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Estimation of Stature Based on Metatarsal Bones in a Thai Population

Estimación de la Estatura Basada en los Huesos Metatarsianos en una Población Tailandesa

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SUMMARY: Stature estimation is one of the essential procedures for personal identification in forensic osteology. Therefore, the purposes of this study are to analyze the correlation between length and width of metatarsal measurements and stature, and to develop the regression equations for a Thai population. In this study, the samples were divided into two groups. The first group was called the "training group" for generating stature estimation equations, comprised of 200 skeletons, aged between 19-94 years. The second group was called the "test group" for evaluating the accuracy of generated equations, comprising 40 skeletons. The correlation between metatarsal parameters and stature were moderate to high, and all variables had positive significant correlation with stature. For males, the left ML2 is the length variable that showed the most correlation degree against stature (r=0.702), and the left MSW4 is the width variable that had the most correlation degree against stature (r=0.483). For females, right ML1 is the length variable that had the most correlation degree against stature (r=0.632), and right PW3 is the width stature that had the most correlation degree against stature (r=0.481). For all samples, left ML1 was the length variable that had the most correlation degree against stature (r=0.796) and right PW3 was the width variable that had the most correlation degree against stature (r=0.712). The results of generating multiple regression equations using a stepwise method reveals that the correlation coefficient (R) and standard error of estimate (SEE) were 0.761 and 4.96 cm, respectively, for males, and 0.752 and 4.93 cm for females, with 0.841 and 5.26 cm for all samples, respectively. According to these results, the mean of absolute error from the test group ranged from 3 to 5 cm. Therefore, stature estimation equations using length and width of metatarsals from our study can be applied to estimate stature in the Thai population.

KEY WORDS: Stature estimation; Metatarsal bones; Osteometry; Thai population; Forensic osteology.

INTRODUCTION

Personal identification is an important step in forensic anthropology. Personal identification can lead to crucial information to help trace the victims or stakeholders. In the case of crime or mass natural disaster, there are two kinds of personal data that can be used to identify personal identification – primary data, and secondary data. In a practical scenario, primary data including DNA, dental records, or fingerprints are the favored indicators that can be used as a personal identification method (Wright *et al*., 2015). However, in the case of unidentified remains that have limitations such as bad decomposition, burnt, a corpse soaked in water for a long time, or a corpse with no dental records, it may be impossible to identify the corpse. It is then necessary to consider secondary data and other information conjointly for attesting and narrowing down the pool of possible victim matches in any ongoing investigation. Secondary data includes that from eye witnesses, personal data in crime scenes, facial reconstruction (Navic *et al*., 2022), craniofacial superimposition (Gordon & Steyn, 2012), and bones (Cattaneo, 2007). Among secondary data, the bone element can be one of the most important clues collected from a crime scene. Because it is a hard biological tissue and also more resistant to degeneration from the environment than other types of tissue, it can remain in appropriate condition for analyzing data, which is useful for personal identification metrics such as sex, age, ancestry and stature.

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As stated previously, stature estimation is one of the most crucial elements of biological identification, and has been used for more than a century. Previous studies have found that stature can be estimated from various bones, e.g., long bones (Mahakkanukrauh *et al*., 2011), upper limb bones (Duangto & Mahakkanukrauh, 2019), lower limb bones (Lee *et al*., 2014), sternum (Jeamamornrat *et al*., 2022), vertebrae (Inchai *et al*., 2019), metacarpal (Zaher *et al*., 2011) and metatarsal (Byers *et al*., 1989; Bidmos, 2008; Cordeiro *et al*., 2009). Although a previous study states that long bones – femur, tibia and fibula – can be used to estimate the stature precisely (Mahakkanukrauh *et al*., 2011), some conditions such as severe disaster mean these long bones might not be recovered, or found only in fragments (Fongkete *et al*., 2016). Alternatively, it is possible to use other bones, i.e., the metatarsal, which is a smaller long bone for estimating stature. Due to its outstanding characteristics, it can be found in crime scenes and remain as a complete structure (Cordeiro *et al*., 2009). Moreover, population-specific regression equations from metatarsals have been conducted in various ethnic groups, such as Mexicans (Byers *et al*., 1989), South Africans (Bidmos, 2008), and Portuguese (Cordeiro *et al*., 2009). Due to different physiques of each population caused by genetics, environment, activity, weight and so on, this makes the stature different between each population. Moreover, stature can be affected by secular variation. Therefore, specific data collected from a specific population is required. To make anthropological standards for the Thai population, it is necessary to conduct a study in the Thai population. From literature reviews, there are no stature estimation studies using metatarsal length and width conducted in Thais, to the best of our knowledge. The purposes of this study are, therefore, to analyze the correlation between length and width of the metatarsal with stature, and develop regression equations for stature estimation using the length and width of metatarsals in the Thai population.

MATERIAL AND METHOD

The study protocol was approved by the Research Ethics Committee, Faculty of Medicine, Chiang Mai University, Thailand. (Research ID: ANA-256).

The composition of samples. This study was conducted using skeletons (died between 2006 - 2019) donated for educational and research purposes at the Osteology Research and Training Center (ORTC), Faculty of Medicine, Chiang Mai University. The sample of this study was separated into two groups. The first group was the "Training group", including 200 skeletons (100 males and 100 females) aged between 19 to 94 years, the mean for age is 62.47±13.28 years (62.33±13.28 years for males and 62.61±16.45 years for females), used for generating the stature estimation equations. The second group was the "Test group", including 40 skeletons (25 males and 15 females), for evaluating the accuracy of generated equations. The two groups of samples presented with no data of height, endocrine disorders such as growth hormone deficiency, rickets, osteomalacia, acromegaly, osteoporosis or damaged bones that would affect measurement morphology and measurement accuracy, and would be excluded from this study.

Metatarsal measurements. Metatarsal measurements were taken by Digital vernier caliper (Mitutoyo®) and recorded in millimeters.

Maximum length (ML) and mid-shaft width (MSW) were measured using the measurement method described in White & Folkens (2000) and Cordeiro *et al*. (2009) (Fig. 1).

