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# Utility of the metatarsal diaphyseal nutrient foramen in estimating sex in the South African Africans population

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ABSTRACT

*Introduction:* Sex estimation is challenging in cases where dismembered or non-intact skeletal remains are recovered. Therefore, the development of sex estimation standards using various bones that present with high recovery rates during forensic investigations, like the metatarsal bones, is needed. The usefulness of the dimensions around the metatarsal diaphyseal nutrient foramen in sex estimation has not been assessed in South African Africans (SAA), constituting the majority of the country's population.

*Materials and methods:* Five measurements around the nutrient foramen were taken from 995 metatarsal bones (first to fifth) from 200 individual skeletons (100 males, 100 females). Measurements subjected to direct and stepwise discriminant function (DFA) and logistic regression (LRA) analyses included the total length, distance from proximal end to nutrient foramen, circumference, and mediolateral and dorsoplantar diameters at the level of the nutrient foramen.

*Results:* The original classification accuracies for multivariable functions of the stepwise and direct DFA ranged from 75.1 to 80 % and 76–79.5 % respectively. The original classification accuracies for multivariable functions of the stepwise and direct LRA ranged from 76.3% to 79.5 % and 75%–80.5 % respectively. The cross-validation classifications showed a drop of 0–2% for DFA and 0.2–1.9 % for LRA. Overall breadth measurements showed better classification accuracies than length measurements and females were classified with higher accuracy rates than males.

*Conclusion:* The dimensions around the nutrient foramen of the metatarsal bones show sexual dimorphism in the SAA. The generated DFA and LRA functions produced high average classification accuracies which can be appropriate for use in sex estimation in forensic settings, especially when an isolated foot is recovered.

## 1. Introduction

Biological sex estimation in forensic analysis is considered simple as the external and internal genitalia can directly suggest the sex of an individual [1]. However, sex estimation from skeletal remains becomes challenging more so in cases where fragmentary and incomplete skeletal remains are recovered. This presents an opportunity to develop new standards of estimating sex to aid in the accurate identification of individuals [2–4]. Previous studies have reported high accuracies for estimating sex from skeletal remains using a variety of cranial and postcranial elements, with the pelvis and skull being the most sexually dimorphic. However, these bones are often missing, decomposed, and or fragmented due to poor preservation, taphonomical alterations, predation, and or dismemberment [3–6]. Recently, there has been a surge in the studies focusing on postcranial elements in various populations, particularly the long bones and their performance in sex estimation equations [4,7–11]. Still, alternative techniques must be developed using other skeletal elements and features to advance the methods of sex estimation in forensic and archaeological settings.

Sex estimation from skeletal remains is crucial in medico-legal settings, as it helps researchers to identify victims of crime from various contexts. These may include recovered mutilated or dismembered body parts, burned remains, and fragmented or intact skeletal remains [9]. There are subjective and objective methods/techniques used to estimate

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the sex of an individual from skeletal remains. Subjective techniques require having a complete skeleton or access to bones that display typical sexually dimorphic anatomical features, but this scenario is uncommon in forensic cases. In addition, subjective techniques require anthropologists who are highly qualified and experienced to identify precise morphological features that lead to accurate sex estimations [12]. In contrast, objective techniques utilise standardised anatomical landmarks for measurements and employ various statistical models such as discriminant function analysis and logistic regression analysis to develop sex estimation functions/equations [13–16]. Objective techniques are considered ideal for bones that do not present obvious sexual dimorphic traits like most postcranial elements [15,17]. Objective techniques are also useful in sex estimation in cases of commingled remains, like in mass disasters, mass graves or secondary burials [18,19]. While objective techniques are more favourable than subjective techniques, they are population-specific especially for bones that do not exhibit obvious sexually dimorphic traits [20–23]. This necessitates the creation of sex estimation functions/equations for each population group, particularly those most affected by violent crimes and murder, to ensure accurate sex classifications and subsequent positive identification [15].

South Africa has one of the highest crime rates in the world [3,24]. South African Africans, also known as Black South Africans, make up about 80 % of the total South African population, and individuals of this group are most often victims of murder in the country [3,4]. It is, therefore, essential to have a variety of methods for estimating sex in order to improve the establishment of the biological profile of victims during forensic investigations. Previous studies developed metric methods of estimating sex in the South African Africans using anatomical features of various bones like the humerus, radius, ulna [3,25], femur, tibia, fibular [26], calcaneus [22], talus [21], and metatarsals [4]. The dimensions around the nutrient foramina of the upper and lower limb long bones have shown to be useful in estimating sex of individuals in various populations [3,26–30]. Recently, in the South Africans of European descent population, the dimensions around the nutrient foramen of the metatarsal bones demonstrated high sex estimation accuracies [11]. Nutrient foramina are external openings to the nutrient canal on the bone diaphysis that convey blood vessels and nerves [31–33]. Nutrient foramina can be identified macroscopically in almost 100 % of the metatarsal diaphyses, and in cases of multiple nutrient foramina, a dominant one presents as the largest in diameter when compared to the rest [31]. Dimensions around the nutrient foramina can also serve as substitutes for midshaft measurements in cases where fragmentary or broken bones are recovered. During forensic and archaeological settings metatarsal bones have an advantage of being recovered in large quantities and generally in well-preserved states possibly due to their size and numbers compared to other long bones [4,34]. The purpose of the current study was to determine the utility of the dimensions around the metatarsal diaphyseal nutrient foramen in sex estimation using the discriminant function and logistic regression analyses in the South African Africans population.

