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Determining Sex from Thai Radius: Discriminant Function Analysis Including the Dry Bone Weight as an Effective Variant

Determinación del Sexo a Partir del Radio Tailandés: Análisis de Función Discriminante que Incluye el Peso del Hueso Seco como Variante Eficaz

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SUMMARY: In forensic anthropology, the radius bone has been shown to determine the sex of human remains in a number of different populations. The dry mass and growth of long bones, including the radius, are associated with sex hormone levels; however, the use of bone weight to determine sex has not been sufficiently investigated. The aim of this study was to apply bone morphometric parameters, including maximum length of radius (MLR), circumference at the midshaft of radius (CMR), and weight of radius (WR), to 400 sample radii from a Northeastern Thai population. Univariate and multivariate discriminant functions of all parameters were systemically applied. Equations for calculating sex classification were also determined. Descriptive data analysis showed significant sexual dimorphism in all variables ($p < 0.05$). The canonical correlation was highest in CMR (0.772) and the ratio of weight to length (0.747). Multivariate discriminant function analysis showed that the measured indices of the right radius were slightly greater than those of the left radius. The parameters demonstrating the highest values of the standardized canonical discriminant function coefficients were CMR (Rt. = 0.496, Lt. 0.431) and WR (Rt. = 0.681, Lt. = 0.715). Moreover, the results of the multivariable (stepwise method) indicated that the best accuracy rates for using combinations of CMR and WR were 94 % (right side) and 92 % (left side). In conclusion, the weight of the radius (rather than the length) is an effective parameter in determining sex.

KEY WORDS: Radius; Sex determination; Discrimination analysis; Accuracy rate.

INTRODUCTION

In forensic anthropology, sex determination from bones is an important method used to identify human remains. The complete forensic analysis of bones is important for understanding the details of skeletal remains, such as stature, sex, race, and age (Austin & King, 2016; Spradley, 2016; Hughes *et al*., 2021). In many cases, bone parameters can help investigators resolve problems. Sex determination has been performed based on parameters of the pelvis (Steyn & Iscan, 2008) and skull (Luo *et al*., 2013; Zhan *et al*., 2019), and analysis of the bones is considered the best approach for determining sex. However, in some cases, only a part of the skeleton or parts of bones are all that remain as physical evidence. In these cases, sex can be determined from bones by measuring the lengths of the upper limb bones (Lee *et al*., 2014), lower limb bones (Robinson & Bidmos, 2011), vertebrae (Yu *et al*., 2008; Zheng *et al*., 2012; Rozendaal *et al*., 2020), and scapula (Ali *et al*., 2018).

In determining sex from long bones, the morphometric parameters measured are the maximum length and width, as well as the circumference at the mid-shaft. The radius, a long bone of the antebrachium, has no prominent tubercle or bony crest and is usually found with other bone remains. Statistical analysis has been applied to identify sex based on the radii in the following populations: Japanese (Sakaue, 2004), German (Mall *et al*., 2001), Turkish (Uzün *et al*., 2011), Greek (Charisi *et al*., 2011), Indian (Waghmare *et al*., 2012), and Northern Thai (Duangto & Mahakkanukrauh, 2020). The standard measurements made are maximum length, diameters of the sagittal and transverse

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heads, distal end width, maximum diameter of the head, and circumference at mid-shaft of the radius; these measurements are used in variant combinations in calculations to determine sex. Although the bone mass or weight of long bones is associated with the levels of sex hormones, the weight of the dried radius has not been included in the univariate and multivariate discriminant functions for index measurements. More research is needed to evaluate the use of radius in estimating the sex of human remains (Ubelaker & DeGaglia, 2017). Accordingly, we used multivariate discriminant functions and stepwise methods to investigate the potential of radius weight as a reliable indicator of sex.

