Sexual Dimorphism and Population-Specific Sex Estimation Equations Using Morphometric Analysis of Dry Lumbar Vertebrae in a Northeastern Thais

Dimorfismo Sexual y Ecuaciones de Estimación de Sexo Específicas de la Población Mediante Análisis Morfométrico de Vértebras Lumbares Secas en una Población del Noreste de Tailandia

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SUMMARY: Sex estimation from skeletal remains, particularly incomplete or fragmented ones, is crucial for forensic anthropology. This study aimed to investigate the morphometric characteristics of the lumbar vertebrae and their potential for sex estimation in the Northeastern Thai population. A cross-sectional study was conducted using 1000 identified dry lumbar vertebrae (L1-L5) collected in the Unit of Human Bone Warehouse for Research, Department of Anatomy, Faculty of Medicine, Khon Kaen University, Thailand. Eight morphometric parameters were measured using a digital Vernier caliper. The independent t-test and discriminant function analysis were performed to evaluate sexual dimorphism and generate equations. The results showed that most parameters on all lumbar levels of males were significantly greater than those of females (p < 0.05). Discriminant function analysis revealed that L2 had the strongest association between the discriminant function and sex groups. The correct classification rates determined by sex estimation equations ranged from 77.80 % to 85.00 %. Interestingly, the highest accuracy rate was achieved by the equation for L1 (85.00 %). Among all parameters in both males and females, the width of the pedicle isthmus and the distance from the junction of the superior facet and transverse process to the anterior cortex on the right side at L1 were systematically selected to be used in the equation of sex classification for the highest correct classification rate. This present study also attempted to compare sex estimation accuracy among populations as previously documented and showed that the upper lumbar vertebrae had higher reliability. These findings have contributed to the knowledge of population-specific sex estimation methods for applying dry lumbar vertebrae as a reliable skeletal element for sex determination in forensic contexts.

KEY WORDS: Lumbar vertebra; Sexual dimorphism; Morphometric Analysis; Northeastern Thais.

INTRODUCTION

The primary identification of human skeletal remains in forensic contexts is an important task, particularly when the forensic scientist is dealing with cases involving mass disasters, severe body damage, or criminal dismemberment (Kranioti & Paine, 2011). The challenges posed by the decomposition of soft tissues and the fragmentation of skeletal elements require the use of surviving skeletal structures to reconstruct the biological profile of the individual deceased body (Krishan *et al.*, 2016). Previously, many studies have highlighted the reliability of the skull and pelvic bones in determining sex through both morphological and quantitative analyses (Duric *et al.*, 2005; Franklin *et al.*, 2012). Since the incidence of torso murders with dismemberment has recently tended to increase, sex identification from other bones is very important to be documented as individual knowledge for each population. Therefore, sex estimation from other skeletal elements, including the upper limb bones (Lee *et al.*, 2014), lower limb bones (Ahmed, 2013), and lumbar vertebrae,

particularly the first lumbar (L1) vertebra (Zheng *et al*., 2012; Bozdag & Karaman, 2021), has been demonstrated in individual populations.

Based on a literature review, the basic data on using the morphological characteristics from the lumbar vertebrae (L1-L5) for sex identification has never been reported, particularly in the Northeastern Thai population, which is the largest region in Thailand. In addition, the study of the association between the accessory process and pedicle of the lumbar vertebrae in our population is still limited. The relationship between such accessory process and lumbar pedicle may suggest some advantages for use in basic sex estimation. It will provide additional parameters for determining sex in vertebrae when certain lumbar processes are incomplete or fragmented. Such anatomical landmarks are also well-defined and easily measurable, facilitating rapid initial screening. The integration of data from many reference points on lumbar vertebrae can enhance the accuracy of sex determination. Finally, population-specific studies can generate tailored morphological data that may improve the precision of sex dimorphism. Therefore, the present study aimed to investigate the anatomical and morphological features of the dry lumbar vertebrae (L1-L5) in the Northeastern Thai population to apply this advancement of sex estimation techniques in Thai forensics.