## 2. Materials and methods

### 2.1. Study population

The current study was conducted under the ethical clearance waiver number W-CBP-22050401 obtained from the Faculty of Health Sciences at the University of the Witwatersrand. The study utilised 995 left foot metatarsal bones (first to fifth) from 200 adult individuals (100 males, 100 females) aged 25–65 years (mean age 39.78 ± 10.32 years). The left foot was chosen because it is less likely to be affected by physical activity-related changes since it is the non-dominant side in the majority of the global populations. The metatarsal bones were obtained from the skeletal remains of the 20th century South African Africans (SAA) housed in the Raymond A. Dart Modern Skeletal Collection in the School of Anatomical Sciences at the University of the Witwatersrand in South Africa [35]. The SAA mainly consists of various ethnic tribes including the Pedi, Sotho, Tswana, Ndebele, Zulu, Venda, Xhosa, Swazi and Tsonga. These ethnic groups do not exhibit significant osteometric differences, hence are considered as a homogeneous population group [36,37]. Metatarsal bones showing gross pathologies, deformities, fractures and degradation were excluded from the study. The metatarsal bones without visible nutrient foramen were also excluded.

### 2.2. Osteometric measurements around the metatarsal diaphyseal nutrient foramen

A diaphyseal nutrient foramen was identified macroscopically as a raised margin that surrounds the opening of a groove leading into the foramen on each metatarsal bone. A total of five osteometric measurements: total length (TL), proximal end to nutrient foramen (NFPE), circumference at the level of the nutrient foramen (CNF), dorsoplantar diameter at the level of the nutrient foramen (DPNF) and mediolateral diameter at the nutrient foramen (MLNF), were taken on each metatarsal bone (MT1–MT5) as previously described by Manjatika et al. [11] and as shown in Fig. 1. In addition, the foramina indices (FI) for each metatarsal bone were also calculated using the Hughes' formula: **FI= (NFPE/TL) X 100.** Foramina index (FI) is the percentage of the total length of the bone that is represented by the distance between the proximal end and the nutrient foramen [38].

### 2.3. Data management and statistical analysis

The data were managed in Microsoft Excel 365 (Microsoft Corporation) and analysed using IBM® SPSS® version 23 statistical software. Intra and inter-observer error statistics were calculated using the Lin's concordance coefficient of reproducibility [39]. The primary observer took five measurements on 200 metatarsal bones from 40 randomly selected individuals (20 males and 20 females) and repeated this two weeks later to check for intra-observer repeatability. No significant difference between the two separate measuring occasions was observed (RC = 1.000, 95%CI for RC = 1.000 lower and upper = 1.000). For inter-observer repeatability, the primary and secondary observers took the same measurements on 100 metatarsal bones from 20 randomly selected individuals (10 males, 10 females) one month apart. There was an almost perfect agreement between the two observers (RC = 0.998, 95%CI for RC = 0.997 lower and upper 0.998).

Descriptive statistics (mean and standard deviations) were calculated for each measurement on all metatarsal bones. The Kolmogorov-Smirnov tests were used to test the normality of the data. The data showed variable distribution, with only the total length (TL) measurements being normally distributed across all metatarsal bones. Hence, both discriminant function analysis (DFA) and logistic regression analysis (LRA) were utilised. The student t-test and the Mann Whitney *U* test were conducted to determine the significant mean differences between sex depending on the distribution of the data. The direct DFA was performed to develop univariable (individual measurement separately) and multivariable equations (combination of measurements for each bone and multiple bones). The stepwise DFA (Wilk's Lambda) was performed to select the combination of measurements that best estimate sex. The functions generated were then cross-validated using the "leave-one-out" classification protocol as previously described [3,40]. The stepwise and direct binary LRA were also performed to develop multivariable equations/functions. Collinearity diagnostics were conducted, and the presence of significant multicollinearity was confirmed when a Variance Inflation Factor (VIF) value greater than 10 and Tolerance test value less than 0.1 was observed. The variables affected by multicollinearity were then either removed or retained in the functions, depending on their impact on the classification accuracy percentage.

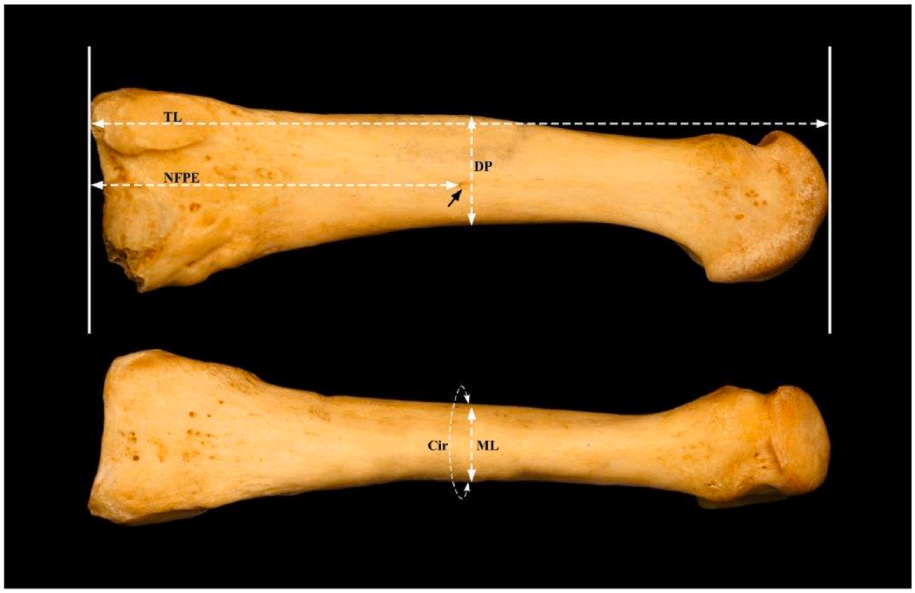


**Fig. 1.** Photographs of the second metatarsal bones showing the measurements that were taken. The black arrow points at the nutrient foramen. Cir = Circumference, DP = Dorsoplantar diameter, ML = Mediolateral diameter, NFPE = Distance from proximal end to the nutrient foramen, TL = Total length.

## 3. Results

All the measured parameters showed significant mean differences, with males having higher means than females across all the metatarsal bones ($p < 0.05$) (Table 1). The mean foraminal index (FI) of the fifth metatarsal bone was higher in males than in females ($p = 0.040$) (Table 2).

