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Sex estimation using radius in a Thai population

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Abstract: The estimation of sex is an essential component of forensic osteological analyses, and the potential of an incomplete radius for sex determination of human remains is investigated. The present study was conducted on 200 left-right pairs of radial bone from a northern Thai population (100 males and 100 females). The most dimorphic single parameter was maximum head diameter (MDH) with accuracies 92.0% for the right side and 90.5% for the left side. At the distal part of radius, the distal end width of the radius (RDEW) was the best sex indicator, in which the sex classification accuracies were 91.5% and 89.0%, for the right and left sides, respectively. Stepwise discriminant function analysis was performed for all measurements and specified separately to the proximal and distal radius. The circumference of the radial neck, head-tuberosity length, MDH, and RDEW were selected for the stepwise procedure as these parameters produced the best correct classification results for both sides. The use of proximal radius for sex estimation was examined, with accuracies of 95.0% and 93.0% for the right and left sides, respectively. The sex classification functions for distal radius provided the accuracies of 92.5% and 89.5%, for the right and left sides, respectively. In summary, the fragments of radius indicated a high ability to estimate sex in the Northern Thai population.

Key words: Sex estimation, Radius, Thailand

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Introduction

Establishing a biological profile, which consists of sex, age, stature, and ethnicity, from unknown skeletal remains, is a crucial process in postmortem identification. This procedure assists in narrowing down the number of possible matches before applying a specific identification technique. Sex estimation is an important step in the identification of an unknown decedent because it influences other biological parameters, such as age and stature [1]. Moreover, correct sex classification will reduce the number of possible missing persons by half [1]. The sex of complete and well-preserved cadavers could simply be determined by external and internal genital organs. However, in the cases of severely decomposed, burned, dismembered and skeletonized human remains, bones are considered the second-best sex indicators.

The sex estimation methods for the skeletal remains are categorized into morphologic and metric. The sex determination from the pelvis is the most reliable morphologic method because it is proven to be the most sexually dimorphic skeletal element [2]. No instrument is needed for the morphologic analysis although the accuracy significantly depends on the expertise of the observer [3]. In addition, the incomplete condition of the bone will reduce the accuracy of the morphological method [4]. Furthermore, a pelvis may not always be recovered or complete in some cases. In contrast, metric approaches for sexing skeletons yield low

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subjectivity, and the accuracy of the method relies less on the experience of the practitioner than that of morphological observation [1, 3].

The measurements of long bone dimensions are actively studied for sex estimation using the metric techniques due to the sexual differences in size and robustness [3]. Various long bones show the potential in estimating sex [5]. Some studies reported that the dimensions of upper limb demonstrated higher ability to determine sex than those of lower limb [6, 7]. In 2001, Mall et al. [7] stated that radius performed the best among the three upper limb bones in sex estimation of samples from the contemporary German population. Similarly, previous studies also highlighted that the radius showed high degree of sexual dimorphism, and its dimensions could be used for estimating sex with high classification rates across many populations [6-13]. For instance, the antero-posterior diameter of the radial mid-shaft could predict the sex with the accuracy of 90.4% in the Indian population [11]. The radial length demonstrated accuracies of 86.7% and 89.4% in discriminating sexes for the right and left sides in Greek population, respectively [14].

Even though the radii may be promising candidates for metric sexing methods, most sex discriminant functions are derived from a specific population and may not be appropriate for different populations. Therefore, there is a need for developing a population-specific sex estimation function for each population. The assessment of sex using a complete radius in the northern Thai population was reported in 2004, with the accuracies of 86.9% and 89.4% for the right and left sides, respectively [8]. However, as their methodology requires an intact radius to estimate the sex, it may not be applicable to forensic settings where radius might be recovered in a fragmented condition due to the decomposition process and scavenging. Therefore, the aim of this study was to establish the population-specific sex estimation method from the fragments of the radius for the Northern Thai population.

Materials and Methods

Two hundred left-right pairs of radii (100 males and 100 females) were collected from the blind peer review. The source of radius bones were donated cadavers obtained from the northern region of Thailand. Exclusion criteria included bones with fractures, gross pathologic changes, and severe degenerative diseases. Sex, age at death, stature, race, occupation, and cause of death of all samples in this study were documented. The studied population consisted of individuals who were born between 1921 and 1995, and died between 2003 and 2015. The mean age for male samples was 63.92 years (range, 19–90 years); the mean age for female samples was 63.37 years old (range, 29–91 years). For age distribution of the samples used in this study, see Table 1.

