

Sex and Age Estimation Using Acetabulum Digital Image Processing in a Thai Population

Estimación del Sexo y la Edad Mediante el Procesamiento Digital de Imágenes del Acetábulo en una Población Tailandesa

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SUMMARY: This study focuses on utilizing digital image analysis techniques for forensic sex and age determination through analysis of the acetabulum's morphology. The lunate surface served as a key indicator for sex estimation, while porosity in the acetabular fossa was analyzed to estimate age. A total of 237 adult pelvic bones (122 males, 115 females) were obtained from the Osteology Research and Training Center (ORTC), Thailand. High-resolution photographs of the acetabulum were obtained with a DSLR camera and ImageJ software was used for processing and quantitative evaluation of the images. Statistical analysis revealed a significant difference in lunate surface size between sexes ($p < 0.001$), with males showing larger dimensions. A logistic regression model developed for sex estimation achieved 87.3 % accuracy. For age estimation, the percentage of porosity varied significantly across age groups, as confirmed by the Kruskal–Wallis test and Mann–Whitney U tests. Linear regression showed a moderate correlation between estimated and actual age ($r = 0.45$), with a mean absolute error of approximately 14 years. These findings highlight the potential of 2D digital image analysis in assessing acetabular features for forensic applications. The non-invasive nature of this method supports routine forensic documentation and reduces direct handling of skeletal remains, preserving them for further analyses such as DNA testing. Given its high accuracy in sex estimation and moderate effectiveness in age assessment, this technique provides a practical tool for constructing biological profiles. Future studies should examine image quality differences between DSLR and smartphone cameras to improve accessibility in various field settings.

KEY WORDS: Acetabulum; Sex estimation; Age estimation; Digital Image Processing; Forensic science.

INTRODUCTION

Estimating sex and age is essential for developing a biological profile in forensic anthropology. These assessments can be made using various skeletal elements, including the pelvis (Phenice, 1969), skull (Meindl & Lovejoy, 1985; Ramsthaler *et al.*, 2007), vertebral (Garoufi *et al.*, 2020), which commonly display characteristics indicative of an individual's biological identity.

The hip bone, or os coxae, serves as a key structural element of the hip joint, which is a synovial ball-and-socket joint created by the articulation between the rounded femoral head and the acetabular fossa (cotyloid) of the hip bone.

This joint plays a vital role in providing structural support, mobility, and weight-bearing capacity for locomotion, enabling functions such as standing, walking, and running (Harty, 1984; Team, 2025). Males and females typically experience different patterns of mechanical loading and engage in distinct physical activities, which can influence the size and morphology of the hip bone. These variations in biomechanical demands contribute to sexually dimorphic characteristics observable in pelvic bone structure (Hara *et al.*, 2016). Moreover, the morphological characteristics of the hip joint are significantly associated with age, exhibiting gradual anatomical and structural alterations that reflect the

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degenerative changes inherent to the ageing process (Müller-Gerbl *et al.*, 1993; Hawellek *et al.*, 2022). So, the hip bone is commonly used in age estimation and provides valuable indicators for sex determination. This bone is not only crucial for forensic analysis but is also frequently recovered during archaeological excavations involving skeletal remains (Singsuwan *et al.*, 2019). The specific region of the hip bone (i.e., pubic symphysis, auricular surface, and acetabulum) is by far the most employed skeletal indicator for age estimation of adults. However, age estimation based on the pubic symphysis and auricular surface has notable limitations. In individuals over the age of 40, the anterior surface of the pubic symphysis undergoes significant morphological changes (Rissech *et al.*, 2006). Moreover, individuals with a body mass index (BMI) of 30 or higher may show changes in the auricular surface of the ilium, which can further affect the precision of age estimation techniques relying on this anatomical area (Wescott & Drew, 2015).