MATERIAL AND METHOD

Sample collection and ethics: In this cross-sectional study, a total of 1000 dry human lumbar vertebrae (L1-L5) were kindly provided by the Unit of Human Bone Warehouse for Research (UHBWR), 7th floor, Preclinical building, Department of Anatomy, Faculty of Medicine, Khon Kaen University, Thailand. The lumbar vertebral columns (L1-5), belonging to males (n = 100) and females (n = 100), were randomly collected from the identified skeletons of individuals who have donated their bodies for medical and paramedical studies and researches. The age range of vertebrae samples was from 20 to 90 years. The inclusion criteria for these vertebrae were completeness, good preservation, and no obvious abnormalities or signs of deformity. The study has been approved for human ethics by the Ethics Committee of Khon Kaen University (code number HE661389).

Points and parameters used for morphometric measurements: Morphometric measurements on each lumbar vertebra point were performed with different internal and external observers by using a digital Vernier caliper (Digimatic caliper, model No. CD-8CSX, Mitutiyo Corp., Kawasaki, Japan). A total of eight parameters were determined and measured as shown in Figure 1 and they are described as followings:

1. The length of the accessory process (AP)
2. The width of the pedicle isthmus (L)
3. The diameter of the pedicle isthmus (M)
4. The distance from the tip of the accessory process to the medial margin of the pedicle isthmus (DM)
5. The distance from the tip of the accessory process to the lateral margin of the pedicle isthmus (DL)
6. The distance from the junction between the superior facet and transverse process to the anterior cortex on the right side (C)
7. The width of the pedicle isthmus on the right side (P)
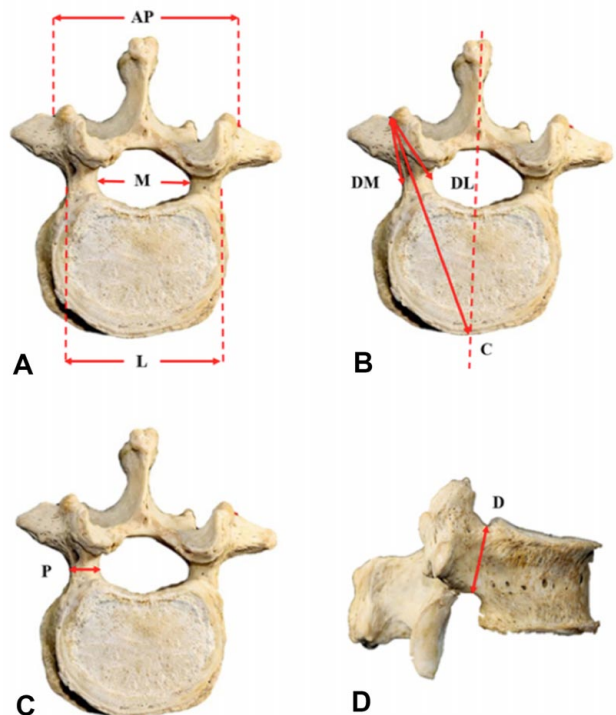8. The height of the pedicle isthmus on the right side (D)

Fig. 1. Showing 8 parameters used for measurements on lumbar vertebra. a) length of the accessory process, width of the pedicle isthmus, diameter of the pedicle isthmus. b) distance from the tip of the accessory process to the medial margin of the pedicle isthmus, distance from the tip of the accessory process to the lateral margin of the pedicle isthmus, distance from the junction of the superior facet and transverse process to the anterior cortex on the right side. c) width of the pedicle isthmus on the right side. d) height of the pedicle isthmus on the right side.

Statistical analysis: Statistical analyses were performed using SPSS version 23.0. Descriptive statistics, including mean, standard deviation (SD) and box plots, were calculated and expressed for each parameter. An independent t-test was employed to compare the means of each parameter between males and females. A statistically significant difference between sexes was set up when the p value was < 0.05. Subsequently, discriminant function analysis was used to generate equations for sex estimation, and the accuracy rate of the equations was also evaluated.

RESULTS

The results showed that the mean values of most parameters including AP, DL, DM, P, L, M, C, and D measured in males were significantly higher than those of females (p < 0.05) as shown in Table I. However, it was found that only the D parameter (the height of the pedicle isthmus on the right side) at the L4 had no significant difference between sexes (p = 0.48).

In Figure 2, the box plot illustrated the distribution of the data for the eight parameters measured on all lumbar levels. The plot clearly showed that all data follow a normal distribution with no significant skewness or kurtosis beyond the specified thresholds. Many parameters including D, P, DL, DM, and M exhibited relatively narrow ranges, indicating a higher concentration of data as compared to other parameters such as L and AP (Fig. 2). In addition, the outliers for each parameter were within acceptable limits and predominantly observed in both L1 and L2 vertebrae.