Additional 40 left-right pairs of radii (20 males and 20 females) were selected to evaluate the accuracy of sex discriminant functions. The mean age was 63.05 years (range, 36–78.2 years) for male test samples, and that of female test samples was 59.3 years (range, 43–76 years). The test samples for both sexes were born between 1924 and 1974, and died between 2005 and 2014. This study was approved by the Research Ethics Committee of the Faculty of Medicine, Chiang Mai University, Thailand (No. FOR-2560-04927). Study period in a research was one year for data collection and data analysis.

Measurement

Eight measurements were taken from the right and left radii. Four of the eight measurements were taken according

Table 1. The age distribution of the samples regarding to sex

Age range (yr)	Male (n=100)		Female (n=100)		Total (n=200)	
	Frequency	Age (yr)	Frequency	Age (yr)	Frequency	Age (yr)
10–19	0	-	1	19	1	19
20–29	2	27.5±2.12	1	22	3	25.7±3.51
30–39	5	36.8±1.09	6	33.7±3.72	11	35.1±3.17
40–49	9	46.3±2.00	13	45.9±2.69	22	46.1±2.38
50–59	22	54.3±2.78	14	54.4±3.02	36	54.4±2.84
60–69	25	64.5±3.20	26	65.1±3.16	51	65.0±3.18
70–79	19	74.7±3.25	26	74.7±2.86	45	74.7±2.63
80–89	17	83.4±3.46	12	83.5±3.20	29	83.4±3.12
90–99	1	91.0	1	90.0	2	90.5±0.70

Values are presented as mean±SD.

Table 2. The definition of the radial measurements

Measurement	Description
1. Maximum diameter of head	Maximum value measured by digital Vernier caliper that rotates around the radial head [8, 9].
2. Minimum diameter of head	Minimum value measured by digital Vernier caliper that rotates around the radial head [8, 9].
3. Circumference of neck	Circumference at mid neck of radius (present study). The radius is placed with the anterior surface facing up. Circumference at mid radial neck were measured in millimeters by a standard tape.
4. Head-tuberosity length	Distance between the most proximal point on the head to the most proximal point on the tuberosity of the radius (present study). This measurement is taken by holding the radius so that the radial tuberosity faces towards the individual taking the measurement. The sliding calipers are positioned parallel to the longitudinal axis of the proximal radius with fixed arm on the most proximal point on the radial head. The calipers are then adjusted to meet the most proximal point on radial tuberosity.
5. Circumference of tuberosity	Circumference at mid tuberosity of radius [8].
6. Ulnar notch length	Maximum distance between the most anterior and posterior side of ulnar notch (present study).
7. Ulnar notch width	Maximum distance between the most distal and proximal side of ulnar notch. (present study).
8. Distal end width of the radius	Maximum distance between the most medial and lateral point on the distal epiphysis of radius [8].

Fig. 1. Eight measurements of radius. A: maximum diameter of head, B: minimum diameter of head, C: circumference of neck, D: head-tuberosity length, E: circumference of tuberosity, F: ulnar notch length, G: ulnar notch width, H: distal end width of the radius.

to the standards presented by Suwanlikhid and Mahakanukrauh (2004) [8] and Barrier and L'Abbé (2008) [9], and the remaining four measurements were devised for this study. Each sample was measured by the forensic physician (WJ). Twenty pairs of training samples were randomly chosen and measured again by the forensic physician (WJ) and another forensic physician (MB) to evaluate the intra and inter-observer reliability. For the descriptions of the eight measurements used in this study, see Table 2 and Fig. 1.

Statistics

The intra- and inter-observer errors were analyzed by the technical error of measurement (TEM), relative technical error of measurement (rTEM), and coefficient of reliability (R) [15, 16]. The descriptive statistics, such as mean, standard deviation and range was used to describe the value of each measurement. Independent *t*-test was performed to assess the differences in each measurement between both sexes, and normality of the data was tested by 1 sample Kolmogorov–Smirnov statistic. The measurements that showed statistically significant differences between both sexes were subjected to direct and stepwise discriminant function analyses. For the stepwise procedure, all selected variables were entered into a stepwise discriminant function using Wilks' lambda, in order to determine which variables would provide the best discrimination between male and female groups. The discriminant functions were generated separately for the right and left sides. The accuracy of sex estimation functions was expressed in percentage. Statistical significance was observed at the *P*-value below 0.05, and all data were analyzed by IBM SPSS Statistics ver. 22.0. (IBM Corp., Armonk, NY, USA).