The acetabulum, a cup-shaped structure of the hip bone, undergoes structural changes that correlate with age. Age-associated changes encompass modifications to the acetabular margin, the development of osteophytes, and alterations in the lunate surface. Although the pubic symphysis and auricular surface are considered reliable anatomical structures for age and sex estimation, their accuracy may be compromised by various external factors, such as pathological conditions, body weight, and inter-observer variability. To minimize these confounding influences and enhance the reliability of age estimation, forensic anthropologists have increasingly turned to the acetabulum as an alternative and potentially more stable indicator (San-Millán *et al.*, 2017). Moreover, other variables such as BMI, metabolic rate, obesity, and daily life activities were not statistically significant predictors of morphological changes in the acetabulum. Furthermore, statistically significant differences in acetabular characteristics were observed across different age groups (Winburn, 2019).

To the best of our knowledge, this study aims to assess sex estimation based on the size of the lunate surface and age estimation using the percentage of porosity in the acetabular fossa.

MATERIAL AND METHOD

Sample Collection and Ethical Approval. All skeletal samples used in this study were obtained from the Osteology Research and Training Center (ORTC), Faculty of Medicine, Chiang Mai University. The sample consisted of 237 individuals, including 122 males and 115 females, with ages at death ranging from 22 to 95 years. Inclusion criteria required that all specimens were of Thai and had a verified age at death. Acetabulum included in the study was structurally intact and free from fractures, pathological changes, or disease-related bone alterations.

Ethical approval was granted by the Human Research Ethics Committee, Faculty of Medicine, Chiang Mai University (Exemption No. 0154/2025; Research Project Code: NONE-2568-0154).

Image Acquisition and Standardization. This study utilized data collected from photographs of the acetabulum. Photographs were acquired using a DSLR (digital single-lens reflex) camera set to automatic ISO, an aperture of f/4.0, and a shutter speed of 1/80 second. During photography, each pelvic bone was placed on a support box with the posterior superior iliac spine (PSIS) facing downward and the acetabulum oriented upward. The superior margin of the greater sciatic notch was aligned to extend beyond the top of the box. The parallelism between the acetabulum and the camera lens was confirmed by placing a leveling ruler on the acetabular margin. Moreover, the digital camera was fixed on tripod levelled with a spirit level.

Sex estimation. The lunate area, horseshoe-shaped morphology along the peripheral region of the acetabulum,

was then delineated as the region of interest (ROI) for area calculation (Fig. 1A). Image analysis was performed using ImageJ software (Fig. 1B).

Photographic images were imported into ImageJ. A measurement scale was then calibrated based on known reference values within each image.



Fig. 1. A. The selected area of the lunate surface for measurement. B. Calculated by ImageJ.

Age estimation. The acetabular fossa was selected as a ROI for further morphometric analysis using Image J (Fig. 2A). A measurement scale was calibrated within each image to ensure that one unit corresponded to 1 cm in actual length. Each image was then converted to 8-bit grayscale format to facilitate porosity analysis. Subsequently, a threshold value was applied to distinguish porosity areas from the normal bone structure (Fig. 2B). Once thresholding was completed, the percentage of porosity in the acetabular fossa was then analyzed (% Area). The resulting data were then exported to SPSS for statistical analysis. For age estimation, subjects were divided into three categories: under 40 years, 40 to 60 years, and over 60 years.

Statistical analysis

The Kolmogorov–Smirnov test was employed to evaluate the normality of the complete dataset. Variations in lunule surface size were examined with the Mann–Whitney U test. A logistic regression model was developed to predict sex based on these differences. For age estimation based on the percentage of bone porosity, the Kruskal–Wallis test was first used to identify differences in % porosity among age groups. Subsequently, pairwise comparisons among the three groups were conducted using the Mann–Whitney U test. Finally, a linear regression model was developed to estimate age from % porosity.

