Int. J. Morphol.,
43(2):675-682, 2025.

Sex Determination by Two-Dimensional Photographs of Cuboid Bone Based on Deep Learning Classification in a Thai Population

Determinación del Sexo Mediante Fotografías Bidimensionales del Hueso Cuboides Basado en la Clasificación de Aprendizaje Profundo en una Población Tailandesa

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INTASUWAN, P.; TEVAVICHULADA, K.; MURAMUN, M.; SUKSAWAT, L.; NONTRASIRI, W.; PRASITWATTANASEREE, S. & MAHAKKANUKRAUH, P. Sex determination by two-dimensional photographs of cuboid bone based on deep learning classification in a Thai population. *Int. J. Morphol., 43(2)*:675-682, 2025.

SUMMARY: Sex determination is one of the most essential steps for creating a biological profile of human skeletal remains in forensic and physical anthropology. The os coxae is the most efficient bone for sex determination. Since the os coxae, or skull, is not always present, the tarsal bones, which preserve well, serve as excellent candidates for sex determination. The cuboid is an interesting tarsal bone for sex determination, preserved well from a natural taphonomy environment. Deep learning techniques showed outstanding performance for tasks such as detection and classification based on vast amounts of unlabeled or labeled data. This study aimed to search for the performance of CNN to increase a reliable tool of sex determination using cuboids based on deep learning techniques in a Thai population. The samples comprised 352 individuals divided into 302 individuals for a training dataset (156 individuals or 257 bones for females, 146 individuals or 256 bones for males) and 50 individuals for a test dataset (25 females, 25 males). All cuboids were taken by the digital camera consisting of six views: dorsal (superior) view, plantar (inferior) view, lateral view, medial view, distal view (metatarsal facet), and proximal view (calcaneal facet). We adjusted the pre-trained GoogLeNet model for classifying sex by 2D images of cuboids in each view. The results showed that the proximal view (calcaneal facet) achieved the highest validation accuracy with 87.01 % and test accuracy with 78 %. Our study demonstrated that the pre-trained GoogLeNet model performed the effective method with the limitation of small datasets. Moreover, our technique could perform as an alternative for the rapid, comfortable, and objective tool of sex determination using the human skeletons in a Thai population used in law enforcement and the forensic anthropological field.

KEY WORDS: sex determination, deep learning, GoogLeNet, cuboid, forensic anthropology

INTRODUCTION

Sex determination is the most essential step for creating a biological profile by the human skeletal remains in forensic anthropologists. Many human bones have been shown for sexing in previous studies. The os coxae performed the most efficiently, capable of sex determination with up to 98 % accuracy (Listi & Bassett, 2006), and the cranium is often the second choice for sexing with up to 92 % accuracy (Oikonomopoulou *et al*., 2017). However, in reality, the os coxae or skull cannot be found in all situations; the tarsal bones are excellent candidates for sex determination because of being well-preserved (Mahakkanukrauh *et al*., 2014). Since footwear typically contains tarsal bones, a natural taphonomy environment preserves them well and maintains the entire tarsal bone structure. (Viwatpinyo *et al*., 2014). Furthermore, tarsals have a sturdy and compact structure (Navega *et al*., 2015).

In previous studies, the talus and calcaneus are popular bones for sexual assessment among many populations. The accuracy ratio ranged from 85 % to 94 % in Japanese populations using talus and calcaneus bones (Sakaue, 2011) and 84.5 % to 91.4 % in Thai populations (Mahakkanukrauh *et al*., 2014). However, some studies used the cuboid for sexual dimorphism with slightly higher

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funding. This work was supported by the Faculty of Medicine, Chiang Mai University (Grant No. MC036/2565).

Received: 2024-07-15 Accepted: 2024-10-16

accuracy than the talus only (Mahakkanukrauh *et al*., 2014; Navega *et al.*, 2015). The cuboid also proved to be suitable and was one of the interesting tarsal bones for sex determination.

Sex determination is based on three processes, including DNA analyses, observation of morphological traits, and morphometrical data with discriminant analysis (Sakaue, 2011). DNA analysis can be performed with a high accuracy depending on the number and property of DNA samples. However, the DNA leads to degrade because of the cell death, the environment can destroy the bone fossils and reduces the accuracy of DNA analysis. Therefore, this method is not an accurate application (Liu *et al*., 2021). The morphological method can be used for sex determination. Although it provides valuable results, this method requires experts in the forensic anthropological field to assess the bone features and is a more subjective method (Etli *et al*., 2019). Therefore, the morphometric method was developed for this purpose. A caliper and radiology are used for measuring bones, and the discriminant analysis is used in predicting sex. Although discriminant analysis is strongly responsive, the rates of error are higher too (Turan *et al*., 2019). Alternatively, deep learning is a growing interest for sex determination methods in the forensic anthropological field (Etli *et al*., 2019).