The discriminant function analysis generated the equations for sex estimation by using morphometric parameters of the lumbar vertebrae. Initially, the discriminant scores of lumbar vertebrae morphometric parameters were calculated for both males and females at L1-L5. As shown in the Figure 3, the discriminant scores indicated that such scores of females were dominated by those of males at all lumbar levels. Furthermore, the analysis using the normality curve revealed that the discriminant scores of both sexes followed the normal distribution, which meets the preliminary assumptions for discriminant function analysis (Fig. 3).

The statistical values obtained from the analysis in Table II showed that the second lumbar vertebra (L2) had the strongest association between the discriminant function and sex groups, with the highest canonical correlation (0.711) and eigenvalue (1.022). The Wilks' lambda values for all lumbar vertebral levels ranged from 0.495 to 0.608, and the chi-square values were statistically a significant difference (p < 0.01), indicating the high discriminatory power of the morphometric parameters.
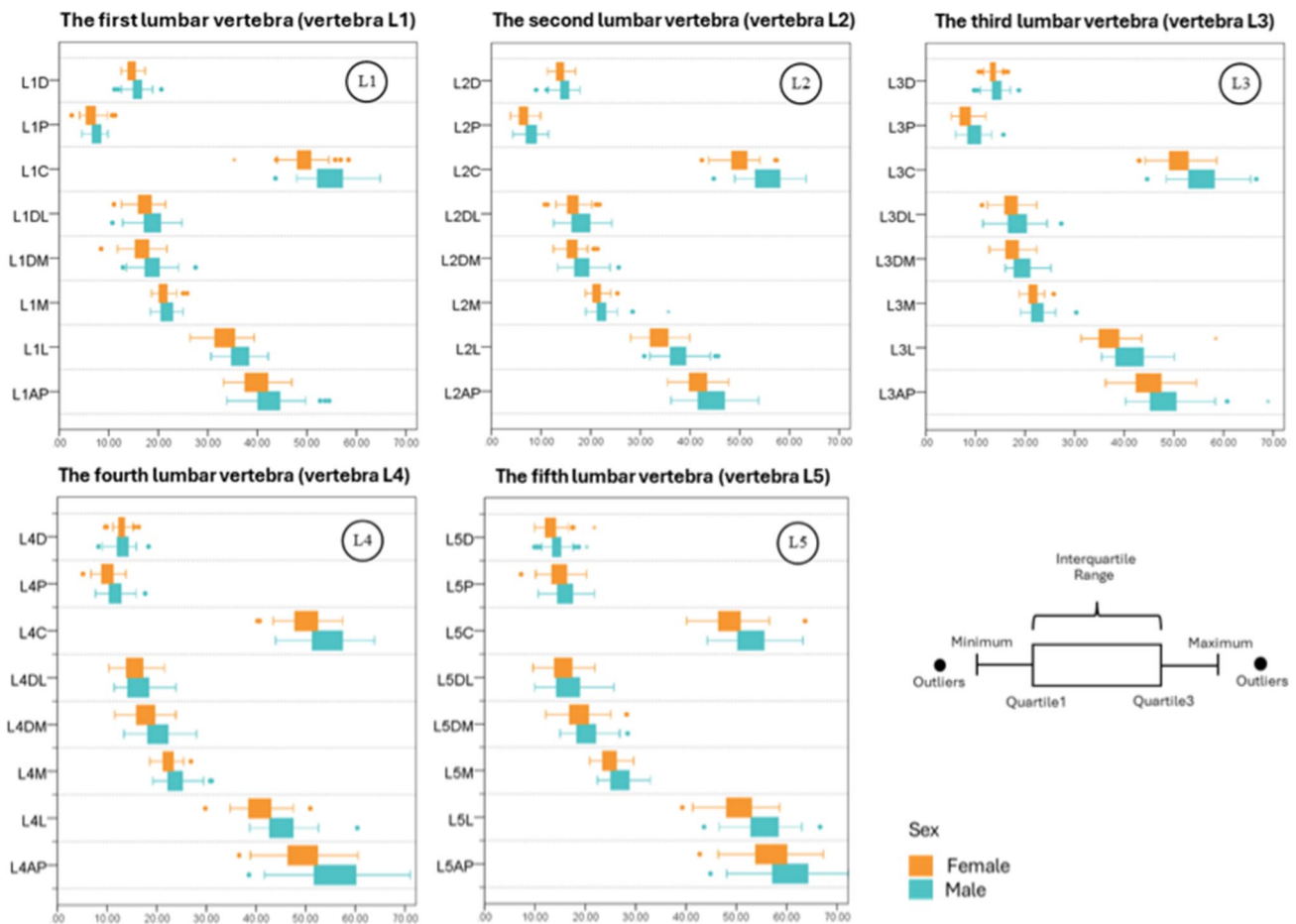

