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Machine learning-based sex estimation from photogrammetric hand images using deep features

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Abstract

Sex determination constitutes one of the most critical stages in the identification process within forensic anthropology. The morphological characteristics of the hand such as shape, size, finger lengths, and the proportional relationships among these measurements exhibit distinct differences between sexes and therefore serve as important biometric indicators in sex estimation. This study aimed to determine individuals' sex from hand photographs using a deep feature–based machine learning approach. A total of 400 healthy volunteers (192 males and 208 females) without any pathology, deformity, or history of surgical intervention in the hand region were included in the study. Hand photographs were obtained using a professional camera and tripod under standardized conditions with a fixed angle and distance and homogeneous lighting. A hybrid approach was used in which anonymized images were processed with deep learning for feature extraction and evaluated by machine learning classifiers. The highest accuracy in sex estimation was achieved with the Quadratic SVM (Support Vector Machine) model (training accuracy: 95.92%; test accuracy: 95.96%). In addition, the Cubic SVM and Medium Gaussian SVM models also demonstrated comparably high classification performance. The analysis of hand images using deep learning–based feature extraction combined with machine learning classifiers yielded high levels of accuracy and reliability in sex prediction. The findings demonstrate that proposed models provide highly accurate and reliable results for sex estimation from hand photographs. The effectiveness and reproducibility of these models offer a powerful alternative to traditional anthropometric methods. Accordingly, this study is expected to make significant scientific and methodological contributions to the fields of anatomy, forensic medicine, and forensic anthropology.

Keywords: Hand, sex estimation, deep learning, forensic anthropology

Introduction

Identification is the process of determining an individual's physical characteristics and defining the person through these features. Among these characteristics, sex is one of the most crucial, as determining it can reduce the potential identity pool by approximately half, thereby significantly enhancing the efficiency of the identification process. Consequently, sex determination plays a critical role in forensic cases such as mass disasters, explosions, traffic accidents, and natural catastrophes [1-10].

Forensic experts and anthropologists often prefer bone tissue in sex estimation studies because of its compact structure, which provides reliability and durability [11-16]. However, in certain forensic situations, the integrity of soft tissues may remain intact (for example, in cases involving amputation of the hand during a traffic accident). In such instances, it may not be possible to access bone tissue. Therefore, the availability of hand photographs containing soft tissue can serve as an alternative and valuable data source in sex estimation and personal identification procedures.

Various methods have been developed for sex determination; however, their applicability may be limited depending on factors such as time, environmental conditions, and available resources. In such cases, alternative approaches that are less dependent

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on laboratory infrastructure can play a complementary and supportive role in forensic investigations [16].

In recent years, significant advances have been made in medical image analysis through artificial intelligence approaches. These methods can identify complex patterns that are imperceptible to the human eye, enabling a more in-depth and reliable evaluation of visual biometric data. In this context, the present study aimed to perform automatic sex estimation using a deep feature–based machine learning approach applied to hand photographs. It is anticipated that this approach, which does not require morphometric measurements derived from hand photographs, may enhance the speed and efficiency of identification processes in forensic and anthropological contexts.

Material and Methods

Ethical Approval

The study was approved by the Non-Interventional Clinical Research Ethics Committee of Tokat Gaziosmanpaşa University Faculty of Medicine (No: 25-MOBAEK-026 Date: 27 January 2025). Written informed consent was obtained from all participants, confirming that the acquired images would be used solely for scientific research purposes.

Study Population

A total of 400 healthy volunteers (208 females and 192 males) without any scar tissue, deformities, dermatological disorders, trauma, or other pathologies in the hand region were included in the study. All participants were aged 18 years or older and were recruited voluntarily from students of Artova Vocational School. Particular attention was paid to maintaining a balanced ratio between male and female participants.

