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A Metrical Method of Sex Estimation for Two Mediaeval Scottish Populations

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Abstract

Calcanei and tali are robust, sexually dimorphic, weight bearing foot bones that survive well in forensic and archaeological contexts. In this study, sex estimations were conducted on calcanei and tali from the Ballumbie and St. Andrews library mediaeval Scottish populations provided by the University of Edinburgh, Scotland, applying the Alonso-Llamazares and Pablos method. This method has proven accuracy of up to 96.4% for the Hamann-Todd human osteological collection, 91.4% for *Homo sapiens* from data published by other authors and 100.0% for both the Sima de los Huesos hominids and homo neanderthalensis, based on discriminant functions for the calcaneus and talus.

In this study, 39 calcanei from 19 males and 20 females and 56 tali from 25 males and 31 females were used. The functions obtained produced accuracies varying from 67.3%-88.4% for univariate and from 79.1%-100.0% for the multivariate discriminant formulae. This study confirms the finding of Alonso-Llamazares and Pablos that multivariate statistical analysis of the calcaneus and talus combined generally produce more accurate sex estimations than univariate statistical methods. Measurements yielding the highest accuracy for sex estimation were the maximum length of the calcaneus, posterior talar articular surface length of the calcaneus, talar length and total length of the talus. The Alonso-Llamazares and Pablos formulae applied to these two mediaeval populations produced accuracies ranging from 43.9%-89.4% for univariate and from 75.6%-97.1% accuracy for multivariate formulae. The best predictor for sex from both studies was the total talar length (M1a).

Keywords: Osteology; Sex estimation; Calcaneus; Talus; Archaeology

Introduction

Analysis of archaeological skeletal populations can reveal past demographics, mortality and pathology. Fundamental to the determination of the biological aspects of age, height, ancestry, and prevalence of pathology in an assemblage, is estimation of sex. In forensic contexts, sex estimation is vital to victim identification. In the case of multiple victims, mixed remains, or mass casualty events, the rapid and correct identification and return of human remains is a necessary part of the psycho-social healing process for survivors [1].

Morphological and metrical sex estimation rely on sexual dimorphism. Sexual dimorphism is observable morphological and size differences between males and females of the same species. Genetics, diet, disease and environmental variation experienced by individuals during their lives shape the human skeleton. At the onset of puberty, sex hormones impacting growth and development drive skeletal and soft tissue structural changes [2,3]. To facilitate childbirth the female pelvis widens. Male bone density increases, resulting in entheseal site structural changes as musculature develops. Distinguishing between post pubertal male and female human skeletal remains is possible using features of the pelvis and the skull.

When the absence of skeletal elements, deliberate destruction or poor preservation hinders morphological methods of sex estimation, the employment of metrical methods is useful because they rely on bone measurements and not visual characteristics. Male body mass tends to be greater than that of females, this is often reflected in the length and diameter of bones. Metrical methods exist for numerous skeletal elements including teeth, the femur, the humerus, tarsals and the tibia.

In forensic contexts, lone feet frequently wash ashore in shoes or boots along coastal beaches and waterways. Due to the process of aquatic decomposition and marine organism predation the foot becomes detached from the lower leg and the disarticulated feet disassociate from the rest of the remains and may be deposited on nearby shorelines through wave action. This process is also present in the archaeology of shipwrecks, ancient flooding events and aquatic funerary practices. Disarticulated remains are not uncommon in archaeological contexts, making metrical sex estimation situationally more suitable than morphological methods [4,5].

DNA testing is the most definitive sex identification method available but it is destructive to skeletal material, time consuming and expensive. It should be used sparingly. In the cases of earthquake and tsunami disasters, disarticulated remains may result in delays to the identification process. A sex estimation method requiring less specialised training and equipment could provide fast and reliable sex estimations to aid identification. The calcaneus and talus are dense bones due to the force of the entire body weight being transmitted through them during locomotion. This places these bones under significant stress and requires the bones to be resistant to breakage. Thus they tend to preserve well in the archaeological record.

Numerous metrical methods have been previously employed to investigate sexual dimorphism in the human calcaneus, talus, and other tarsal bones. The metrical method proposed by Alonso-Llamazares and Pablos, was developed from the Hamann-Todd Human Osteological Collection, which contains roughly 3000 human skeletons, and is housed at the Cleveland Museum of Natural History in Ohio, USA. The Alonso-Llamazares and Pablos study produced high accuracy formulae from a 20th century mixed population of African and European ancestry on calcanei from 164 skeletons, 162 of which also had their tali investigated. The Alonso-Llamazars and Pablos method was also successfully applied to other members of *Homo* spp., therefore it is potentially applicable to a wide range of populations. Having a reliable sex estimation method that can be successfully applied to partial remains would be invaluable, especially in instances where the origin or provenance of the osteological material is unknown. However, its applicability to specific archaeological populations from differing geographic and temporal contexts requires testing. The pelvis remains the most diagnostic element for sex estimation. The subpubic angle, greater sciatic notch, shape of the obturator foramen, pubic bone and the auricular surface of the pelvis are used to estimate sex by osteoarchaeologists. Accurate application of these methods requires education, experience and good bone preservation. Even then, the application of morphological methods is subjective based on the experience, bias and cultural influence of the individual applying them [6].

Alonso-Llamazares and Pablos method

The Hamann-Todd Human Osteological Collection (HTHOC) is housed in the Cleveland Museum of Natural History in Ohio, USA. The HTHOC is an early 20th century American population of African and European ancestry ranging from 14 to 50 years of age at death. The skeletal material in the study was not separated by ancestry. They achieved high accuracy for sex estimation on HTHOC ranging from 66.1% to 90.2% for the talus and70.2% to 86.0% for the calcaneus in univariate accuracy; 86.6% and 96.4% for the talus and 83.3% to 87.7% for the calcaneus single bone multivariate accuracy and 90.2% and 95.5% for combined talus and calcaneus multivariate accuracy. Only accuracies above 80.0% for other authors' data were reported and these ranged from 82.7% to 92.6% accuracy for 21 different formulae on data from 8 separate studies. Alonso-Llamazares and Pablos achieved 100.0% accuracy when estimating sex of the fossil hominid populations from Cueva Sima de los Huesos and Homo Neanderthalensis remains collected from different sites which showed promise for the application to other fossil hominid remains. Alonso-Llamazares and Pablos proposed that the formulae generated from their study could therefore be appropriate for assessing populations outside the collection from which they were generated [7]. The formulae generated on the HTHOC will be tested on the two mediaeval populations investigated in this study.

Current study

The current study aims to investigate a broader application of the Alonso-Llamazares and Pablos metrical univariate and multivariate method for sex estimation by developing discriminant functions based on measurements of the calcanei and tali from individuals of known sex from the Ballumbie and St. Andrews Library (BSTAL) cemetery populations [8]. This study also seeks to apply the Alonso-Llamazares and Pablos generated from the HTHOC to the BSTAL cemetery populations to evaluate their accuracy for these populations. If successful, the Alonso-Llamazares and Pablos formulae could be used with confidence on similar populations where the sex of the individual is unknown, or when other sexually dimorphic skeletal material is absent or indeterminate.

Research questions to be investigated include:

- Which measurements of the calcaneus and talus provide the most accurate basis for sex estimation for the BSTAL mediaeval cemetery populations?
- Which discriminant functions provide the best accuracy for sex estimation for these mediaeval populations?
- How do these formulae compare with those of the Alonso-Llamazares and Pablos study results?
- Does the Alonso-Llamazares and Pablos metrical method provide good accuracy for these mediaeval populations?

