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Insights from dental resilience and artificial intelligence for sex determination: literature review *

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Abstract

Sex determination is crucial in forensic investigations, with skeletal bones traditionally utilized for this purpose. However, dental remains have emerged as invaluable sources of information in cases where skeletal elements are lacking. Recent advancements in AI have opened new possibilities for refining sex-determination techniques in forensic odontology. This literature review explores studies employing AI techniques, such as machine learning and deep learning algorithms, for sex determination based on dental characteristics. Studies discussed in this review encompass various dental features, including canine and molar teeth, analyzed through the AI approaches. In addition, the utilization of maxillofacial structures for sex determination was explored. Furthermore, advancements in AI technology have enabled automated approaches for sex determination, offering high accuracy and efficiency. Studies employing convolutional neural networks (CNN) and hybrid deep learning (DL) models have shown promising results in sex estimation from radiographic images, such as orthopantomograms and CBCT.

Keywords: artificial intelligence; forensic dentistry; human rights; legal identity; sex determination

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Introduction

Forensic odontology is a specialized field within forensic science that focuses on identifying individuals based on dental evidence (1). The identification process starts with the construction of the biological profile of an individual, including age and sex. In the discussion regarding sex determination, the morphological analysis of the pelvis, skull, and long bone can provide reliable results with high accuracy. However, in cases where these skeletal elements are unavailable or extensively damaged, dental remains become invaluable sources of information (2,3).

In recent years, the advent of artificial intelligence (AI) has brought about transformative advancements across various domains, including forensic science. AI techniques, such as machine learning and deep learning algorithms, have shown immense potential in enhancing the accuracy and efficiency of forensic analyses. Fingerprint analysis, facial recognition, and forensic DNA profiling have all witnessed significant improvements in accuracy and processing time through the integration of AI. These achievements underscore the potential benefits that AI can offer to forensic odontology, including dental age estimation and sex determination (4).

Forensic odontologists can utilize AI approaches to create prediction models trained on extensive dental records datasets and data categorized by sex. Machine learning algorithms, such as support vector machines or random forests, can be employed to train these models by utilizing pertinent dental measurements and patterns, resulting in the development of precise sex determination models. The incorporation of AI has the capacity to fundamentally transform the process of identifying the sex of an individual based on dental characteristics, thereby significantly advancing the area of forensic dentistry (5).

This literature review discussed the potential of AI in improving the accuracy of sex determination through the analysis of dental characteristics. For this purpose, this literature review included studies on the application of AI for sex determination in forensic odontology. A thorough search of academic literature was undertaken in the PubMed databases with a combination of search terms constructed from "artificial intelligence," "forensic dentistry," "forensic odontology," and "sex determination." In addition to online literature searches, reference lists from all the included articles were manually examined for further discussion. The inclusion criteria for this study consisted of studies published within the past decade (2014-2024), written in English, focused on using teeth and maxillo-mandibular structures as indicators of sexual dimorphism, and had full text available.

Artificial intelligence and sex determination

Sex determination is important in individual identification during mass disasters and in medicolegal and forensic cases. Skeletal bones, including the skull and pelvis, have been extensively utilized for determining sex within an anthropological perspective. Besides, extensive scientific efforts have been devoted to clarifying methods for determining sex (6). Capitaneanu et al. (2017) stated that the biochemical analysis of teeth was the most accurate odontological sex determination method (82.5 – 100%). However, it has limitations in forensic practice, including the necessity of having high-quality and quantity biochemical predictors in the available odontological evidence and the costs and time needed to perform the required analyses (7).

Sexual dimorphism represents the inherent differences in size, shape, and morphological characteristics between males and females across species. This phenomenon is conspicuous in dental anatomy, serving as an invaluable tool for sex differentiation, particularly in forensic identification. In the pursuit of sex determination, various odontometric analyses have been harnessed, encompassing the canine index, tooth crown mesiodistal dimensions, and tooth height (8–10). The collective findings of several investigations exploring the integration of AI techniques for sex determination based on human dentition and surrounding tissues are presented in Table 1.

Recently, the integration of AI into forensic odontology has become a significant improvement that aims to enhance precision and productivity across a range of identification procedures (4). AI can imitate human intelligence and is seen as being comparable to the human brain in certain respects. The use of AI technology in forensic odontology has the promise of transforming the discipline through the automation of certain operations, augmentation of job precision, and optimization of overall efficiency in forensic identification. Frequent AI-based technologies employed in forensic odontology include deep neural networks, artificial neural networks, machine learning, and computational technology (11–13).

Table 1. The details of studies about the utilization of AI models with dental and maxillofacial structures for sex determination.