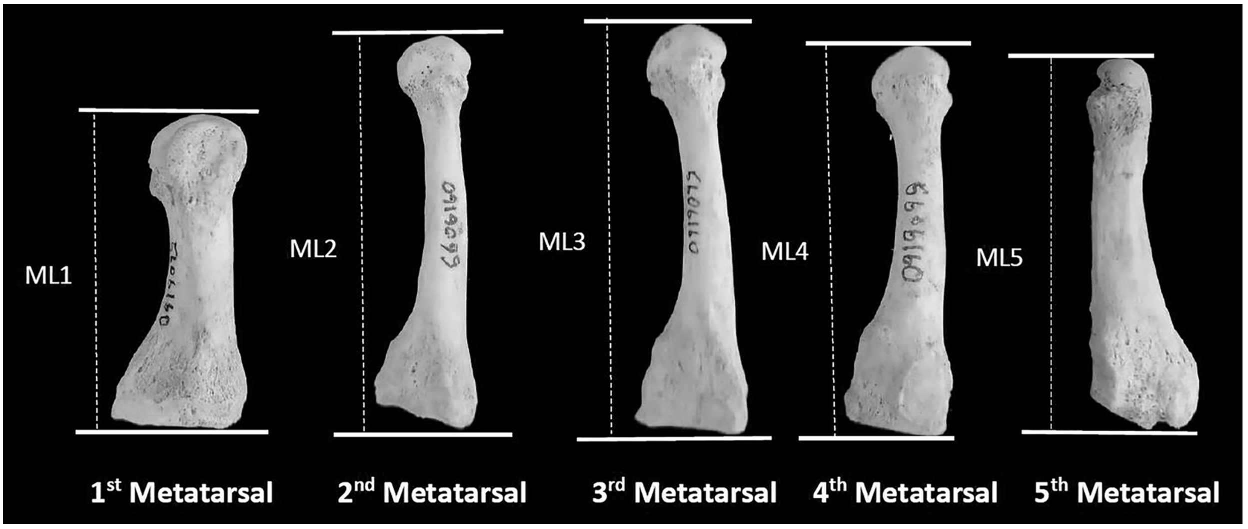

Fig. 1. Maximum length (ML) of 1st – 5th metatarsal bone measurement.

Distal width (DW) and proximal width (PW) were measured using the measurement method described (Torres *et al*., 2020), which originated from (Robling & Ubelaker, 1997) (Fig. 2).

1. Maximum length (ML) – length of bone or distance from the proximal point on the head of the metatarsal to the distal point of the metatarsal tuberosity (Fig. 1).

2. Distal width (DW) – distance from the most medial point to the most lateral point on the head of the metatarsal bone (Fig. 2).

3. Mid-shaft width (MSW) – distance from the most medial point to the most lateral point at 50 % of the biomechanical length (distance from the tarsal articular surface to the most distal point on the head of the metatarsal bone) (Fig. 2).

4. Proximal width (PW) – distance from the most medial point to the most lateral point on the base of the metatarsal bone (Fig. 2).

Statistical analysis. Twenty samples (10 males and 10 females) from the training group were randomly selected to evaluate inter-observer reliability. Basic descriptive statistics (i.e., minimum, maximum, mean and standard deviation) were used to describe each variable. Kolmogorov-Smirnov statistics were used for a normality test. Paired sample T-Test statistics were used to test the difference between left and right metatarsals. Spearman's rank correlation coefficient was used to determine the correlation between metatarsal measurements and stature.

Population specific regression functions in the form of simple linear regression and multiple linear regression were used to generate stature estimation equations for males, females and overall. Evaluating the efficiency of generated linear regression equations against the test group were irrelevant to the training group.

IBM SPSS software version 22 was used to analyze data at a 95 % confident interval.

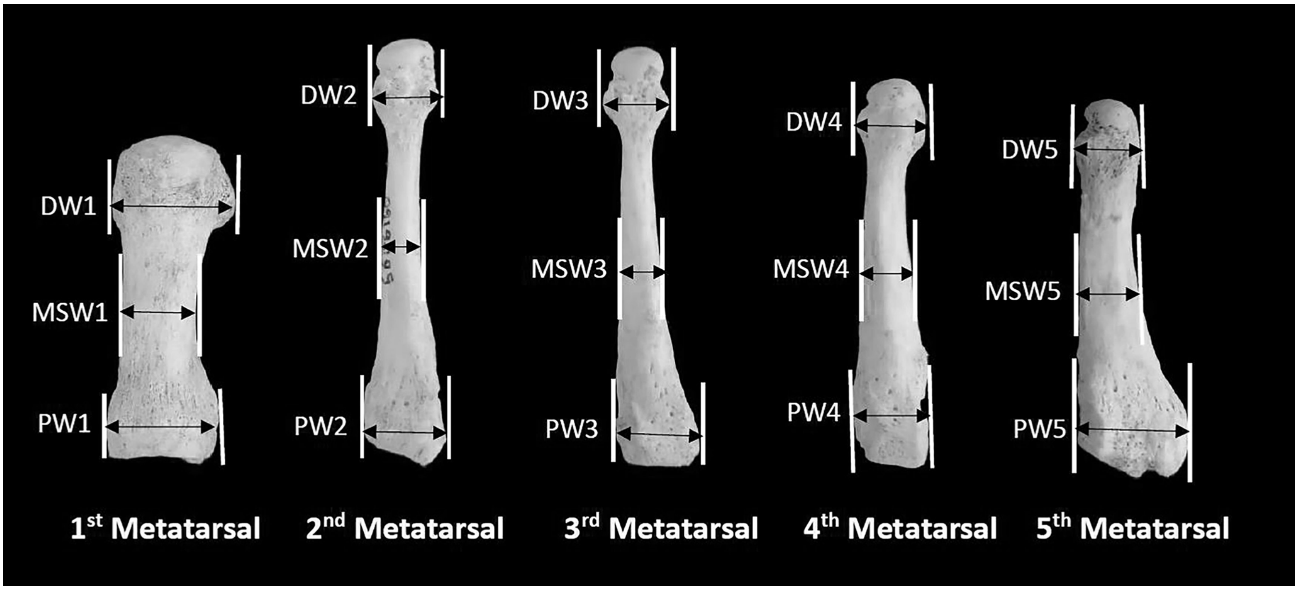

Fig. 2. Distal width (DW), Mid-shaft width (MSW), and Proximal width (PW) of 1st – 5th metatarsal bone measurement.

RESULTS

The results of reliability testing between inter-observers revealed that all variables had a correlation coefficient between 0.99 and 1.00, which indicated high and congruent measurement reliability.