Image Acquisition Procedure

Hand photographs were captured using a professional digital camera mounted on a fixed tripod under standardized conditions with homogeneous lighting. A neutral-colored background was used, and a shadow-free arrangement was established to minimize light reflections. Participants were instructed to place their hands on a flat surface in a natural resting position. For each participant, photographs of both the palmar and dorsal surfaces of the right and left hands were taken in two different positions with the fingers open and closed. Accordingly, a total of eight images per individual (four positions × two hands) were obtained. All images were anonymized and securely stored in a protected digital environment.

Dataset and Preprocessing

The selected hand images were categorized into two groups: male and female. Several preprocessing steps were applied to prepare the data for input into the pre-trained deep neural network used in the study. Initially, raw images with varying resolutions were resized to a square format (224×224 pixels) while maintaining their aspect ratio. To ensure that the analysis focused on the morphological structure rather than color information, all color images were converted to grayscale (Figure 1).

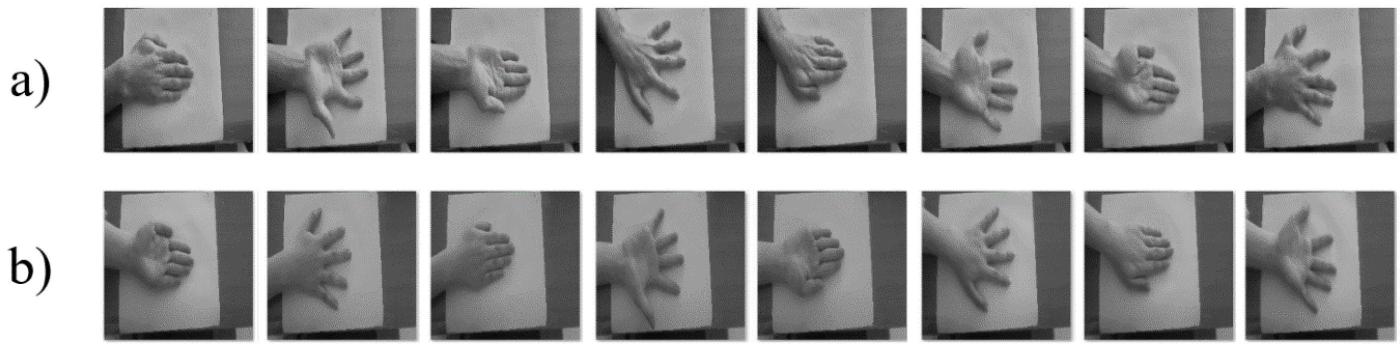

Figure 1. Sample images from the created dataset: (a) Male, (b) Female

Data Analysis and Modeling Process

The model developed for this study consisted of four main stages. In the first stage, hand images belonging to male and female individuals were categorized and standardized to a uniform size. In the second stage, image features were extracted using a pre-trained ResNet50 deep neural network. In the third stage, the data set was randomly divided into five parts, independent of the subject. It was evaluated in five separate iterations, with four different parts used for training (80%) and another part for testing (20%) in each iteration. In the final stage, the performance of the models was evaluated using various metrics, including accuracy, sensitivity, specificity, and precision (Figure 2).

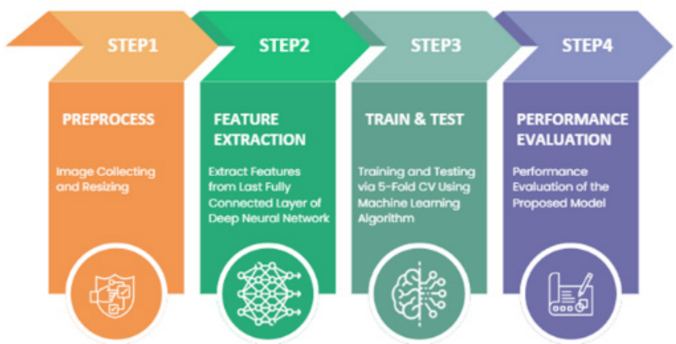

Figure 2. General workflow of the model

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Results

For both the training and testing processes of all proposed models, the same dataset was used. This approach ensured a homogeneous and comparable evaluation across all models. A five-fold cross-validation technique was applied, allowing the entire training dataset to be utilized for both training and validation purposes. This validation strategy provided a more balanced assessment of performance and effectively prevented overfitting.