Fig. 2. Box plot illustrating the distribution of all morphometric parameters measured on L1-L5 between males and females.

Table I. Comparison of morphometric parameters between males and females on the lumbar vertebrae (L1-L5).

Parameters	Lumbar Level	Overall		Male		Female		t	Sig.
		Mean	SD	Mean	SD	Mean	SD		
AP	1	41.05	3.57	42.37	3.69	39.76	2.95	5.58	0.00
	2	42.73	3.49	44.04	3.78	41.45	2.62	5.76	0.00
	3	46.57	4.46	48.22	4.69	44.95	3.55	5.60	0.00
	4	52.39	5.95	55.47	5.62	49.37	4.57	8.39	0.00
	5	59.19	5.66	61.25	5.79	57.18	4.75	5.42	0.00
L	1	34.87	3.06	36.50	2.54	33.25	2.65	8.86	0.00
	2	35.83	3.23	37.75	2.76	33.90	2.43	10.47	0.00
	3	39.14	4.05	41.17	3.58	37.12	3.45	8.14	0.00
	4	43.09	4.07	45.32	3.59	40.86	3.23	9.22	0.00
	5	52.84	4.70	55.22	4.19	50.46	3.92	8.30	0.00
M	1	21.38	1.45	21.73	1.52	21.02	1.29	3.57	0.00
	2	21.75	1.73	22.26	2.01	21.25	1.20	4.34	0.00
	3	22.09	1.59	22.62	1.72	21.57	1.26	4.93	0.00
	4	22.95	2.08	23.66	2.26	22.24	1.59	5.14	0.00
	5	25.84	2.40	26.81	2.42	24.88	1.96	6.19	0.00
DM	1	17.56	2.42	18.48	2.42	16.66	2.06	5.87	0.00
	2	17.27	2.21	18.23	2.31	16.33	1.65	6.79	0.00
	3	18.51	2.38	19.56	2.28	17.48	2.00	6.85	0.00
	4	19.08	2.91	20.29	2.74	17.89	2.57	6.36	0.00
	5	19.54	2.93	20.27	2.88	18.82	2.82	3.57	0.00
DL	1	17.84	2.44	18.56	2.60	17.13	2.04	4.38	0.00
	2	17.21	2.34	18.04	2.40	16.39	1.97	5.40	0.00
	3	17.75	2.57	18.47	2.84	17.05	2.06	4.16	0.00
	4	15.98	2.64	16.38	2.82	15.59	2.39	2.17	0.03
	5	16.13	2.85	16.52	3.18	15.76	2.44	1.88	0.06
C	1	52.09	4.27	54.80	3.60	49.43	3.02	11.45	0.00
	2	52.65	4.32	55.58	3.77	49.78	2.52	12.68	0.00
	3	53.34	4.36	55.77	4.07	50.96	3.16	9.39	0.00
	4	52.05	4.55	54.34	4.45	49.81	3.40	8.13	0.00
	5	50.74	4.37	53.00	3.82	48.53	3.70	8.38	0.00
P	1	6.92	1.49	7.43	1.23	6.40	1.55	5.23	0.00
	2	7.28	1.55	8.04	1.46	6.52	1.23	7.95	0.00
	3	8.88	1.80	9.69	1.80	8.06	1.39	7.17	0.00
	4	10.84	1.91	11.56	1.90	10.13	1.63	5.72	0.00
	5	15.41	2.31	15.96	2.38	14.86	2.12	3.43	0.00
D	1	15.21	1.41	15.82	1.47	14.61	1.06	6.68	0.00
	2	14.31	1.40	14.71	1.51	13.92	1.17	4.17	0.00
	3	13.88	1.33	14.22	1.52	13.54	1.02	3.72	0.00
	4	12.97	1.44	13.04	1.71	12.90	1.11	0.71	0.48
	5	13.73	1.84	14.28	1.77	13.18	1.75	4.42	0.00

Table II. Statistical values obtained from the discriminant function analysis of morphometric parameters (L1-L5).