Descriptive statistics are described in Tables Ia and Ib. Mean of stature was 167.03±7.51 cm for males, 154.92±7.29 cm for females, and 160.98±9.56 cm for all samples, respectively. The results of normality testing revealed that most of all variables had normal distribution, except the right ML1, right MSW2, right DW2, and left MSW4. Measurement of the left MSW5, left DW5, right DW5, left MSW1 and left DW3, had non-normal distributions for females, males, and all samples, respectively.

Table Ia Descriptive statistics of all variables for males and females (mm)

Measurements	Males					Females				
	n	Min	Max	Mean	SD	n	Min	Max	Mean	SD
leftML1	100	54.24	72.21	63.57	3.41	100	51.41	67.58	58.76	3.68
leftML2	100	63.15	88.93	76.99	4.28	100	59.71	81.77	71.01	4.38
leftML3	100	63.78	83.30	72.33	3.82	100	58.69	80.12	66.90	4.62
leftML4	100	60.77	82.92	70.43	4.09	100	56.37	79.44	65.24	4.34
leftML5	100	59.88	83.66	71.15	4.35	100	54.67	77.86	65.62	4.62
leftMSW1	100	11.71	18.87	14.28	1.27	100	10.42	14.09	12.25	0.92
leftMSW2	100	6.35	12.29	8.11	0.86	100	5.84	11.35	7.36	0.89
leftMSW3	100	5.88	10.81	8.44	0.92	100	5.66	10.92	7.73	1.05
leftMSW4	100	6.36	11.58	9.13	1.05	100	6.34	11.25	8.45	1.06
leftMSW5	100	7.76	14.20	10.48	1.12	100	6.86	11.66	9.58	1.02
leftDW1	100	18.11	27.61	23.51	1.79	100	11.71	26.13	20.98	1.89
leftDW2	100	9.87	15.68	12.92	0.92	100	8.65	14.15	11.70	0.95
leftDW3	100	9.72	14.89	12.08	1.11	100	8.64	13.42	10.84	1.03
leftDW4	100	9.38	14.54	12.11	1.22	100	8.48	13.86	10.93	1.11
leftDW5	100	9.16	15.89	11.82	1.22	100	8.61	13.54	10.37	0.95
leftPW1	100	17.56	24.79	20.60	1.37	100	15.53	21.16	17.94	1.21
leftPW2	100	13.38	20.93	16.74	1.19	100	11.65	17.55	14.93	1.11
leftPW3	100	12.36	33.92	15.24	2.17	100	11.28	15.91	13.37	1.09
leftPW4	100	11.49	17.17	14.15	1.17	100	10.90	15.19	12.70	0.91
leftPW5	100	16.37	25.36	20.83	1.74	100	14.80	21.66	18.50	1.38
rightML1	100	49.20	71.73	63.21	3.71	100	51.33	67.79	58.68	3.75
rightML2	100	62.72	88.38	76.41	4.38	100	61.01	83.00	71.23	4.32
rightML3	100	63.05	83.31	72.44	3.83	100	58.29	80.56	66.95	4.50
rightML4	100	60.80	81.65	70.55	4.04	100	56.66	80.02	65.50	4.43
rightML5	100	59.09	85.36	71.41	4.49	100	53.32	76.99	65.74	4.97
rightMSW1	100	7.85	17.64	14.19	1.33	100	10.44	14.61	12.31	0.93
rightMSW2	100	6.04	9.85	8.26	0.73	100	5.67	11.68	7.48	0.96
rightMSW3	100	6.14	10.66	8.48	0.88	100	6.01	10.97	7.73	1.02
rightMSW4	100	6.00	11.96	9.34	0.99	100	6.11	11.46	8.60	1.05
rightMSW5	100	8.32	13.07	10.55	0.98	100	7.43	12.26	9.69	0.93
rightDW1	100	10.68	27.57	23.39	2.19	100	17.91	23.62	20.98	1.31
rightDW2	100	9.67	15.25	12.96	1.00	100	9.01	14.99	11.74	1.04
rightDW3	100	9.91	14.86	11.99	0.98	100	8.97	14.01	10.73	0.87
rightDW4	100	9.47	15.29	12.46	1.19	100	7.76	13.58	11.14	1.04
rightDW5	100	9.32	16.03	11.89	1.21	100	8.47	15.03	10.42	1.01
rightPW1	100	13.64	23.97	20.52	1.54	100	15.35	21.04	17.95	1.23
rightPW2	100	12.76	19.40	16.60	1.32	100	12.00	18.01	14.90	1.06
rightPW3	100	12.06	17.38	14.96	1.01	100	10.52	15.32	13.07	0.96
rightPW4	100	11.71	17.58	14.01	1.03	100	11.15	14.74	12.79	0.81
rightPW5	100	16.87	25.10	20.72	1.67	100	13.75	22.94	18.44	1.46

For the results of symmetry tests, seven measurements, including ML1, ML2, ML5, PW2 MSW2, MSW4 and DW4 were significantly different for males. Only two measurements, including PW3 and DW4, were significantly different between the left and right sides for females. According to this symmetry test result, stature estimation equations specific for left and right are required.

The results of correlation analysis between metatarsals and stature are shown in Tables IIa and IIb. All variables indicate positive significant correlation with stature. For males, left ML2, left MSW4 of length and width measurements show the most correlation coefficient (r=0.702) (r=0.483), respectively. For females, right ML1 and left MSW4 measurements had the most correlation coefficient (r=0.632) and (r=0.481), respectively. For all samples, left ML1 and right PW3 had most correlation coefficient (r=0.796) and (r=0.712), respectively.

The results of generating simple and multiple linear regressions for males, females, and all samples are shown in Tables IIIa and IIIb. As simple linear regression, the

Table Ib Descriptive statistics of all measurements (mm) for each group.