Deep learning is a subfield of machine learning within artificial intelligence (AI). Deep learning is derived from the convolutional neural network and comprises considerable multilayer networks that can encounter useful features to represent the input dataset (Sahiner *et al*., 2019). Deep learning techniques showed good outstanding performance for tasks such as detection and classification based on a vast amount of unlabeled or labeled data. Moreover, deep learning is useful in some situations for solving problems; for example, experts are not available or unable to explain some features (Alzubaidi *et al*., 2021).

Convolutional neural network (CNN) is the most famous class of deep learning field. The structure was inspired by human neurons consisting of an input, the multi-hidden layers which increase the extraction of complex features, and output (Wang *et al*., 2021). Image classification was one of the tasks in which deep learning made the image analysis. LeNet and AlexNet are two types of CNNs that are general classification architectures. Afterward, more complex layers were built to improve the efficiency of the training data, GoogLeNet (Litjens *et al*., 2017). GoogLeNet was the winner of the ImageNet visual recognition challenge, which had the best ability to detect the best features, and fine-tuned a pre-trained model on the data and nearly achieved human expert performance (Alaskar *et al*., 2019). In this experiment, we used a pre-trained GoogLeNet model for classifying 2D images of the cuboid bones to determine sex. This study aims to search for the performance of CNN and to increase reliable tools of sex determination using cuboids based on the deep learning technique in a Thai population.

MATERIAL AND METHOD

Data Acquisition. The study protocol was approved by the Research Ethics Committee, Faculty of Medicine, Chiang Mai University, Thailand (Research ID: ANA-2564-08724). The cuboids were obtained from the Osteology Research and Training Center (ORTC), Faculty of Medicine, Chiang Mai University. The overall samples comprised 352 individuals divided into 302 individuals for a training dataset (156 individuals or 257 bones for females, 146 individuals or 256 bones for males) and 50 individuals for a test dataset (25 females, 25 males). The selected cuboids for this study were both sides; some individuals may have one side, complete bones, and a Thai population. The age at death ranged between 15 - 94 years. The mean age at death in the samples was 64 years. Cuboids were excluded from the data based on the following: incomplete or fragmentary cuboids, a pathological bone, a non-Thai population, and an age under 15 years.

Image Processing. This study used 2D images of cuboids. Cuboid bones, including the left and right sides, were photographed by a digital camera with the following technical specs: Sony a57 Lens; Sony dt 18 – 55mm F3.5-5.6 SAM, at focus depending on each picture, autofocus mode iso 3200. Every picture was recorded in ARW file format for the best quality. Every cuboid was taken by two positions of the digital camera consisting of 1) top view position including four views of the cuboids: dorsal (superior) view, plantar (inferior) view, lateral view, medial view, and 2) front position including two views of the cuboids: distal view (metatarsal facet), proximal view (calcaneal facet) (Fig. 1). Each one of the top view positions was placed on black silk velvet with a photo taken with a ruler, which was a landmark in all pictures. For the front view position, each bone was set in a studio box and on black silk velvet, and the facet of cuboids on the marker was fixed in the same place in every photograph. Moreover, the length between the lens and cuboid bones was equal in every picture. The position of the camera, bones, and equipment were set with a standardized procedure every time.

The training and test datasets were derived from photography. All cuboid images of the two groups were cropped using the Adobe Photoshop 2020 program to highlight the regions of interest (ROIs) (Fig. 1) before training with the GoogLeNet model.