The performance metrics of the models developed using hand images are presented in Table 1. As shown in the table, the highest training accuracy was achieved by the Medium Gaussian SVM model (95.92%), whereas the highest test accuracy was obtained from the Quadratic SVM model (95.96%).

Among the models used in the study, the confusion matrices of the three best-performing models are presented in Figure 3.

The ROC curves for the three models with the highest performance among the models used in the study are shown in Figure 4.

Table 1. Performance metrics of the proposed models (%)

Model	Accuracy		Precision		Sensitivity		Specificity		F1 score	
	Train	Test	Train	Test	Train	Test	Train	Test	Train	Test
Quadratic SVM	93.21	95.96	92.93	95.13	92.85	96.38	93.53	95.59	92.89	95.75
Cubic SVM	95.92	95.19	95.28	94.16	96.14	95.71	95.73	94.72	95.71	94.93
Medium Gaussian SVM	95.26	93.63	94.80	93.18	95.26	93.49	95.27	93.77	95.03	93.33
Fine KNN	88.04	87.11	86.50	87.01	88.23	86.17	87.88	87.99	87.36	86.59
Cosine KNN	87.31	86.96	88.54	91.56	85.41	82.94	89.16	91.45	86.95	87.04
Medium KNN	87.42	85.56	85.61	83.44	87.75	85.95	87.14	85.22	86.67	84.68

