig 1. Measurements were taken to the nearest 0.01 mm using a mini-osteometric board available from Paleo-Tech Concepts and a sliding digital caliper. For naming convention in our study, the abbreviations of all dimensions are followed by a dash and indication of side (L for left side, and R for right side). All measurements were taken three times by the same investigator. The first, second and third rounds of data collections were conducted from January to March 2012, June to August 2012 and February to April 2013, respectively. The intraclass correlation coefficient was used to analyse the repeatability and consistency of each measurement.

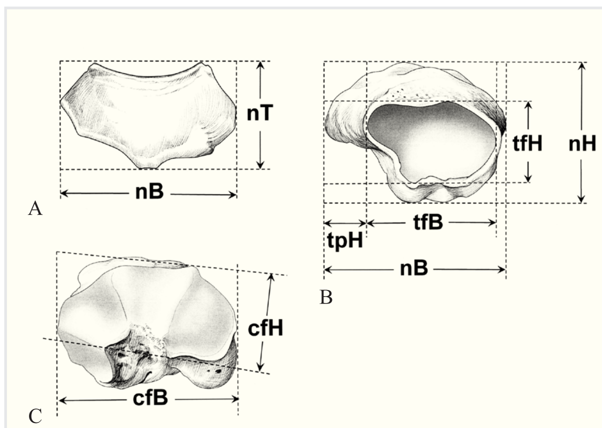

Fig 1. Illustrations of navicular bone dimensions: Maximum navicular breadth (nB), maximum navicular height (nH), maximum navicular thickness (nT), maximum talar facet height (tfH), maximum talar facet breadth (tfB), maximum cuneiform facet height (cfH), maximum cuneiform facet breadth (cfB) and maximum tuberosity projection height (tpH). *A*: Dorsal surface, *B*: Talar articular surface, *C*: Cuneiform articular surface.

Statistical analyses were performed using SPSS for Windows (SPSS, Inc., Chicago, IL). Descriptive statistics of the data from our sample were evaluated. A one-sample Kolmogorov-Smirnov test was conducted to assess the goodness of fit with a normal distribution. Student's *t*-test was applied to each parameter on both the left and right sides in order to compare mean differences between males and females, with $p<0.05$ considered to be statistically significant. Cohen's *d* effect sizes were calculated from mean differences and standard deviations of each dimension between the sexes, with $d > 0.80$ considered a large effect size. Discriminant analyses, using a multiple model with all of the independent variables, and stepwise method on all eight variables, were performed to construct discriminant equations for sex estimation by the left and right navicular bones. Cross-validation of the constructed discriminant functions was applied to verify their predicted accuracy.

RESULTS

The intraclass correlation coefficient values for 14 of the 16 variables had values greater than 0.85.The exceptions were maximum navicular tuberosity projection height on both sides, as shown in Table 2. The one-sample Kolmogorov-Smirnov test for goodness of fit of each parameter with a normal distribution had a significance value

TABLE 1. Descriptions of measurements.

Parameter	Abbreviation	Definition
Maximum navicular breadth	nB	Linear distance in the transverse plane between the most medial point of the navicular tuberosity and the most lateral point of the navicular bone
Maximum navicular height	nH	Linear distance in the sagittal plane between the most superior point of the navicular bone and the most inferior point of the navicular bone
Maximum navicular thickness	nT	Linear distance in the anteroposterior plane between the line made from the medial and lateral ends of the talar facet and the most distal point on the cuneiform facet of the navicular bone
Maximum talar facet height	tfH	Linear distance in the sagittal plane between the most superior point of the talar facet on the navicular bone and the most inferior point of the talar facet on the navicular bone
Maximum talar facet breadth	tfB	Linear distance in the transverse plane between the most medial point of the talar facet on the navicular bone and the most lateral point of the talar facet on the navicular bone
Maximum cuneiform facet height	cfH	Linear distance in the sagittal plane between the most superior point of the cuneiform facet on the navicular bone and the most inferior point of the cuneiform facet on the navicular bone
Maximum cuneiform facet breadth	cfB	Linear distance in the transverse plane between the most medial point of the cuneiform facet on the navicular bone and the most lateral point of the cuneiform facet on the navicular bone
Maximum navicular tuberosity projection height	tpH	Linear distance in the transverse plane from the medial margin of talar facet of the navicular bone to the most medial point on the navicular tuberosity

TABLE 2. Results of Intraclass correlation coefficient (ICC) and Kolmogorov-Smirnov test of goodness of fit results for each measured parameter.