Results

The difference between observations is described in Table 3. The R-value of all measurements was more than 0.9., and the ulnar notch width (UNW) demonstrated the highest percentage of rTEM for the inter-observer error whereas the

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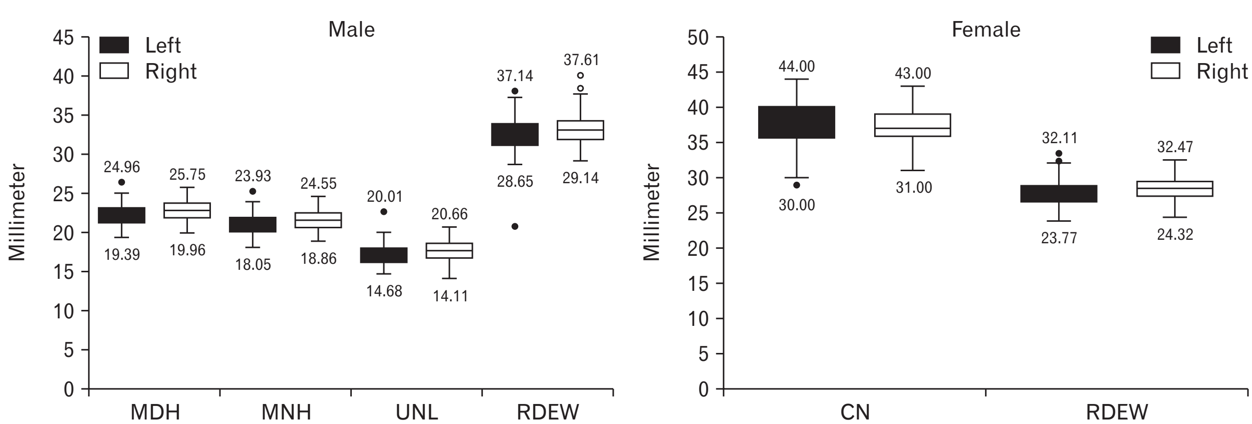
Table 3. The technical error of measurement (TEM) and coefficient of reliability of intra and inter-observer error

Measurement	Number	Side	Intra-observer error			Inter-observer error		
			TEM (mm)	Relative TEM (%)	R	TEM (mm)	Relative TEM (%)	R
Maximum diameter of head	20	Left	0.06	0.29	0.999	0.11	0.51	0.997
		Right	0.07	0.34	0.999	0.15	0.72	0.994
Minimum diameter of head	20	Left	0.08	0.43	0.998	0.08	0.43	0.998
		Right	0.08	0.42	0.998	0.09	0.46	0.998
Circumference of neck	20	Left	0.36	0.90	0.993	0.27	0.67	0.996
		Right	0.35	0.88	0.994	0.35	0.86	0.995
Head-tuberosity length	20	Left	0.18	0.86	0.994	0.29	1.31	0.980
		Right	0.18	0.86	0.994	0.30	1.38	0.981
Circumference of tuberosity	20	Left	0.32	0.68	0.995	0.32	0.69	0.992
		Right	0.38	0.82	0.993	0.39	0.85	0.989
Ulnar notch width	20	Left	0.12	1.02	0.996	0.22	1.83	0.989
		Right	0.10	0.86	0.996	0.23	1.95	0.979
Ulnar notch length	20	Left	0.17	1.01	0.987	0.21	1.33	0.959
		Right	0.18	1.11	0.987	0.27	1.68	0.958
Distal end width of the radius	20	Left	0.23	0.77	0.993	0.28	0.93	0.987
		Right	0.22	0.71	0.994	0.25	0.82	0.991

Table 4. The average value of measurements according to the side and sex

Measurement (mm)	Male			Female		
	Left	Right	*P*-value	Left	Right	*P*-value
Maximum diameter of head	22.29	22.71	<0.001	19.36	19.43	0.396
Minimum diameter of head	21.07	21.55	<0.001	18.35	18.42	0.385
Circumference of neck	43.78	43.56	0.226	37.61	36.99	<0.001
Head-tuberosity length	22.71	22.72	0.912	20.06	19.79	0.011
Circumference of tuberosity	49.86	50.12	0.160	43.63	43.75	0.449
Ulnar notch width	12.32	12.49	0.164	10.48	10.71	0.030
Ulnar notch length	17.26	17.71	<0.001	15.54	15.73	0.039
Distal end width of the radius	32.40	33.09	<0.001	27.86	28.41	<0.001



	MDH		MNH		UNL		RDEW	
Med	22.35	22.74	21.11	21.57	17.24	17.73	32.33	33.07
SD	1.21	1.19	1.24	1.25	1.28	1.36	2.17	1.82

	CN		RDEW	
Med	38.00	37.00	27.82	27.47
SD	1.86	1.67	1.86	1.61

Fig. 2. The boxplot diagram shows median values (Med), outliers, and standard deviation (SD) of maximum diameter of head (MDH), minimum diameter of head (MNH), ulnar notch length (UNL), distal end width of the radius (RDEW) in male samples and circumference of neck (CN) and RDEW in female samples.

highest percentage TEM for the intra-observer error was the ulnar notch length (UNL). However, none of the variables in which the value of rTEM was more than 1.5 for intra-observation error or more than 2 for inter observation error, which fell within the acceptable range [16]. These results indicated that the devised measurements in this study were reliable and reproducible. The high values of rTEM in inter-observation error of UNW and the intra-observation error of UNL might be contributed to the unclear margin of ulnar notch.