Measurements	n	Min	Max	Mean	SD
leftML1	200	51.41	72.21	61.18	4.28
leftML2	200	59.71	88.93	74.00	5.28
leftML3	200	58.69	83.30	69.62	5.03
leftML4	200	56.37	82.92	67.83	4.93
leftML5	200	54.67	83.66	68.39	5.27
leftMSW1	200	10.42	18.87	13.26	1.49
leftMSW2	200	5.84	12.29	7.73	0.94
leftMSW3	200	5.66	10.92	8.09	1.05
leftMSW4	200	6.34	11.58	8.79	1.11
leftMSW5	200	6.86	14.20	10.03	1.16
leftDW1	200	11.71	27.61	22.26	2.22
leftDW2	200	8.65	15.68	12.33	1.14
leftDW3	200	8.64	14.89	11.50	1.25
leftDW4	200	8.48	14.54	11.54	1.32
leftDW5	200	8.61	15.89	11.10	1.31
leftPW1	200	15.53	24.79	19.25	1.85
leftPW2	200	11.65	20.93	15.84	1.47
leftPW3	200	11.28	17.51	14.22	1.38
leftPW4	200	10.90	17.17	13.43	1.26
leftPW5	200	14.80	25.36	19.69	1.97
rightML1	200	49.20	71.73	60.93	4.36
rightML2	200	61.01	88.38	73.88	5.05
rightML3	200	58.29	83.31	69.74	5.02
rightML4	200	56.66	81.65	68.06	4.94
rightML5	200	53.32	85.36	68.60	5.54
rightMSW1	200	10.44	17.64	13.29	1.43
rightMSW2	200	5.67	11.68	7.86	0.94
rightMSW3	200	6.01	12.64	8.13	1.07
rightMSW4	200	6.00	11.96	8.99	1.11
rightMSW5	200	7.43	13.07	10.12	1.05
rightDW1	200	16.20	27.57	22.26	2.01
rightDW2	200	9.01	15.45	12.36	1.21
rightDW3	200	8.97	14.86	11.38	1.13
rightDW4	200	7.76	15.29	11.82	1.31
rightDW5	200	8.47	16.03	11.16	1.33
rightPW1	200	15.35	23.97	19.28	1.86
rightPW2	200	12.00	19.40	15.75	1.44
rightPW3	200	10.52	17.38	14.03	1.38
rightPW4	200	11.15	17.58	13.43	1.14
rightPW5	200	13.75	25.10	19.62	1.97

Table IIa. Correlation coefficient of metatarsal length against stature.

Measurement	Males (n=100)	Females (n=100)	Overall (n=200)
leftML1	0.645	0.631	0.796
leftML2	0.702	0.563	0.787
leftML3	0.623	0.601	0.790
leftML4	0.604	0.601	0.764
leftML5	0.539	0.535	0.698
rightML1	0.598	0.632	0.763
rightML2	0.633	0.603	0.761
rightML3	0.630	0.591	0.782
rightML4	0.630	0.594	0.776
rightML5	0.572	0.559	0.721

correlation coefficient of all sample equations was more than the correlation coefficient of male and female equations. The standard error of estimate (SEE) was 5.84-8.76 cm, 5.48-7.50 cm, and 5.39 cm to 7.32 cm for all samples, males, and females, respectively. As for multiple linear regressions, correlation coefficient (R) and SEE were 0.761 and 4.96 cm respectively for males, 0.752 and 4.93 cm respectively for females, and 0.841 and 5.26 cm respectively for all samples.

Multiple linear regression equations were evaluated for efficiency using the test group (Table IV).

Table IIb. Correlation coefficient of metatarsal width against stature.

Measurement	Males (n=100)	Females (n=100)	Overall (n=200)
leftMSW1	0.281	0.382	0.634
leftMSW2	0.362	0.202	0.474
leftMSW3	0.424	0.294	0.499
leftMSW4	0.483	0.291	0.503
leftMSW5	0.225	0.466	0.507
leftDW1	0.261	0.271	0.572
leftDW2	0.281	0.119	0.487
leftDW3	0.176	0.171	0.475
leftDW4	0.182	0.175	0.413
leftDW5	0.073	0.224	0.464
leftPW1	0.279	0.341	0.614
leftPW2	0.34	0.424	0.655
leftPW3	0.315	0.412	0.629
leftPW4	0.368	0.412	0.624
leftPW5	0.208	0.295	0.578
rightMSW1	0.256	0.374	0.626
rightMSW2	0.386	0.243	0.493
rightMSW3	0.457	0.358	0.546
rightMSW4	0.449	0.28	0.523
rightMSW5	0.238	0.415	0.511
rightDW1	0.288	0.267	0.593
rightDW2	0.293	0.146	0.49
rightDW3	0.142	0.087	0.448
rightDW4	0.159	0.074	0.426
rightDW5	0.299	0.203	0.531
rightPW1	0.272	0.358	0.632
rightPW2	0.289	0.385	0.625
rightPW3	0.385	0.481	0.712
rightPW4	0.384	0.225	0.587
rightPW5	0.163	0.263	0.551

Table IIIa. Equations of the simple linear regression for stature estimation of males, females and overall, respectively.