Parameter	Intraclass correlationcoefficient	Kolmogorov-Smirnov test Z value	Asymptotic significance value (2-tailed)
nB-L	0.987	0.900	0.393
nH-L	0.960	0.964	0.311
nT-L	0.977	0.557	0.915
tfH-L	0.853	1.124	0.159
tfB-L	0.954	1.035	0.234
cfH-L	0.855	1.014	0.256
cfB-L	0.949	0.997	0.273
tpH-L	0.755	1.008	0.261
nB-R	0.987	0.796	0.550
nH-R	0.961	0.744	0.637
nT-R	0.981	0.867	0.439
tfH-R	0.867	0.989	0.282
tfB-R	0.942	1.020	0.250
cfH-R	0.935	0.731	0.659
cfB-R	0.943	0.883	0.417
tpH-R	0.774	0.885	0.414

greater than 0.05, which implies that our navicular bone samples were a good representative of the Thai population (Table 2). Descriptive statistics including the mean, standard deviation and standard error of the mean for each parameter and each sex have been shown in Table 3. Comparison of the means between the sexes revealed that all parameters of the male sample were larger than of the female sample (Table 4). Student's *t*-test of mean differences showed that all parameters exhibited significant differences between the sexes ($p < 0.001$). Assessment of effect size by calculating Cohen's d value for each parameter revealed that all measured variables had high effect sizes ($d > 0.80$), with exceptionally high values for cfB-L, tfH-R and cfB-R.

We derived discriminant functions for sexing of navicular bones using all of the independent variables, as well as by using a stepwise method. The unstandardized function coefficients, eigen values, correlation cofficients, Wilks' lambda values, group centroids and cross-validation results have been shown in table 5. Sectioning points for all functions were at zero, and a positive value indicates male, while a negative value indicates female. Using all eight variables, the discriminant functions for the left side (F1) and right side (F2) were as follows:

F1 = (-0.245)(nB-L) x (-0.075)(nH-L) x (0.148)(nT-L) x (0.295)(tfH-L) x (0.189)(tfB-L) x (0.107)(cfH-L) x (0.317)(cfB-L) x (0.309)(tpH-L) – 18.919

F2 = (-0.299)(nB-R) x (-0.081)(nH-R) x (0.120)(nT-R) x (0.391)(tfH-R) x (0.235)(tfB-R) x (0.000)(cfH-R) x (0.309)(cfB-R) x (0.407)(tpH-R) – 18.603

Cross-validation of both discriminant functions was performed. According to that calculation, the predicted accuracies of male and female estimation by the F1 equation were 92.9% and 89.4%, respectively. Similarly, the predicted accuracies by the F2 equation were 91.8% and 92.3% for males and females, respectively.

For the stepwise method, the parameters that minimized the overall Wilks' lambda value were included in the function. On the left side, only three parameters (tfH-L, cfB-L and tpH-L)

TABLE 3. Means, standard deviations and standard error of means of each measured parameter by sex (in millimeters).

Parameter	Sex	Mean	Standard deviation	Standard error of mean
nB-L	Female	36.06	2.46	0.249
	Male	40.02	2.73	0.268
nH-L	Female	24.03	1.54	0.155
	Male	27.25	2.01	0.197
nT-L	Female	18.30	1.29	0.131
	Male	20.48	1.43	0.140
tfH-L	Female	19.27	1.52	0.154
	Male	23.03	1.83	0.179
tfB-L	Female	24.26	1.41	0.142
	Male	27.52	1.82	0.178
cfH-L	Female	19.39	1.39	0.140
	Male	22.13	1.39	0.136
cfB-L	Female	31.07	1.41	0.143
	Male	35.04	1.90	0.187
tpH-L	Female	10.31	1.54	0.155
	Male	11.89	1.55	0.152
nB-R	Female	35.82	2.52	0.254
	Male	39.78	2.98	0.293
nH-R	Female	24.20	1.62	0.164
	Male	27.46	1.96	0.192
nT-R	Female	18.17	1.33	0.135
	Male	20.43	1.71	0.167
tfH-R	Female	19.03	1.43	0.144
	Male	22.79	1.64	0.160
tfB-R	Female	24.20	1.45	0.147
	Male	27.64	1.99	0.196
cfH-R	Female	19.33	1.45	0.146
	Male	21.99	1.47	0.144
cfB-R	Female	31.21	1.49	0.151
	Male	35.00	1.77	0.173
tpH-R	Female	9.99	1.47	0.148
	Male	11.86	1.59	0.156

were sufficient to construct the discriminant function, while five parameters (nB-R, tfH-R, tfB-R, cfB-R and tpH-R) were included in the function for the right side. By the stepwise method, the discriminant functions for the left side (F3) and right side (F4) were as follows:

F3 = (0.318)(tfH-L) x (0.331)(cfB-L) x (0.135)(tpH-L) – 19.228

F4 = (-0.273)(nB-R) x (0.337)(tfH-R) x (0.229)(tfB-R) x (0.324)(cfB-R) x (0.485)(tpH-R) – 18.733

Cross-validation of these functions was also performed, and we found that the predicted accuracy of the discriminant function using the stepwise method was very similar to those using all variables with the enter method. The results showed that the predicted accuracies of male and female estimation using the F3 equation from the left navicular bone were 90.8% and 88.5%, respectively. Also, the F4 equation for the right side showed 93.9% and 90.4% accuracy for male and female bones, respectively.

In order to further expand the usefulness of our equations, we also classified the sexes from right navicular bones using equations made from the left side (F1 and F3), and vice versa. Equations for the left side made using all variables (F1) could correctly predict right female bones with an accuracy of 94.9%, and right male bones with 91.4% accuracy, while equations from the stepwise method (F2) had 92.9% accuracy for female bones, and 88.7% accuracy for male bones. The equation for the right side using all variables (F3) could correctly classify left female bones 92.9% of the time and left male bones 90.4% of the time. Finally, the equation for the right side made using the stepwise method produced 92.9% and

TABLE 4. Mean difference between the sexes (in millimeters), 95% confidence interval (CI) of mean difference, two-tailed significance values from Student's *t* test of mean difference between the sexes, and Cohen's *d* value of effect size between the sexes.

Parameter	Mean difference	95% CI of the difference		Sig. (2-tailed)	Cohen's *d*
		Lower	Upper		
nB-L	3.96394	4.68634	3.24154	0.000	1.526
nH-L	3.21650	3.71163	2.72137	0.000	1.797
nT-L	2.18201	2.56022	1.80380	0.000	1.604
tfH-L	3.76144	4.22946	3.29342	0.000	2.237
tfB-L	3.25724	3.70733	2.80715	0.000	2.002
cfH-L	2.74404	3.12980	2.35828	0.000	1.975
cfB-L	3.96668	4.43028	3.50308	0.000	2.366
tpH-L	1.57982	2.00877	1.15088	0.000	1.023
nB-R	3.95471	4.71901	3.19041	0.000	1.433
nH-R	3.25078	3.75159	2.74996	0.000	1.807
nT-R	2.25547	2.67932	1.83161	0.000	1.472
tfH-R	3.75314	4.17996	3.32632	0.000	2.446
tfB-R	3.43877	3.92080	2.95673	0.000	1.972
cfH-R	2.65448	3.05901	2.24996	0.000	1.822
cfB-R	3.79001	4.24473	3.33528	0.000	2.320
tpH-R	1.86985	2.29460	1.44511	0.000	1.223

TABLE 5. Discriminant functions and analytical results for the Thai navicular bone.

Functions	Eigenvalue	Canonical correlation	Wilks' lambda	Group centroid		Accuracy (%) from Cross-validation		
				Male	Female	Male	Female	Pooled
F1: Independent variables (left side)	2.082	0.822	0.324	1.394	-1.479	92.9	89.4	91.1
F2: Independent variables (right side)	2.503	0.845	0.285	1.528	-1.622	91.8	92.3	92.1
F3: Stepwise method (left side)	1.874	0.808	0.348	1.322	-1.403	90.8	88.5	89.6
F4: Stepwise method (right side)	2.436	0.842	0.291	1.507	-1.600	93.9	90.4	92.1

89.4% accuracy for left female and male bones, respectively. These high accuracy values showed that discriminant functions from either the right or left side can be applied to the opposite side.