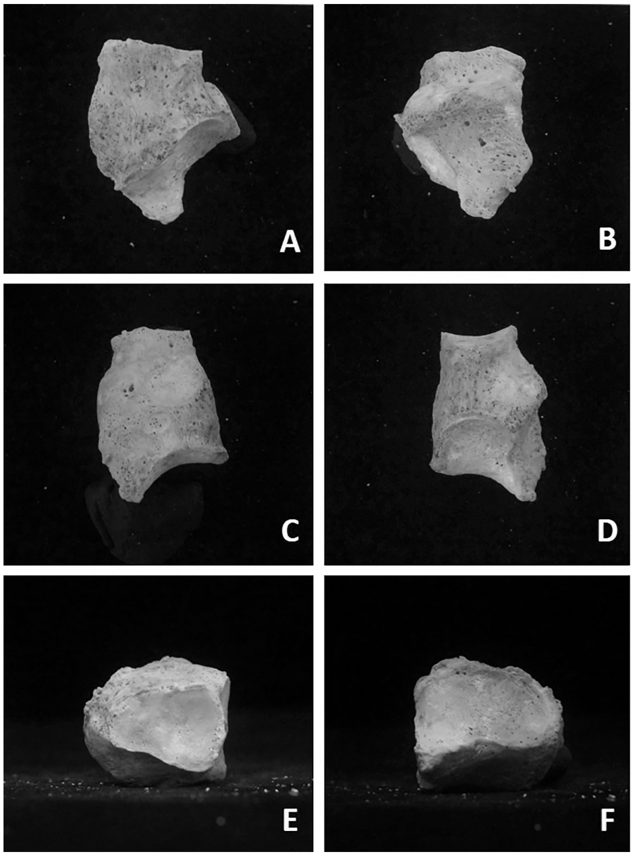

Fig. 1. 2D images of the right-side cuboid: dorsal (superior) view (A), plantar (inferior) view (B), lateral view (C), medial view (D), distal view (metatarsal facet) (E), proximal view (calcaneal facet) (F).

Deep Convolutional Neural Network. A pre-trained GoogLeNet model was applied for predicting sex. GoogLeNet is optimized for object recognition and classification. Transfer learning occurs when the pre-trained GoogLeNet model is adjusted for a new task (Bewes *et al*., 2019). Transfer learning requires large data sets to train a deep neural network for strong results (Litjens *et al*., 2017). The software MATLAB 2020a with neural network toolbox is used for training the dataset. The GoogLeNet model was adjusted within the MATLAB program to classify cuboid images into female or male.

The convolutional neural network (CNN) is the most employed algorithm applied in various fields and the most famous in image classification. The CNN structure was inspired by human neurons for identifying complex sequences (Alzubaidi *et al*., 2021). The CNN architecture includes numerous layers called the convolutional layer. GoogLeNet architecture consists of 22 layers. The fully connected layer was changed from 10 to 2 of the output size number in a new task to predict either male or female.

Data augmentation was performed before training datasets to avoid over-fitting (Alzubaidi *et al*., 2021). To accomplish this, random rescaling is used for rotating, translating, and flipping of training images. A 0.9 – 1.1 range of random rescaling was used in this experiment. The GoogLeNet model requires the input images to sizes 224 x 224 pixels and was resized before data augmentation.

The 563 cuboidal images were divided into 513 training and 50 test datasets. The validation dataset was separated from 30 % of the training set. Before training datasets, modifications to the hyperparameters were tried for the best validation accuracy of each position, such as tuning the initial Learning rate which is defined as the step size of the parameter updating (Alzubaidi *et al*., 2021), validation frequency, mini-batch size which is can be considered an undersized collection of data with no overlap and the training datasets are partitioned into it (Alzubaidi *et al*., 2021), max epochs, L2-regularization which is several ways to reduce overfitting and adjusted to 1e-4 in this experiment (Sahiner *et al*., 2019) and momentum which is manipulated in the objective function and resolves the issues of the invisible convex surface (Alzubaidi *et al*., 2021) and this experiment used 0.9 (Fig. 2). Validation accuracy (%) was shown after the training processes (Fig. 3).

Subsequently, we exported the best training model of the highest validation accuracy in each position to the command window, testing the 50 test datasets not used in the training set for predicting sex (Fig. 2). The training datasets were trained on Notebook Lenovo IdeaPad Gaming3 15IMH05 81Y400PATA with 512 GB of memory and 4GB GDDR6 of GPU memory (NVIDIA GeForce GTX 1650 Ti).

Statistics. The validation datasets were analyzed by the GoogLeNet model.

RESULTS

Dorsal (superior) View. The best model of the dorsal (superior) view was derived from the adjusted hyperparameters following: an initial learning rate = 1e-3, validation frequency = 25, mini-batch size = 8, max epochs = 100, and random rotation (degree) = (-90) – 90. After training this dataset, the results achieved 72.08 % and 56 % accuracies of the validation and test sets, respectively (Table I).

