Sex estimation through discriminant analysis of the scapula in a contemporary Northern Thai population

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SUMMARY

This study evaluates sexual dimorphism in the scapula and develops population- specific discriminant functions for sex estimation in a Northern Thai population. Measurements of four scapular dimensions – maximum length, maximum breadth, glenoid cavity length, and glenoid cavity breadth – were taken from the left and right scapulae of 252 northern Thai individuals using a digital caliper. Discriminant functions using maximum length and maximum breadth were developed and tested for their accuracy in sex estimation. The cross-validation accuracy of these functions ranged from 81.67% to 86.67%, while functions using glenoid cavity dimensions ranged from 80.00% to 83.33%. Among the univariate functions, maximum length and glenoid cavity breadth provided the highest accuracies for sex estimation (86.67% and 83.33%, respectively), indicating that these dimensions are more sexually dimorphic and effective than the others measured. These findings contribute valuable morphometric data to physical anthropology and suggest that a multivariate discriminant function incorporating maximum length and glenoid cavity breadth could further enhance classification accuracy across diverse populations. This research highlights the importance of accounting for regional anatomical variations in forensic and anthropological applications.

Key words: Sex estimation – Scapular morphometrics – Glenoid cavity – Discriminant analysis – Forensic anthropology

INTRODUCTION

Sex estimation is a critical initial step in forensic investigations involving human skeletons, as it informs subsequent analyses of age at death and stature, which are sex- specific (Ozer et al., 2006). Traditionally, this process relies on the sexual dimorphism of the skull (Haas et al., 1994; Franklin et al., 2005) and pelvis (Haas et al., 1994; Steyn et al., 2008; Franklin et al., 2014), which are the most frequently utilized skeletal elements. However, when these are unavailable, other bones such as the metatarsals (Robling et al., 1997), fe-

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mur (Steyn et al., 1997), tibia (Steyn et al., 1997) and ribs (Wiredu et al., 1999) can also provide useful indicators.

The scapula, with its attachment to multiple muscles, such as the rotator cuff, levator scapulae, rhomboid muscles, serratus anterior (Miniato et al., 2023), has been increasingly recognized as a valuable alternative for sex estimation due to its sexual dimorphism. Various studies have demonstrated significant differences between males and females in scapular measurements (Ozer et al., 2006; Chawinamnuaykij, 2008; Dabbs, 2010; Dabbs et al., 2010; Papaioannou et al., 2012; Camily et al., 2016; Hudson et al., 2016; Torimitsu et al., 2016; Zhang et al., 2016; Ashwin Kumar et al., 2017; Koukiasa et al., 2017; Peckmann et al., 2017; Debnath et al., 2018; Omar et al., 2019), including maximum length (ML), maximum breadth (MB), glenoid cavity length (GL), and glenoid cavity breadth (GB). The growth of the scapula, largely driven by muscle development and activity (Hrdlička, 1942), typically results in larger scapulae in males, influenced by higher testosterone levels (Singh et al., 1998).

Given that skeletal dimensions vary across populations due to genetic and environmental factors, population-specific standards are generally more accurate for forensic applications (Patriquin et al., 2005; Ross et al., 2011; Franklin et al., 2005). While previous research has developed discriminant functions for sex estimation based on scapular measurements in different populations, the Northern Thai population has been underrepresented in these studies. Specifically, the use of ML and MB in discriminant analyses for this group has not been thoroughly explored, despite their potential for higher accuracy compared to GL and GB (Peckmann et al., 2017).

This study aims to fill this gap by evaluating the sexual dimorphism of the maximum length and breadth of the scapula in a Northern Thai population and developing population-specific discriminant functions. These will be compared to existing functions based on the length and breadth of the glenoid cavity (Peckmann et al., 2017) to determine the most accurate method for sex estimation in this demographic. The findings are expected to contribute to the broader understanding of human skeletal variation and enhance forensic practices.