Samples		Equation	R	R^2	Adjust R^2	SEE
1	Males	S = 70.388 + 1.520 ∈ leftML1	0.69	0.474	0.468	5.48
	Females	S = 76.409 + 1.336 ∈ leftML1	0.68	0.455	0.449	5.41
	Overall	S = 52.860 + 1.767 ∈ leftML1	0.79	0.628	0.626	5.84
2	Males	S = 75.343 + 1.191 ∈ leftML2	0.69	0.469	0.464	5.50
	Females	S = 85.011 + 0.985 ∈ leftML2	0.59	0.350	0.343	5.90
	Overall	S = 55.561 + 1.148 ∈ leftML2	0.77	0.588	0.568	6.15
3	Males	S = 74.623 + 1.278 ∈ leftML3	0.65	0.424	0.418	5.73
	Females	S = 83.371 + 1.070 ∈ leftML3	0.68	0.459	0.453	5.39
	Overall	S = 58.696 + 1.469 ∈ leftML3	0.77	0.598	0.596	6.08
4	Males	S = 87.206 + 1.133 ∈ leftML4	0.61	0.375	0.368	5.97
	Females	S = 84.505 + 1.079 ∈ leftML4	0.64	0.413	0.407	5.61
	Overall	S = 62.851 + 1.447 ∈ leftML4	0.75	0.557	0.555	6.38
5	Males	S = 95.688 + 1.003 ∈ leftML5	0.58	0.340	0.334	6.13
	Females	S = 97.623 + 0.873 ∈ leftML5	0.55	0.306	0.299	6.10
	Overall	S = 73.339 + 1.281 ∈ leftML5	0.71	0.499	0.497	6.78
6	Males	S = 87.975 + 1.251 ∈ rightML1	0.62	0.386	0.380	5.92
	Females	S = 79.878 + 1.279 ∈ rightML1	0.66	0.432	0.426	5.52
	Overall	S = 60.614 + 1.647 ∈ rightML1	0.75	0.564	0.562	6.33
7	Males	S = 87.282 + 1.042 ∈ rightML2	0.60	0.354	0.348	6.06
	Females	S = 79.346 + 1.061 ∈ rightML2	0.63	0.396	0.390	5.69
	Overall	S = 58.103 + 1.392 ∈ rightML2	0.74	0.542	0.540	6.48
8	Males	S = 75.157 + 1.267 ∈ rightML3	0.65	0.419	0.413	5.76
	Females	S = 86.294 + 1.025 ∈ rightML3	0.63	0.400	0.394	5.67
	Overall	S = 59.803 + 1.451 ∈ rightML3	0.76	0.581	0.579	6.20
9	Males	S = 81.716 + 1.208 ∈ rightML4	0.65	0.420	0.414	5.75
	Females	S = 86.857 + 1.039 ∈ rightML4	0.63	0.399	0.392	5.68
	Overall	S = 62.089 + 1.453 ∈ rightML4	0.75	0.564	0.562	6.33
10	Males	S = 96.154 + 0.992 ∈ rightML5	0.59	0.356	0.349	6.06
	Females	S = 98.207 + 0.863 ∈ rightML5	0.59	0.347	0.340	5.92
	Overall	S = 75.812 + 1.241 ∈ rightML5	0.72	0.518	0.515	6.66
11	Males	S = 144.745 + 1.561 ∈ leftMSW1	0.26	0.067	0.057	7.30
	Females	S = 117.686 + 3.039 ∈ leftMSW1	0.38	0.147	0.138	6.77
	Overall	S = 109.330 + 3.893 ∈ leftMSW1	0.61	0.368	0.365	7.62
12	Males	S = 139.789 + 3.366 ∈ leftMSW2	0.38	0.147	0.138	6.98
	Females	S = 144.184 + 1.458 ∈ leftMSW2	0.18	0.032	0.022	7.21
	Overall	S = 126.112 + 4.512 ∈ leftMSW2	0.45	0.199	0.195	8.58
13	Males	S = 136.840 + 3.569 ∈ leftMSW3	0.44	0.189	0.181	6.80
	Females	S = 141.246 + 1.769 ∈ leftMSW3	0.26	0.066	0.056	7.08
	Overall	S = 126.629 + 4.244 ∈ leftMSW3	0.47	0.218	0.214	8.48
14	Males	S = 135.259 + 3.477 ∈ leftMSW4	0.48	0.234	0.226	6.61
	Females	S = 140.411 + 1.717 ∈ leftMSW4	0.25	0.063	0.053	7.09
	Overall	S = 125.447 + 4.040 ∈ leftMSW4	0.47	0.218	0.214	8.47
15	Males	S = 147.296 + 1.884 ∈ leftMSW5	0.28	0.079	0.070	7.25
	Females	S = 122.130 + 3.422 ∈ leftMSW5	0.48	0.231	0.223	6.42
	Overall	S = 118.731 + 4.213 ∈ leftMSW5	0.51	0.262	0.258	8.23
16	Males	S = 136.956 + 1.278 ∈ leftDW1	0.30	0.089	0.079	7.21
	Females	S = 136.667 + 0.870 ∈ leftDW1	0.23	0.051	0.041	7.14
	Overall	S = 110.197 + 2.281 ∈ leftDW1	0.53	0.281	0.277	8.13
17	Males	S = 139.516 + 2.123 ∈ leftDW2	0.27	0.073	0.063	7.27
	Females	S = 149.337 + 0.477 ∈ leftDW2	0.06	0.004	-0.006	7.31
	Overall	S = 113.579 + 3.844 ∈ leftDW2	0.46	0.211	0.207	8.51
18	Males	S = 152.687 + 1.181 ∈ leftDW3	0.17	0.030	0.020	7.44
	Females	S = 140.721 + 1.309 ∈ leftDW3	0.19	0.034	0.024	7.20
	Overall	S = 121.369 + 3.445 ∈ leftDW3	0.45	0.203	0.199	8.56
19	Males	S = 151.785 + 1.254 ∈ leftDW4	0.21	0.042	0.032	7.39
	Females	S = 146.983 + 0.726 ∈ leftDW4	0.11	0.012	0.002	7.28
	Overall	S = 127.044 + 2.940 ∈ leftDW4	0.41	0.165	0.161	8.76

DISCUSSION

Average human height and human body proportions change over time. In terms of 'secular trends' (Roche, 1979) as referred to in reference to human change, the trend is towards increasing human height observed worldwide, including in the Thai population (Silventoinen, 2003; Mahakkanukrauh *et al*., 2011). Therefore, it is still important to study stature estimation for forensic anthropology and develop appropriate methods to obtain the most accurate stature estimation. Consequently, it is imperative to rely on contemporary skeletal data; as well, the appropriate data for specific populations is required. In addition to estimating stature, there are a number of factors that need to be taken into account. One of which is age factor, therefore, we suggest that the age of samples should be more than 19 years, because that age range has completed the growth of the epiphysis (Trotter & Gleser, 1952). As a result, all samples in this study were adults that were aged more than 19 years, and equations from this study may be inappropriate to apply to the sample if they have ages less than 19 years.

Most previous studies have found that metatarsals can also be a reliable stature estimator (Cordeiro *et al*., 2009), with the metatarsal length variable being popular and rated in strong correlation with height. In order to optimize the efficiency of stature estimation and width variables, distal width, mid-shaft width and proximal width of the metatarsal were proposed in this study and also added in the equation. According to literature reviews, metatarsal width is an efficient sex