The objectives of the current study are:

- To determine which of the skeletal remains of the BSTAL mediaeval populations are appropriate for the generation of discriminant formulae for sex estimation (male/female ratio, age, completeness, lacking pathologies) and estimate their sex using standard morphological methods.
- Measure the calcaneus and talus of each skeleton using the Alonso-Llamazares and Pablos metrical method.
- Undertake statistical analyses to develop population specific discriminant functions for sex estimation and cross validate the results with the morphological sex estimation.
- Compare these formulae generated in this study to the Alonso-Llamazares and Pablos formulae to investigate their accuracy on the BSTAL cemetery populations.

Materials and Methods

Osteological samples used

The skeletal populations used in this study are from the Ballumbie mediaeval cemetery near the Burnside of Duntrune, and St. Andrews Library cemetery, recovered from the old site of the Holy Trinity Church, St. Andrews. Both cemeteries are located in Scotland, UK. The site of Ballumbie Parish Church and its associated cemetery were rediscovered during construction on a new building development. Prior to that, the site's location had been lost in the post mediaeval period. While Ballumbie Church was incorporated in C.E. 1470, an earlier chapel, the Chapel of Lundie, and a cist cemetery existed on the site [9].

64 of the 307 skeletons housed in the BSTAL cemetery collections at the University of Edinburgh were deemed suitable for this investigation based on taphonomic conditions and the ability to apply standard morphological sex estimation methods. Individuals selected for this study were assessed for completeness of the cranium and pelvis which were required for morphological sex estimation. Individuals who displayed tarsal bone pathology, individuals lacking at least one complete calcaneus or talus, and individuals for whom standard sex estimation was not possible were rejected from this study.

In total, 39 skeletons met the criteria for the calcaneus (19 males and 20 females); 56 skeletons (25 males and 31 females) for the talus and 34 skeletons had both a calcaneus and a talus (16 males and 18 females) and were selected for the generation of discriminant functions in this study. The individuals used were estimated to be over 14 years of age based on epiphyseal fusion of the calcaneus, the head of the femur, the head of the humerus, the condyles of the humerus, the condyles of the femur and, when present, the iliac crest. These age estimations were checked against the supporting documents with the skeletal material which included a skeletal report detailing the completeness of the skeleton, an age estimation, a sex estimation and any notable pathologies.

Once selected, skeleton numbers and burial numbers were written on the recording forms which were then secured in a laboratory notebook specific to this project. Morphological sex estimation was undertaken after the calcaneal and talar measurements and input into a sex estimation recording sheet

Metrical measurements

Measurement abbreviations from Alonzo-Llamazares and Pablos were retained for comparison of the results between the two studies. Measurements were taken primarily from the left side of the skeleton where possible, the right side was used in the absence of, or poor taphonomic condition of, the left bone. In two cases, both the right and left tali were measured from the same individual.

The metrical measurements in the current study were conducted by one individual. While interobserver error between researchers is expected, dividing the population into two groups, group 1 for discriminant function development and group 2 for testing of the formulae and the confirmation of measurement accuracy by a second researcher as was done in the Alonso-Llamazares and Pablos study, was not an option due to sample size in the current study [10]. Skeletal elements from BSTAL were measured three times using Draper Expert digital callipers, the average was calculated and the discriminant equations developed from the averages.

Anatomical variables studied

The variables investigated in this study are those from Pablos et al., which are based on measurements originally taken by Martin and Saller and compiled by Brauer (**Figure 1**).

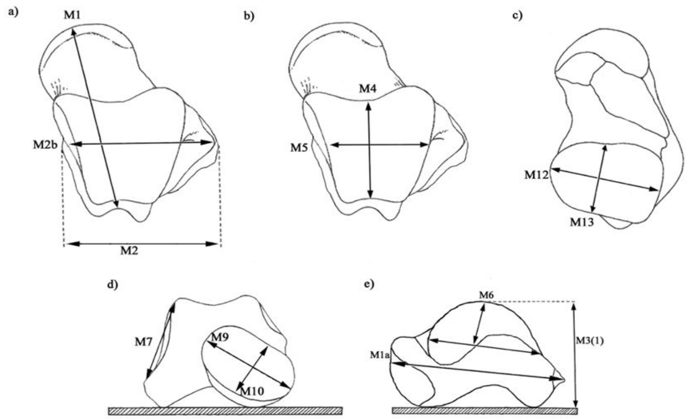

Figure 1: Talar variables used in this study: (a, b) dorsal view of talus (c) plantar view of talus (d) anterior view of talus (e) medial view of talus. The measurements taken were (M1), (M1a), (M2), (M4), (M6), (M7), (M9), (M12) and (M13) as these were the measurements reported by Alonzo-Llamazares and Pablos showing the highest accuracy results for sex estimation in data from other authors. The images used in this figure are taken from Alonzo-Llamazares and Pablos.

All measurements descriptions and their abbreviations below are variations of those taken from Alonso-Llamazares and Pablos. Talar variables studied in **Figure 1**.

- **Talar length (M1):** From the flexor hallucis longus muscle tendon groove to the anterior most point of the head. For correct measurement, the calliper points need to be in simultaneous contact with the bone when the measurement is taken.
- **Total length of the talus (M1a):** From the posterior-most point of the posterior tubercle to the anterior-most point of the head.
- **Total breadth of the talus (M2):** Measured in the transverse plane, this measurement is taken from the lateral process of the talus to the medial side maximum projected point. To correctly take this measurement both points of the calliper must be in simultaneous contact with the bone where it would rest when placed plantar side down on a flat surface.
- **Trochlear length of the talus (M4):** The maximum trochlear length measured on the median sagittal plane of the talus. This is best measured by placing the bone plantar side down on a flat surface. Both points of the calliper must be in simultaneous contact with the bone when measurement is taken.
- **Trochlear height of the talus (M6):** Measured perpendicular to the sagittal plane as it bisects the tibiotalar articular surface, the maximum distance from the highest point on the tibial trochlea of the talus superior to the medial articular surface of the tibial articular facet bisected by the median sagittal talar plane (trochlear length) of the talus which rises at a slight upward angle from the posterior to the anterior of the talus. To take this measurement correctly it is best to place the talus on an osteo-board with the medial side of the bone facing upwards and use the osteo-board slide to hold the bone in place while noting where the median sagittal plane bisects the articular facet, and precise measurement from this point to the highest point of the trochlea can be taken.

- **Lateral malleolar oblique height of the talus (M7):** Measured in the transverse plane, the distance between the lateral process inferior edges to the trochlear superior border.
- **Length of the head of the talus (M9):** The navicular articular surface maximum length.
- **Length of the calcaneal posterior articular surface of the talus (M12):** Measured parallel to the long axis along the articular surface, the maximum calcaneal posterior articular surface length.
- **Breadth of the calcaneal posterior articular surface of the talus (M13):** Measured perpendicular to the articular surface long axis, the maximum width of the posterior calcaneal articular surface of the talus.

Calcaneal variables studied in the **Figure 2**.

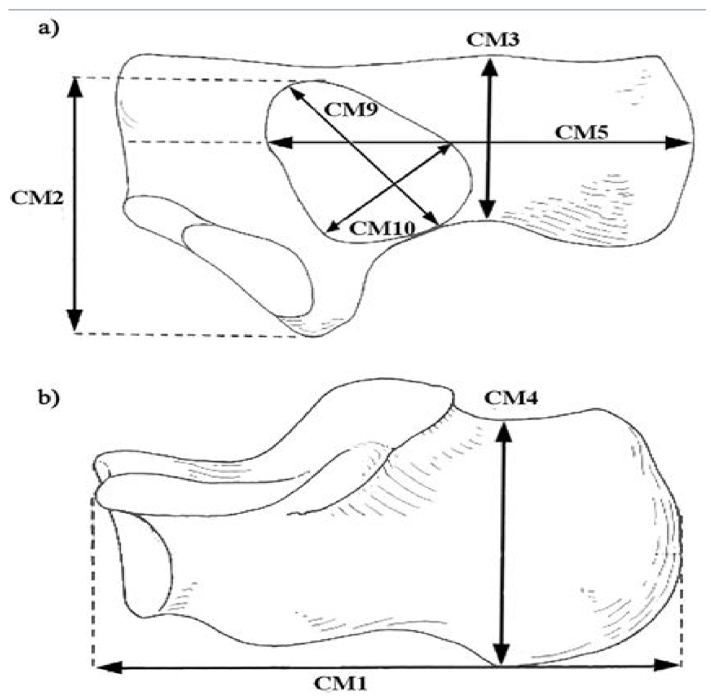

Figure 2: Calcaneal variables a) dorsal view of calcaneus b) medial view of calcaneus. Calcaneal measurements taken as part of the study (CM1), (CM2), (CM3), (CM4), (CM5), (CM9), and (CM10).