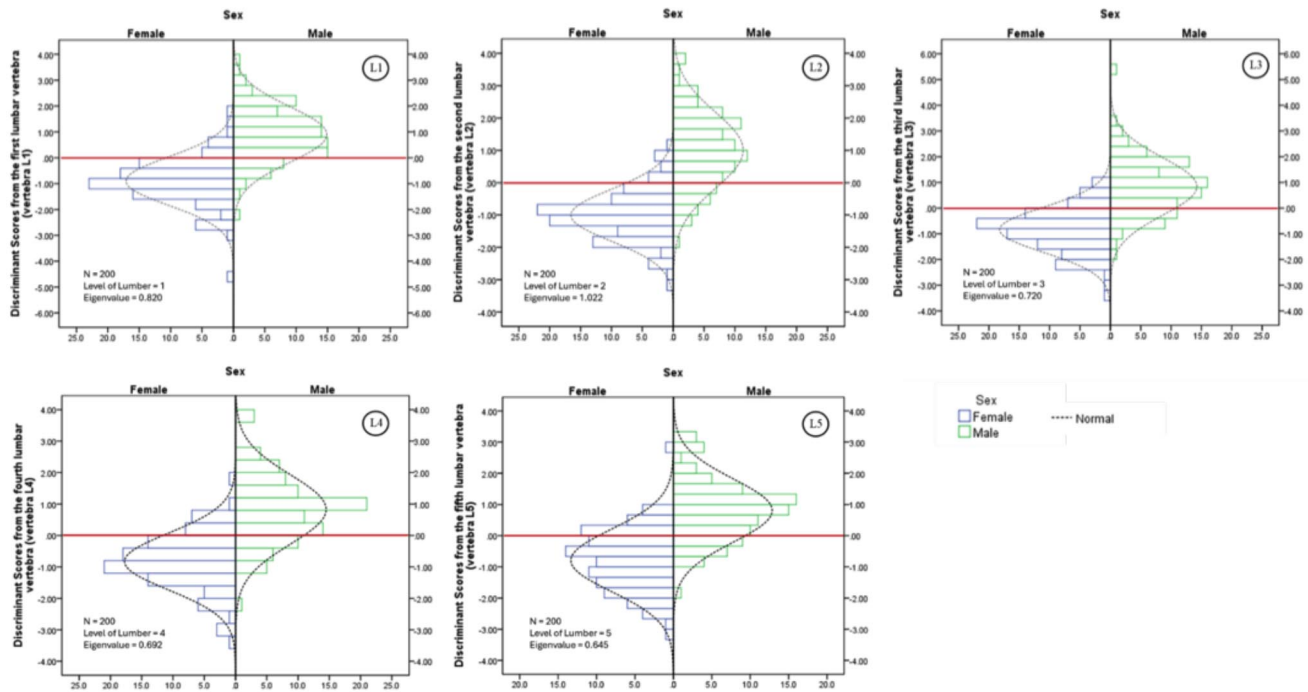| levels of Lumbar	Canonical correlation	Eigenvalue	Wilks' lambda	Chi-square	Sig.
1	0.671	0.820	0.549	117.963	0.00
2	0.711	1.022	0.495	138.712	0.00
3	0.647	0.720	0.581	106.576	0.00
4	0.640	0.692	0.591	103.384	0.00
5	0.626	0.645	0.608	96.780	0.00

Fig. 3. Discriminant scores of lumbar vertebrae morphometric parameters between males and females at each level of the lumbar vertebrae.

The sex classification equations for each lumbar vertebral level derived from the stepwise method. These equations incorporated many combinations of morphometric parameters (Table III). These parameters included the width of the pedicle isthmus (L), the diameter of the pedicle isthmus (M), the distance from the junction of the superior facet and transverse process to the anterior cortex (C), the width of the right pedicle isthmus (P), and the length of the accessory process (AP), respectively. It was found that the equation of L1 (L+C), which achieved the highest correct classification rate at approximately 85.00 %, followed by that of L2 equation (C+P) with a correct classification rate of 84.50 % (Table III). The equations for L3, L4, and L5 yielded the correct classification rates of 80.50 %, 80.50 %, and 77.80 %, respectively. These results highlighted the potential utility of lumbar vertebral morphometric parameters in estimating sex, particularly when other primary indicators were unavailable or incomplete, with the first and second lumbar vertebrae indicated the highest reliability in Thai population.