Table 3 shows the discriminant function equations generated using individual metatarsal bone measurements. The average classification accuracy rates ranged from 53.5 to 75.5 % for all the metatarsal bones. MT1MLNF and MT1CNF presented with the high classification rates of 75 %, and 75.5 % respectively (Table 3).

From the stepwise discriminant function analysis (DFA) of the combination of all the metatarsal bone measurements, the average classification accuracy rates ranged from 75.1 to 80 % in the original classification and from 75.1 to 78.5 % in the cross-validation (Table 4). The drop in the classification accuracy between the original and the cross-validation rates ranged from 0 to 2%. Females were classified with higher accuracy rates (77–84 %) than males (72.6–79 %) throughout using the original classification (Table 4). The MT2CNF exhibited multicollinearity in functions 1 and 2 (Table 4). Removal of MT2CNF from the affected predictor functions led to a drop in the classification

**Table 1**
Descriptive statistics of the measured parameters.

| Bone | Variable | Male | | | Female | | | P-Value |
|---|---|---|---|---|---|---|---|---|
| | | No | Mean | SD | No | Mean | SD | |
| Metatarsal 1 | TL | 100 | 64.67 | 4.06 | 100 | 60.72 | 3.41 | <0.0001 |
| | NFPE | 100 | 34.52 | 7.00 | 100 | 32.07 | 6.24 | 0.01 |
| | DPNF | 100 | 13.80 | 1.84 | 100 | 12.58 | 1.58 | <0.0001 |
| | MLNF | 100 | 14.68 | 1.35 | 100 | 13.19 | 1.37 | <0.0001 |
| | CNF | 100 | 47.19 | 4.01 | 100 | 42.52 | 3.90 | <0.0001 |
| Metatarsal 2 | TL | 100 | 77.58 | 4.60 | 100 | 72.02 | 4.04 | <0.0001 |
| | NFPE | 100 | 34.42 | 6.11 | 100 | 32.05 | 5.46 | 0.004 |
| | DPNF | 100 | 9.85 | 1.11 | 100 | 9.26 | 1.13 | <0.0001 |
| | MLNF | 100 | 8.39 | 0.98 | 100 | 7.63 | 0.93 | <0.0001 |
| | CNF | 100 | 31.07 | 2.80 | 100 | 28.38 | 2.86 | <0.0001 |
| Metatarsal 3 | TL | 98 | 72.94 | 4.46 | 100 | 67.83 | 4.07 | <0.0001 |
| | NFPE | 98 | 31.51 | 5.07 | 100 | 29.78 | 4.25 | 0.01 |
| | DPNF | 98 | 9.84 | 1.16 | 100 | 9.08 | 0.95 | <0.0001 |
| | MLNF | 98 | 8.08 | 1.25 | 100 | 7.15 | 1.07 | <0.0001 |
| | CNF | 98 | 31.18 | 3.02 | 100 | 27.88 | 2.45 | <0.0001 |
| Metatarsal 4 | TL | 97 | 71.31 | 4.40 | 100 | 66.39 | 4.11 | <0.0001 |
| | NFPE | 97 | 33.67 | 4.90 | 100 | 30.32 | 4.28 | <0.0001 |
| | DPNF | 97 | 10.68 | 1.12 | 100 | 9.97 | 1.06 | <0.0001 |
| | MLNF | 97 | 7.59 | 0.82 | 100 | 6.92 | 0.67 | <0.0001 |
| | CNF | 97 | 31.94 | 3.01 | 100 | 29.34 | 2.45 | <0.0001 |
| Metatarsal 5 | TL | 100 | 71.58 | 4.34 | 100 | 66.54 | 4.35 | <0.0001 |
| | NFPE | 100 | 37.29 | 4.00 | 100 | 33.77 | 4.34 | <0.0001 |
| | DPNF | 100 | 8.16 | 1.05 | 100 | 7.41 | 0.76 | <0.0001 |
| | MLNF | 100 | 11.36 | 1.20 | 100 | 10.78 | 1.00 | <0.0001 |
| | CNF | 100 | 33.25 | 2.77 | 100 | 30.73 | 2.42 | <0.0001 |

TL = Total length, NFPE = Distance from the proximal end of the bone to the level of nutrient foramina, DPNF = Dorsoplantar diameter at the level of nutrient foramina, MLNF = Mediolateral distance at the level of the nutrient foramina, CNF= Circumference at the level of the nutrient foramina. All means and SD reported in millimetres.

**Table 2**
Descriptive statistics of the foramina index (FI).

| | Variable | Male | | | Female | | | P-Value |
|---|---|---|---|---|---|---|---|---|
| | | No | Mean | SD | No | Mean | SD | |
| Metatarsal 1 | FI | 100 | 53.38 | 10.33 | 100 | 52.79 | 9.71 | 0.676 |
| Metatarsal 2 | FI | 100 | 44.29 | 6.98 | 100 | 44.47 | 6.94 | 0.857 |
| Metatarsal 3 | FI | 98 | 43.23 | 6.75 | 100 | 43.94 | 5.95 | 0.434 |
| Metatarsal 4 | FI | 97 | 47.16 | 5.74 | 100 | 45.67 | 5.89 | 0.074 |
| Metatarsal 5 | FI | 100 | 52.09 | 4.68 | 100 | 50.69 | 5.00 | 0.040[a] |

[a] Represents significant mean differences.