DISCUSSION

This study has provided strong evidence that the navicular bone can be applied for estimation of sex in Thai populations with relatively high accuracy. Comparison of dimensions of the navicular bone and its articular facets between the sexes showed that the values were highly statistically different between females and males ($p < 0.001$), based on Student's *t*-test. Moreover, all parameters showed very large Cohen's *d* effect sizes, which ranged from 1.023 to 2.446. Such high Cohen's *d* values means simply that male/female differences in dimensions of the navicular bone are substantial, so one might readily distinguish male navicular bones from female bones through visual estimation alone in many cases. We also constructed discriminant functions for accurate estimation of sex using all of the variables and then a stepwise method. Accuracy obtained from the discriminant functions using all variables proved to be very high. It should be noted that the pooled accuracy value for the right navicular bone obtained from functions constructed from all eight variables (F2) and from the stepwise method (F4) were the same (92.1%). Therefore, we suggest that equations derived from the stepwise method, which uses only variables with strong discriminative power, should be applied for sex estimation from the navicular bone, especially in cases of minor damage to the navicular bone. Although we only measured a single tarsal bone and obtained a high sex estimation accuracy, we suggest that other foot bones should be considered for analysis, since estimation of sex by multiple tarsal bones results in higher accuracy when compared with using a single bone.[13]

Application of tarsal bones to sex estimation has often focused on calcaneus and talus measurements, and recent studies have shown that the navicular bone is also useful for sex estimation. Logistic regression analysis made from measurements of only navicular length and breadth showed 81.2% to 86.3% accuracy, while combination with parameters from the cuboid or cuneiforms can increase the accuracy of the function up to 93.4%, which is comparable to functions derived from measurements of the calcaneus or talus.[13] Our constructed model suggests that measurements of the navicular articular facets and tuberosity could be good alternatives for achieving higher accuracy in sex estimation, since the function that relied only on talar facet height, cuneiform facet breadth and tuberosity projection height gave an accuracy of up to 90.8%. The application of articular surfaces of the tarsal bones as determinants of sex has been previously suggested by DiMichele and Spradley[5], who studied American calcaneal samples and found that the articular surfaces of calcaneus showed overall correct classification of sex ranging from 80.0% to 88.1%. Another study conducted on prehistoric Polynesian skeletons by Murphy[15] found that the articular surfaces of the talus and calcaneus could be applied in sex estimation with 92.3% accuracy.

Sexual dimorphism of articular surfaces in the foot have also been previously studied by Eckstein and colleagues[16], who considered the morphology of the articular cartilaginous surface of the talonavicular joint, and concluded that women show a significantly smaller surface area and thinner cartilage than men. Functionally, the navicular bone is known to be a crucial element in maintenance of the medial longitudinal arch of the foot, transmitting force directly from the head of the talus to the cuneiform bones and subsequently the first metatarsal and adjacent sesamoid bones. A radiographic study found that the medial longitudinal arch in the female foot has a greater angle than in the male foot when in a weight-bearing position[17]. A study of the foot in individuals aged 60 years and over suggested that there is a positive correlation between body mass index (BMI) and arch index[18]. Muscle attachments, ligamentous laxity, gait and extrinsic factors may also promote smaller foot bones and shape differences in females compared with males.[19] Analysis of foot structure revealed that females have significantly lower arch stiffness than males, implying that the female foot has more muscle elasticity and ligaments supporting the arch of foot[20], particularly at articular surfaces that permit a greater degree of adduction[21]. We therefore propose that the differences in body weight, together with structural supports of the medial arch of the foot probably account for the sexual dimorphism seen in the articular facets of the navicular bone. We recommend that detailed investigation of the articular surface area and curvature in the navicular bone, and its relationship to sex assessment, be studied in greater detail.

In conclusion, we found that the navicular bone has good potential for sex estimation in Thai skeletons. By measuring talar facet height, cuneiform facet breadth and tuberosity projection height, investigators can estimate the sex of skeletal remains with an accuracy up to 93.9%. We also found that articular facets are often the key parameters in sex assessment, and this might be due to differences in weight bearing and foot biomechanics.

ACKNOWLEDGMENTS

This research was financially supported by the Faculty of Medicine, Chiang Mai University. The authors would like to express gratitude to Assistant Professor Sukon Prasitwattanaseree (Department of Statistics, Faculty of Science, Chiang Mai University) for his statistical guidance, and Miss Ruchira Kamsrichan for her illustrations. We would like to thank the Forensic Osteology Laboratory for providing their skeleton database and equipment, and the staff of the Gross Anatomy Laboratory, Faculty of Medicine, Chiang Mai University, who prepared these skeletons for research purposes.

Conflict of Interest Notification Page

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