- **Maximum calcaneal length (CM1):** The maximum projected length from the posterior most point of the tubercle to the anterior most point of the cuboid facet.
- **Medial breadth of the calcaneus (CM2):** The maximum projected width of the sustentaculum tali to the most lateral point of the posterior talar articular surface of the calcaneus.
- **The minimum breadth of the calcaneus (CM3):** The minimum calcaneal body breadth.
- **Total body height of the calcaneus (CM4):** total height of the calcaneus measured from the enthesis of the plantar fascia to the top of the calcaneal body at the middle point of the “saddle” posterior to the posterior articular surface of the talus.
- **Body length of the calcaneus (CM5):** The distance from the anterior-most point to the posterior talocalcaneal joint surface to the posterior most point of the calcaneal tubercle.
- **Talar posterior articular surface length (CM9):** The most medial posterior points to the lateral anterior most points of the posterior talocalcaneal articular surface measured parallel to the long axis of the articular surface.
- **Talar posterior articular surface breadth (CM10):** The medial anterior most to lateral posterior most points of the posterior talocalcaneal articular surface measured perpendicularly along the long axis of the articular surface.

Standard morphological sex estimation methods

Sex estimations for BSTAL were conducted in the osteology lab at the University of Edinburgh. The minimum requirements for sex estimation in this study were at least one complete pelvic bone, and either the glabellar region of the skull, a mandibular ramus and partial dental arcade with mental process intact, a temporal bone with intact mastoid process, or an occipital bone with intact nuchal eminence. Skeletons that did not have these skeletal elements were difficult to estimate sex for and were rejected from the study. In the absence of a skull, two fragmentary pelvic bones or one well preserved, intact pelvis were the minimum requirements for sex estimation. Fragmentary long bones were investigated for robusticity at entheseal sites and for length and density as male individuals in these populations tended to be more robust in the appendicular skeleton than the females and had significant development at entheseal sites [11-13].

The morphological sex estimations employed in this study were those discussed in chapter 19.4 in The Human Bone Manual which are compilations of commonly used morphological sex estimation methods.

Statistical methodology

Sixteen measurements were taken, seven from the calcaneus and nine from the talus, in millimetres. Each variable was measured three times and input into a physical recording form. The measurements were then input into a Google Sheets spreadsheet. Calculations were undertaken using IBM SPSS for Statistics software version 25. Calcanei and tali measurements were separated and sorted by variable. These were then copied into the program past 4 for univariate analysis. Each measurement variable had summary statistics, normality tests and, dependent on the normality tests, either a Student’s t-test for equivalency of the means or a Mann-Whitney U test conducted.

Descriptive statistics were generated in the software Past4. In the descriptive analyses the Standard Deviation (SD), the Mean (M), the Minimum (Min), Maximum (Max) and the p-value for all the individual variables were obtained for each bone as indicated in **Table 1**. The next tests undertaken, again in Past4, were Normality tests to determine whether or not the data was normally distributed and what kind of comparative tests to use. In this research significance levels for the t-tests and the Mann-Whitney U tests were set at 0.05. To ascertain the sexual dimorphism in the calcaneal and talar measurements, t-tests and Mann-Whitney U tests were employed to compare the means between the groups depending on whether the data were normally distributed.

The measurement values for each skeleton were copied into IBM SPSS 25 by variable and sex estimation. These were analysed using the discriminant function analysis with sex estimation “male” or “female” rendered as 1 and 0 respectively.

A series of measurements were taken from bones of each individual and the discriminant analysis was used to determine predictors from the data that would classify an individual as male or female. Cross validated accuracy percentages for correct sex estimation were then evaluated. Univariate discriminant variables were generated from the Canonical Discriminant Functions Coefficients table in the Output window and input into the Google Sheets document set up for univariate discriminant function analysis. Using the discriminant functions, histograms for each of the measurement variables for the talus and calcaneus were generated individually to visualise which ones showed the greatest distance from the sectioning point of 0.0 and which were the least accurate for sex estimation.

After the creation of univariate functions, multivariate functions were generated. Combination accuracies were checked in the classification results output for predicted group membership output for the cross validated percentage values. As with the univariate functions, these were then input into tables in Google Sheets and appear in the results section in **Tables 2 and 3**.

Tables were then generated to investigate the accuracy of the Alonso-Llamazares and Pablos univariate and multivariate functions in Google Sheets compared to the functions generated in this study. Reported accuracy percentages from group 1 in the Alonso-Llamazares and Pablos study were used because this was the group from which their discriminant functions were generated. The data for comparison from the original study upon which this one was based can be found in **Tables 1, 2, 4, 6 and 8** in Alonso-Llamazares and Pablos. The tables with the results of the Alonso-Llamazares and Pablos functions applied to the Scottish mediaeval populations that are the subject of this study are listed in the Results section in **Tables 4 and 5**.

Results

To ascertain the sexual dimorphism seen in the calcaneal and talar measurements, descriptive statistics for each measurement were generated (**Table 1**). The following variables were found to be statistically significant between males and females: (CM1), (CM2), (CM4), (CM5), (CM9), (CM13), (M1), (M1a), (M2), (M4), (M7), and (M12). Measurements that indicated low sexual dimorphism were (M6), (M9), (CM10), and (CM3) and were not included in the creation of discriminant formulae [14].

Table 1: Descriptive analysis of measured variables in the Ballumbie and St. Andrews Library cemetery populations for each sex.

Variable	SexEst	N	Mean	SD	p-value	Minimum	Maximum
Maximum length of the calcaneus (CM1)	Male	19	77.4	1.27	<0.01	68.91	92.55
	Female	20	70.4	1.01		62.67	81.2
Medial breadth of calcaneus (CM2)*	Male	19	44	1.07	0.01*	37.22	57.49
	Female	20	40.6	1.1		34.81	52.82
Minimum breadth of the calcaneus (CM3)*	Male	19	27.1	1.34	0.16*	22.18	43.77
	Female	20	25.5	1.23		18.64	37.63
Calcaneal body height (CM4)*	Male	19	42	1.14	<0.01*	24.32	47.11
	Female	20	37.5	0.79		30.76	44.26
Calcaneal body length (CM5)	Male	19	53.5	0.99	<0.01	45.47	63.11
	Female	20	48.8	1		38.95	55.94

Posterior talar articular surface length of the calcaneus (CM9)	Male	19	31.5	0.54	<0.01	28.17	37.64
	Female	20	28.4	0.36		25.67	31
Talar articular surface breadth of the calcaneus (CM10)	Male	19	20.8	0.67	0.2	15.2	25.63
	Female	20	19.6	0.53		16.37	25.49
Talar length (M1)	Male	25	54.3	0.74	<0.01	46.83	60.86
	Female	31	49.4	0.59		41.03	56.89
Total length of the talus (M1a)	Male	25	59.3	0.83	<0.01	49.62	69.08
	Female	31	53.2	0.63		44.9	60.78
Total breadth of the talus (M2)*	Male	25	44.6	0.87	<0.01*	38.91	57.59
	Female	31	39.1	0.64		30.54	47.29
Trochlear length of the talus (M4)*	Male	25	33.9	0.7	<0.01*	27.64	44.33
	Female	31	28.9	0.67		20.26	34.81
Trochlear height of the talus (M6)*	Male	25	14.5	0.99	0.41*	11.14	37.04
	Female	31	13.4	0.37		10.58	19.33
Lateral malleolar oblique height of the talus (M7)*	Male	25	25.9	0.67	<0.01*	14.67	31.51
	Female	31	23.5	0.37		18.67	28.79
Length of the head of the talus (M9)*	Male	25	32.9	0.68	0.06*	26.86	39.16
	Female	31	31	0.54		19.86	37.51
Length of the calcaneal	Male	25	33.6	0.58	<0.01*	24.59	38.61

posterior articular surface of the talus (M12)*							
	Female	31	30.7	0.53		23.69	37.54
Breadth of the calcaneal posterior articular surface of the talus (M13)*	Male	25	21.3	0.64	<0.01*	16.6	34.33
	Female	31	19.2	0.43		13.82	23.62

Note: *Statistical tests conducted as Mann-Whitney U tests, all others as Student's t-test.