The dimensions of the right radius were larger than those of the left side in most parameters except head-tuberosity length (HTL) of female and circumference of the radial neck (CN), where the right side was smaller than the left side. Statistical significant differences between both sides were found at most dimorphic single parameter was maximum head diameter (MDH), minimum diameter of head (MNH), UNL and the distal end width of the radius (RDEW) in males, and CN and RDEW in females (Table 4). To investigate the effect of outliers causing false statistical significance in the present data, boxplot diagram with median values, outliers, and standard deviation for MDH, MNH, UNL, RDEW in males and CN, RDEW in females were created (Fig. 2). Outliers in the measurement data were identified, but the statistical significant difference between both sides was still observed even though the outliers were excluded from the analysis.

All measurements of males were significantly larger than those of females (Fig. 3, Table 5). The dimensions of the right

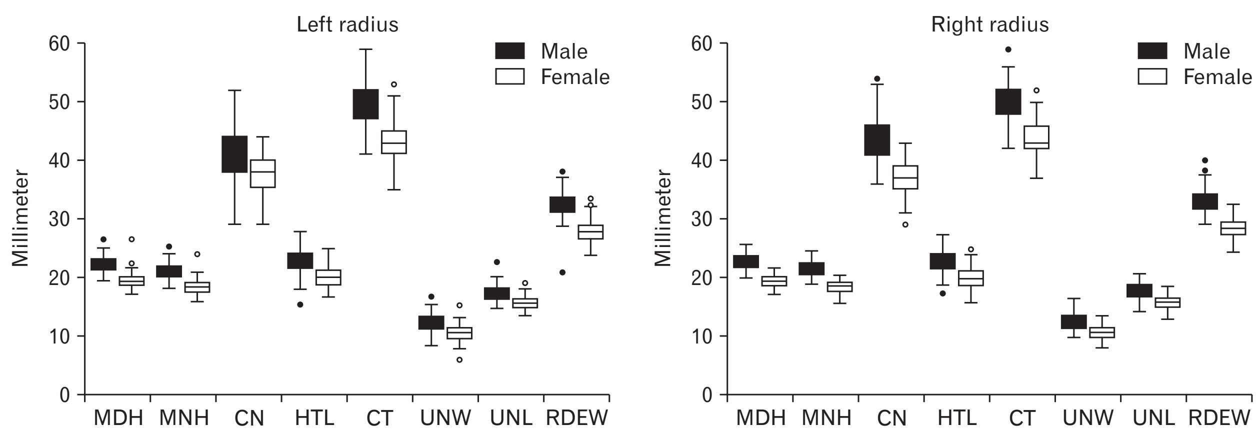


Fig. 3. The distribution of eight measurements of male and female samples for each side. MDH, maximum diameter of head; MNH, minimum diameter of head; CN, circumference of neck; HTL, head-tuberosity length; CT, circumference of tuberosity; UNW, ulnar notch width; UNL, ulnar notch length; RDEW, distal end width of the radius.

Table 5. Descriptive statistics independent *t*-test differences between sexes of the variables