MATERIAL AND METHOD

Sample collection and ethics. We used as study materials 400 dried radial bones (200 pairs of left and right radii) from 200 skeletons (age 20-75 years; 100 females and 100 males) provided by the Unit of Human Bone Warehouse for Research (UHBWR), Department of Anatomy, Faculty of Medicine, Khon Kaen University, Thailand. From this initial group, we excluded from the analysis of parameters those radii that were found to be incomplete due to morphological changes, including malignant bone tumors, pathological fractures, lytic lesions, and deformities. This study was approved by the Center for Ethics in Human Research at Khon Kaen University (code number: HE661238).

Measurements and metric analysis. The maximum length (cm) of the radius (MLR) on each side was randomly measured using an osteometric board, as shown in Figure 1A. The circumference at the mid-shaft of the radius (CMR) was measured using a nylon filament before measuring its length using a standard ruler (Fig.1B & C).

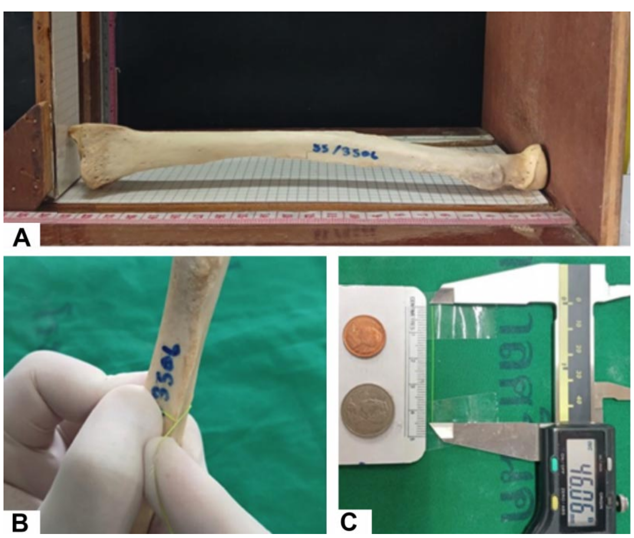

Fig. 1. Measurement of the maximum length of radius (MLR) using an osteometric board (A) and circumference at midshaft of radius (CMR) using nylon filament (B) before measuring its length with digital vernier caliper (C).

The weight of the radius (WR) was determined using a digital scale. All raw data were obtained from duplicate measurements performed at different times by two observers. The ratio of WR to MLR was then determined and used as the derived variable in this study.

Statistical analysis. All of the measurements made in this study were analyzed using SPSS V.23.0, to compare the average values of each side by the independent t-test. Discriminant function analysis was used for sex determination using univariate and multivariate equations. The data are expressed as mean ± SD, and differences were considered statistically significant at $p < 0.05$.

RESULTS

The average age of the individuals from which the radii (n = 400) were obtained was 57.12±9.85 years (female, 55.22±9.27 years; male, 59.02±10.07 years). Descriptive statistical analyses (Table I) showed that both the left and right MLR and CMR values were significantly greater in males than in females ($p < 0.05$). In addition, the ratio of WR to MLR (W/L) of the left and right radii was higher in males, as shown in Table I.

As shown in Table II, the results of the univariate discriminant function analysis demonstrated that the canonical correlation in group determination was highest in the parameter of WR (0.772), followed by that of W/L (0.747). The highest eigenvalue was associated with the left WR (1.476), whereas the lowest was associated with the right MLR (0.579). Applying the Wilks' lambda test to determine the power of group classification, the WR of both sides (Lt. and Rt.) had the best power value (0.404) (Table II). This finding is corroborated by the value of the canonical correlation.

The results of the multivariate discriminant functions, analyzed using the stepwise method, showed that the statistical values of the right radius were slightly greater than those of the left radius (Table III). As selected by the stepwise method, the best parameters -those demonstrating the highest values of the standardized canonical discriminant function coefficients -were the CMR and WR of either side (Rt. and Lt.), as shown in Table III.

After the selection of potential parameters based on the stepwise method (Table III), the calculations of sex classification were performed (as shown in Table IV). The accuracy rate of all radial variables was greater than 80 %. The results for these equations indicated that the best accuracy rates for sex determination were 94 % and 92 % for the multi-variable right and left radii, respectively.