20	Males	S = 158.283 + 0.740 ∈ leftDW5	0.12	0.015	0.005
	Females	S = 136.787 + 1.748 ∈ leftDW5	0.23	0.052	0.042
	Overall	S = 123.969 + 3.334 ∈ leftDW5	0.46	0.210	0.206
21	Males	S = 135.070 + 1.554 ∈ leftPW1	0.28	0.080	0.071
	Females	S = 129.769 + 1.402 ∈ leftPW1	0.23	0.054	0.044
	Overall	S = 101.678 + 3.080 ∈ leftPW1	0.60	0.354	0.350
22	Males	S = 125.456 + 2.482 ∈ leftPW2	0.40	0.156	0.148
	Females	S = 119.796 + 2.353 ∈ leftPW2	0.36	0.129	0.120
	Overall	S = 96.800 + 4.052 ∈ leftPW2	0.62	0.389	0.386
23	Males	S = 136.944 +1.995 ∈ leftPW3	0.29	0.081	0.072
	Females	S = 116.343 + 2.886 ∈ leftPW3	0.43	0.186	0.177
	Overall	S = 100.636 + 4.242 ∈ leftPW3	0.61	0.373	0.370
24	Males	S = 137.129 + 2.112 ∈ leftPW4	0.32	0.101	0.092
	Females	S = 112.935 + 3.305 ∈ leftPW4	0.41	0.171	0.163
	Overall	S = 100.405 + 4.510 ∈ leftPW4	0.59	0.353	0.349
25	Males	S = 142.976 + 1.152 ∈ leftPW5	0.27	0.070	0.061
	Females	S = 125.556 + 1.587 ∈ leftPW5	0.30	0.091	0.082
	Overall	S = 107.655 + 2.708 ∈ leftPW5	0.56	0.311	0.307
26	Males	S = 144.338 + 1.591 ∈ rightMSW1	0.25	0.060	0.050
	Females	S = 116.002 + 3.161 ∈ rightMSW1	0.40	0.163	0.154
	Overall	S = 106.867 + 4.072 ∈ rightMSW1	0.61	0.372	0.369
27	Males	S = 133.507 + 4.069 ∈ rightMSW2	0.41	0.165	0.157
	Females	S = 142.571 + 1.651 ∈ rightMSW2	0.22	0.048	0.038
	Overall	S = 123.663 + 4.748 ∈ rightMSW2	0.47	0.219	0.215
28	Males	S = 132.176 + 4.081 ∈ rightMSW3	0.53	0.281	0.273
	Females	S = 136.146 + 2.430 ∈ rightMSW3	0.34	0.116	0.107
	Overall	S = 121.155 + 4.896 ∈ rightMSW3	0.55	0.304	0.301
29	Males	S = 134.299 + 3.490 ∈ rightMSW4	0.48	0.229	0.221
	Females	S = 141.044 + 1.614 ∈ rightMSW4	0.23	0.054	0.045
	Overall	S = 123.685 + 4.149 ∈ rightMSW4	0.48	0.232	0.228
30	Males	S = 142.404 + 2.333 ∈ rightMSW5	0.30	0.092	0.082
	Females	S = 121.968 + 3.400 ∈ rightMSW5	0.44	0.189	0.181
	Overall	S = 112.768 + 4.761 ∈ rightMSW5	0.52	0.271	0.268
31	Males	S = 138.877 + 1.196 ∈ rightDW1	0.28	0.079	0.069
	Females	S = 121.859 + 1.576 ∈ rightDW1	0.28	0.080	0.071
	Overall	S = 100.550 + 2.715 ∈ rightDW1	0.57	0.326	0.323
32	Males	S = 142.236 + 1.909 ∈ rightDW2	0.26	0.069	0.059
	Females	S = 145.640 + 0.791 ∈ rightDW2	0.11	0.013	0.003
	Overall	S = 116.532 + 3.595 ∈ rightDW2	0.45	0.206	0.202
33	Males	S = 153.050 + 1.162 ∈ rightDW3	0.15	0.023	0.013
	Females	S = 150.502 + 0.412 ∈ rightDW3	0.05	0.002	-0.008
	Overall	S = 119.734 + 3.624 ∈ rightDW3	0.43	0.185	0.181
34	Males	S = 149.815 + 1.377 ∈ rightDW4	0.22	0.048	0.038
	Females	S = 148.587 + 0.569 ∈ rightDW4	0.08	0.007	-0.004
	Overall	S = 123.438 + 3.176 ∈ rightDW4	0.44	0.189	0.185
35	Males	S = 147.527 + 1.638 ∈ rightDW5	0.26	0.068	0.059
	Females	S = 141.574 + 1.281 ∈ rightDW5	0.18	0.032	0.022
	Overall	S = 121.189 + 3.565 ∈ rightDW5	0.50	0.248	0.244
36	Males	S = 136.210 + 1.495 ∈ rightPW1	0.27	0.074	0.064
	Females	S = 116.600 + 2.135 ∈ rightPW1	0.36	0.130	0.122
	Overall	S = 99.216 + 3.203 ∈ rightPW1	0.62	0.390	0.387
37	Males	S = 134.160 + 1.981∈ rightPW2	0.33	0.110	0.100
	Females	S = 112.262 + 2.863 ∈ rightPW2	0.42	0.173	0.165
	Overall	S = 97.605 + 4.024 ∈ rightPW2	0.61	0.366	0.363
38	Males	S = 122.430 + 2.974 ∈ rightPW3	0.41	0.164	0.156
	Females	S = 108.685 + 3.536 ∈ rightPW3	0.47	0.218	0.210
	Overall	S = 94.630 + 4.727 ∈ rightPW3	0.68	0.467	0.464
39	Males	S = 126.738 + 2.862 ∈ rightPW4	0.40	0.158	0.149
	Females	S = 130.442 + 1.914 ∈ rightPW4	0.21	0.046	0.036
	Overall	S = 97.357 + 4.736 ∈ rightPW4	0.56	0.317	0.313
40	Males	S = 143.218 + 1.145 ∈ rightPW5	0.26	0.066	0.057
	Females	S = 129.446 + 1.382 ∈ rightPW5	0.28	0.077	0.067
	Overall	S = 109.015 + 2.648 ∈ rightPW5	0.55	0.298	0.295

S = stature; R =a correlation coefficient; R2 = coefficient of determination; AdjR2 = Adjusted coefficient of determination; SEE = standard error of estimation

determiner (Mountrakis *et al*., 2010; Meesuk, 2013; Torres *et al*., 2020). This could create a hypothesis of whether the metatarsal may be useful for other biological identifications, especially for stature, as there are no previous studies (Byers *et al*., 1989; Bidmos, 2008; Cordeiro *et al*., 2009) that used metatarsal width to estimate stature. Therefore, the aforementioned width measurement variables were considered interesting and have been analyzed in our stature estimation study.