MATERIALS AND METHODS

This cross-sectional analytical study was conducted at the Osteology Research and Training Center, Faculty of Medicine, Chiang Mai University, and was approved by the Research Ethics Committee of the Faculty of Medicine, Chiang Mai University (Exemption No. 6816/2019). The skeletal collection at the Osteology Research and Training Center consists of individuals who were native to the northern region of Thailand and who legally donated their bodies to the Department of Anatomy for academic and research purposes. Detailed records, including age at death, sex, cause of death, and domicile, are maintained in the center's database.

At the time of this study, the collection comprised the skeletons of 479 individuals (292 males and 187 females), all of whom had lived in northern Thailand. From this collection, the sample size for the study was determined using the following formula:

$$n = \frac{N\sigma^2 z^2_{1-\frac{\alpha}{2}}}{d^2(N-1) + \sigma^2 z^2_{1-\frac{\alpha}{2}}}$$

Here, N represents the total number of northern Thai individuals in the collection, and the standard deviation (σ) was taken from a prior study on Thai scapulae (Chawinamnuaykij, 2008) with a 99% confidence level ($N = 471$, $\sigma = 1.36$, $z = 2.58$, $d = 0.15$). The final sample size was increased by one to ensure equal representation of males and females, yielding a total of 252 individuals (126 males and 126 females).

Only adult Northern Thai individuals with intact left and right scapulae were included in this study. Those with damaged or missing scapulae, fractured bones in the measurement areas, bones exhibiting pathological changes, ambiguous anatomical landmarks, or non-representative abnormal sizes (i.e., significantly smaller or larger than typical anatomical norms) were excluded. The individuals included in the analysis ranged in age from 22 to 94 years, with an average age of 62.25 years (±14.64 SD) for males and 65.23 years (±16.18 SD) for females.

Four measurements were taken from each scapula following the description defined in Table 1 and shown in Fig. 1, using a digital caliper to the nearest 0.01 mm. IBM SPSS Statistic 26.0 (IBM Corp., Armonk, NY, USA) was used for the statistical analysis with a level of significance $\alpha = 0.01$. The Kolmogorov-Smirnov test was used in order to evaluate the normality of data, and the descriptive statistics were reported. Correlation statistics were applied to assess the observer variability in 30 randomly selected scapulae (15 males and 15 females) two days apart (Haas et al., 1994) for all measurements. The difference between left and right scapula measurements were also inspected.

In this study, only the maximum scapular length (ML) and maximum scapular breadth (MB) measurements from both left and right scapulae were used in order to compare sex differences and to develop population-specific discriminant functions for the Northern Thai population using direct and stepwise discriminant analysis, assuming that no significant side differences were present, whilst the glenoid cavity length (GL) and the glenoid cavity breadth (GB) measurements of the left scapulae obtained from this study were collected to substitute in the discriminant functions using only the left glenoid cavity measurements, created by Peckmann et al. (2017). Cross-validation then was performed in the left and right scapulae of 60 known-sex individuals (30 males and 30 females) to compare the discriminant function accuracy between such those of Peckmann et al. (2017) and this study.

RESULTS

Assessment of observer variability

During the assessment of observer variability, the two observers showed no statistically significant differences with the very strong correlation in all measurements (Table 2).