Table III. Sex classification equations for each lumbar vertebral level derived using the stepwise method and their corresponding correct classification rates.

levels of Lumbar	Equation of sex classification		Correct classification rate (%)
	Male	Female	
1	3.807 L + 4.088 C - 182.141	3.486 L + 3.676 C - 149.503	85.00
2	5.269 C + 2.895 P - 158.589	4.744 C + 2.213 P - 125.984	84.50
3	8.204 M + 3.267 C + 3.887 P - 203.408	7.894 M + 2.949 C + 3.276 P - 174.162	80.50
4	0.733 AP + 2.675 L + 2.775 C - 157.008	0.620 AP + 2.425 L + 2.566 C - 129.460	80.50
5	1.898 L + 3.727 M + 3.176 C - 187.367	1.709 L + 3.496 M + 2.911 C - 157.931	77.80

DISCUSSION

This current study has demonstrated the potential parameters on the lumbar vertebrae to be developed and applied as a primary method for sex estimation in the Northeastern Thai population for the first time. Consistently, the higher mean values of most morphometric parameters in males as compared to those of females on all lumbar vertebral levels were corroborated with previous explanations on hormonal and genetic factors influencing bone growth and development (Ruff, 2002; Spradley & Jantz, 2011; Krishan *et al.*, 2016). Therefore, the sexual dimorphism

observed in the Thai lumbar vertebrae could be attributed to such factors. This basic knowledge is pivotal for forensic anthropologists to understand the expected differences between male and female skeletal remains, aiding in the accurate assessment of biological sex (Spradley & Jantz, 2011). Another critical aspect to consider was the variations in the discriminatory power of different lumbar vertebral levels for sex estimation. Herein, the first lumbar vertebra (L1) showed the highest accuracy in sex classification (85.00 %), followed by the second one (L2) with an accuracy of approximately 84.50 % as compared to that of the lower levels (L3-L5). Our findings suggest that the upper lumbar vertebrae may be used for more reliability for sex estimation. This could be attributed to the greater mechanical loading and stress experienced from the upper lumbar region, leading to more pronounced sexual dimorphism in the morphometric parameters as previously described (Pal & Routal, 1987). Further studies could explore the functional and biomechanical factors that may contribute to the varying levels of sexual dimorphism across the lumbar vertebrae. It has been suggested to provide the valuable insights into the adaptive changes in the human skeleton and their implications for forensic and physical anthropology (Ruff, 2002). We found that the equations derived from each lumbar vertebral level were incorporated with various parameters including the width and diameter of the pedicle isthmus, the distance from the junction of the superior facet and transverse process to the anterior cortex, and the length of the accessory process. It was demonstrated that the integrations of multiple parameters within the equations have underscored the importance of considering the interplay between different anatomical features with sexualdimorphism assessment. This approach was aligned with the recommendations of a previous study, emphasizing the value of combining multiple skeletal elements and measurements to enhance the accuracy of sex estimation (Krishan *et al.*, 2016). By incorporating a holistic analysis of the lumbar vertebrae, this current study contributed to the development of more robust and reliable sex estimation methods in the forensic anthropology (Bidmos *et al.*, 2010). The population-specific nature of this study was also noteworthy. The equations generated were tailored to the Northeastern Thai population, which may limit their direct applicability to other populations. However, the methodology employed in our study could serve as a