For the results of this study, metatarsal length and width had a positive significant correlation with stature. The correlation coefficient between metatarsal length and stature was between 0.698 and 0.796, which is consistent with Byers *et al*. (1989) (correlation coefficient was 0.59 to 0.89), Bidmos's study (2008) (correlation coefficient was 0.44 to 0.73) and Codeiro's study (2009) (correlation coefficient was 0.7 to 0.8). In addition, the correlation coefficient between metatarsal width and stature was 0.413 to 0.712. Although the correlation coefficient between metatarsal width and stature is mostly rated in moderate width variables – proximal width and mid-shaft width – they were still selected in stepwise multiple linear regression (Table IIIb). In the results, it was confirmed that not only the length variable was reliable for stature estimation, but also the width variables resulted in variables that can be used as stature parameters.

When compared to previous studies, the correlation coefficient (R) and standard error of estimate (SEE) of the regression were consistent with other populations, *i.e*., South Africans (Bidmos, 2008) and Portuguese (Cordeiro *et al*., 2009) (Table V) with the R ranging from 0.675 to 0.841 and

Table IIIb. Equations of the stepwise multiple linear regression for stature estimation of males, females and overall, respectively.

Sample	Equation	R	R2	Adjust R2	SEE
Males	S = 51.054 + 0.872 ∈ leftML1 + 0.565 ∈ leftML2 + 2.065 ∈ rightMSW2	0.761	0.578	0.565	4.96
Females	S = 76.043 + 0.487 ∈ leftML3 + 0.566 ∈ leftML1 -1.818 ∈ leftDW2 + 1.395 ∈ rightPW2 + 1.401 ∈ leftMSW5	0.752	0.566	0.543	4.93
Overall	S = 45.188 + 0.909 ∈ leftML1 + 1.217 ∈ rightPW3 + 0.442 ∈ leftML3 + 0.872 ∈ rightMSW1 + 0.953 ∈ rightPW2 - 1.066 ∈ leftPW4	0.841	0.706	0.697	5.26

S = stature; R = correlation coefficient; R2 = coefficient of determination; AdjR2 = Adjusted coefficient of determination; SEE = standard error of estimation.

Table IV. Efficiency of the stepwise multiple linear regression (N = 40; M=25 and F=15).

Equation	MAE	Error of prediction					
		±0-6 cm		±6.01-12 cm		±12.01-18 cm	
		n	%	n	%	n	%
Males	3.81	20	80	5	20	0	0
Females	4.47	10	66.67	5	33.33	0	0
Overall	4.05	32	80	8	20	0	0

MAE = Mean of absolute error.

SEE ranging from ±3 to 5 cm. Moreover, when testing other population-specific equations using metatarsals on Thai individuals in order to identify the error rate of each method when applied to a Thai sample (Table V), the mean of absolute error (MAE) was in quite a wide range (±2.94 to 12.90 cm.). For instance, Bidmos (2008), generating stature estimation equations in the South African population, reported that the SEE of Bidmos's equation was lower than in our study; however, after testing Bidmos's equations with Thai individuals (n=40), the MAE was quite high, with 12.90 cm and 8.21 cm for males and females, respectively. The same results were seen in the Portuguese population (Cordeiro *et al*., 2009). Although the SEE of the Portuguese population for females and the overall sample was close to that of this study, and mean of stature of the Portuguese population was also close to that of the Thai population (in this study), the mean of stature of the Portuguese population was 170.4±7.16 cm and 161.9±6.19 cm for males and females, while the MAE, after testing Portuguese's equations with the Thai data, was slightly higher than that of this study for females and the overall sample. The results of this study confirmed that an equation generated from each population should be developed for specific populations appropriately. It also demonstrated that, not only the difference in the sample size, but other factors, including genetics, lifestyle, as well as environmental and geographic factors, also affect the accuracy of stature estimation.

Comparing the efficiency of generated multiple regression equations from metatarsals and other long bones (humerus, radius, ulna, femur, tibia and fibula) obtained from (Mahakkanukrauh *et al*., 2011) (Table VI), the SEE of metatarsals is close to those of long bones. It demonstrated that long bones, especially lower limbs, are efficient stature estimators, and metatarsals can estimate stature from skeletal remains for biological identification. As recent evidence indicates, the metatarsal is a reliable sex determiner, since accuracy is 81.5 % - 91.5 % (Meesuk, 2013) and after testing in a Thai population from another region of Thailand, the metatarsal is still a reliable determiner (80 % - 95.6 % of accuracy) (Phatsara *et al*., 2016). This empirical evidence suggests that the metatarsal is an attractive bone that can be used to determine sex and to effectively estimate stature at the same time.

Table V. Stature estimation efficiency compared to the previous studies.

Samples	Country	Author	Parameters	N	R	SEE	MAE
Males	South Africa	Bidmos, 2008	M1, M2, M4, M5p	60	0.710	3.81	12.90
	Portugal	Cordeiro *et al*., 2009	M2	88	0.762	4.71	2.94
	Thailand	Our study	leftML1, leftML2, rightMSW2	100	0.761	4.96	3.81
Females	South Africa	Bidmos, 2008	M1, M2	55	0.750	4.10	8.21
	Portugal	Cordeiro *et al*., 2009	M1	20	0.675	4.69	5.42
	Thailand	Our study	leftML3, leftML1, leftDW2, rightPW2, leftMSW5	100	0.752	4.93	4.47
Overall	Portugal	Cordeiro *et al*., 2009	M2	108	0.793	4.75	4.91
	Thailand	Our study	leftML1, rightPW3, leftML3, rightMSW1, rightPW2, leftPW4	200	0.841	5.26	4.05

N= Number of samples; R = correlation coefficient; SEE = standard error of estimation; MAE = Mean of absolute error.

Table VI. Comparison of the standard error of stature estimation between long bones and metatarsal bones.