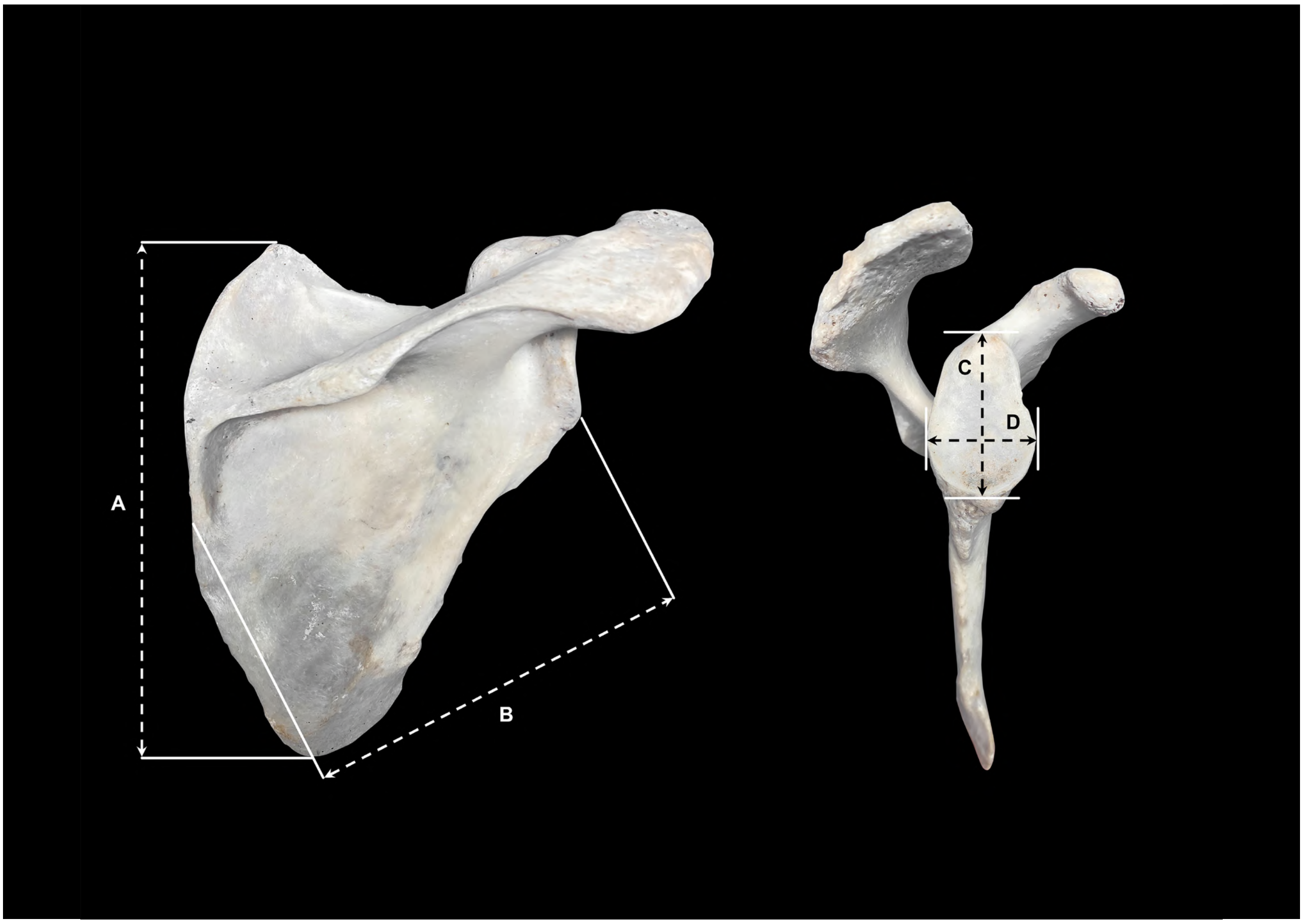

Fig. 1. - Scapular measurements as described in Table 1. A- Maximum scapular length (ML), B- Maximum scapular breadth (MB), C- Glenoid cavity length (GL), D- Glenoid cavity breadth (GB).

Table 1. Definitions of scapular measurements.

Measurements	Definitions
Maximum scapular length (ML)	Distance between the superior angle and the inferior angle*
Maximum scapular breadth (MB)	Distance between the posterior margin of the glenoid cavity and the point of intersection of the scapular spine and the medial border*
Glenoid cavity length (GL)	Greatest length across the glenoid cavity perpendicular to the anterior- posterior axis†
Glenoid cavity breadth (GB)	Greatest width across the glenoid cavity perpendicular to the axis of the length of the glenoid cavity†
* Scapular measurements from White et al. (2011) † Glenoid cavity measurements from Peckmann et al. (2017)	

Table 2. Intra- and inter-observer errors and side-difference test for scapular measurements between males and females.