framework for conducting similar investigations in different populations. The development of population-specific sex estimation equations is important in forensic anthropology as it has been reported to account for the variation in skeletal morphology across different ancestral groups (Iscan, 2005). This study focused on the need of region-specific studies in physical anthropology, contributing to a more comprehensive understanding of human skeletal diversity (Pietrusewsky, 2008; Ubelaker & DeGaglia, 2017). Comparison of the sex estimation accuracy from lumbar vertebrae of the different populations may reveal interesting patterns and the importance of population-specific studies in forensic anthropology. The present study on the Northeastern Thai population using dry bone samples has provided the accuracy rates ranging from approximately 77.8 % to 85.0 %, which was the highest in the L1 and the lowest in the L5 . Such results were comparable to those findings previously reported in Spanish (Azofra-Monge & Alemán Aguilera, 2020), South African (Ostrofsky & Churchill, 2015), and some Northern Thai populations (Malatong *et al.*, 2023). Interestingly, the accuracy demonstrated from the Northeastern Thai population was slightly lower as compared to that of the Spanish and South African populations (Ostrofsky & Churchill, 2015; Azofra-Monge & Alemán Aguilera, 2020). Taken together, it was suggested that parameters on lumbar vertebrae have the population-specific variations in sexual dimorphism. Interestingly, a study on the North American population (Decker *et al.*, 2019) observed from CT scans was similar to the accuracy of our present study, indicating the potential comparability of results obtained from CT scans and dry bone samples as compared in Table IV.

In conclusion, the present study has demonstrated the potential parameters on the lumbar vertebrae to be used in the sex estimation equations for the significant sexual estimation in Northeastern Thai population. This study did not only provide the additional knowledge for the field of forensic anthropology but also provided the insights into the factors influencing lumbar vertebral variation in human populations. Further study needs to explore the factors contributing to population differences and investigate the potential parameters in combinations of lumbar vertebral measurements with other skeletal elements to enhance sex estimation accuracy and validity.

Table IV. Comparison of sex estimation accuracy from lumbar vertebrae across different populations.

Populations	Method and samples used	Correction classification rate of lumbar vertebra (%)				
		L1	L2	L3	L4	L5
South African (Ostrofsky & Churchill, 2015)	Dry bone	87.1	83.0	85.9	80.2	76.8
North American (Decker *et al.*, 2019)	CT scans	83.1	81.0	85.1	82.5	81.2
Spanish (Azofra-Monge & Alemán Aguilera, (2020)	Dry bone	90.1- 94.5	85.4 - 89.4	85.3 - 88.3	85.3 - 88.2	80.0 - 85.3
Northern Thai (Malatong *et al.*, 2023)	Dry bone	79.5-82.7	78.2-82.7	77.3-80.0	76.8-77.3	75.9-79.1
Northeastern Thai (Boonthai *et al.*, present study)	Dry bone	85.0	84.5	80.5	80.5	77.8

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RESUMEN: La estimación del sexo a partir de restos esqueléticos, en particular los incompletos o fragmentados, es crucial para la antropología forense. Este estudio tuvo como objetivo investigar las características morfométricas de las vértebras lumbares y su potencial para la estimación del sexo en la población del noreste de Tailandia. Se realizó un estudio transversal utilizando 1000 vértebras lumbares secas identificadas (L1-L5) recolectadas para Investigación, en la Unidad de Almacenamiento de Huesos Humanos del Departamento de Anatomía, de la Facultad de Medicina, de la Universidad de Khon Kaen, Tailandia. Se midieron ocho parámetros morfométricos utilizando un calibrador Vernier digital. Se realizó la prueba t independiente y el análisis de la función discriminante para evaluar el dimorfismo sexual y generar ecuaciones. Los resultados mostraron que la mayoría de los parámetros, en todos los niveles lumbares de los hombres fueron significativamente mayores que los de las mujeres (p < 0,05). El análisis de la función discriminante reveló que L2 tenía la asociación más fuerte entre la función discriminante y los grupos de sexo. Las tasas de clasificación correcta determinadas por las ecuaciones de estimación del sexo variaron del 77,8 % al 85 %. Curiosamente, la tasa de precisión más alta se logró con la ecuación para L1 (85 %). Entre todos los parámetros, tanto en hombres como en mujeres, se seleccionaron sistemáticamente el ancho del istmo peduncular y la distancia desde la unión de la faceta superior y el proceso transverso hasta la cortical anterior en el lado derecho en L1 para utilizarlos en la ecuación de clasificación sexual y así obtener la tasa de clasificación correcta más alta. Este estudio comparó la precisión de la estimación del sexo entre poblaciones, como se documentó previamente, y demostró que las vértebras lumbares superiores tenían una mayor confiabilidad. Estos hallazgos han contribuido al conocimiento de métodos de estimación del sexo, específicos de la población, para aplicar las vértebras lumbares secas como un elemento esquelético confiable en la determinación del sexo en contextos forenses.

PALABRAS CLAVE: Vértebra lumbar; Dimorfismo sexual; Análisis morfométrico; Tailandeses del noreste.

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