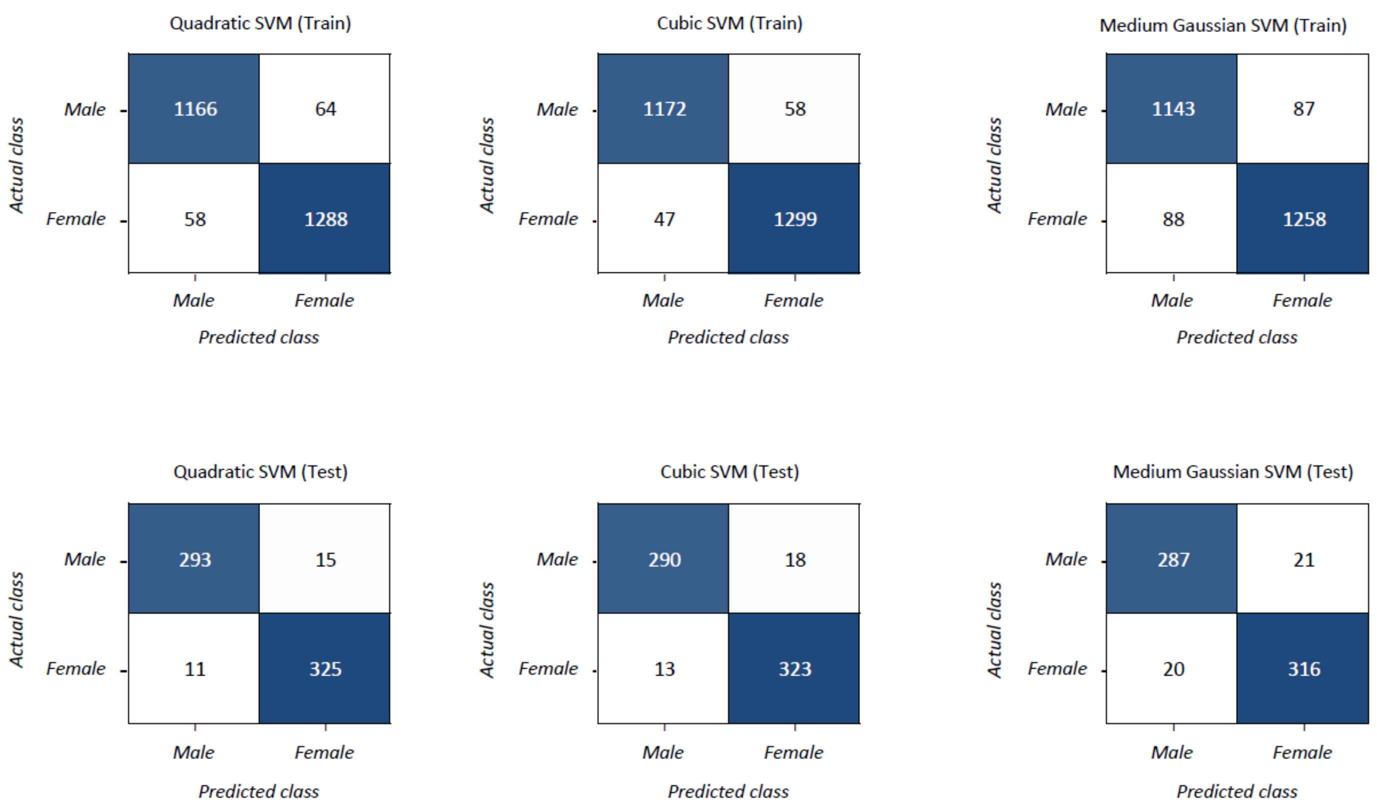

Figure 3. Confusion matrices of the three models that achieved the highest performance

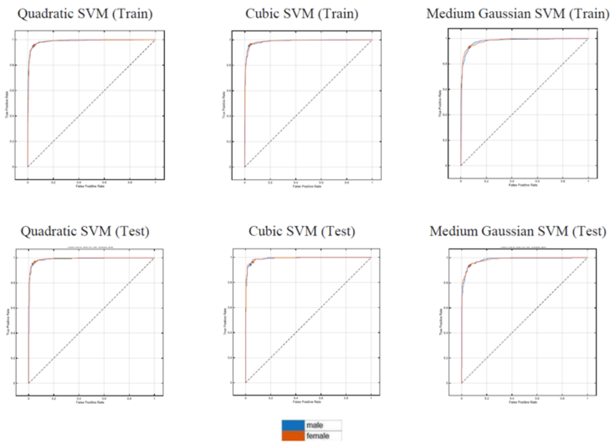

Figure 4. The ROC curves of the three models with the highest performance

Discussion

In this study, it was demonstrated that high accuracy rates in sex estimation from hand photographs can be achieved by combining deep learning–based feature extraction with traditional machine learning classifiers. The highest test accuracy (95.96%) was achieved with the Quadratic SVM model, indicating a performance level considerably higher than that of most measurement-based approaches reported in the literature.

A review of current studies reveals that numerous investigations have been conducted to estimate sex from various skeletal structures, including the mandible [17], the os hyoideum [18], the radius [19], the sternum [20], and the os femoris [21]. Additionally, Sahin et al. [22] conducted a comprehensive multinational assessment of hand morphometry and demonstrated significant population-dependent morphological variation. However, since these studies rely on morphometric measurements taken directly from bone tissue, variability due to inter-observer differences and measurement errors can limit the reliability and reproducibility of the results.

Kanchan et al. reported accuracy rates ranging between 87% and 91% for sex estimation using hand length and breadth in the Indian population. They noted a strong correlation between these two parameters in males [23]. Similarly, Jee et al. achieved accuracies of 88.6% in males and 89.6% in females based on measurements of hand, finger, and wrist circumference in a Korean sample [24]. Dey et al. found that hand breadth was the most potent predictor of sex, with accuracies exceeding 85% in the Indian population [25]. All of these classical anthropometric studies depend on direct physical measurements, with accuracy rates generally ranging between 80% and 90%. In contrast, the present study achieved higher accuracy using only deep features extracted from photographs, without any manual measurement. This highlights the ability of deep learning algorithms to capture morphological patterns imperceptible to the human eye.