Measurements		N	Pearson's correlation coefficient		N	*p-value*
			Intra-observer	Inter-observer		
ML	Males	30	0.980	0.998	126	0.014†
	Females	30	1.000	0.999	126	0.486†
MB	Males	30	0.901	0.962	126	0.316^
	Females	30	0.988	0.989	126	0.496†
GL	Males	30	0.848	0.677	126	0.018†
	Females	30	0.954	0.842	126	0.001^*
GB	Males	30	0.874	0.922	126	0.000^*
	Females	30	0.953	0.975	126	0.000^*

† Statistical analysis was conducted using a paired sample t-test with significant level at 0.01.
^ Statistical analysis was conducted using a Wilcoxon signed-rank test with significant level at 0.01.
* Significant difference between sides (p-value < 0.01)

Assessment of left and right scapular differences

The scapular measurements in this study revealed no significant difference between the left and right in the maximum scapular length (ML) and the maximum scapular breadth (MB). However, significant side differences were observed in the glenoid cavity breadth (GB) for both sexes and in the glenoid cavity length (GL) for females (Table 2).

Sexual differences in ML and MB measurements

Comparatively, both maximum scapular length (ML) and maximum scapular breadth (MB) measurements are significantly larger in males than in females, with differences between the sexes being statistically significant ($p < 0.01$) (Table 3). Therefore, ML and MB are sexually dimorphic traits in the Northern Thai population and can be reliably used for sex estimation.

Discriminant functions using ML and MB measurements

Table 4 shows the discriminant functions created using the maximum scapular length (ML) and maximum scapular breadth (MB) measurements from a northern Thai population. Function 1, which uses both ML and MB, has the highest eigenvalue and canonical correlation, indicating that it has the greatest discriminating effect. This is further supported in Table 5, as function 1 displays the highest overall accuracy (88.29% for the model set and 86.67% for cross-validation), proving that multivariate discriminant functions are more accurate for sex estimation than univariate discriminant functions. On the other hand, function 3, which uses only MB, has the lowest eigenvalue, canonical correlation and overall accuracy (80.48% for the model set and 81.67% for cross-validation). Hence, it can be inferred that ML is more sexually dimorphic than MB in the northern Thai population. Initially, more males were correctly classified than females in the model set, indicating a potential sex bias towards males. However, this did not persist, as the cross- validation of functions 1 and 2, both of which use ML and the former also uses MB, shows the same classification accuracy for both sexes (86.67% for both functions). Meanwhile, more females were correctly classified than males during the cross-validation of function 3 (83.33% for females and 80.00% for males).

Comparison with discriminant functions using GL and GB measurements

When comparing the discriminant functions using ML and MB from this study with those using GL and GB from the previous study by Peckmann et al. (2017), the multivariate functions continue to demonstrate higher overall accuracy than the univariate functions. Specifically, Function 1, which uses ML and MB, achieves a higher overall accuracy (88.29% for the model set and 86.67% for cross-validation) compared to Function 4, which uses GL and GB, with an overall accuracy of 87.96% for the model set and 81.67% during cross-validation. Among the univariate functions, Function 2, which uses only ML, (86.11% for the model set and 86.67% for cross-validation) and Function 6, which uses only GB (86.39% for the model set and 83.33% for cross- validation), yield higher overall accuracies. Conversely, Function 3, which uses only MB (80.48% for the model set and 81.67% for cross-validation), and Function 5,

Table 3. Descriptive statistics for the maximum scapular length (ML) and the maximum scapular breadth (MB) measurements and sex-difference test between males and females in the northern Thai population.

Measurements (mm)	Males					Females					p-value
	N	Min	Max	Mean	SD	N	Min	Max	Mean	SD	
ML†	252	123.06	171.78	148.31	7.83	252	106.10	152.84	129.88	8.27	0.000*
MB^	252	89.64	119.19	103.59	5.70	252	79.89	113.76	94.01	6.30	0.000*

† Statistical analysis was conducted using a Mann-Whitney U test with significant level at 0.01.
^ Statistical analysis was conducted using an independent samples t-test, and the assumption of homoscedasticity was met at the 0.01 significance level (Levene's test for equality of variances: $F(1,502) = 1.208$, $p = 0.272$).
* Significant difference between sexes (p-value < 0.01)

Table 4. Discriminant function equations for the maximum scapular length (ML) and the maximum scapular breadth (MB) measurements in the northern Thai population.