Measurement (mm)	Side	Male				Female				Independent *t*-test	
		Min.	Max.	Mean	SD	Min.	Max.	Mean.	SD	*t*-value	*P*
Maximum diameter of head	Left	19.39	26.52	22.29	1.27	17.03	24.49	19.36	1.14	17.192	<0.001
	Right	19.96	25.75	22.71	1.19	17.09	21.63	19.43	1.09	20.360	<0.001
Minimum diameter of head	Left	18.05	25.21	21.07	1.25	15.88	23.91	18.35	1.13	16.171	<0.001
	Right	18.86	24.55	21.55	1.26	15.66	20.42	18.42	1.03	19.278	<0.001
Circumference of neck	Left	36.00	52.00	43.78	3.36	29.00	44.00	37.61	2.91	13.878	<0.001
	Right	36.00	54.00	43.56	3.66	29.00	43.00	36.99	2.90	14.073	<0.001
Head-tuberosity length	Left	15.28	27.76	22.71	2.07	16.56	24.84	20.06	1.72	9.831	<0.001
	Right	17.32	27.37	22.72	1.89	15.61	24.82	19.79	1.74	11.404	<0.001
Circumference of tuberosity	Left	41.00	59.00	49.86	3.36	35.00	53.00	43.63	3.09	13.660	<0.001
	Right	42.00	61.00	50.12	3.48	37.00	52.00	43.75	3.16	13.546	<0.001
Ulnar notch width	Left	8.26	16.71	12.32	1.62	6.89	15.18	10.48	1.39	8.620	<0.001
	Right	9.79	16.43	12.49	1.56	8.01	13.45	10.71	1.18	9.129	<0.001
Ulnar notch length	Left	14.68	22.55	17.26	1.28	13.42	18.97	15.54	1.09	10.219	<0.001
	Right	14.11	20.66	17.71	1.36	12.89	18.58	15.73	1.16	11.079	<0.001
Distal end width of the radius	Left	20.80	38.07	32.40	1.28	23.77	33.39	27.86	1.86	17.367	<0.001
	Right	29.14	39.99	33.09	1.80	24.32	32.47	28.41	1.62	19.324	<0.001

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Table 6. Direct discriminant function percent of accuracy and corrected percentage of accuracy for radius

Function	Variable	Unstandardized coefficients	Group centroid	Predicted group	Accuracy (%)		
					M	F	Total
Right							
1	MDH	0.876	M=1.440	Original	92.0	92.0	92.0
	Constant	−18.465	F=−1.440	Cross-validated	92.0	92.0	92.0
2	MNH	0.871	M=1.363	Original	90.0	93.0	91.5
	Constant	−17.417	F=−1.363	Cross-validated	90.0	93.0	91.5
3	CN	0.303	M=0.995	Original	81.0	92.0	86.5
	Constant	−12.201	F =−0.995	Cross-validated	81.0	92.0	86.5
4	HTL	0.550	M=0.806	Original	83.0	80.0	81.5
	Constant	−11.698	F=−0.806	Cross-validated	83.0	80.0	81.5
5	CT	0.310	M=0.958	Original	86.0	82.0	84.0
	Constant	−14.115	F=−0.958	Cross-validated	86.0	82.0	84.0
6	UNW	0.724	M=0.646	Original	69.0	77.0	73.0
	Constant	−8.397	F=−0.646	Cross-validated	69.0	77.0	73.0
7	UNL	0.792	M=0.783	Original	75.0	83.0	79.0
	Constant	−13.244	F=−0.783	Cross-validated	75.0	83.0	79.0
8	RDEW	0.584	M=1.366	Original	91.0	93.0	92.0
	Constant	−17.953	F=−1.366	Cross-validated	91.0	92.0	91.5
Left							
9	MDH	0.831	M=1.216	Original	90.0	91.0	90.5
	Constant	−17.295	F=−1.216	Cross-validated	90.0	91.0	90.5
10	MNH	0.840	M=1.143	Original	87.0	94.0	90.5
	Constant	−16.568	F=−1.143	Cross-validated	87.0	94.0	90.5
11	CN	0.318	M=0.981	Original	86.0	85.0	85.5
	Constant	−12.944	F=−0.981	Cross-validated	86.0	85.0	85.5
12	HTL	0.525	M=0.695	Original	77.0	77.0	77.0
	Constant	−11.237	F=−0.695	Cross-validated	77.0	77.0	77.0
13	CT	0.310	M=0.966	Original	82.0	82.0	82.0
	Constant	−14.494	F=−0.966	Cross-validated	82.0	82.0	82.0
14	UNW	0.663	M=0.609	Original	72.0	77.0	74.5
	Constant	−7.559	F=−0.609	Cross-validated	72.0	76.0	74.0
15	UNL	0.843	M=0.723	Original	72.0	79.0	75.5
	Constant	−13.827	F=−0.723	Cross-validated	72.0	79.0	75.5
16	RDEW	0.540	M=1.228	Original	89.0	90.0	89.5
	Constant	−16.283	F=−1.228	Cross-validated	89.0	89.0	89.0

M, male; F, female; MDH, maximum diameter of head; MNH, minimum diameter of head; CN, circumference of neck; HTL, head-tuberosity length; CT, circumference of tuberosity; UNW, ulnar notch width; UNL, ulnar notch length; RDEW, distal end width of the radius.

radius demonstrated a higher t-value than those of the left side except for circumference of tuberosity (CT) (Table 5). The MDH showed the highest sexual dimorphism (*t*: 20.360) in right radius followed by RDEW (*t*: 19.324) and MNH (*t*: 19.278) while RDEW was the most sexually dimorphic parameter in the left radius (*t*: 17.367) followed by MDH (*t*: 17.192) and MNH (*t*: 16.171). On the contrary, UNW indicated the lowest sexual dimorphism for both sides (*t*: 9.129, 8.620). The result of 1 sample Kolmogorov–Smirnov test suggested all variables were distributed normally.