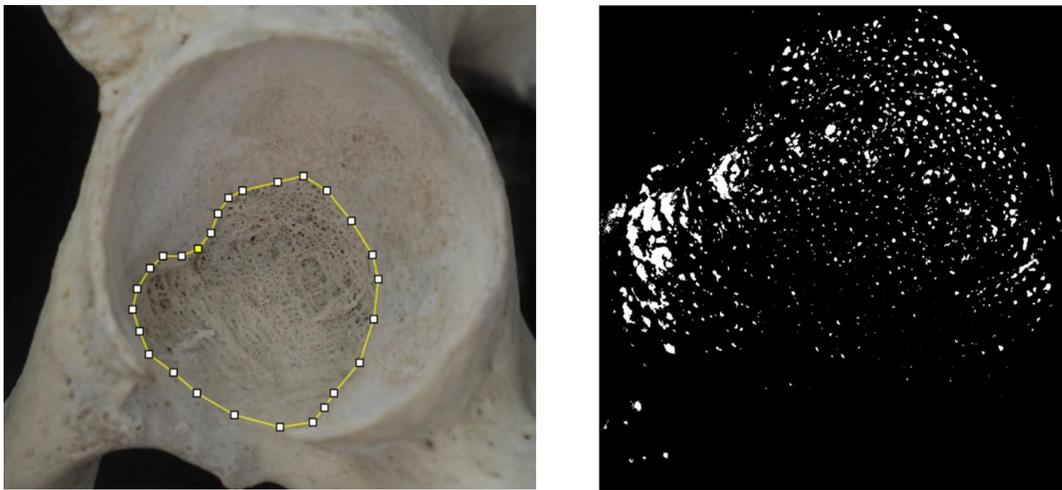


Fig. 2. A. The selected area of the acetabular fossa for measurement. B. The porosity shown in ImageJ.

RESULTS

To test intra-observer reliability, 30 samples were randomly selected for repeated analysis. The observer re-identified the ROI for each sample after a two-week interval. The consistency between the first and second measurements was evaluated using Pearson’s correlation coefficient. The results indicated a statistically significant positive correlation between the two sets of measurements ($r=0.998$), confirming high intra-observer reliability in the ROI selection process.

Sex estimation

To assess the distributional normality of the data, the Kolmogorov–Smirnov test was applied. Results indicated that the female sample group followed a normal distribution, with a p-value greater than 0.05. In contrast, the male sample group showed a p-value of 0.019, indicating a non-normal distribution. Owing to intergroup differences in data distribution, the Mann–Whitney U test, a non-parametric method, was utilized to examine variations in lunule surface area by sex.

The Mann–Whitney U test showed a highly significant difference in lunule surface area between sexes, with a p-value less than 0.001, with males exhibiting significantly larger surface areas than females. Female specimens had a mean lunule surface area of 13.15 cm² (SD = 0.17), with a median of 12.91 cm². In contrast, male specimens exhibited a larger mean area of 16.90 cm² (SD = 0.18), a median of 16.76 cm².

A logistic regression model was developed to predict sex using lunule surface area as the sole predictor. The resulting logistic regression equation for estimating the probability (P) is as follows:

$$P = \frac{1}{1 + e^{-(1.075 \times \text{Area} - 16.046)}}$$

A cut-off value of 0.50 was applied to classify sex. If the calculated P is less than 0.50, the individual is classified as female; if P is greater than or equal to 0.50, the individual is classified as male. “e” is Euler’s number, approximately

equal to 2.71828. The regression model demonstrated a statistically significant ability to distinguish between sexes, with a p-value of < 0.001. This indicates that lunate surface area is an effective and significant predictor of sex in this sample.

As shown in Table I, the logistic regression model achieved a classification accuracy of 85.2 % for females and 89.3 % for males, with an overall average accuracy of 87.3 %. These results suggest that lunate surface area is a highly effective variable for sex estimation in osteological analysis.

Table I. Classification rate for sex estimation based on lunate surface area.

Sex	Percentage Correct
Female	85.2
Male	89.3
Overall	87.3

Age estimation

Descriptive statistical analysis of porosity in the acetabular fossa was performed by dividing the samples into three age groups. In individuals aged below 40 years, the mean porosity was 1.75 (SD = 0.29), with a range from 0.04 to 4.53. In the 40–60-year group, the mean porosity increased to 2.69 (SD = 0.13), ranging from 0.27 to 6.12. The highest mean porosity was observed in the group over 60 years, at 4.36 (SD = 0.19) (Fig. 3), with values ranging from 0.80 to 12.23. This finding reflects age-related degenerative changes in the acetabular region.