Functions	Discriminant function equations	Eigenvalue	Canonical correlation	Box's M test†		Cut-off value	Group Centroid	
				Statistic	p-value		M	F
Multivariate function								
1	y = 0.10 (ML) + 0.05 (MB) – 19.27	1.42	0.77	3.458	0.328*	0.00	1.190	-1.190
Univariate functions								
2	y = 0.12 (ML) – 17.28	1.32	0.75	0.877	0.349*	0.00	1.155	-1.155
3	y = 0.17 (MB) – 16.46	0.64	0.62	1.429	0.232*	0.00	0.717	-0.717

† Box's M test was used to assess the equality of variance-covariance matrices across groups.
* Homogeneity of variance-covariance matrices was suggested across the sexes ($p > 0.01$), validating the use of linear discriminant analysis.

Table 5. Classification accuracy of the discriminant functions.

Functions			Model set accuracy^						Cross-validation accuracy					
			Male		Female		Overall		Male		Female		Overall	
			N	%	N	%	N	%	N	%	N	%	N	%
Multivariate functions														
1		ML MB	228/252	90.48	217/252	86.11	445/504	88.29	52/60	86.67	52/60	86.67	104/120	86.67
	4†	GL GB	84/95	88.42	84/96	87.50	168/191	87.96	26/30	86.67	23/30	76.67	49/60	81.67
Univariate functions														
2		ML	220/252	87.30	214/252	84.92	434/504	86.11	52/60	86.67	52/60	86.67	104/120	86.67
3		MB	205/252	81.35	199/252	78.97	404/504	80.48	48/60	80.00	50/60	83.33	98/120	81.67
	5†	GL	74/95	77.89	84/96	87.50	158/191	82.72	26/30	86.67	22/30	73.33	48/60	80.00
	6†	GB	82/95	86.32	83/96	86.08	165/191	86.39	26/30	86.67	24/30	80.00	50/60	83.33

† Discriminant functions from Peckmann et al. (2017); function 4: y = 0.15 (GL) + 0.38 (GB) – 15.01, cut-off value = 0.01; function 5: y = 0.43 (GL) – 14.55, cut-off value = 0.01; function 6: y = 0.51 (GB) – 13.27, cut-off value = 0.01
^ Data for functions 4, 5 and 6 taken from Peckmann et al. (2017)

which uses only GL (82.72% for the model set and 80.00% for cross-validation), show lower accuracies compared to Functions 2 and 6.

DISCUSSION

The morphometric analysis of the scapula in the Northern Thai population provides valuable insights into population-specific characteristics that can enhance sex estimation practices, facilitate comparative studies with other populations, and inform evolutionary models tracing morphological adaptations. Understanding the functional implications of scapular dimensions, particularly their influence on upper limb mobility and strength, highlights the importance of these measurements in assessing the evolutionary pressures shaping skeletal morphology.

Assessment of observer variability

In forensic anthropology, the reliability of measurements is critical, and observer variability testing plays a key role in ensuring this reliability. This study's findings of no statistically significant differences between intra- and inter-observer assessments underscore the consistency and accuracy of the scapular measurements taken. Such consistency is essential for maintaining the validity of the data and for ensuring that conclusions drawn from the analysis are robust.

Left and right scapular differences

The investigation into side differences in scapular measurements revealed no significant differences except for the glenoid cavity breadth (GB) in both sexes and the glenoid cavity length (GL) in females. These findings are consistent with previous studies (Torimitsu et al., 2016; Omar et al., 2019) that reported no side differences in maximum scapular length (ML) and breadth (MB). However, they differ from the findings of Peckmann et al. (2017), which reported no side differences in glenoid cavity dimensions within a Northern Thai population. The discrepancy may be attributed to observer error or individual variations in the shape of the glenoid cavity (Vardhan et al., 2019), which can influence measurement outcomes. These results highlight the need for careful consideration of the glenoid cavity's variable morphology in future research, as these variations may affect the accuracy of sex estimation methods.