Table I. Descriptive statistics of the radius: comparison by sex of right (Rt) and left (Lt) sides.

Variables	Males			Females			Sectioning point	p-value
	Min-max	Mean	SD	Min-max	Mean	SD		
Rt.MLR (cm)	19.30-27.20	24.11	1.34	20.30-27.40	22.23	1.13	23.15	0.001*
Lt.MLR (cm)	19.00-26.80	24.07	1.33	20.10-26-40	22.01	0.97	23.06	0.001*
Rt.CMR (cm)	3.50-5.30	4.43	0.32	3.30-4.50	3.79	0.28	4.11	0.001*
Lt.CMR (cm)	3.60-5.20	4.42	0.33	3.30-4.50	3.80	0.27	4.11	0.001*
Rt.WR (g)	18.85-60.50	40.48	6.88	16.85-42.30	26.34	4.60	33.42	0.001*
Lt.WR (g)	21.00-60.75	39.69	6.83	16.35-40.60	25.72	4.48	32.62	0.001*
Rt.W/L ratio	0.86-2.31	1.67	0.23	0.80-1.86	1.19	0.20	1.43	0.001*
Lt. W/L ratio	0.94-2.28	1.64	0.23	0.71-1.80	1.17	0.19	1.41	0.001*

* Significant statistical difference when $p < 0.05$, compared between the sexes.

Table II. Univariate discriminant functions of index measurements of radius.

Variables	Canonical correlation	Eigenvalue	Wilks' lambda	Chi-square	p-value
Rt.MLR	0.606	0.579	0.633	90.272	0.001
Lt.MLR	0.665	0.791	0.558	115.084	0.001
Rt.CMR	0.731	1.146	0.466	150.858	0.001
Lt.CMR	0.716	1.050	0.487	141.983	0.001
Rt.WR	0.772	1.473	0.404	178.844	0.001
Lt.WR	0.772	1.476	0.404	179.056	0.001
Rt.W/L ratio	0.747	1.259	0.443	160.987	0.001
Lt. W/L ratio	0.739	1.206	0.453	156.224	0.001

Table III. Multivariate discriminant functions for measurement index of radius.

Side of radius	Canonical correlation	Eigenvalue	Wilks' lambda	Chi-square	p-value	Standardized canonical discriminant function coefficients
Right radius	0.805	1.842	0.352	205.765	<0.001	Rt.CMR = 0.496 Rt.WR = 0.681
Left radius	0.795	1.719	0.368	197.026	<0.001	Lt.CMR = 0.431 Lt.WR = 0.715

Table IV. Equations of sex classification using indices of radius.

Variables	Equations of sex classification		Accuracy rate (%)
	Male	female	
Rt.MLR	15.717(Rt.MLR)-190.121	14.493(Rt.MLR)-161.784	81.50
Lt.MLR	17.799(Lt.MLR)-214.919	16.278(Lt.MLR)-179.853	82.50
Rt.CMR	49.390(Rt.CMR)-110.042	42.273(Rt.CMR)-80.801	86.00
Lt.CMR	47.766(Lt.CMR)-106.280	41.057(Lt.CMR)-78.701	82.00
Rt.WR	1.182(Rt.WR)-24.606	0.769(Rt.WR)-10.819	91.50
Lt.WR	1.189(Lt.WR)-24.285	0.770(Lt.WR)-10.601	90.50
Rt.W/L Ratio	34.959(Rt. W/L Ratio)-29.947	24.752(Rt. W/L Ratio)-15.359	88.00
Lt. W/L Ratio	34.700(Lt. W/L Ratio)-29.214	24.661(Lt. W/L Ratio)-15.099	88.50
Multi-variable (stepwise method)			
Rt. radius	48.424(Rt.CMR)+0.115(Rt.WR)-110.225	43.953(Rt.CMR)-0.20(Rt.WR)-81.357	94.00
Lt. radius	48.334(Lt.CMR)-0.061(Lt.WR)-106.327	44.635(Lt.CMR)-0.384(Lt.WR)-80.566	92.00