Plantar (inferior) View. The best model of the plantar (inferior) view was derived from the adjusted hyperparameters following: an initial learning rate = 1e-4, validation frequency = 25, mini-batch size = 8, max epochs = 50, and random rotation (degree) = (-60) – 60. After training this dataset, the results achieved 72.73 % and 66 % accuracies of the validation and test sets, respectively (Table I).

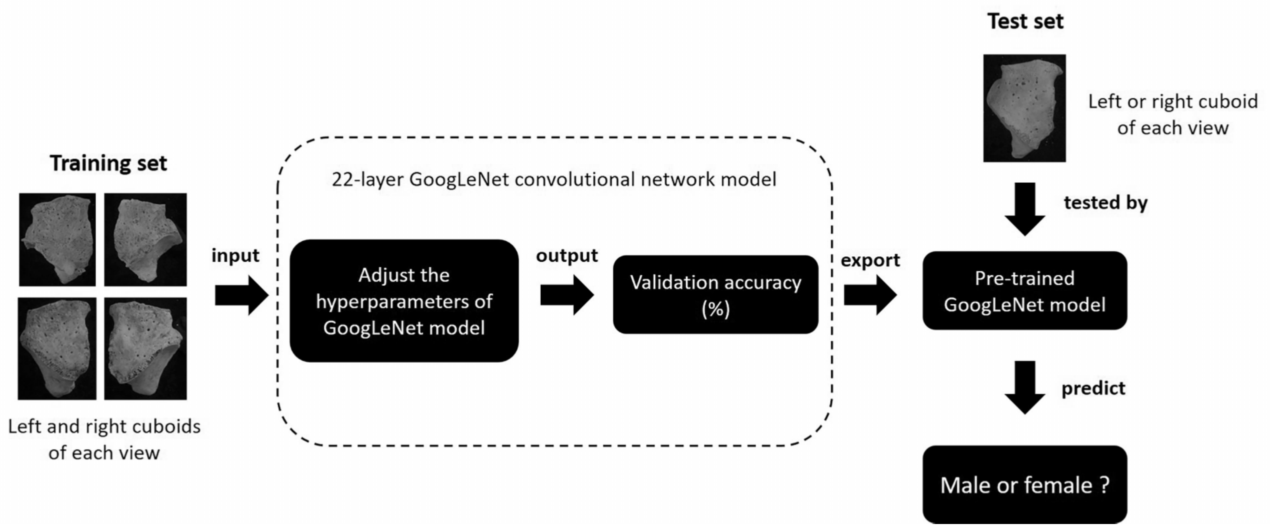

Fig. 2. Schematic diagram of the overall process of fine-tuning GoogLeNet model for the training set, and then the test set was tested by this model for predicting sexes.