To compare porosity levels in the acetabular fossa across three age groups, the Kruskal-Wallis’s test was used due to the non-normal distribution of the data. The results revealed an increasing trend in mean rank values with age: individuals under 40 years had a mean rank of 56.29, the 40–60-year group had a mean rank of 96.00, and those over 60 years had the highest mean rank of 154.19, respectively. These results indicate a clear increase in porosity with age. Pairwise comparisons confirmed statistically significant differences in porosity across all age groups (<0.001), suggesting that age strongly influences the degree of porosity in the acetabular fossa (Table II).

A linear regression analysis revealed a statistically significant positive correlation between age and porosity ($r = 0.45, p < 0.001$). The regression equation, $y = 3.833x + 48.102$, suggests that porosity increases with age, indicating a gradual degeneration of the acetabular fossa bone structure over time.

DISCUSSION

High-quality imaging plays a critical role in modern forensic identification, as photographs are increasingly relied upon for documentation, comparison, and long-term data preservation. To ensure that essential anatomical details are accurately captured without loss or distortion, it is imperative to use imaging tools that provide precision, clarity, and control. One such forensic imaging tool is widely recognized by DSLR camera. The DSLR cameras offer superior image resolution and allow precise control over lighting conditions compared to smartphone cameras (Healy & Stephan, 2023).

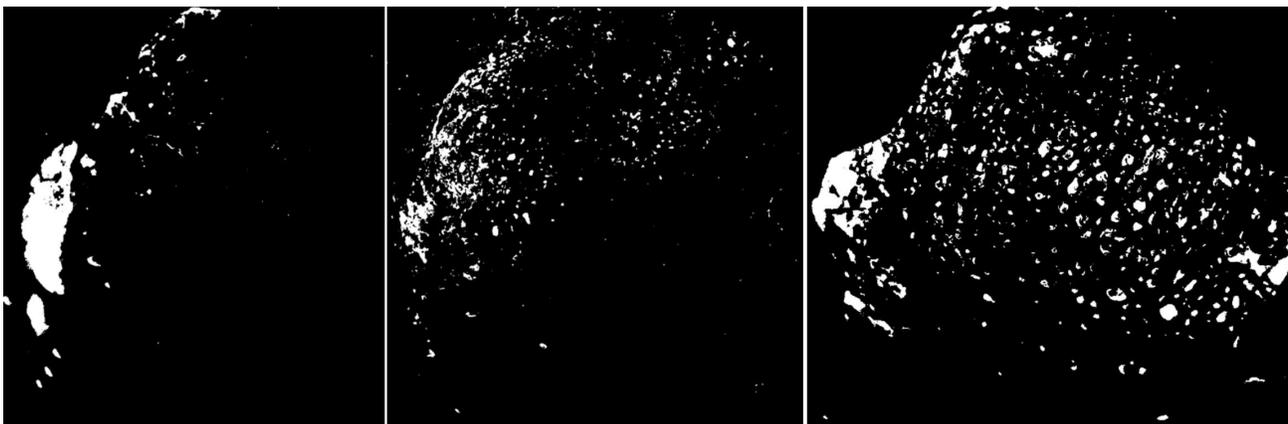


Fig. 3. Porosity differences across age groups analyzed in ImageJ A. at 22 years old. B. at 54 years old. C. at 87 years old.

Table II. Comparison of acetabular fossa porosity across age groups using the Kruskal-Wallis test and Mann–Whitney U test between group.

Age group	N	Mean Rank	p-values	Group	p-values
< 40	21	56.29		(1:2)	0.003
40-60	108	96.00	<0.001	(1:3)	<.001
> 60	108	154.19		(2:3)	<.001

Adjustable settings, including aperture, shutter speed and ISO sensitivity, enable operators to optimize image sharpness and depth of field. These ensure that subtle anatomical features (i.e., morphology of the acetabular bone) are preserved for detailed and accurate analysis. In this study, a DSLR camera was selected as the primary imaging tool to capture high-resolution photographs of the acetabulum. The intra-observer reliability results from this study confirmed that images captured using the DSLR camera provided consistency, reproducibility, and the preservation of critical osteological details. These qualities are essential for both qualitative and quantitative assessments in forensic contexts.