Measurements in mm, SD: Standard Deviation, N: Number of individuals studied, SexEst: Sex Estimation.

For the calcaneus the least accurate cross validated measurement score was the medial breadth of the Calcaneus (CM2) with a score of 71.1% accuracy. The cross validated measurement with the highest accuracy was the calcaneal body height (CM4) at 84.2%, followed by the posterior talar articular surface length of the calcaneus (CM1) at 81.6%. For the talus the least accurate measurement score was the breadth of the calcaneal posterior articular surface of the talus (M13) at 67.3% and the most accurate variable was total talar length (M1a) at 88.4% followed by talar length (M1) at 86.5% (**Tables 2 and 3**) [15].

Table 2: Univariate discriminate functions score equations, using varieties measured in calcaneus and talus from the ballumbite and st. Andrew library cemetery population.

Variable	Equations	N (male)	Accuracy % (male)	N (female)	Accuracy % (female)	N Total	Total % Accuracy	(M-F)
Maximum length of the calcaneus (CM1)	CM1 X 0.201-14.887	19	83.3	20	80	39	81.6	3.3
Medial breadth of the calcaneus (CM2)	CM2 X 0.209-8,876	19	61.1	20	80	39	71.1	-18.9
Calcaneal body height (CM4)	CM4 X 0.230-9.131	19	88.9	20	80	39	84.2	8.9
Calcaneal body length (CM5)	CM5 X 0.230-11.757	19	75	20	72.2	39	73.5	2.8
Posterior talar articular surface length of the calcaneus (CM9)	CM9 X 0.512-15.318	19	72.2	20	80	39	76.3	-7.8
Talar length (M1)	M1 X 0.314-16.157	25	81.8	31	90	56	86.5	-8.2

Total length of the talus (M1a)	M1a X 0.275-15.389	25	81.8	31	93.3	56	88.4	-11.5
Total length of the talus (M2)	M2 X 0.261-10,849	25	72.7	31	86.7	56	80.8	-14
Trochlear length of the talus (M4)	M4 X 0.285-8,902	25	81.8	31	86.7	56	84.6	-4.9
Lateral malleolar oblique height of the talus (M7)	M7 X 0.358-8.789	25	54.5	31	96.7	56	78.9	-42.2
Length of the calcaneal posterior articular surface of the talus (M12)	M12 X 0.338-10.828	25	68.2	31	83.3	56	76.9	-15.1
Breadth of the calcaneal posterior articular surface of the	M13 X 0.366-7376	25	45.5	31	83.3	56	67.3	-37.8
Note: N: Sample size; M-F: Difference between male and female %.								

Multivariate discriminant functions

The discriminant functions obtained in the multivariate analysis of calcaneal measurement variables, talar measurement variables, and combined calcaneal and talar measurement variables are shown in **Table 3**.

Table 3: Multivariate discriminate functions score equations, using variables measured in calcaneus and talus from the ballumbite and st. Andrew library cemetery population.

Variables	N	Equations	Accuracy male %	Accuracy female %	Total accuracy	(M-F)
CM1+CM2+CM4 +CM5+CM9	39	CM1 x 0.145+CM2 x (-0.008)+CM4 x -0.096+CM5 x (-0.054)+CM9 x 0.247-18.795	77.8	80.0	79.1	-2.2
CM1+CM4+CM5 +CM9	39	M1 x 0.143+CM4 x 0,097+39CM5 x (-0.054)+CM9 x 0.24118,845	77.8	80.0	79.1	-2.2
CM1+CM5+CM9	39	CM1 x 0.113+CM5 x	77.8	85.0	82.0	-7.2

		(-0.016)+CM9 x 0.338-17.704				
CM1+CM2+CM9	39	CM1 x 0.105+CM2 x (-0.012)+CM9 x 0.347-17,643	77.8	90.0	84.2	-12.2
CM9+CM4	39	CM9 x 0.426+CM4 x 0,086-16,147	77.8	85.0	82.0	-7.2
CM1+CM9	39	CMI X 0.102+CM9 x 0.339-17.707	77.8	90.0	84.8	-12.2
M1+M1a +M2+M4+M7+MI 2+M13	56	(M1 x (0.059)+Mla x 0.124-M2 x 0.053+M4 x 0.161+M756 x 0.030+M12 x 0.040+M13 x (-0.083)-17.556	77.3	93.3	86.5	-16.0
M1+M1a +M2+M4+M7 +MI2	56	M1 x 0.057+M1a x 0.106+M2 x 0.022+M4 x 0.159+M7 x 0.068 +M12x 0.040-17.726	86.4	90.0	88.5	-3.6
M1+M1a +M2+M4	56	M1 x 0.089+Mla x 0.111 +M256 x 0.043+M4 x 0.143-17.020	81.8	86.7	84.6	-4.9
MI+M1a+M4	56	M1 x 0.701+Mla x 0.117+M4 x 0.161-17.045	77.3	90.0	84.0	-12.7
MI+Mla+MI2	56	M1 x 0.120+Mla x 0.155 +M12 x 0.077-17,355	77.3	90.0	84.0	-12.7
MI+Mla	56	M1 x 0.156+Mla x 0.15416,660	77.3	90.0	84.0	-12.7
MI+M4	56	M1 x 0.219+M4 x 0.170-16,574	86.4	90.0	87.7	-3.6
M1a+M4	56	Mla x 0.194+M4 x 0.16916,134	81.1	90.0	86.5	-8.9
M1a+M4+M12	56	Mla x 0.171+M4 x 0.163 +M12 x 0.079-17.198	90.9	86.7	88.5	4.2
CM1+CM4+CM5 +CM9+MI+M1a +M2	34	CMI x 148+CM4 x 0.086 + CM5 x (-0.096) CM9 x 0.095+MI x 0.104 Mla x 0.190+M2 x 0.086-27.289	88.9	100.0	94.1	-11.1