The accuracy rates of sex estimation functions using single parameter of the radius in this study ranged from 73.0% to 92.0%, and most of the radial dimensions could predict the sex with accuracy over 80% except for both sides of the UNW, UNL and left HTL (Table 6). Some of the devised measurements in this study, namely CN and HTL, indicated high ability to predict sex. The CN performed the best among the four devised radial measurements in correct sex classification, in which the percentage of accuracy of right and left were 86.5% and 85.5%, respectively. The sex discriminant function for right HTL provided the accuracy of 81.5% whereas left HTL could predict the sex with the accuracy of only 77.0%. The UNW showed the lowest ability to predict the sex among the devised and all measurements in this study, in which the classification rates were 73.0% and 74.0% for the right and left sides, respectively. The MDH dis-

Table 7. Stepwise discriminant function, percent of accuracy and corrected percentage of accuracy for radius

Function	Variable	Unstandardized coefficient	Group centroid	Predicted group	Accuracy (%)		
					M	F	Total
17	Right radius						
	MDH	0.332	M=1.810	Original	96.0	96.0	96.0
	CN	0.090	F=–1.810	Cross-validated	96.0	96.0	96.0
	HTL	0.204					
	RDEW	0.286					
	Constant	–23.754					
18	Right proximal						
	MDH	0.569	M=1.622	Original	95.0	95.0	95.0
	CN	0.101	F=–1.622	Cross-validated	95.0	95.0	95.0
	HTL	0.243					
	Constant	–21.216					
19	Right distal						
	UNW	0.144	M=1.443	Original	91.0	94.0	92.5
	UNL	0.181	F=–1.443	Cross-validated	91.0	94.0	92.5
	RDEW	0.485					
	Constant	–19.611					
20	Left radius						
	MDH	0.270	M=1.623	Original	95.0	96.0	95.5
	CN	0.111	F=–1.623	Cross-validated	95.0	95.0	95.0
	HTL	0.205					
	RDEW	0.271					
	Constant	–22.667					
21	Left proximal						
	MDH	0.524	M=1.472	Original	94.0	92.0	93.0
	HTL	0.210	F=–1.472	Cross-validated	94.0	92.0	93.0
	CT	0.137					
	Constant	–21.810					
22	Left distal						
	UNW	0.167	M=1.266	Original	90.0	89.0	89.5
	RDEW	0.490	F=–1.266	Cross-validated	90.0	89.0	89.5
	Constant	–16.658					

M, male; F, female; MDH, maximum diameter of head; CN, circumference of neck; HTL, head-tuberosity length; RDEW, distal end width of the radius; UNW, ulnar notch width; UNL, ulnar notch length; CT, circumference of tuberosity.

played the highest ability to estimate sex in this study, with accuracies of 92.0% and 90.5% for the right and left sides, respectively.

Stepwise discriminant function analysis was carried out for all measurements and for different segments of radius (proximal and distal). The right radius showed higher ability to estimate sex than the left, and the accuracy rate of proximal part was higher than that of distal part of radius. MDH, CN, HTL, and RDEW were chosen for stepwise discriminant functions for both sides as these parameters presented high classification accuracies of 96.0% and 95.0% for the right and left sides, respectively. The proximal radius could be used for sex estimation with accuracy rates of 95.0% for the right radius and 93.0% for the left radius. MDH, CN and HTL were selected for sex estimation function for the right proximal radius whereas the parameters of the function for left proximal radius were MDH, HTL and CT. The sex estimation functions of distal radius provided accuracy rates of 92.5% and 89.5% for the right and left radius, respectively; UNW, UNL and RDEW were selected for right distal radius while only UNW and RDEW were chosen for left distal radius (Table 7).