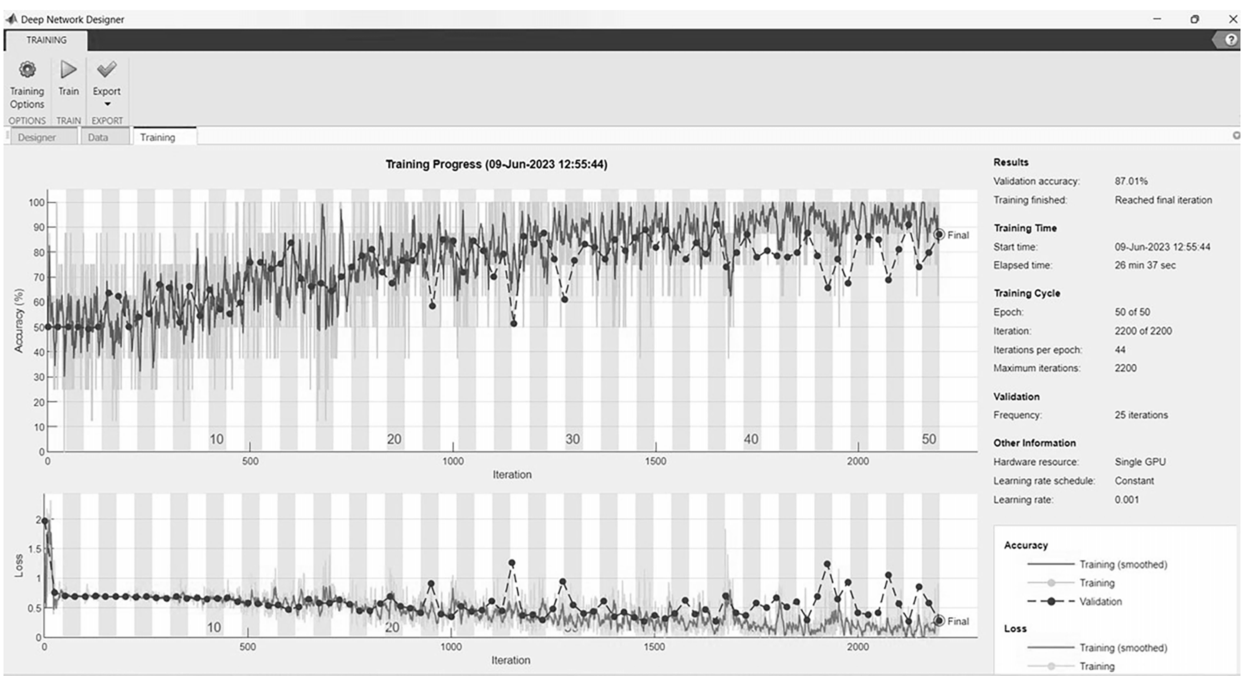

Fig. 3. Validation accuracy of the proximal view (calcaneal facet) for sex determination using a training set of cuboids trained by a pre-trained GoogLeNet model.

Table I. Performance of the pre-trained GoogLeNet model for classifying sex using 2D cuboid images in each view

	Validation accuracy (%)	Test accuracy (%)
Dorsal (superior) view	72.08	56
Plantar (inferior) view	72.73	66
Lateral view	62.34	56
Medial view	62.99	68
Distal view (metatarsal facet)	81.17	70
Proximal view (calcaneal facet)	87.01	78

Lateral View. The best model of the lateral view was derived from the following adjusted hyperparameters: an initial learning rate = 1e-3, validation frequency = 25, mini-batch size = 8, max epochs = 30, and random rotation (degree) = (-120) – 120. After training this dataset, the results achieved 62.34 % and 56 % accuracies of the validation and test sets, respectively (Table I).

Medial View. The best model of the medial view was derived from the following adjusted hyperparameters: an initial learning rate = 1e-3, validation frequency = 25, mini-batch size = 8, max epochs = 100, and random rotation (degree) = (-60) – 60. After training this dataset, the results achieved 62.99 % and 68 % accuracies of the validation and test sets, respectively (Table I).

Distal View (metatarsal facet). The best model of the distal (metatarsal facet) view was derived from the adjusted hyperparameters following: an initial learning rate = 1e-3, validation frequency = 25, mini batch size = 8, max epochs = 30, and random rotation (degree) = (-90) – 90. After training this dataset, the results achieved 81.17 % and 70 % accuracies of the validation and test sets, respectively (Table I).

Proximal View (calcaneal facet). The best model of the proximal (calcaneal facet) view was derived from the adjusted hyperparameters following: an initial learning rate = 1e-3, validation frequency = 25, mini-batch size = 8, max epochs = 50, and random rotation (degree) = (-30) – 30. After training this dataset, the results achieved 87.01 % and 78 % accuracies of the validation and test sets, respectively (Table I).

DISCUSSION

This study aimed to classify sexes with cuboidal images using a pre-trained GoogLeNet model in a Thai population. The cuboidal images used in this experiment were divided into six views: dorsal (superior) view, plantar (inferior) view, lateral view, medial view, distal view (metatarsal facet), and proximal view (calcaneal facet) (Fig. 1). Table I1 shows the performance of the pre-trained GoogLeNet model in each view. The proximal view (calcaneal facet) is the best view for sexing with 87.01 % accuracy of the validation set, and the distal view (metatarsal facet) is the second-best view with 81.17 % accuracy. Dorsal (superior) and plantar (inferior) views achieved moderate accuracy with 72.08 % - 72.73 %. Lateral and medial views showed the worst views in this experiment with 62.34 % 62.99 % accuracy. The validation accuracy was calculated by the last layer of the GoogLeNet model.