CM1+CM5+CM9 +MI+M1a+M2	34	CMI x 0.111 + CM5 x (-0.065)CM9 x 0.144 MI x 0.018Mla x 0.182+M2 x 0.133-25,866	88.9	93.8	91.5	-4.9
CM1+CM5+CM9 +MI+M1a +M2+M12	34	CMI x 0.095+CM5 x (-0.057)+CM9 x 0.128+M1 x 0006+M1a0.206 +M2 x 0114+M12 x 0.058-26,507	94.4	93.4	93.9	1.0
CMI +CM5+CM9+MI +M1a	34	CM1 x 0.098+CM5 x (-0.056)34H CM9 x 0.202+M1 x 0063+Mla x 1.90-24.380	94.4	100.0	97.0	-5.6
CM1+CM9+MI +M1a+M2	34	CM1 x 0.063+CM9 x 0.147+34 MI 0.021 Mla x 0.176+M20.130- 25.513	100.0	100.0	100.0	0.0
CM1+CM9+MI +Mia	34	CMI x 0.058 CM9 x 0.203 MI 0.065 Mla 0.185 24,135	100.0	100.0	100.0	0.0
CM1+CM2+MI +M1a	34	CMI x 0.047+CM2 x 0.076+34MI x 0.167+Mla x 0.150-23,770	88.9	93.3	91.0	-4.4
CM1+CM4+MI +M1a	34	CMI x 0.090+CM4 x 0.117+Mla x 0.214-25,207	88.9	100.0	94.1	-11.1
CMI +CM2+CM9+MI +M1a	34	CM1 x 0.041+CM2 x 0050+4CM9 x 0.170+M1 x 0.134 34+M1a x 0.138-24.942	100.0	94.4	97.4	5.6
CMI+MI+Mia	34	CM1 x 0.077 MI x0.061+M1a x 00.235-22.053	88.9	93.8	91.3	-4.9
CMI+MI	34	CMI x 0.124 Mla x 0.228-20,987	87.5	88.9	88.2	-1.4
CMI+M1a	34	CMI x 0.082 Mla x 0.280 .21,761	93.8	88.9	91.2	4.9

CM9+M1a	34	CM9 x 0.226 +M1a x 0.284-22.709	93.8	100	97.1	-6.2
CM9+M1	34	CM9 x 0.303+M1 x 0.251-22.130	87.5	100	94.1	-12.5
CM5+M1	34	CM5 x 0.071+M1 x 0.296-18.942	87.5	94.4	91.2	-6.9
CM5+M2+M12	34	CM5 x 0.133+M2 x 0.204+M12 x 0.079-17.893	87.5	88.9	88.2	-1.4
Note: N: Sample size; M-F: Difference between male and female%.						

The multivariate discriminant formulae derived from variables measured in the calcaneus ranged from 79.1% to 84.8% accuracy for correct sex estimation allocation with (4/6) formulae being >80.0% (**Table 3**). The highest accuracy was the combination of (CM1+CM9). For the talus, the most accurate results with the least number of variables was (M1a+M4+M12) with a correct sex estimation allocation of 88.5%. Accuracy of correct sex estimation ranged from 84.0% to 88.5% for discriminant formulae derived from variables measured in the talus. For the talus and calcaneus combined, the highest accuracy for cross validated formulae yielded a result of 100.0% for (CM1+CM9+M1+M1a) and (CM1+CM9+M1+M1a+M2). Correct allocation of sex estimation for discriminant functions derived from calcaneal and talar measurements ranged from 88.2% to 100.0% in accuracy.

Intrarater error was investigated using the reliability analysis in SPSS on the three separate measurements taken for each variable for 39 calcanei and 56 tali. All average measures for intraclass correlation produced values above 0.7 with the majority above 0.9 indicating acceptable intrarater reliability.

Population specific formulae

Univariate discriminant functions: Univariate discriminant function formulae were generated for each of the variables showing significant sexual dimorphism for the calcaneus and talus individually. Prediction accuracies obtained for all variables are shown in **Table 2**.

Results of the formula (CM1+CM9+M1+M1a) corresponded with the morphological sex assessment 100.0% for all cases tested and was the most accurate formula using the fewest variables for assessing sex in these populations (**Figures 3 and 4**). As previously discussed, some of the females in this population appeared particularly robust during their morphological assessment (well-developed entheseal sites on the skull, gonial flaring, robust long bones). **Figure 3** shows that there is very little difference in the measurements between 2 males and 2 females of the 34 tested, indicating 11.8% showed lower than average sexual dimorphism for these variables.

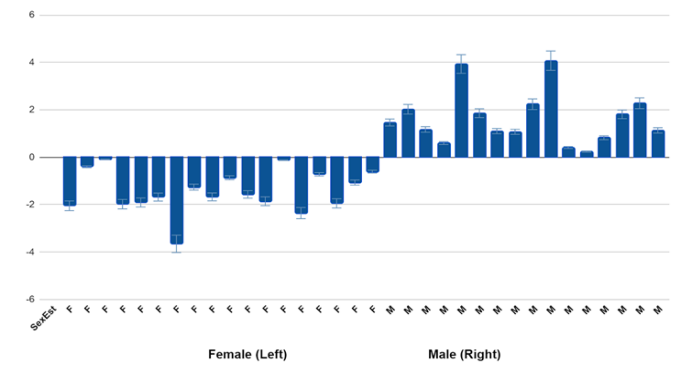

Figure 3: Sex-estimation using discriminant formula (CM1+CM9 +M1a).

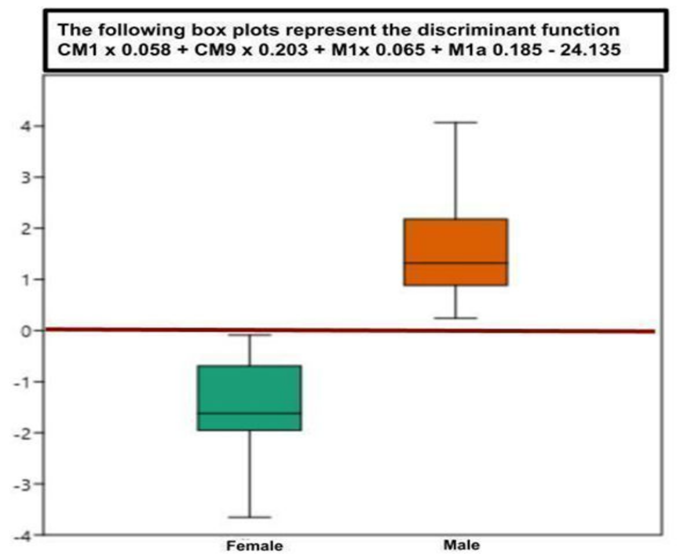

Figure 4: Illustration of the differences between the male and female values derived from the most accurate multivariate discriminant formula using the fewest variables generated in this study (CM1+CM9+M1+M1a). Low sexual dimorphism was observed among some of the males and females tested for these variables.

Accuracy of population specific formulae *vs.* Alonso-Llamazares and Pablos formulae. When the Alonso-Llamazares and Pablos formulae were used to estimate sex in the mediaeval Scottish populations, only one univariate formula (M1a) produced sex estimation accuracies above 80.0% for both male and female (**Table 4**) [16].

Table 4: Alonzo-Liamazares and pablos univariate discriminate functions score equations, using varieties measured in calcaneus and talus from the ballumbite and st. Andrew library cemetery population and the current study comparision.

Variable	N	Male %	Female %	ALP Total %	(M-F)	Current study Total accuracy %	(ALP-CS)
M1	56	76	90	83.8	6.2	86.5	-2.7
M1a	56	84	93.8	89.4	4.3	88.4	1
M2	56	96	75	84.4	-9.4	80.8	3.6
M4	56	44	90.6	70.2	20.5	84.6	-14.5
M6	56	100	0	43.9	-43.9		
M7	56	84	43.8	61.4	-17.7	78.9	-17.5
M9	56	60	71.9	66.7	5.2		
M12	56	84	65.6	73.7	-8.1	76.9	-3.2
M13	56	56	87.5	73.7	13.8	67.3	6.4
CM1	39	33.3	95.2	68.1	27.2	81.6	-13.5
CM2	39	50	76.2	63.8	12.4	71	-7.2
CM3	39	22.2	100	65.9	34.1		
CM4						84.2	
CM5	39	83.3	76.2	79.3	-3.1	73.5	5.8
CM9	39	50	85.7	68.8	16.9	76.3	-7.5
CM10	39					68.5	
Note: Missing varibles are poor predictors of sex for the populations studied (the Hamman-Todd ostelogoical collection for Alonso-Llamazerens and Pablos and the combined Ballumbie and st. Andrews library cemetry populations in this study.							