**Table 3**
Direct discriminant coefficients, constants and classification accuracies for individual measurements of the metatarsals.

| Variable | Unstandardised Coefficient | Constant | Sectioning point | Classification accuracy % | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Original classification | | | Cross validation | | |
| | | | | M | F | Average | M | F | Average |
| MT1TL | 0.267 | −16.727 | 0.000 | 66 | 73 | 69.5 | 65 | 73 | 69 |
| MT1NFPE | 0.151 | −5.024 | 0.000 | 58 | 49 | 53.5 | 58 | 49 | 53.5 |
| MT1DPNF | 0.583 | −7.694 | 0.000 | 60 | 66 | 63 | 60 | 65 | 62.5 |
| MT1MLNF | 0.737 | −10.275 | 0.000 | 73 | 77 | 75 | 73 | 77 | 75 |
| MT1CNF | 0.253 | −11.335 | 0.000 | 78 | 73 | 75.5 | 78 | 73 | 75.5 |
| MT2TL | 0.231 | −17.273 | 0.000 | 74 | 74 | 74 | 74 | 74 | 74 |
| MT2NFPE | 0.173 | −5.734 | 0.000 | 56 | 56 | 56 | 56 | 56 | 56 |
| MT2DPNF | 0.895 | −8.550 | 0.000 | 56 | 69 | 62.5 | 56 | 69 | 62.5 |
| MT2MLNF | 1.043 | −8.356 | 0.000 | 59 | 71 | 65 | 57 | 71 | 64 |
| MT2CNF | 0.353 | −10.503 | 0.000 | 71 | 70 | 70.5 | 71 | 70 | 70.5 |
| MT3TL | 0.235 | −16.501 | 0.006 | 71.4 | 68 | 69.7 | 71.4 | 68 | 69.7 |
| MT3NFPE | 0.214 | −6.552 | 0.002 | 55.1 | 59 | 57.1 | 55.1 | 59 | 57.1 |
| MT3DPNF | 0.946 | −8.944 | 0.004 | 59.2 | 72 | 65.7 | 58.2 | 72 | 65.2 |
| MT3MLNF | 0.859 | −6.541 | 0.004 | 56.1 | 75 | 65.7 | 56.1 | 75 | 65.7 |
| MT3CNF | 0.364 | −10.758 | 0.006 | 69.4 | 75 | 72.2 | 69.4 | 75 | 72.2 |
| MT4TL | 0.235 | −16.175 | 0.009 | 69.1 | 71 | 70.1 | 69.1 | 71 | 70.1 |
| MT4NFPE | 0.218 | −6.957 | 0.006 | 56.7 | 64 | 60.4 | 56.7 | 64 | 60.4 |
| MT4DPNF | 0.917 | −9.462 | 0.005 | 64.9 | 70 | 67.5 | 64.9 | 70 | 67.5 |
| MT4MLNF | 1.341 | −9.717 | 0.007 | 57.7 | 73 | 65.5 | 57.7 | 73 | 65.5 |
| MT4CNF | 0.365 | −11.178 | 0.007 | 66 | 70 | 68 | 66 | 70 | 68 |
| MT5TL | 0.230 | −15.885 | 0.000 | 66 | 72 | 69 | 66 | 72 | 69 |
| MT5NFPE | 0.239 | −8.503 | 0.000 | 66 | 60 | 63 | 66 | 60 | 63 |
| MT5DPNF | 1.094 | −8.517 | 0.000 | 58 | 66 | 62 | 58 | 66 | 62 |
| MT5MLNF | 0.906 | −10.031 | 0.000 | 53 | 63 | 58 | 53 | 63 | 58 |
| MT5CNF | 0.385 | −12.304 | 0.000 | 74 | 61 | 67.5 | 74 | 61 | 67.5 |

Discriminant function score (DFS) equation = unstandardised coefficient × variable (in millimetres) + constant. DFS greater than the sectioning point indicates male, and DFS less than the sectioning point indicates female.
MT1 = First metatarsal bone, MT2 = Second metatarsal bone, MT3 = Third metatarsal bone, MT 4 = Fourth metatarsal bone, MT 5 = Fifth metatarsal bone TL = Total length, NFPE = Distance from the proximal end of the bone to the level of nutrient foramina, DPNF = Dorsoplantar diameter at the level of nutrient foramina, MLNF = Mediolateral distance at the level of the nutrient foramina, CNF= Circumference at the level of the nutrient foramina, F= Female, M = Male.

accuracy rates of 5 % in function 1 and 5.5 % in function 2. As such, MT2CNF was retained.

The functions generated from the direct DFA are presented in a descending order of average classification accuracies (79.5%–76 %) in Table 5. The drop in the classification accuracy between the original and the cross-validation rates ranged from 0 to 1.5 %. Females were classified with higher accuracy rates (76–84 %) than males (73–79 %) throughout using the original classification (Table 5). The MT1CNF exhibited multicollinearity in function 5 (Table 5). Removal of MT1CNF from the affected predictor function led to a drop of 3.1 % in classification accuracy rates. As such, MT1CNF was retained.

From the stepwise logistic regression analysis (LRA) of the combination of all the metatarsal measurements, the average classification accuracy rates ranged from 76.3 to 79.5 % in the original classification and from 75.8 to 79.8 % in the cross-validation (Table 6). The drop in the classification accuracy between the original and the cross-validation classifications ranged from 0.2 to 1.9 %. The classification accuracy between the original and the cross-validations increased for some functions ranging from 0.3 to 1%. Functions 3, 5 and 7 classified females with higher accuracy rates than males (Table 6). The MT2CNF exhibited multicollinearity in functions 1 and 2 (Table 6). Removal of MT2CNF from the affected predictor functions led to a drop in the classification accuracy rates of 3 % in function 1 and 6.5 % in function 2. As such, MT2CNF was retained.

Table 7 shows the functions generated from the direct LRA, presented in a descending order of average classification accuracies (80.5–75 %). The drop in the classification accuracy between the original and the cross-validation classifications ranged from 0 to 1.7 % while increases in classification accuracy ranged from 0.2 to 2.9 % (Table 7). Except Function 1, females were classified with higher accuracy rates (76–82 %) than males (72.6–81 %) throughout using the original classification. The MT2CNF exhibited multicollinearity in functions 1 and 3 (Table 7). Removal of MT2CNF from the affected predictor functions led to a drop in the classification accuracy rates of 3.5 % in function 1 and 6.5 % in function 3. Hence, MT2CNF was retained.