The sectioning point of the discriminant functions was calculated from the average of the summation of group centroid value. In the present study, the sectioning point of all functions was 0, so if the score of the discriminant function analysis was more than 0, then the sample would be classified as male whereas if the score was less than 0, the result

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Table 8. The accuracy of testing sex discriminant function to the test samples

Function	Variable	Accuracy (%)		
		Male	Female	Total
Right				
1	MDH	95.0	100.0	97.5
2	MNH	95.0	95.0	95.0
3	CN	90.0	90.0	90.0
4	HTL	85.0	85.0	85.0
5	CT	90.0	90.0	90.0
6	UNW	87.5	87.5	87.5
7	UNL	90.0	90.0	90.0
8	RDEW	95.0	95.0	95.0
17	MDH, CN, HTL, RDEW	95.0	100.0	97.5
18	MDH, CN, HTL	100.0	100.0	100.0
19	UNW, UNL, RDEW	90.0	95.0	92.5
Left				
9	MDH	90.0	90.0	90.0
10	MNH	95.0	95.0	95.0
11	CN	92.5	92.5	92.5
12	HTL	85.0	85.0	85.0
13	CT	95.0	95.0	95.0
14	UNW	90.0	90.0	90.0
15	UNL	95.0	95.0	95.0
16	RDEW	85.0	85.0	85.0
20	MDH, CN, HTL, RDEW	90.0	100.0	95.0
21	MDH, HTL, CT	95.0	100.0	97.5
22	UNL, RDEW	85.0	100.0	92.5

MDH, maximum diameter of head; MNH, minimum diameter of head; CN, circumference of neck; HTL, head-tuberosity length; CT, circumference of tuberosity; UNW, ulnar notch width; UNL, ulnar notch length; RDEW, distal end width of the radius.

Table 9. Comparison the percentage of accuracy of sex estimation using radial dimension with other populations

Author (yr)	Population	Parameter	Accuracy (%)
Mall et al. (2001) [7]	German	MDH, MRL, RDEW	88.6–89.1
Safont et al. (2000) [6]	Late Roman period site of Mas Rimbau/Mas Mallol	CT, Msc	90.0–93.0
Suwanlikhid and Mahakkanukrauh (2004) [8]	Northern Thai	MRL, MDH, MNH, RDEW, W, HC, CT, Msc	86.9–89.4
Sakaue (2004) [17]	Japanese	MRL, SHD, THD, RDEW, NB, MSA	80.0–98.0
Barrier and L'Abbé (2008) [9]	South African	MRL, RDEW, Min-Ms, Max-Ms, VHD, MDH, MNH, HC, CT	81.0–86.5
Charisi et al. (2011) [14]	Greek	MRL, MRPW, RDEW	93.5–95.1
Uzün et al. (2011) [10]	Turkish	MRL, Ms-AP, Ms-tran, RDEW	90.4–91.9
Waghmare et al. (2012) [11]	Indian	MSc, Ms-AP, Ms-tran, CT, AP-RT, V-RT	71.7–90.4
Martin et al. (2016) [12]	British medieval populations	MRL, MRPW, RDEW	91.2–95.5
Duangto and Mahakkanukrauh (2020) [18]	Northern Thai	MRL, Ms-AP, MLR	77.6–95.2
Current study (2020)	Northern Thai	MDH, MNH, CN, CT, UNL, UNW, RDEW	76.0–96.0

MDH, maximum diameter of head; MRL, maximum length; RDEW, distal end width of the radius; CT, circumference of tuberosity; Msc, mid shaft circumference; MNH, minimum diameter of head; W, weight; HC, head circumference; SHD, sagittal head diameter; THD, transverse head diameter; NB, notch breadth; MSA, mid shaft area; Min-Ms, minimum midshaft diameter; Max-Ms, maximum midshaft diameter; VHD, vertical head diameter; MRPW, maximum radial proximal width; Ms-AP, midshaft anteroposterior; Ms-tran, midshaft transverse; AP-RT, antero-posterior diameter of the radial tuberosity; V-RT, vertical diameter of tuberosity; MLR, medio-lateral diameter at midshaft of radius; CN, circumference of neck; UNL, ulnar notch length; UNW, ulnar notch width.

would suggest female. On the test sample, the accuracy of the single-variable sex discriminant function for the right radius ranged from 85.0% to 97.5% and around 85.0% to 95.0% for the left radius, which performed better than those of the studied samples (Table 8). MDH was still regarded the best sex discriminator for the right radius although MNH, CT, and UNL indicated the highest classification accuracy for the left radius among the test samples. Multivariate discriminant function increased the accuracy rate of sex prediction for both sides, and the accuracy rates of sex estimation function for the right radius and proximal part were better than those of the left radius and distal part, as illustrated by the results of the training samples.

Discussion

Identification of the skeletal fragments remains a challenging task for forensic pathologists. According to our results, fragmented radius showed potential for sex estimation with a high classification rate, and the devised measurements of this study were reproducible without significant errors. The right radius indicated higher ability to predict the sex than the left side while proximal part was more reliable than the distal part for sex determination in fragmented radius.