DISCUSSION

The radial bones used in this study were obtained from a Northeastern Thai population. In this population, bone development is complete at approximately 20 years of age, when the epiphyseal plate is usually closed. It has been documented that the radius ceases development between 15 and 18 years in both sexes (Kraus *et al*., 2011). In contrast, the structural maturation of the clavicle occurs at approximately 26 years of age (26.3 yr in males; 26.8 yr in females; Pattamapaspong *et al*., 2015), Therefore, three variants used to measure in our study did not affect all analyses because the lowest age of radii was 24 years. Indeed, in a previous study, it was reported that MLR was a variant factor for bone analysis because of the unclosed epiphyseal plate (Pines & Hurwitz, 1991). In the present study, we found significant differences in all measured parameters between male and female radii. Three radial parameters, namely length, circumference, and dried weight, were significantly greater in males than in females. This could be because testosterone begins to stimulate long bone growth during the male embryonic period (Handelsman *et al*., 2018). The testosterone hormone in blood serum is directly involved in musculoskeletal development to facilitate the strengthening of the human body (Handelsman *et al*., 2018). Particularly during puberty, this hormone increases the growth rate of long bones, resulting in what is known as the growth spurt. In contrast, increasing estrogen hormone levels in female serum are involved in the maturation of long bones by stimulating the closure of the epiphyseal plate. Soliman *et al*. (2014) showed that the growth spurt in male puberty was approximately 4 years compared to 3 years in females, which suggests that females have shorter bone development period than do males. In the same vein, the weight of the male radius in our samples was greater than that of females, most likely because the average age of our samples was over 50 years, which is the age at which menopause causes reduced estrogen hormone levels; lower estrogen levels can increase the risk of developing osteoporosis (Ji & Yu, 2015). Additionally, it has been confirmed that estrogen deficiency stimulates osteoclast production in cancellous bone, resulting in decreased bone mass and disruption of bone microarchitecture (Väänänen & Härkönen, 1996; Cawthon, 2011; Sözen *et al*., 2017).

The results of the discriminant function analysis in this study showed high statistical values of the canonical correlation and eigenvalue, especially with regard to WR (Lt. and Rt. sides), indicating that WR is a useful parameter in determining sex from bone remains. A contributing factor is the lower bone mass of menopausal women as evidenced in the radii we analyzed as well as the results of a previous study (Sipilä *et al*., 2020). We used multi-variable methods (canonical correlation and Eigenvalue) to classify the differences between groups. The values of 0.805 (canonical-correlation) and 1.842 (Eigenvalue) in the right radius indicate that this parameter can be used to discern male and female bone remains. The accuracy of the determination of sex from the Rt. WR was (91.50%. In addition, the ratio of weight to length of the radius (W/L, either Rt. or Lt.) was found to be an accurate predictor of sex, with an accuracy rate of 88.00%. The parameter MLR was also found to be highly accurate in determining sex: 81.50% accurate in the case of the Rt. MLR and 82.50% for the Lt. MLR. Moreover, the multi-variable (stepwise method) showed an accuracy rate of up to 94.00% and 92.00% for the right and left radii, respectively. Considering the results together, we conclude that the best radial parameters for determining the sex of human remains are CMR and WR, both of which had high values of the standardized canonical discriminant function coefficients. Our results specific to a Thai population were similar to the results reported for other populations, as summarized in Table V. We found that the average values of all radial parameters were greater in male than in female specimens. Interestingly, Sakaue (2004) found that radius-based sex determination (using six parameters) was as much as 80.0% accurate; the most useful parameter was the sagittal head diameter (92.0% accurate). The parameters were then combined to achieve an accuracy rate of 95.0% (Sakaue, 2004). These results are similar to those reported for other

Table V. Summary of sex determination from radius parameters in diverse populations.