## 4. Discussion

South Africa has high crime statistics in the world, hence, it is crucial to develop sex estimation equations using various skeletal elements in order to positively identify victims [2,24]. Accurately determining the sex of unknown individuals is essential in both forensic and

**Table 4**
Stepwise discriminant function coefficients, constants, and classification rates for a combination of measurements for multiple metatarsals.

| Function | Measurement combination | Unstandardised Coefficient | Centroids | Sectioning point | Classification accuracy % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Original classification | | | Cross validation | | |
| | | | | | M | F | Average | M | F | Average |
| 1 | MT2TL | 0.136 | F = −0.849 | 0.000 | 76 | 84 | 80 | 75 | 81 | 78 |
| | MT2DPNF | −0.900 | M = 0.849 | | | | | | | |
| | MT2MLNF | −0.498 | | | | | | | | |
| | MT2CNF | 0.532 | | | | | | | | |
| | MT5MLNF | −0.471 | | | | | | | | |
| | MT5CNF | 0.273 | | | | | | | | |
| | Constant | −16.922 | | | | | | | | |
| 2 | MT2TL | 0.167 | F = −0.785 | 0.000 | 79 | 79 | 79 | 79 | 78 | 78.5 |
| | MT2DPNF | −0.923 | M = 0.785 | | | | | | | |
| | MT2MLNF | −0.428 | | | | | | | | |
| | MT2CNF | 0.561 | | | | | | | | |
| | Constant | −16.901 | | | | | | | | |
| 3 | MT1CNF | 0.094 | F = −0.782 | 0.008 | 77.6 | 80 | 78.8 | 76.5 | 79 | 77.8 |
| | MT3NFPE | 0.092 | M = 0.798 | | | | | | | |
| | MT3DPNF | −0.363 | | | | | | | | |
| | MT3CNF | 0.381 | | | | | | | | |
| | Constant | −14.861 | | | | | | | | |
| 4 | MT1CNF | 0.101 | F = −0.775 | 0.021 | 74.5 | 82 | 78.3 | 74.5 | 72 | 78.3 |
| | MT2TL | 0.101 | M = 0.816 | | | | | | | |
| | MT3DPNF | −0.350 | | | | | | | | |
| | MT3CNF | 0.248 | | | | | | | | |
| | Constant | −16.091 | | | | | | | | |
| 5 | MT3NFPE | 0.129 | F = −0.723 | 0.008 | 75.5 | 79 | 77.3 | 75.5 | 79 | 77.3 |
| | MT3CNF | 0.375 | M = 0.738 | | | | | | | |
| | Constant | −15.016 | | | | | | | | |
| 6 | MT1CNF | 0.147 | F = −0.686 | 0.019 | 73.5 | 80 | 76.8 | 73.5 | 80 | 76.8 |
| | MT3CNF | 0.218 | M = 0.723 | | | | | | | |
| | Constant | −13.011 | | | | | | | | |
| 7 | MT1MLNF | 0.471 | F = −0.627 | 0.017 | 72.6 | 80 | 76.4 | 70.5 | 80 | 75.4 |
| | MT3MLNF | 0.304 | M = 0.660 | | | | | | | |
| | MT4MLNF | 0.436 | | | | | | | | |
| | Constant | −12.028 | | | | | | | | |
| 8 | MT1CNF | 0.157 | F = −0.690 | 0.011 | 73.2 | 77 | 75.1 | 73.2 | 77 | 75.1 |
| | MT4TL | 0.137 | M = 0.712 | | | | | | | |
| | Constant | −16.454 | | | | | | | | |

Discriminant function score (DFS) equation = unstandardised coefficient × variables (in millimetres) + constant. DFS greater than the sectioning point indicates male, and DFS less than the sectioning point indicates female.
MT1 = First metatarsal bone, MT2 = Second metatarsal bone, MT3 = Third metatarsal bone, MT 4 = Fourth metatarsal bone, MT 5 = Fifth metatarsal bone TL = Total length, NFPE = Distance from the proximal end of the bone to the level of nutrient foramina, DPNF = Dorsoplantar diameter at the level of nutrient foramina, MLNF = Mediolateral distance at the level of the nutrient foramina, CNF= Circumference at the level of the nutrient foramina, F= Female, M = Male.

archaeological settings as it helps in establishing the age, stature, and population affinity of the unknown individuals [3,25,26,41]. Dimensions around the nutrient foramen of the long bones have been utilised to generate sex estimation equations and have showed acceptably high sex classification accuracies [3,8,11,26,28,29] while no studies have reported on the usefulness of these dimensions on the metatarsal bones in South African Africans.

In the current study, the dimensions around the nutrient foramen (with the exception of the foramina index) showed sexual dimorphism with larger means in males as compared to females (Tables 1 and 2). Similar findings were observed previously in other upper limb long bones including the humerus, radius and ulna, and lower limb long bones like the femur and tibia in the South African Africans population [3,26]. Except the foramina index of the fifth metatarsal bones which exhibited sexual dimorphism, the rest of the foramina indices were found to be poor estimator of sex in the South African Africans population. The foramina index was also a poor estimator of sex in a similar study on the metacarpal and metatarsal bones [8,11].

Previous studies established that the sex estimation equation need to produce classification rates of 80 % and above to be recommended for use in forensic and archaeological settings [8,21,22,42]. Other studies also consider average classification rates between 75 % and 80 % to be useful especially if the drop between original and cross-validated classification rates is less than 5 %, and the bias (sex-specific classification accuracies) is also less than 5 % [26,43,44]. The results in the current study show that the MT1MLNF and MT1CNF are the only individual measurements around the nutrient foramen of the metatarsal bones that produced high sex estimation accuracies (75 % and 75.5 %, respectively) and a bias within a recommended range. Thus, the univariable MT1MLNF and MT1CNF can be recommended for forensic utility. The other individual measurements showed low to moderate sexual dimorphism with average classification accuracies ranging from 53.5 % to 74 %, and these classification accuracies are similar to those previously reported in a study that focused on the length of the metatarsal bones only in the South African Africans population [4].