The majority of their multivariate formulae (8/12) yielded total accuracies above 80.0%, but only a third (4/12) produced accuracies of 80.0% or above for both male and female samples (**Table 5**) with all skewing towards female sex estimation. By contrast the current study produced (6/12) univariate (Table 2) and (30/32) multivariate (Table 3) formulae with total accuracies of 80.0% or better. Of these, (5/12) univariate and (20/32) multivariate had accuracies of >80.0% for both the male and female samples.

Table 5: Alonzo-Liamazares and pablos Multivariate discriminate functions on ballumbite and st. Andrew library cemetery population.

Variable ALP	N	Total accuracy %	Male accuracy %	Female accuracy%	(M-F)
CM1+CM3+CM5+CM9+CM10	39	75.6	50	100	-50

CM1+CM3+CM9	39	84.8	68.8	100	-31.3
CM5+CM9+CM10	39	81.6	62.5	100	-37.5
CM9+CM10	39	81.6	62.5	100	-37.5
CM3+CM9+CM10	39	78.7	56.3	100	-43.8
M1+M1a +M2+M4+M6+M7+ M9+M12+M13	56	75.4	100	55.6	44.4
M1+M1a +M4+M12+M13	56	94.4	87.5	100	-12.5
M1+M12	56	94.4	87.5	100	-12.5
M1+M1a +M2+M4+M6+M7+ M9+M12+M13+ CM1+CM3+CM5+C M9+CM10	34	76.5	100	55.6	44.4
M1+M4+M12+M13+ CM1+CM9+CM10	34	97.1	93.8	100	-6.3
M1+M12+M13+CM9 +CM10	34	94.1	87.5	100	-12.5
M1+CM3	34	82.4	62.5	100	-37.5
Note: N: Number of specimens; M-F: Difference between male and female%.					

Discussion

This study was undertaken with two main aims:

- To investigate which variables and discriminant functions of the calcaneus and talus provided the most accurate basis for sex estimation for the BSTAL mediaeval cemetery populations using the Alonso-Llamazares and Pablos method.
- To compare the results of the formulae generated in this study to those of the Alonso-Llamazares and Pablos formulae applied to the BSTAL populations.

Morphological observations of the BSTAL cemetery populations

Full skeletal assessments were not undertaken as part of this study, however, morphologically the BSTAL cemetery populations appeared overall to have compact, robust bodies. Many of the older females in the population exhibited robust characteristics more commonly seen in males. This included square jawlines with gonial flaring, a prominent mental eminence, robust supraorbital tori and well developed nuchal entheses. Overall, the female individuals tended to have smaller, more gracile long bones than the males, the size differences in the humeral and femoral heads being visually distinct between the sexes. As previously discussed, sexual dimorphism is strongly governed by hormonal activity in the body. Post-menopausal women no longer produce oestrogens from their ovaries which greatly reduces the levels in their bodies, and at this time the pelvis begins to narrow. It would appear that other changes may start affecting peri-and post-menopausal women as younger females in this population did not show this level of robusticity in their craniofacial bones, and their pelvic bones were more sexually dimorphic than those of the older females. While there were a few large males (possibly over 183 cm), the majority of the males appeared to be short (under 175 cm) by modern standards and stocky. The long bones exhibited significant entheseal development, suggestive of prolonged physical labour [17,18].

The morphology of the male and female calcanei and tali in this population were visually distinct, however this was not as noticeable in the variables measured as part of this study. Additional measurements in this population may prove to be more accurate predictors of sex than those used in this study (**Figures 5 and 6**). Female tali overall were shorter in length than those of the males, appearing more compact in height with the talar neck posterior to the navicular articular surface being shorter and wider than that of the males in relation to the total dimensions of the bone. Male tali tended to be longer and narrower overall than the female tali, suggesting that variables comparing length and height in relation to width could be good predictors for sex in this population. The calcanei followed a similar pattern to that of the talus. They tended to be more compact and shorter in length in the females than the males with narrower calcaneal tuberosities. The affected location is the entheses of two major tendons, the plantar fascia and the Achilles tendon, both of which are subject to the significant strains of body mass during locomotion, necessitating more developed attachment sites in individuals of greater mass or those engaged in weight-bearing activities. Sexual dimorphism in the gastrocnemius muscles have been previously reported and calcaneal tuberosity morphology may reflect this.

Species wide, male body masses are greater overall than those of females. The calcaneus and talus being irregular bones are not subject to the same processes of formation as the long bones of the lower leg or even the metatarsals of the foot. Investigation of overall volume or surface area of the calcanei and tali should return sexually dimorphic results in theory as the larger bodied males would require larger support structures. One need only look at studies of the differences between male and female footwear throughout history to see the trend towards larger male feet, not just in length, but in overall volume, as is evident in the differences between current men's and women's athletic footwear. Female footwear of corresponding male size tend to be wider in the forefoot and narrower in the heel than male versions. In a footwear based study conducted on 1.2 million foot scans from multiple countries across the globe, populational differences in foot shape were recorded between males and females as well as differences between the sexes of multiple populations using three dimensional scanning technology. Figures 5 and 6 are suggestions for additional variables to be tested in future studies based on observances made in the BSTAL collection (**Table 6**) [19].

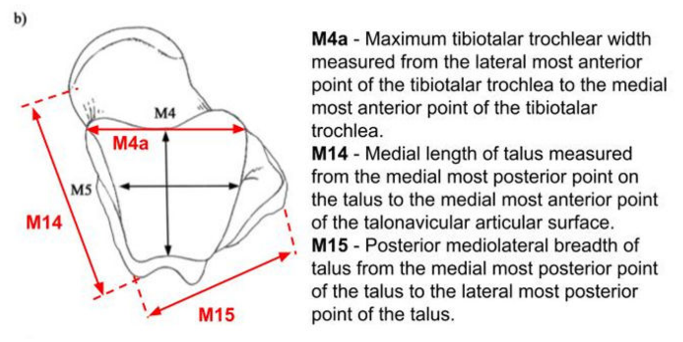

Figure 5: Suggested measurements to take in the BSTAL cemetery population from the talus.

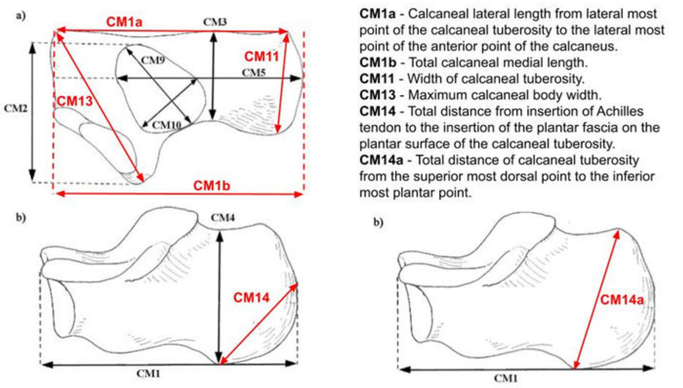

Figure 6: Suggested additional measurements for the calcaneus in the BSTAL cemetery populations.

Table 6: Comparision of best results of the current study and Alonzo-Liamazares and pablos on the mediaevial populations of accuracy.

Current study	Accuracy	ALP	Accuracy
	Variable-Univariate		
CM4	84.20%	CM5	79.30%
M1a	88.40%	M1a	89.50%
	Variable-Multivariate single bone		
CM1+CM9	84.80%	CM1+CM3+CM9	91.20%
M1a+M4+M12	88.50%	M1+M12	97.10%
M1+M1a+M2+M4+M7+M12	88.50%	M1+M1a+M4+M12+M13	94.10%
	Variable-Multivariate combinations		
CM1+CM9+M1+M1a	100.00%	M1+M4+M12+M13+CM1+CM9 +CM10	97.10%
CM1+CM9+M1+M1a+M2	100.00%	M1+M12+M13+CM9+CM10	94.10%

Discriminant formulae comparisons between this study and Alonso-Llamazares and Pablos.