Title	Authors (years)	Study factor	Image type	Algorithm architecture	Findings
Dental features					
Automation of gender determination in human canines using artificial intelligence	Fidya et al. (2017)	Canine teeth	Dental study model	ANN, Naive Bayesian, decision tree, and multi-layer perceptron (MLP)	The Naive Bayes method achieved an accuracy rate of 82%, whereas both the decision tree and MLP methods reached 84%. Additionally, the MLP method demonstrated a lower absolute error than the decision tree approach. Overall, artificial intelligence methods significantly enhanced the accuracy of gender determination for canine teeth.
Artificial neural network model for predicting sex using dental and orthodontic measurements	Milosevic et al. (2023)	Canine teeth	Dental study model	ANN	Sex-specific variations were observed in all odontometric measurements, leading to the development of an ANN model. This model utilized odontometric data to predict the sex of individuals with an accuracy exceeding 80%.
Sex and age estimation with machine learning algorithms with parameters obtained from cone beam computed tomography images of maxillary first molar and canine teeth	Senol et al. (2023)	Canine and molar teeth	CBCT	Logistic regression, decision tree, linear discriminant analysis, AdaBoost classifier, quadratic discriminant analysis, extra tree classifier, and random forest	The AdaBoost Classifier algorithm achieved the highest accuracy rate of 0.81 in sex estimation. For age estimation, the random forest algorithm exhibited the highest accuracy rates, reaching 0.84 for the age groups 25–30 and 31–36. Moreover, it achieved accuracies of 0.74 for the age groups 25–30 and 37–49 when used with random forest and AdaBoost Classifier algorithms and 0.85 for the age groups 25–30 and 50–54, respectively, when utilized alone.
Sex classification of first molar teeth in cone beam computed tomography images using data mining	Esmaeilyfard et al. (2021)	First molar teeth	CBCT images	RF algorithm, Naïve Bayesian, and Support Vector Machine	The study findings showed that Naive Bayes (NB) performed the best for sex classification, with a notable accuracy rate of 92.31% compared to using Gonial Angle (GA) over NB. As a result, first molar teeth exhibited a high accuracy in distinguishing sex. Thus, these odontometric parameters could serve as valuable additional tools for sex differentiation in forensic anthropology.
Gender estimation with parameters obtained from the upper dental arcade by using machine learning algorithms and artificial neural networks	Erkartal et al. (2023)	Upper dental arcade	CBCT	linear discriminant analysis (LDA), quadratic discriminant analysis (QDA), logistic regression (LR), and random forest (RF) algorithms	The study revealed high accuracy rates of 0.86 with machine learning (ML) models, including linear discriminant analysis (LDA), quadratic discriminant analysis (QDA), logistic regression (LR), and random forest (RF) algorithms. Analysis using the SHAP analyzer identified the width at the level of third molar teeth as the most significant contributor to gender determination in the RF algorithm. Additionally, after training the multi-layer classifier perceptron (MLCP) for 500 iterations, an impressive accuracy rate of 0.92 was achieved. Overall, the findings demonstrate that parameters from the upper dental arcade are highly accurate in estimating gender, offering valuable insights for forensic sciences.
Maxillo-mandibular structures					
Artificial neural network for gender determination using mandibular morphometric parameters: A comparative retrospective study	Patil et al. (2020)	Mandibular parameters	Panoramic radiograph	logistic regression, discriminant analysis, ANN	Discriminant analysis achieved 69.1% accuracy, logistic regression 69.9%, and artificial neural networks (ANN) reached a higher accuracy of 75%. These findings highlight ANN as a reliable tool for gender prediction in forensic science, offering near-accurate results. Its potential lies in automating and simplifying the process of identifying unknown gender or age with minimal errors, making it a promising approach for forensic applications.
Diagnostic performance of convolutional neural networks for dental sexual dimorphism	Ademir Franco et al. (2022)	Dentomaxillo facial region	Panoramic radiograph	CNN	A comparison was made between CNN architectures trained from scratch (FS) and using transfer learning (TL), with diagnostic accuracy tests applied. TL exhibited superior performance with an accuracy of 82%, surpassing FS at 71%. Correct classifications for females and males aged 15 years and above were 87% and 84%, respectively. The correct classifications for individuals below 15 years old were 80% for females and 83% for males. Receiver-operating Characteristic (ROC) curves demonstrated high classification accuracy, with Area Under the Curve (AUC) values ranging from 0.87 to 0.91.
Semi-supervised automatic dental age and sex estimation using a hybrid transformer model	Fan et al. (2023)	Tooth and surrounding bones	Panoramic radiograph	Hybrid DL (CNN and transformer model)	The precision and area beneath the receiver operating characteristic (ROC) curve for sex prediction were 95.54% and 0.984, respectively. The heatmap analysis revealed that premolars and molars' crown and pulp chamber harbor the most age-related data.
Automatic sex estimation using deep convolutional neural network based on orthopantomogram images	Bu et al. (2023)	Teeth, maxillary sinus, mandibular parameters	Panoramic radiograph	CNN	The CNN model showed higher accuracy in sex determination for adults (90.97%) than for minors (82.64%). This study highlights the potential of using this model, trained on a large dataset, for automated sex identification, which is especially useful for forensic applications in adults in northern China. It also provides valuable insights that could be somewhat relevant for sex determination in minors.