Habib et al. achieved an accuracy of 89.6% in sex differentiation using hand and phalanx lengths in an Egyptian population [26]. However, because their method relied on manual measurements, it was susceptible to observer bias and a lack of standardization. In the present study, a non-contact, measurement-free, image-based approach was employed to eliminate human-related errors. Moreover, with ResNet50-based feature extraction, the model could assess multidimensional visual cues such as finger shape, overall hand contour, and surface characteristics.

Uhrova et al. reported nearly 90% accuracy in sex estimation from hand and foot dimensions in a Slovak population [27], while Krishan et al. obtained 87.5% accuracy in North Indian individuals [3]. The superior results of the current study demonstrate that deep learning–based approaches can recognize more complex patterns than traditional measurement-based methods. Additionally, the application of five-fold cross-validation maintained a balance between training and testing sets, thereby minimizing the risk of overfitting. The proximity between training accuracy (95.92%) and test accuracy (95.96%) further confirms the generalizability of the proposed model.

Mollineda et al. evaluated a zero-shot Segment Anything Model (SAM)–based approach on pediatric hand radiographs and reported that improvements in segmentation accuracy were directly reflected in the classification performance [28]. They achieved approximately 90–93% accuracy for sex classification and emphasized that SAM enhanced model stability by delineating structural boundaries more consistently in radiological images. This finding highlights that segmentation plays a critical role in classification performance, particularly in pediatric radiographs where bone development varies considerably. Similarly, Nonthasaen et al. applied CNN-based models to hand radiographs from a Thai population and reported sex classification accuracies ranging from 88% to 92% [29]. Their results demonstrated that the high tissue contrast available in radiographic images allows CNNs to effectively capture subtle dimorphic differences in the metacarpal and phalangeal bones. However, the requirement for clinical X-ray equipment, the associated cost, and the limited accessibility of radiographs pose important practical constraints, especially for large-scale population studies.

Yune et al. also investigated sexual dimorphism in hand and wrist radiographs using a deep learning model and reported an accuracy of 92.1% [30]. The authors showed that the model successfully detected morphological differences that are imperceptible to the human eye, underscoring the superior discriminative capacity of deep learning compared with traditional anthropometric methods. Their work further demonstrated that machine learning models can automatically identify dimorphic features in radiological images without the need for manual intervention.

Conclusion

The findings of this research are consistent with previous reports, which emphasize the hand as a strong biometric indicator for sex differentiation. However, the distinctive contribution of this work lies in achieving comparable or superior accuracy solely from digital images, without requiring any physical measurements. Accordingly, this study introduces a rapid, objective, and reproducible approach to forensic identification that is independent of manual anthropometry.

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A major limitation of previous studies was the potential for inter-observer variability inherent in manual measurements. In contrast, the present study employed a hybrid approach that combines deep learning for feature extraction from raw hand images with machine learning for classification, achieving an accuracy of 95.96% and thereby reducing variability associated with manual measurements. Another limitation is that the dataset was obtained from a single population, which may restrict the generalizability of the model across different ethnic groups. Additionally, all images were captured under controlled laboratory conditions, and the effects of variations in lighting and hand positioning on model performance should be explored in future research. Employing larger and more diverse datasets may further enhance model robustness. Moreover, integrating additional biometric features, such as three-dimensional hand scans, could improve diagnostic performance. Overall, this study provides a foundation for developing a contact-free, measurement-independent reference method with potential applications in forensic medicine, anatomy, anthropology, security, and biometric identification research.

Ethical Approval

Approved by the Tokat Gaziosmanpaşa University Faculty of Medicine Non-Interventional Clinical Research Ethics Committee (No: 25-MOBAEK-026 Date: 27 January 2025).

Patient Consent

Written informed consent was obtained from all participants, confirming that the acquired images would be used solely for scientific research purposes.

Conflict of Interest

The authors declare no conflict of interest.

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