Samples	Author	N	Bone	Measurement	SEE
Males		114	Humerus	Humerus(max)	5.69
		114	Radius	Radius (max)	5.73
		115	Ulna	Ulna (max)	5.79
	Mahakkanukrauh *et al*., 2011	94	Femur	Femur (max)	5.10
		97	Tibia	Tibia(max)	5.15
		98	Fibula	Fibula (max)	4.89
		93	Femur + Tibia	Femur (max), Tibia (max)	4.95
	Our study	100	Metatarsals	leftML1, leftML2, rightMSW2	4.96
Females		51	Humerus	Humerus(max)	6.05
		49	Radius	Radius (max)	5.63
		48	Ulna	Ulna (max)	5.86
	Mahakkanukrauh *et al*., 2011	37	Femur	Femur (max)	5.21
		36	Tibia	Tibia(max)	5.94
		41	Fibula	Fibula (max)	5.82
		33	Femur + Tibia	Femur (max), Tibia (max)	5.10
	Our study	100	Metatarsals	LeftML3, leftML1, leftDW2, rightPW2, leftMSW5	4.96
Overall		103	Humerus	Humerus(max)	5.91
		101	Radius	Radius (max)	5.80
		101	Ulna	Ulna (max)	5.97
	Mahakkanukrauh *et al*., 2011	82	Femur	Femur (max)	5.38
		83	Tibia	Tibia(max)	5.52
		88	Fibula	Fibula (max)	5.39
		78	Femur + Tibia	leftML1, leftML2, rightMSW2	5.27
	Our study	200	Metatarsals	LeftML1, rightPW3, leftML3, rightMSW1, rightPW2, leftPW4	5.26

N= Number of samples; SEE = standard error of estimation.

In the application of forensic science, this study has presented stature estimation equations from the metatarsal for males, females, and all samples. In the form of simple linear regression (Table IIIa), we recommend using these equations when only one bone is found at the crime scene, while stepwise multiple linear regressions (Table IIIb) are suggested when complete bones are found at a crime scene. Moreover, when skeletal remains are found, sex determination is the first thing to realize. Per recommendation, the osteometric method based on the os coxa (Mahakkanukrauh *et al*., 2017) or skull (Mahakkanukrauh *et al*., 2016) is efficient as a sex determiner, so the os coxa or skull should be the first choice to use as the sex determiner. However, in cases where the os coxa or skull is fragmented or is an incomplete bone, the metatarsal would be the second choice to determine sex, by referring to the method of sex determination using the metatarsal in the Thai population (Meesuk, 2013). After determining sex, stature estimation equations obtained from our study (Tables IIIa and IIIb) should be used using the specific sex equation, *e.g*., if male or female, we suggest using male/female equations, or if an unknown case, the overall equation should be used, respectively.

This study can be further developed in the future by developing measurements to improve the accuracy, increasing the sample size, or evaluating the efficiency of generated equations by testing in a Thai population from other regions to increase credibility. Furthermore, medical imaging technology and artificial intelligence methods may provide some hope for improvement in the outcome of stature estimation from metatarsal bones and increase the performance of personal identification in forensic osteology.

CONCLUSION

The purposes of this study are to analyze the correlation of metatarsal length and width of the left and right metatarsal against stature, and to generate linear regression equations for stature estimation in the Thai population. The study has found that metatarsals can be used as a stature estimator. Moreover, this study presented two kinds of stature estimation equations, which are a simple linear regression when only one bone is found at a crime scene, and a stepwise multiple linear regression to use when some bones are found at a crime scene. The correlation degree is rated moderate to strong. The correlation coefficient (R) of stepwise linear regression was 0.761, 0.752 and 0.841, and the standard error of estimate (SEE) was 4.96, 4.93 and 5.26 cm for males, females, and all samples, respectively.

After evaluating the equation efficiency, the mean of absolute error (MAE) was 3 to 5 cm. Compared with other long bones, metatarsals can be used as efficient stature estimators, since stature estimation equations from metatarsals have SEE close to that of long bones. As a result, it confirms that the metatarsal bone can estimate stature from skeletal remains in the Thai population and can be applied for forensic osteology to contribute to biological identification. To improve the method, we suggest that the researchers increase the sample size or evaluate the efficiency of generated equations by testing groups in Thai populations from other regions. Medical imaging technology and artificial intelligence methods may provide some hope for improvement in the outcome of stature estimation.

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NANAGARA, P.; MAHACHAROEN, T.; NAVIC, P.; INTASUWAN, P. & MAHAKKANUKRAUH, P. Estimación de la estatura basada en los huesos metatarsianos en una población tailandesa. *Int. J. Morphol., 41(3)*:985-995, 2023.

RESUMEN: La estimación de la estatura es uno de los procedimientos esenciales para la identificación personal en osteología forense. Por lo tanto, los propósitos de este estudio fueron analizar la correlación entre la longitud y el ancho de las medidas metatarsianas y la estatura, y desarrollar las ecuaciones de regresión para una población tailandesa. Las muestras se dividieron en dos grupos. El primer grupo se denominó “grupo de entrenamiento” para generar ecuaciones de estimación de estatura, compuesto por 200 esqueletos, con edades comprendidas entre los 19 y los 94 años. El segundo grupo se denominó "grupo de prueba" para evaluar la precisión de las ecuaciones generadas, que comprende 40 esqueletos. La correlación entre los parámetros metatarsianos y la estatura fue de moderada a alta, y todas las variables tuvieron una correlación significativa positiva con la estatura. Para el sexo masculino, la variable longitud ML2 izquierda es la que mayor grado de correlación presentó con la estatura (r=0,702), y la izquierda MSW4 fue la variable ancho la que mayor grado de correlación presentó con la estatura (r=0,483). Para el sexo femenino, ML1 derecho fue la variable longitud que tuvo mayor grado de correlación con la estatura (r=0,632), y PW3 derecha fue la variable ancho estatura que tuvo mayor grado de correlación con la estatura (r=0,481). Para todas las muestras, ML1 izquierdo fue la variable longitud que tuvo mayor grado de correlación con la estatura (r=0,796) y PW3 derecha fue la variable ancho que tuvo mayor grado de correlación con la estatura (r=0,712). Los resultados de generar ecuaciones de regresión múltiple usando un método paso a paso revela que el coeficiente de correlación (R) y el error estándar de estimación (SEE) fueron 0,761 y 4,96 cm, respectivamente, para los hombres y 0,752 y 4,93 cm para las mujeres, con 0,841 y 5,26 cm para todas las muestras, respectivamente. De acuerdo con estos resultados, la media del error absoluto del grupo de prueba osciló entre 3 y 5 cm. Por lo tanto, las ecuaciones de estimación de la estatura que utilizan la longitud y el ancho de los metatarsianos de nuestro estudio se pueden aplicar para estimar la estatura en la población tailandesa.

PALABRAS CLAVE: Estimación de estatura; Huesos metatarsianos; Osteometría; Población tailandesa; Osteología forense.

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