Population and references	Variable	Accuracy rate (%)
Japan (Sakaue, 2004)	MLR, SHD, THD, RDEW, NB, MSA	80.0-95.0
German (Mall *et al*., 2001)	MDH, MLR, RDEW	88.6-89.1
Turkish (Uzün *et al*., 2011)	MLR, MS-AP, MS-Tran, RDEW	90.4-91.9
Greek (Charisi *et al*., 2011)	MLR, MRPW, RDEW	93.5-95.1
Indian (Waghmare *et al*., 2012)	CMR, MS-AP, MS-Tran, CT, AP-RT, V-RT	71.7-90.4
Northern Thais (Duangto & Mahakkanukrauh, 2020)	MLR, MS-AP, MLDM	77.6-95.2
Northeastern Thais (This study, 2024)	MLR, CMR, WR	81.5-94.0

MLR, maximum length of radius; SHD, sagittal head diameter; THD, transvers head diameter; RDEW, distal end width of the radius; NB, notch breadth; MSA, mid shaft area; MDH, maximum diameter of head; MS-AP, midshaft anteroposterior of radius; MS-Tran, midshaft transverse; MRPW, maximum radial proximal width; CMR, circumference at mid shaft of radius; CT, circumference of tuberosity; AP-RT, antero-posterior diameter of the radial tuberosity; V-RT, vertical diameter of tuberosity; MLDM, medio-lateral diameter at midshaft of radius; WR, weight of radius.

populations, including German (Mall *et al*., 2001), Turkish (Uzün *et al*., 2011), and Greek (Charisi *et al*., 2011); the accuracy of the radius-based determination of sex being greater than 80.0% in each of these studies (Table V). In contrast, the accuracy rate was found to be approximately 70 % in Indian (Waghmare *et al*., 2012) and Northern Thai populations (Duangto & Mahakkanukrauh, 2020); such differences between populations can be attributed to both environment and genetics (Ubelaker & DeGaglia, 2017), as well as different measuring points. The results we report here agree with those of a previous study, in which it was found that bone mass and age of radius were important parameters in determining sex (Wright *et al*., 2014; Padilla Colón *et al*., 2018). The key finding from our study is that the sexual dimorphism of bone mass should be considered together with age differences to increase the accuracy of determining sex. Further research, in which the parameters are classified by age interval, is required to confirm the utility of radial parameters as a means to determine the sex of human remains.

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RESUMEN: En antropología forense, se ha demostrado que el hueso radio determina el sexo de los restos humanos en varias poblaciones diferentes. La masa seca y el crecimiento de los huesos largos, incluido el radio, están asociados con los niveles de hormonas sexuales; sin embargo, el uso del peso de los huesos para determinar el sexo no se ha investigado suficientemente. El objetivo de este estudio fue aplicar parámetros morfométricos óseos, incluida la longitud máxima del radio (LMR), la circunferencia en la mitad del radio (CMR) y el peso del radio (PR), a 400 radios de muestra de una población del noreste de Tailandia. Se aplicaron sistémicamente funciones discriminantes univariadas y multivariadas de todos los parámetros. También se determinaron ecuaciones para calcular la clasificación por sexo. El análisis descriptivo de los datos mostró un dimorfismo sexual significativo en todas las variables ($p < 0,05$). La correlación canónica fue mayor en CMR (0,772) y la relación peso-longitud (0,747). El análisis de función discriminante multivariante mostró que los índices del radio derecho eran ligeramente mayores que los del radio izquierdo. Los parámetros que demostraron los valores más altos de los coeficientes de la función discriminante canónica estandarizada fueron CMR (Rt. = 0,496, Lt. 0,431) y PR (Rt. = 0,681, Lt. = 0,715). Además, los resultados del método multivariable (método paso a paso) indicaron que las mejores tasas de precisión al usar combinaciones de CMR y PR fueron del 94 % (lado derecho) y del 92 % (lado izquierdo). En conclusión, el peso del radio (más que la longitud) es un parámetro eficaz para determinar el sexo.

PALABRAS CLAVE: Radio; Determinación del sexo; Análisis discriminativo; Tasa de precisión.

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