Results from the stepwise discriminant function analysis (DFA) and logistic regression analysis (LRA) showed that the multivariate analyses of measurements around the nutrient foramen of the second metatarsal bone have the highest correct classification accuracy for sex estimation than from other individual metatarsal bones. This contrast previous findings observed in the Greek and South Africans of European descent populations whereby the dimensions from the first metatarsal bone yielded high sex estimation accuracies compared with the other metatarsal bones [11,34]. Notably, MT1CNF and MT2CNF exhibited multicollinearity in a few of the generated multivariable function equations in both the DFA and LRA. However, when MT1CNF and MT2CNF were removed from the multivariable function equations, the sex estimation classification accuracy rates dropped significantly (range 3–6.5 %). These findings further suggest that MT1CNF and MT2CNF are significant predictors of sex in the current studied population.

**Table 5**
Direct discriminant function coefficients, constants, and classification rates for a combination of measurements for multiple metatarsals.

| Function | Measurement combination | Unstandardised Coefficient | Centroids | Sectioning point | Classification accuracy % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Original classification | | | Cross validation | | |
| | | | | | M | F | Average | M | F | Average |
| 1 | MT1DPNF | −0.229 | F = −0.664 | 0.000 | 76 | 83 | 79.5 | 75 | 83 | 79 |
| | MT1CNF | 0.262 | M = 0.664 | | | | | | | |
| | MT2CNF | 0.144 | | | | | | | | |
| | Constant | −12.993 | | | | | | | | |
| 2 | MT1MLNF | 0.515 | F = −0.630 | 0.000 | 78 | 79 | 78.5 | 78 | 79 | 78.5 |
| | MT2CNF | 0.182 | M = 0.630 | | | | | | | |
| | Constant | −12.595 | | | | | | | | |
| 3 | MT1DPNF | −0.179 | F = −0.746 | 0.000 | 73 | 84 | 78.5 | 73 | 82 | 77.5 |
| | MT1CNF | 0.195 | M = 0.746 | | | | | | | |
| | MT2TL | 0.144 | | | | | | | | |
| | Constant | −17.162 | | | | | | | | |
| 4 | MT2TL | 0.163 | F = −0.764 | 0.000 | 75 | 80 | 77.5 | 75 | 79 | 77 |
| | MT2DPNF | −0.751 | M = 0.764 | | | | | | | |
| | MT2CNF | 0.396 | | | | | | | | |
| | Constant | −16.759 | | | | | | | | |
| 5 | MT1CNF | 0.244 | F = −0.709 | 0.007 | 73.5 | 81 | 77.3 | 72.4 | 79 | 75.8 |
| | MT1DPNF | −0.220 | M = 0.723 | | | | | | | |
| | MT1MLNF | −0.081 | | | | | | | | |
| | MT3CNF | 0.207 | | | | | | | | |
| | Constant | −12.991 | | | | | | | | |
| 6 | MT1MLNF | 0.357 | F = −0.715 | 0.000 | 76 | 77 | 76.5 | 76 | 76 | 76 |
| | MT2TL | 0.162 | M = 0.715 | | | | | | | |
| | Constant | −17.054 | | | | | | | | |
| 7 | MT1CNF | 0.378 | F = −0.617 | 0.000 | 76 | 76 | 76 | 74 | 75 | 74.5 |
| | MT1DPNF | −0.319 | M = 0.617 | | | | | | | |
| | MT1MLNF | −0.094 | | | | | | | | |
| | Constant | −11.442 | | | | | | | | |

Discriminant function score (DFS) equation = unstandardised coefficient × variables (in millimetres) + constant. DFS greater than the sectioning point indicates male, and DFS less than the sectioning point indicates female.
MT1 = First metatarsal bone, MT2 = Second metatarsal bone, MT3 = Third metatarsal bone, MT 4 = Fourth metatarsal bone, MT 5 = Fifth metatarsal bone TL = Total length, NFPE = Distance from the proximal end of the bone to the level of nutrient foramina, DPNF = Dorsoplantar diameter at the level of nutrient foramina, MLNF = Mediolateral distance at the level of the nutrient foramina, CNF= Circumference at the level of the nutrient foramina, F= Female, M = Male.

In the current study, the average correct classification accuracy of the combination of multiple metatarsal bone measurements obtained from the stepwise and direct DFA ranged from 75.1 to 80 % and 76–79.5 %, respectively. Similarly, the average correct classification accuracy of the combination of multiple metatarsal bone measurements obtained from the stepwise and direct LRA ranged from 76.3 to 79.5 % and 75–80.5 %, respectively. Thus, the current study supports prior studies that the stepwise DFA and LRA, and the direct DFA and LRA produce relatively similar classification accuracy rates though these statistical methods operate on different normality assumptions [4,13,45,46]. However, LRA equations are more applicable for not normally distributed data than the DFA equations/functions [47]. Except for the total length (TL) of the metatarsal bones, the data in the current study was not normally distributed and this suggests that the LRA equations/functions may be more appropriate than the DFA equations in the current population.

Previous studies utilising the dimensions around the base, midshaft, head and length of the metatarsal bones in different populations reported classification accuracies higher than those in the current study [4,34,48–50]. The classification accuracies in the current study are lower than those reported in the South African Africans utilising the talus and calcaneus which ranged from 80 to 89 % [21,22]. Additionally, studies in the South African Africans population using dimensions around the nutrient foramen of the humerus, radius, and ulna also produced high classification accuracies ranging from 83 to 86 % [3]. A study in the South African Africans population using the dimensions around the nutrient foramen of the tibia however produced classification accuracies ranging from 79 to 82 % [26], relatively similar to the current study. This suggests that the dimensions around the nutrient foramen of the metatarsal bones are weaker estimators of sex than other upper limb and foot bones in the South African Africans populations. Notably, the use of the dimensions around the nutrient foramen of the metacarpals and metatarsals in the South Africans of European descent produced higher sex classification accuracies which ranged from 82 to 94 % [8,11]. Higher sex classification accuracies in one population compared to others while utilising similar measurements around the nutrient foramen of the miniature long bones indicates population-specificity of the sex estimation equations [23].