This study utilized ImageJ software to analyze the size of lunate surface, a part of acetabulum, for development of a predictive model for sex estimation. Results indicated that the lunate surface tends to be larger in male individuals compared to females. As previously, the hip bone exhibits clear sexual dimorphism between males and females, which may be attributed to functional demands such as physical activity or load-bearing differences (Hara *et al.*, 2016). These factors contribute to size variations in specific regions of the hip bone. This study is consistent with previous studies reporting that size of lunate surface, a component of the hip bone, also reflects sexual dimorphism.

The logistic regression model developed in this study demonstrated high classification accuracy, ranging from 85 % to 89 %, indicating that lunate surface dimensions are a reliable indicator for sex estimation. When compared to previous studies (Table III), the results of the present study are consistent with those reported by Macaluso (2010), who examined pelvic bones from a French population by measuring three acetabular parameters. Using discriminant function analysis, they developed sex estimation equations that yielded classification accuracies of approximately 84 % to 85 %. Despite differences in anatomical focus and

population samples, the results of the present study are consistent with those of Macaluso (2011) who focused specifically on acetabular dimensions and employed logistic regression analysis, reporting classification accuracies ranging from 84 % to 89 %. Therefore, this highlights that the lunate surface, a subcomponent of the acetabulum, holds substantial discriminative power for sex estimation.

The acetabulum is commonly utilized in skeletal age estimation, often in conjunction with the femoral head. Age estimation commonly relies on factors such as bone porosity and morphological variation (Müller-Gerbl *et al.*, 1993; Whitmarsh *et al.*, 2019). Moreover, the acetabulum has received increasing attention as a valuable region for age estimation. Its structural durability and relative resistance to external factors, such as variations in physical activity levels or body weight throughout life, enhance its reliability. Moreover, the acetabular area is less susceptible to postmortem taphonomy changes, making it particularly suitable for forensic identification, even under challenging recovery conditions (Winburn, 2019). Our study focused on porosity in the acetabular fossa between age group. Notably, age-related morphological changes have been observed in this region, including increased porosity and irregular bone growth. These alterations are thought to result from the gradual degeneration of intra-articular tissues, leading to diminished protection of the acetabular fossa. Consequently, the bone experiences a loss of density and structural integrity with increasing age. Our finding demonstrated significant variation in % porosity across different age groups; however, using % porosity alone as an indicator for age estimation still carries a substantial degree of variability. Discrepancies between actual chronological age and estimated age based on % porosity were observed to reach as high as ± 14 years. This suggests that while age-related changes in bone porosity are evident, its application as a standalone criterion for precise age estimation remains limited due to its wide error of estimation.

Table III. Comparison of sex estimation accuracy using different areas and methods.

The study	Area	Method	Percentage of estimation (%)
Present study	Lunate surface	Image processing	85-89
Phenice <i>et al.</i> , 1969.	Pelvis	Morphology	90
Macaluso, 2010.	Acetabulum	Measuring three parameters	84-85
Macaluso, 2011.	Acetabulum	Measuring	84-89

Table IV. Comparison of age estimation accuracy using different areas and methods.

Study	Area	Method	Age estimation error (years)	Percentage of estimation (%)
Present study	Acetabular fossa	Image processing	14	N/A
Calce & Rogers, 2011	Acetabulum	Morphology	10	83
Krudtong & Mahakkanukrauh, 2024	Acetabular fossa	Image processing	16	N/A
Schmelting <i>et al.</i> , 2007	Auricular surface	Morphology	13-18	N/A
Belghith <i>et al.</i> , 2021	Acetabular joint	CT scanning	6-7	84-85

N/A = Not Available

Compared to earlier studies (Table IV), the results of this research align with those reported by Calce & Rogers (2011), who examined seven morphological variables of the acetabulum and reported an average age estimation error of approximately 10 years. Similarly, Khomkham *et al.* (2017) in their study of a Thai population, also analyzed seven acetabular variables and found that only three variables, acetabular groove, acetabular margin porosity, and apex activity, showed strong correlations with age. These results suggest that incorporating multiple morphological variables can reduce the discrepancy between estimated and actual chronological age (Botha *et al.*, 2016). More recently, Krudtong & Mahakkanukrauh (2024) investigated the percentage of porosity using histogram analysis and found no significant correlation between porosity and age in females, although a positive association was observed in males. However, when regression models were applied for age estimation, the correlation coefficients remained low ($r = 0.006-0.24$), with the highest r values seen among males. These outcomes are consistent with findings by Schmitt *et al.* (Schmelting *et al.*, 2007), who assessed age estimation using auricular surface morphology and reported estimation errors ranging from 13 to 18 years. Together, these results underscore the inherent variability and limited precision of using a single morphological feature for age estimation. Despite the observed error margins in age estimation, the method presented in this study remains a viable approach for age estimation, particularly when used in conjunction with other morphological indicators.