The high sex discrimination rate in the present study is consistent with previous studies using radius for sex estimation in various populations (Table 9) [6, 7, 10, 12, 14, 17, 18]. In a study of German population, Mall et al. [7] found that maximum diameter of head, maximum length, and distal end width of the radius produced a high accuracy of 94.93% when all three variables were applied together. Moreover, the correct sex discriminant rates for Japanese [17], Greek [14], Turkish [10], and British medieval populations [12] were also over 90%. However, the level of accuracy was only 86.5% for complete radius from South African samples whereas the incomplete radius resulted in 86% of accuracy [9]. In addition, the accuracy of sex estimation function using radius from Indian and archaeological Polish population was less than 90% [9, 11, 13]. The discrepancy might be caused by the variation across different populations, in which differential environmental and genetic factors affect the degree of sexual dimorphism expression in each population [19]. Moreover, inconsistent standard measurements in various studies may also affect the accuracy of sex estimation model.

Most of the radial dimensions in this study, such as MDH, CT, HTL and RDEW, were smaller than those of other populations [6, 7, 9, 10, 14]. However, our results suggested that the dimensions of radius still demonstrated significant sexual dimorphism in the Northern Thai population. MDH indicated the highest sexual dimorphism of all measurements used in this study, in which the classification rate of right MDH was 92% and 90.5% for the left side. The accuracy rate was higher than those of German and South African populations [7, 9]. The sex classification accuracy of MNH was equal to left MDH (90.5%), and the classification rate of MNH was equal to right RDEW (91.5%). However, there was no report of accuracy rate for single variable sex estimation function using MNH to compare with other populations. CT showed fair accuracy in estimating sex in Thai population, but the classification rate was dramatically lower than those of archaeological Spanish population (92.8%) [6]. The RDEW was the best discriminant parameter for distal radius, in which the accuracy rates were 91.5% and 89% for the right and left sides, respectively. The accuracy of sex estimation using RDEW in this study was higher than those of German and South African populations but slightly lower than those of European white and black samples [7, 9, 20].

The average dimensions of MDH, MNH, CT and RDEW, which were also used for estimating sex in previous study on the Northern Thai population [8], in our study were different from the aforementioned report. However, the significant difference was only found in the RDEW and MNH dimensions. The dimensions of right and left RDEW in male samples in our study were 2.72 mm and 3.02 mm larger than those of previous study, respectively (*t*-test, $P<0.001$). For female samples, the dimensions of right and left RDEW were 1.79 mm and 1.88 mm larger than those of previous study, respectively (*t*-test, $P<0.001$). The average of left MNH from male samples was 0.51 mm larger than those of previous study (*t*-test, $P<0.05$) but the average of right MNH from female samples was 0.37 mm smaller than those of previous study (*t*-test, $P<0.05$). The different in size of present and past study might be explained by the different of sample selection and the secular changes in Thai population [21]. Our report studied the individuals who died between 2003 and 2015 whereas the previous report obtained the specimens who died between 1993 and 2001. In addition, the difference in overall living conditions between these two generational populations might impact skeletal dimensions [21].

Bilateral asymmetry was detected in some dimensions among our samples; the right radius was more accurate in predicting sex than left radius. The result of this study is consistent with the previous study focused on Greek population [14], in which maximum radial length, maximum radial proximal width, and maximum radial distal width of right radius could estimate sex with higher accuracy than those of left side. However, the sex estimation functions using maximum head diameter and midshaft circumference of left radius were more accurate than those of right radius in the Northern Thai population [8].

The accuracy of sex estimation functions using proximal radius was higher than those of distal radius in the present study. This phenomenon could be contributed to the fact that the proximal part was more affected by a carrying angle of the elbow, where sexual dimorphism is significantly expressed, than the distal part of radius [17].

The sex discriminant functions in our study are applicable to both complete and incomplete radius of modern Thai skeletons, particularly, from the Northern Thailand region. Nevertheless, the validity of sex estimation functions of tarsal bone, derived from the Northern Thai population, was examined on the Northeastern Thai population in another study [22]. The results suggested that the sex estimation functions derived from Northern Thai samples could also predict the sex in the Northeastern Thai population with high accuracy. However, the misclassification usually occurred among the Northeastern Thai samples that had greater height than the maximum height of the Northern Thai samples [22]. Therefore, the application of sex discriminant functions from this study can potentially extend to other Thai regional populations although caution must be taken when the estimated height is higher than the maximum height in this study (190 cm for male and 170 cm for female).

The use of radial fragments in sex estimation was investigated on the Northern Thai population. This study provides sex estimation functions for various measurements that can be applied to radius from Northern Thai individuals with accuracy over 85%. The stepwise discriminant function analysis of proximal and distal radius could improve the accuracy of sex estimation functions to more than 90%.

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Conflicts of Interest

No potential conflict of interest relevant to this article was reported.

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