In this study, univariate statistical test results indicated that the calcaneal body height (CM4) was the most accurate variable in the calcaneus for correct sex estimation allocation (**Table 2**). For the talus, the most accurate variable was the total length of the talus (M1a). The Alonso-Llamazares and Pablos univariate formulae best predictor for correct sex estimation allocation for the calcaneus was calcaneal body length (CM5) and for the talus, the total length of the talus (M1a). Only one univariate formula

(M1a) from the Alonso-Llamazares and Pablos study produced accuracy above 80.0% as compared to five from this study (CM1), (CM4), (M1), (M1a), (M4), as shown in **Table 2**. Studies by previous authors showed highest sexual dimorphism in talar length. A trend in sexual dimorphism of talus length could be reliably employed for sex estimation across populations if validated through further research. In the BSTAL cemetery populations, erosion of the lateral body of the calcaneus was an issue, as was erosion of the navicular articulation surface of the talus, which contributed to the low sexual dimorphism seen in variables (CM3) and (M9).

The discrepancies in the univariate results between the Alonso-Llamazares and Pablos formulae and the formulae generated in this study suggest that there are significant differences between the two populations from which the original formulae were derived.

Two of the Alonso-Llamazares and Pablos univariate formulae accuracies were higher than those produced in this study (M1a) and (M2) (**Table 6**). Similar findings occurred in the single bone multivariate accuracies. What caused this is unclear, it could be due to the small sample numbers in the current study, it could also indicate cross populational trends for sexual dimorphism in these variable combinations. As a whole the population specific formulae generated in this study produced more accurate results. Both the Alonso-Llamazares and Pablos formula results for (M1a), and those of this study were the best univariate predictors for sex estimation, suggesting that total talar length may be a good predictor of sex across populations.

The population specific formulae for this study had the highest level of accuracy for variable combinations from both bones. The subjects of Alonso-Llamazares and Pablos study numbered 162 as compared to the 34 for which both talus and calcaneus measurements were available in this study. The higher number of individuals in the Alonso-Llamazares and Pablos study makes it more representative and less prone to bias. The St. Andrews Library cemetery was not fully excavated and additional variation in sexual dimorphism of the calcaneus and talus may be present depending on whether the excavated portion of the cemetery is representative of the entire cemetery or not. The HTHOC population is also more heterogeneous than the populations investigated in this study. Some of the univariate and multivariate formulae generated from the HTHOC population may appear to be more accurate at predicting relationships between the measurements in single bones than the ones investigated in this study, but they all skew female. Using the population specific formulae generated in this study will possibly classify lower range value combinations for males as female and females at the high upper range for variable combinations will possibly be classified as male. Application of the Alonso-Llamazares and Pablos formulae to the calcanei and tali of individuals of unknown sex in the BSTAL cemetery populations may result in males with lower measurement variable combinations being classified as female in these populations and few if any of the upper end variable combination females being classed as male.

Potential issues with the application of discriminant functions

Some important issues to consider when creating discriminant functions for populations from skeletal material are taphonomy, cultural practices, pathology, populational differences and co-mingling of remains.

When working with archaeological specimens, poor preservation can be a hindrance to analysis. In this study that was clear when analysing the measurements for (CM3) as the lateral calcaneal body was prone to erosion in these populations. Any conditions that can change the absolute maximum or minimum (erosion, animal activity, fossilisation, etc.) will affect both the generation of and the application of discriminant formulae. Age of the skeletal material does not dictate whether or not it will be well preserved. Rodent gnawing of exposed skeletal remains will sometimes occur even before the body has completely decomposed. Acidic soils, wind, sand, and water erosion can dissolve lamellar bone and demineralize bony tissues resulting in lower measurement values. Fossilisation may also affect the shape of bones, as bony material can be deformed by soil pressures over time that may not be obvious in fossilised material.

Intensity of activity can cause structural changes to the calcaneus. Some populations participate in gendered division of labour. Gender does not necessarily conform to sex. What could be seen as sexual dimorphism may in reality be activity related changes seen disproportionately in one sex over the other. While there is little current literature on skeletal effects of gendered activity, some authors have noted an increase in metatarsal bone fractures of women and children involved in head-loading for the carrying of water and firewood in S. Africa as well as an increase in ankle injuries including fractures.

Environment, disease, genetics, activity, diet, and cultural practices all play a role in the creation of differences between populations. Genetic conditions and pathology can affect the expression of sexual dimorphism, particularly metabolic and endocrine disorders. As previously discussed, acromegaly and achondroplasia both affect skeletal development, but so can vitamin deficiencies that lead to diseases like osteomalacia, rickets, and scurvy. Diseases that affect bone or muscle growth, and bone pathologies, will affect the measurements taken from skeletal elements used for discriminant analysis, thus producing less accurate results.

Mixed remains from multiple individuals are common in small cemeteries used over long periods of time. Bones are sometimes removed to a charnel house or ossuary in some cultures. In some situations multiple individuals are interred in the same grave. Victims of the same disaster, plague or acts of violence are often co-interred. As a result, the commingled remains of multiple individuals creates difficulties in determining how many individuals are in the assemblage and their sexes.

Application of the results of this study

A question for this study was which variable measurements of the calcaneus and talus provide the most accurate basis for sex estimation for the mediaeval Scottish populations in this study (**Tables 2-6**). All variables were taken from the Alonso-Llamazares and Pablos study, which were based on a population distant in both time and location. Morphological examination of the calcaneus and talus for the BSTAL cemetery populations suggests that different measurements may have been more sexually dimorphic. Therefore, while the variables used in this study produced high accuracies, other variables may be superior (**Figures 5 and 6**) which should be considered when applying this method [20].

Another consideration is that male and female accuracies must be balanced to give accurate results. Both the Alonso-Llamazares and Pablos study and this study indicate that multivariate analysis is superior to univariate.

Limitations of the current study

While the population specific multivariate formulae result of this study achieved 100.0% accuracy (**Figure 4**), application of these formulae to other populations requires caution. The sample size used in this study was small and not representative of other mediaeval populations. As demonstrated in comparisons with the formulae from Alonso-Llamazares and Pablos, variation can exist between populations and the variables showing high sexual dimorphism for one does not necessarily show cross population correlations. Those seeking to apply the methods of this study to their own samples should pair it with other metrical and morphological sex estimation methods to ensure the highest level of accuracy. Investigations of other mediaeval skeletal material using these functions should be limited to the communities that generated the skeletal material in these two cemetery populations, that is to say, other mediaeval populations from Duntrune, St. Andrews and their adjacent communities.

Limitations of the Alonso-Llamazares and Pablos formulae and method

The Alonso-Llamazares and Pablos formulae were generated from a narrow segment of the human population of the 20th century that at the time was roughly 6.1 billion people. While accurate in the determination of sex from multiple populations some of the formulae did skew female by as much as 50.0% in the current study. This suggests that populations that do not share similar skeletal proportion relationships as the HTHOC will yield less accurate results. The method may also be less accurate on individuals suffering from malnutrition and metabolic disorders affecting skeletal development during adolescence. Nutritional stress can delay the onset of puberty in female individuals and reduce body mass in males. These issues may not only affect the overall sexual dimorphism of the calcaneus and talus between males and females, but also the creation of population specific formulae using the Alonso-Llamazares and Pablos method.

Conclusion

This study aimed to test the Alonso-Llamazares and Pablos method on two mediaeval Scottish populations. Discriminant functions were generated for the combined BSTAL cemetery populations to test which variables and discriminant functions achieve the best accuracies for sex estimation.