Sexual dimorphism can be attributed to a combination of genetic and biomechanical factors that are influenced by lifestyle activities [51]. Males and females have distinct hormonal differences that may contribute to the differences in the robustness of bones. Estrogen, for example, is predominant in females and promotes bone resorption and remodelling, which may result in less robust bones. Testosterone, on the other hand, is predominant in males and promotes production of bone cells (osteoblasts) and maintenance of bone density, resulting in more robust bones [52]. Biomechanically, males are considered to have larger body sizes and engage in higher levels of physical activity compared to females [34,49]. This increased activity in males may result in greater stress and load exerted on the bones, leading to increased robustness. Large muscle mass coupled with repeated walking movements increases the stress on weight bearing bones, tendons and arches of the foot leading to continued bone remodelling and subsequent robustness [53,54]. The degree of sexual dimorphism varies between population groups due to intra-population variability [26,55]. The average sex classification accuracies in the current study are low compared to those in the South Africans of European descent utilising the dimensions around the nutrient foramen, suggesting that there is increased intra-population variability in the South African Africans population [11]. The degree of sexual dimorphism in a population is also affected by responses to environmental factors (e.g. physical activities) [55]. In population groups where males and females perform similar physical tasks, like

**Table 6**
Stepwise logistic regression coefficients, constants, and classification rates for a combination of measurements for multiple metatarsals.

| Function | Measurement combination | Unstandardised Coefficient | Sectioning point | Classification accuracy % | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Original classification | | | Cross validation | | |
| | | | | M | F | Average | M | F | Average |
| 1 | MT1CNF | 0.215 | 0.50 | 81 | 78 | 79.5 | 81 | 78.5 | 79.8 |
| | MT2TL | 0.220 | | | | | | | |
| | MT2DPNF | −1.621 | | | | | | | |
| | MT2MLNF | −1.144 | | | | | | | |
| | MT2CNF | 0.987 | | | | | | | |
| | Constant | −30.736 | | | | | | | |
| 2 | MT2TL | 0.265 | 0.50 | 79 | 79 | 79 | 82.1 | 72.2 | 77.3 |
| | MT2DPNF | −1.559 | | | | | | | |
| | MT2MLNF | −0.838 | | | | | | | |
| | MT2CNF | 0.970 | | | | | | | |
| | Constant | −26.954 | | | | | | | |
| 3 | MT2TL | 0.250 | 0.50 | 77 | 79 | 78 | 79.8 | 72.2 | 76.1 |
| | MT2DPNF | −1.063 | | | | | | | |
| | MT2CNF | 0.580 | | | | | | | |
| | Constant | −25.686 | | | | | | | |
| 4 | MT1CNF | 0.216 | 0.50 | 78 | 77 | 77.5 | 81 | 75.9 | 78.5 |
| | MT2TL | 0.241 | | | | | | | |
| | Constant | −27.642 | | | | | | | |
| 5 | MT3NFPE | 0.195 | 0.50 | 76.5 | 78 | 77.3 | 78 | 78.5 | 78.3 |
| | MT3CNF | 0.631 | | | | | | | |
| | Constant | −24.556 | | | | | | | |
| 6 | MT4NFPE | 0.145 | 0.50 | 77.3 | 76 | 76.6 | 78 | 74.7 | 76.4 |
| | MT4CNF | 0.328 | | | | | | | |
| | MT5TL | 0.126 | | | | | | | |
| | MT5MLNF | −0.947 | | | | | | | |
| | MT5CNF | 0.325 | | | | | | | |
| | Constant | −23.255 | | | | | | | |
| 7 | MT1TL | 0.178 | 0.50 | 72 | 81 | 76.5 | 76.2 | 78.5 | 77.3 |
| | MT1DPNF | −0.326 | | | | | | | |
| | MT1CNF | 0.348 | | | | | | | |
| | Constant | −22.442 | | | | | | | |
| 8 | MT2TL | 0.229 | 0.50 | 76.5 | 76 | 76.3 | 76.8 | 74.7 | 75.8 |
| | MT3CNF | 0.362 | | | | | | | |
| | Constant | −27.767 | | | | | | | |

Logistic Regression analysis (LRA) model equation = unstandardised coefficient × variables in (in millimetres) + constant. LRA greater than the sectioning point indicates male, and LRA less than the sectioning point indicates female.
MT1 = First metatarsal bone, MT2 = Second metatarsal bone, MT3 = Third metatarsal bone, MT 4 = Fourth metatarsal bone, MT 5 = Fifth metatarsal bone TL = Total length, NFPE = Distance from the proximal end of the bone to the level of nutrient foramina, DPNF = Dorsoplantar diameter at the level of nutrient foramina, MLNF = Mediolateral distance at the level of the nutrient foramina, CNF= Circumference at the level of the nutrient foramina, F= Female, M = Male.

agricultural and industrialised activities, sexually dimorphic traits may not be very distinct, and this may result in low (below 75 %) or moderate to high (75–80 %) sex classification accuracies [54–57]. Notably, females were more accurately classified than males in the current study with a bias between 0 % and 11 %. The moderate to high sex classification accuracies in the current study suggests that South African Africans females in the period studied were engaged in similar occupations to males like agriculture and long distance travelling, resulting in bone robustness relatively similar to that of males.