Sex determination based on human skeletal remains is a first step and significant role in anthropology. Even though the popular bones used in sex determination are the os coxae and skull (Sumati & Phatak*et* 2018), the tarsal bones have become increasingly common in determining sex over the last two decades (Mahakkanukrauh *et al*., 2014]). The tarsal bones are compact and more resistant to a taphonomic environment because of ligaments and footwear. Accordingly, the previous studies used the tarsals for alternative bones. The talus and calcaneus are popular tarsal bones for studying sexual dimorphism. Sumati and & Phatak (2018) used talus for determining sex in Indian populations by discriminant function analysis with a high accuracy of 96.6 %. Similarly, Mahakkanukrauh (2014) used the talus for sex determination in a Thai population and achieved 91.3 % to 91.4% % accuracy. Moreover, Murphy (2002) measured calcanei for sex determination in the prehistoric New Zealand Polynesian samples with 88.4 % - 93.5 % accuracy. Sakaue (2011) measured both the talus and calcaneus in modern Japanese populations. The total accuracy ranged from 85 % to 94 %. From their results, the accuracy performed well with both the talus and calcaneus for sexual dimorphism. Furthermore, the other tarsal bones were studied; for example, Viwatpinyo *et al*. (2014) measured navicular bones for sexing and achieved 89.6 %-92.1 %. Moreover, Navega *et al*. (2015) measured the calcaneus, talus, first and third cuneiforms, and cuboid for sex determination, resulting in 88.3 % accuracy. Their study affirmed a sexually dimorphic pattern of the tarsal bones in Portuguese populations. The calcaneus and talus performed the most sexually dimorphism tarsals and the 1st, 3rd cuneiform and cuboid performed considerable sexual dimorphism. Likewise, our study achieved high accuracy with 87.01 % using only the cuboids. Therefore, the cuboid was influential in sex determination using tarsals. The further study should study the sex determination using dry bones of the only cuboid by morphometric method compared with our result using the convolutional neural network method.

In the forensic anthropological field, AI applications could promote supplemental expert experiments, overbearing the subjective bias of the limitations in the traditional method (Galante *et al*., 2023). Deep learning applications have been advanced by numerous authors for determining sex by human skeletal remains. Bewes *et al*. (2019) created a GoogLeNet model to memorize the skull features and achieved a high validation accuracy of 95 %. Li *et al*. (2022) used a pre-trained ResNet-18 model to classify proximal femur X-ray images for sex determination. Their result demonstrated the effectiveness with 82.9 % - 94.6 % accuracy in the Chinese population. In our study, we applied the GoogLeNet to classify 2D images of cuboids in sex determination. Our results showed

62.34 % to 87.01 % accuracy of the validation set in six views of cuboids. Moreover, in the Thai population, many previous studies used a pre-trained GoogLeNet model for classifying sexes in various human bones. Intasuwan *et al*. (2022a,b; 2024) designed a pre-trained GoogLeNet model to classify 2D images using the greater sciatic notch of the os coxae with high validation accuracy of up to 90 %, the auricular area of the os coxae with 93.33 % validation accuracy, and the whole of the os coxae with 93.33 %. Malatong *et al*. (2023) used GoogLeNet for sexing by the lumbar vertebrae with 92.5 % accuracy. Furthermore, Pichetpan *et al*. (20243) applied GoogLeNet for sex determination using clavicles with an accuracy of 95 % (Table II). From overall results, the CNN method demonstrated a high performance for the determination of sex based on human skeletal remains. Consequently, further study may improve the effectiveness of the sexing tool based on the CNN model in other human bones.

Table II. Studies of sex determination by the human skeletons using the CNNs model

Authors	**Bone**	**Numbers of**	**Population**	**CNNs**	**Accuracy (%)**
Bewes *et al.* (2019)	Skull	900	European	GoogLeNet	95 %
Li *et al*. (2022)	Proximal femur	1,915	Chinese	ResNet-18	82.9 % - 94.6 %
Intasuwan *et al*. (2022)	The greater sciatic notch of the os coxae	200	Thai	GoogLeNet	90 %
Intasuwan *et al*. (2022)	The auricular area of the os coxae	200	Thai	GoogLeNet	93.3%
Intasuwan *et al.* (2022)	Whole os coxae	200	Thai	GoogLeNet	93.3 %
Malatong *et al.* (2023)	Lumbar vertebrae	220	Thai	GoogLeNet	92.5%
Pichetpan *et al.* (2023)	Clavicle	200	Thai	GoogLeNet	95 %
Present study	Cuboid	302	Thai	GoogLeNet	87.01%