Many of the variables studied in this investigation showed significant sexual dimorphism. The best measurement variables for sexual estimation are those with the greatest degree of difference in the average values between the sexes and with the least amount of overlap in their measurements. For this study the measurements that best fit these criteria were the total length of the talus (M1a), the talar length (M1), calcaneal body height (CM4) and the maximum length of the calcaneus (CM1).

The variable (M1a) (total length of the talus) had the highest univariate accuracy for the Alonso-Llamazares and Pablos formulae tested on the BSTAL cemetery populations and the best univariate predictor in the calcaneus was calcaneal body height (CM4).

The BSTAL populations used to generate the formulae in this study and the HTHOC show significant differences in the shape and structure of the calcaneus and talus as indicated by the accuracy discrepancies when using the formulae generated in this study compared to that of Alonso-Llamazares and Pablos. Variable (M1a) was the most diagnostic univariate predictor overall for sex estimation using formulae from either study. Other unmeasured variables of the foot bones based on morphological examination may show greater sexual dimorphism for this population. In both the Alonso-Llamazares and Pablos and this study, multivariate analysis was demonstrated to be superior to univariate.

The most accurate multivariate discriminant functions for sex estimation generated in this study were (CM1+CM9+M1+M1a) and (CM1+CM9+M1+M1a+M2) both with 100.0% cross validated accuracies for variables in the calcaneus and talus. The best result for the calcaneus was (CM1+CM9) with 84.8%, and for the talus (M1a+M4+M12) and (M1+M1a+M2+M4+M7+M12) both with 88.5%.

The best multivariate combinations for Alonso-Llamazares and Pablos were (CM1+CM3+CM9) for the calcaneus with accuracy of 84.8%, (M1+M12) and (M1+M1a+M4+M12+M13) for the talus with accuracy of 94.4%, and (M1+M4+M12+M13+CM1+CM9+CM10) for combined talus and calcaneus variables with accuracy of 97.1%. Formulae with an individual male and female accuracy of 80.0% or better were deemed valid for this study. Compared to multivariate formulae generated in this study, the Alonso-Llamazares and Pablos formulae produced fewer individual male and female results with an accuracy of 80.0% and above for correct sex estimation. In one case the accuracy was as low as 50.0%.

The Alonso-Llamazares and Pablos method for creating population-specific discriminate functions from the calcaneus and talus is valid for sex estimation in this population and shows great promise for application for the creation of other population specific formulae.

Recommendations for future research

Multivariate statistical measurements using the Alonso-Llamazares and Pablos variables and the additional ones proposed in Figures 5 and 6 of this study should be conducted for other populations. These data should be compiled together into a large database from which to generate discriminant functions for the wider world population as well as population specific discriminant functions for each region or community, thus creating more accurate formulae that can be applied regardless of the population or age of the specimen.

To increase the accuracy of the Alonso-Llamazares and Pablos method for application to additional populations, more variables from the calcaneus and talus (in addition to the ones shown in Figures 5 and 6 could be added to the method to encompass a broader range of skeletal variation. Data from numerous populations could be compiled into a database for the generation of new discriminant formulae that could be used with confidence, creating a series of universally applicable formulae. To best effect this, 3D scans or MRIs of tali and calcanei could be used on current international collections. Computer Aided Design (CAD) and similar technologies could be used for the measurement of variables with a high degree of accuracy. Such an undertaking would require years and significant effort to accomplish, but if institutions with skeletal collections of known sex included 3D scanning as part of their conservancy, such an objective would be achievable.

Future research should also be conducted on activity related changes to the calcaneus and talus. It is important to note that some activities are gendered and may appear to be sexual dimorphic when in reality they are culturally, not biologically, based on Garvin. Some high intensity activities such as weightlifting, running and other sports have both male and female participants in modern day society. Life histories for these individuals can be documented and their activities monitored and non-invasive observational methods such as X-rays and MRI scans could be used to measure entheseal sites and bone morphology, particularly that of the calcaneus and talus given the sexual dimorphism of the gastrocnemius muscle. Such investigations would be beneficial to understand the differences between sexual dimorphism and activity related skeletal changes.

Investigation into variables relating to volume and density of tarsal bones may show significant sexual dimorphism across multiple populations. Theoretically, the human foot is subject to the same mechanical laws governing analogous weight bearing, biological support structures in other species. A human foot in locomotion must be able to support body weight; therefore, generally larger bodied males would require larger foot structures than females. This is suggested in the proportional differences between male and female footwear industry lasts.

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References

1. Ahmed AA (2013) Estimation of sex from the upper limb measurements of Sudanese adults. J Forensic Leg Med 20:1041-1047
2. Alonso-Llamazares C, Pablos A (2019) Sex estimation from the calcaneus and talus using discriminant function analysis and its possible application in fossil remains. Archaeol Anthrop Sci 11:4927-4946
3. Atterton T, de Groote I, Eliopoulos C (2016) Assessing size and strength of the clavicle for its usefulness for sex estimation in a British medieval sample. Homo 67:409-416
4. Bidmos MA, Asala SA (2003) Discriminant function sexing of the calcaneus of the South African whites. J Forensic Sci 48:JFS2003104
5. Bidmos M, Asala S (2005) Calcaneal measurement in estimation of stature of South African blacks. Am J Phys Anthropol 126:335-342
6. Blanchard B (2010) A study of the accuracy and reliability of sex estimation methods of the human pelvis. Department of Master of Arts, California State University, Chico, California, the United States of America.
7. Blau S, Robertson S, Johnstone M (2008) Disaster victim identification: New applications for postmortem computed tomography. J Forensic Sci 53:956-961
8. Brauer G (1988) ‘Osteometrie.’ In: Martin, R., Knuβman, R., (eds.) Anthropologie Handbuch der vergleichenden Biologie des menschen. Fisher, Stuttgart, pp 160–232
9. Brenner CH (2006) Some mathematical problems in the DNA identification of victims in the 2004 tsunami and similar mass fatalities. J Forensic Sci 157:172-180
10. Brown RP, Ubelaker DH, Schanfield MS (2007) Evaluation of Purkait's triangle method for determining sexual dimorphism. J Forensic Sci 52:553-556
11. Brzobohata H, Krajicek V, Horak Z, Veleminska J (2016) Sexual dimorphism of the human tibia through time: Insights into shape variation using a surface based approach. PLoS One 11:e0166461
12. Buikstra JE (1994) Standards for data collection from human skeletal remains. Arkansas Archaeol Sur Res Ser 44:18
13. Cohen E (2009) Death in paradise: Tourist fatalities in the tsunami disaster in Thailand. Curr Issues Tour 12:183-199
14. Dayal MR, Spocter MA, Bidmos MA (2008) An assessment of sex using the skull of black South Africans by discriminant function analysis. Homo 59:209-221
15. Dixit S, Kakar S, Agarwal S, Choudhry R (2007) Sexing of human hip bones of Indian origin by discriminant function analysis. J Forensic Leg Med 14:429–435
16. Forbes GB (1962) Methods for determining composition of the human body: With a note on the effect of diet on body composition. Pediatrics 29:477-494
17. Garvin H (2012) The effects of living conditions on human cranial and postcranial sexual dimorphism. Doctor of Philosophy

Dissertation, The Johns Hopkins University, Baltimore, the United States of America.

18. Garvin HM, Sholts SB, Mosca LA (2014) Sexual dimorphism in human cranial trait scores: Effects of population, age, and body size. Am J Phys Anthropol 154:259-269

19. Gualdi-Russo E (2007) Sex determination from the talus and calcaneus measurements. Forensic Sci Int 171:151-156

20. Inamori-Kawamoto O, Ishikawa T, Michiue T, Mustafa AM, Sogawa N, et al. (2016) Possible application of CT morphometry of the calcaneus and talus in forensic anthropological identification. Int J Leg Med 130:575-585