Relationship between muscle development and scapular morphology

This study found statistically significant differences in maximum scapular length (ML) and breadth (MB) between sexes ($p < 0.05$), with males exhibiting larger measurements (Table 3). The observed sexual dimorphism can be attributed to the development of scapular muscles, which is influenced by higher testosterone levels in males, promoting both muscle and bone growth (Hrdlička, 1942; Singh et al., 1998). The attachment of various muscles to the scapula, such as the levator scapulae, latissimus dorsi, and rhomboid muscles (Miniato et al., 2023), likely contributes to the more pronounced differences in ML compared to MB. This relationship between muscle development and scapular morphology supports the use of these measurements in sex estimation.

Discriminant functions

The discriminant functions developed in this study were specifically designed using only maximum scapular length (ML) and breadth (MB) measurements due to the identified variability in the glenoid cavity (Vardhan et al., 2019), which could introduce errors and reduce discriminating accuracy. Function 1, y = 0.10 (ML) + 0.05 (MB) – 19.27, which incorporates both ML and MB, demonstrated the highest accuracy in distinguishing between sexes. Function 2, y = 0.12 (ML) – 17.28, which relies solely on ML, also showed strong discriminative power, though it was slightly less accurate than Function 1. This consistency reinforces the reliability of ML as a key metric for sex estimation. In contrast, Function 3, y = 0.17 (MB) – 16.46, which uses only MB, exhibited the lowest discriminative ability, highlighting that MB alone is less sexually dimorphic than ML. These findings suggest that ML has a stronger influence on sex estimation than other scapular measurements (Torimitsu et al., 2016). Moreover, multivariate discriminant functions, which include multiple variables, consistently result in higher accuracy for sex estimation compared to univariate functions (Dabbs, 2010; Omar et al., 2019; Peckmann et al.,2017).

When comparing these discriminant functions with those developed by Peckmann et al. (2017) for similar Northern Thai populations, such as those using glenoid cavity length (GL) and breadth (GB) measurements, the functions based on ML and MB in this study demonstrated superior accuracy. The higher accuracy of Function 1 in this study, compared to similar multivariate functions using GL and GB, suggests that ML and MB are more robust indicators of sexual dimorphism in the Northern Thai population (Dabbs, 2010; Omar et al., 2019). This may be due to the inconsistent morphology of the glenoid cavity (Vardhan et al., 2019), leading to measurement overlaps between sexes and reduced accuracy in sex estimation. Further studies are needed to better understand the sexual dimorphism of the glenoid cavity, especially given its minimal muscle attachment and variable morphology.

Significance and practical applications

The discriminant functions developed in this study, particularly Function 1, are notable for their ability to accurately distinguish between male and female scapulae within the Northern Thai population. The pronounced sexual dimorphism observed in the maximum scapular length (ML), as evidenced by the high accuracy of Functions 1 and 2, highlights the value of these measurements in forensic contexts. These functions can be effectively utilized in forensic identification, where precise sex estimation is essential, especially in cases where more commonly examined skeletal remains, such as the pelvis or skull, are not available.

Furthermore, these findings contribute significantly to anthropological research by providing population-specific data that can inform studies on human variation and evolution. Expanding the database of discriminant functions with data from diverse populations will enable anthropologists to improve the accuracy of sex estimation methods across different demographic groups.

CONCLUSION

This study highlights the effectiveness of using multivariate discriminant functions for sex estimation, with a combination of ML and MB demonstrating higher overall accuracy than univariate approaches. However, our findings suggest that

ML alone is nearly as effective, offering a time-efficient alternative for sex estimation. Given the greater sexual dimorphism observed in ML and GB compared to MB and GL in this study, incorporating both ML and GB in discriminant function equations could potentially enhance accuracy for sex estimation even further. Future research should focus on developing and validating new discriminant functions that integrate ML and GB across various populations to assess and optimize their accuracy in sex estimation.

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