On the other hand, our result achieved the highest validation accuracy with 87.01 % in the proximal view (calcaneal facet) of cuboids, and the test accuracy was 78 %. The lowest validation accuracy was 62.34 % in the medial view. Since the limitation of this study is the small datasets of cuboids, we used both the right and left sides together (302 individuals) in each view for training data. Applying AI tools in forensic anthropology requires a large dataset of skeletal remains to identify persons for good and promising results (Galante *et al*., 2023). Similarly, Cao *et al*. (2021) constructed a pre-trained CNN model called GoogLeNet Inception V4 for sex determination using 1,000 individuals of CT pelvic images. The accuracy achieved was up to 98 %. Moreover, Bewes *et al*. (2019) achieved a high accuracy of up to 95 % with 900 human skulls. In further study, the large sample sizes of the humanized skeletons could be required in this experiment to increase the validation and test accuracies for the better performance of sexing tools in a Thai population based on the CNN method.

Our study demonstrated that sex determination by 2D images of cuboids using a pre-trained GoogLeNet model has shown surprisingly strong results with the limitation of small datasets, which is the major weakness of AI based on neural networks (Bewes *et al*., 2019). However, our technique could perform as an alternative for the rapid, comfortable, and objective tool of sex determination using human skeletons. In all situations, if someone finds human cuboids, he can take photos of cuboids, especially in proximal view (calcaneal facet), and send these to the experts of the human skeleton for Thai personal identification. Moreover, further study could input the human bone images derived from smartphones, offering a practical technique for sex determination in the archeological and forensic fields.

CONCLUSION

The convolutional neural network technique performed exceptionally well in classifying sex by the cuboidal images, especially in the proximal view (calcaneal facet) in a Thai population with small datasets. This technique is a more reliable and rapid method for sex determination. As a result of the limitation of small datasets, further study could derive a large dataset for increasing accuracy and better results, and this method can be applied to the other human bones for developing sexing tools in a Thai population used in law enforcement and forensic anthropological fields.

ACKNOWLEDGMENTS. The authors are grateful to Chiang Mai University, Chiang Mai, Thailand, for granting a scholarship and to the Osteology Research and Training Center (ORTC), Faculty of Medicine, Chiang Mai University, for the samples used in this study.

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RESUMEN: La determinación del sexo es uno de los pasos más esenciales para crear un perfil biológico de restos óseos humanos en antropología forense y física. El hueso coxal es el hueso más eficiente para la determinación del sexo. Dado que el hueso coxal, o el cráneo, no siempre están presentes, los huesos del tarso, que se conservan bien, son excelentes candidatos para la determinación del sexo. El cuboides es un hueso del tarso interesante para la determinación del sexo, bien conservado en un entorno tafomónico natural. Las técnicas de aprendizaje profundo mostraron un rendimiento excepcional en tareas como la detección y clasificación basadas en grandes cantidades de datos, tanto etiquetados como no etiquetados. Este estudio tuvo como objetivo analizar el rendimiento de las redes neuronales convolucionales (CRN) para aumentar la fiabilidad de la herramienta de determinación del sexo utilizando cuboides basados en técnicas de aprendizaje profundo en una población tailandesa. Las muestras constaba de 352 individuos divididos en 302 individuos para un conjunto de datos de entrenamiento (156 individuos o 257 huesos para mujeres, 146 individuos o 256 huesos para hombres) y 50 individuos para un conjunto de datos de prueba (25 mujeres, 25 hombres). Todos los huesos cuboides se obtuvieron con una cámara digital que constaba de seis vistas: dorsal (superior), plantar (inferior), lateral, medial, distal (faceta metatarsiana) y proximal (faceta calcánea). Ajustamos el modelo preentrenado de GoogLeNet para clasificar el sexo mediante imágenes 2D de cuboides en cada vista. Los resultados mostraron que la vista proximal (faceta calcánea) alcanzó la mayor precisión de validación (87,01 %) y la precisión de la prueba (78 %). Nuestro estudio demostró que el modelo preentrenado de GoogLeNet fue eficaz con la limitación de conjuntos de datos pequeños. Además, nuestra técnica podría ser una alternativa a la herramienta rápida, cómoda y objetiva para la determinación del sexo mediante esqueletos humanos en una población tailandesa, utilizada en las fuerzas del orden y en el campo de la antropología forense.

PALABRAS CLAVE: Determinación del sexo; Aprendizaje profundo; GoogLeNet; hueso cuboides; Antropología forense.

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