The current study shows that the combination of the breadth measurements (CNF, DPNF, MLNF) showed higher sex estimation accuracy rates than the combination of the length measurements (TL and NFPE) in most of the DFA and LRA equations. This finding is consistent with previous studies [8,11,27,28]. Breadth measurements are more susceptible to the influence of lifestyle activities and environmental factors compared to length measurements which appear more affected by genetic factors [49]. In the current study, a combination of the breadth and length measurements as shown in function 1, Table 4 and function 1, Table 7 produced high sex estimation accuracy rates. Hence, it is advisable to utilise both breadth and length measurements for South African Africans individuals to correctly estimate sex, since it factors in both the genetic and physical forces on bone morphology.

## 5. Study limitations

The main limitation of the equations generated in the current study is that some functions were affected by significant multicollinearity, thereby limiting their applicability to a general population. The data was also not normally distributed, and this may add bias to the current findings especially those derived from the DFA functions. It is therefore critical to generate population-specific sex estimating functions to comprehensively validate the utility of the dimensions around the metatarsal diaphyseal nutrient foramina.

## 6. Conclusion

The dimensions around the nutrient foramen of the metatarsal bones show sexual dimorphism in the South African Africans population. A combination of measurements around the nutrient foramen from different metatarsal bones produced sex classification rates of 75–80.5 % which are lower than those using other foot bones and upper limb bones in the same population. The current study suggests that the dimensions around the nutrient foramen of the metatarsal bones can be used with caution in the South African Africans, especially when the foot is the only recovered body part in forensic and archaeological settings.

**Table 7**
Direct logistic regression coefficients, constants, and classification rates for a combination of measurements for multiple metatarsals.

| Function | Measurement combination | Unstandardised Coefficient | Sectioning point | Classification accuracy % | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Original classification | | | Cross validation | | |
| | | | | M | F | Average | M | F | Average |
| 1 | MT1MLNF | 0.484 | 0.50 | 81 | 80 | 80.5 | 82.1 | 78.5 | 80.4 |
| | MT2TL | 0.225 | | | | | | | |
| | MT2DPNF | −1.480 | | | | | | | |
| | MT2MLNF | −0.998 | | | | | | | |
| | MT2CNF | 0.929 | | | | | | | |
| | Constant | −28.965 | | | | | | | |
| 2 | MT1DPNF | −0.279 | 0.50 | 77 | 82 | 79.5 | 79.8 | 78.5 | 79.1 |
| | MT1CNF | 0.355 | | | | | | | |
| | MT2CNF | 0.204 | | | | | | | |
| | Constant | −18.286 | | | | | | | |
| 3 | MT2TL | 0.265 | 0.50 | 79 | 79 | 79 | 82.1 | 72.2 | 77.3 |
| | MT2DPNF | −1.559 | | | | | | | |
| | MT2MLNF | −0.838 | | | | | | | |
| | MT2CNF | 0.970 | | | | | | | |
| | Constant | −26.954 | | | | | | | |
| 4 | MT1DPNF | −0.289 | 0.50 | 76 | 82 | 79 | 78.6 | 79.7 | 79.1 |
| | MT1CNF | 0.318 | | | | | | | |
| | MT2TL | 0.239 | | | | | | | |
| | Constant | −28.300 | | | | | | | |
| 5 | MT1DPNF | −0.275 | 0.50 | 76.5 | 79 | 77.8 | 79.3 | 79.7 | 79.5 |
| | MT1CNF | 0.309 | | | | | | | |
| | MT3CNF | 0.370 | | | | | | | |
| | Constant | −21.078 | | | | | | | |
| 6 | MT1MLNF | 0.254 | 0.50 | 75 | 80 | 77.5 | 82.1 | 78.5 | 80.4 |
| | MT1CNF | 0.185 | | | | | | | |
| | MT2CNF | 0.215 | | | | | | | |
| | Constant | −18.174 | | | | | | | |
| 7 | MT1DPNF | −0.335 | 0.50 | 77 | 76 | 76.5 | 81 | 73.4 | 77.3 |
| | MT1CNF | 0.425 | | | | | | | |
| | Constant | −14.629 | | | | | | | |
| 8 | MT1MLNF | 0.626 | 0.50 | 72.6 | 80 | 76.4 | 73.8 | 74.7 | 74.2 |
| | MT3MLNF | 0.413 | | | | | | | |
| | MT4MLNF | 0.596 | | | | | | | |
| | Constant | −16.205 | | | | | | | |
| 9 | MT5TL | 0.201 | 0.50 | 74 | 76 | 75 | 78.6 | 73.4 | 76.1 |
| | MT5MLNF | −0.925 | | | | | | | |
| | MT5CNF | 0.526 | | | | | | | |
| | Constant | −20.458 | | | | | | | |

Logistic Regression analysis (LRA) model equation = unstandardised coefficient × variables in (in millimetres) + constant. LRA greater than the sectioning point indicates male and LRA less than the sectioning point indicates female.
MT1 = First metatarsal bone, MT2 = Second metatarsal bone, MT3 = Third metatarsal bone, MT 4 = Fourth metatarsal bone, MT 5 = Fifth metatarsal bone TL = Total length, NFPE = Distance from the proximal end of the bone to the level of nutrient foramina, DPNF = Dorsoplantar diameter at the level of nutrient foramina, MLNF = Mediolateral distance at the level of the nutrient foramina, CNF= Circumference at the level of the nutrient foramina, F= Female, M = Male.

## Ethical approval

The current study was conducted under the ethical clearance waiver number W-CBP-220504-01 and was covered by the Human Tissue Act (No. 65 of 1983) and the National Health Act (No. 61 of 2003) on the use of human specimens for research and teaching purposes.

## Ethics statement

The current study was conducted under the ethical clearance waiver number **W-CBP-22050401** obtained from the Faculty of Health Sciences at the University of the Witwatersrand.

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1 All authors contributed to the article. We declare that this work is not being considered by any other journal and no use of generative AI was employed during the preparation of this manuscript.

## CRediT authorship contribution statement

**Arthur Tsalani Manjatika:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Pedzisai Mazengenya:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Joshua Gabriel Davimes:** Conceptualization, Data curation, Formal analysis, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Arthur Tsalani Manjatika reports financial support was provided by

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