Among the methods used for age estimation, CT scans yielded the lowest margin of error. For example, Belghith *et al.* (2021) utilized 3D imaging with CT scanning to analyze three morphological variables. The resulting model achieved an error margin of only 6–7 years. However, in forensic science, photographic documentation remains the standard practice for recording evidence. Therefore, 2D image-based analysis continues to be essential in forensic applications. This approach also minimizes direct contact with the remains, thereby preserving the specimen for other analyses such as DNA testing. Additionally, sex estimation based on these methods still demonstrates high accuracy. Further research may explore a comparison between images captured using smartphone cameras and DSLR cameras to evaluate differences in image quality. Furthermore, these findings highlight the potential of digital imaging technologies to significantly enhance the precision of forensic anthropological assessments.

CONCLUSION

The present study highlights the effectiveness of digital image processing for estimating sex and age from

acetabular characteristics in a Thai population. A clear distinction in lunate surface size found significant difference between males and females, with males showing larger dimensions, leading to an 87.3 % accuracy in sex prediction using a probability-based model. Regarding age estimation, although significant differences in acetabular fossa porosity were observed across age groups, the correlation between estimated and actual age remained relatively weak ($r = 0.45$), with a mean error of approximately 14 years. Despite this limitation, the acetabular region still holds value as an indicator for age estimation. Overall, these findings suggest that image-based analysis of the acetabulum can serve as a practical and non-invasive tool in forensic investigations, supporting the development of biological profiles within a Thai population.

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RESUMEN: El estudio se centra en el uso de técnicas de análisis de imágenes digitales para la determinación forense del sexo y la edad mediante el análisis de la morfología del acetábulo. La superficie semilunar sirvió como indicador clave para la estimación del sexo, mientras que la porosidad de la fosa acetabular se analizó para estimar la edad. Se obtuvieron 237 huesos pélvicos adultos (122 hombres y 115 mujeres) del Centro de Investigación y Formación en Osteología (ORTC) de Tailandia. Se obtuvieron fotografías de alta resolución del acetábulo con una cámara DSLR y se utilizó el software ImageJ para su procesamiento y evaluación cuantitativa. El análisis estadístico reveló una diferencia significativa en el tamaño de la superficie semilunar entre sexos ($p < 0,001$), siendo los hombres los que mostraron mayores dimensiones. Un modelo de regresión logística desarrollado para la estimación del sexo alcanzó una precisión del 87,3 %. Para la estimación de la edad, el porcentaje de porosidad varió significativamente entre los grupos de edad, como lo confirmaron las pruebas de Kruskal-Wallis y la U de Mann-Whitney. La regresión lineal mostró una correlación moderada entre la edad estimada y la real ($r = 0,45$), con un error absoluto medio de aproximadamente 14 años. Estos hallazgos resaltan el potencial del análisis de imágenes digitales 2D para evaluar las características acetabulares en aplicaciones forenses. La naturaleza no invasiva de este método facilita la documentación forense rutinaria y reduce la manipulación directa de restos óseos, preservándolos para análisis posteriores, como las pruebas de ADN. Dada su alta precisión en la estimación del sexo y su moderada eficacia en la determinación de la edad, esta técnica constituye una herramienta práctica para la construcción de perfiles biológicos. Estudios futuros deberían

examinar las diferencias en la calidad de imagen entre las cámaras DSLR y las de teléfonos inteligentes para mejorar la accesibilidad en diversos entornos de campo.

PALABRAS CLAVE: Acetábulo; Estimación del sexo; Estimación de la edad; Procesamiento digital de imágenes; Ciencias forenses.

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