The potential impact of AI in forensic odontology extends far beyond sex determination, encompassing a wide range of applications, including age estimation, analysis of bitemarks, and scrutiny of lip impressions. This trajectory highlights AI's transformative role as a fundamental component in advancing forensic odontology, ushering in opportunities for enhanced precision and innovation in investigative practices (4,14).

AI sex determination using dental features

Canine and first molar teeth exhibit distinct anatomical characteristics that distinguish them from other teeth in the dental arch. These features include crown morphology, root length, and root morphology. Notably, canine teeth manifest prominent sexual dimorphism, with males generally exhibiting larger and more robust canines than females. Furthermore, these teeth demonstrate significant resilience against disease and postmortem alterations (15).

Morphological and odontometric evaluations of canine and molar teeth are crucial in sex determination. A range of measurements, including crown dimensions such as mesiodistal and buccolingual, the crown-to-root ratio and the tooth index, have been instrumental in evaluating sexual dimorphism. Combined with statistical analyses, these measurementsacilitate accurate sex determination based on canine and molar teeth (16,17).

Integrating AI techniques for sex determination utilizing dental characteristics represents a promising direction in forensic odontology. Through AI, forensic experts can exploit dental features to enhance the accuracy and efficacy of sex determination procedures in forensic investigation (18).

Fidya et al. (2017) conducted a research investigation focusing on the application of AI for sex determination utilizing canine teeth. Their study aimed to assess the effectiveness of various machine learning algorithms, namely Naive Bayes, decision tree, and multi-layer perceptron (MLP), in discerning sexual dimorphism in canines. Through the input of mesiodistal, buccolingual, and diagonal measurements of maxillary and mandibular canine models into a computer program employing the MLP algorithm, the researchers sought to quantify the accuracy of these methods. Results indicated that the Naive Bayes method achieved an accuracy rate of 82%, while both the decision tree and MLP methods yielded higher accuracy rates at 84%. Additionally, it was observed that the MLP method exhibited a lower absolute error value compared to its decision tree counterpart. (19).

Milosevic et al. (2023) conducted a comprehensive investigation revealing sex-specific disparities across various odontometric parameters of canine teeth, encompassing cervico-incisal (CI), mesiodistal (MD), and vestibulo-oral (VO) dimensions. Employing an artificial neural network (ANN) model, the researchers crafted a predictive framework utilizing these odontometric variables to ascertain the subjects' sex with a high accuracy surpassing 80% (20).

A study combining AI technique and the assessment of canine teeth using cone beam computed tomography (CBCT) imaginery was conducted by Senol et al. in 2023. Various parameters of canine and molar teeth were analyzed, including inter-canine distance (CT-L), angles of the canine teeth relative to the posterior nasal spine (PNSCT-A) and incisive foramen (IFCT-A), distances between the canine teeth and first molars (FMRCT-L, FMLCT-L), angles of the first molars relative to the posterior nasal spine and incisive foramen (PNSFM-A, IFFMA), curvature lengths of the first molars (RFM-CL, LFM-CL), distances between the first molars (FM-L), and distances between the first and third molars (RFMTM-L, LFMTM-L), alongside the right molar angle (RM-A). The study findings indicated that the ADA Boost Classifier algorithm achieved the highest accuracy rate of 0.81 in sex estimation. In contrast, for age estimation, the random forest algorithm attained the highest accuracy rate of 0.84 for the age groups 25–30 and 31–36, 0.74 for the age groups 25–30 and 37–49 (with both random forest and ADA Boost Classifier algorithms), and 0.85 for the age groups 25–30 and 50–54, respectively (21).

Esmaeilyfard et al. (2020) conducted a study focusing on the sex classification of the first molar utilizing CBCT images through data mining techniques. Their investigation encompassed 485 CBCT images, incorporating nine distinct parameters comprising the pulp chamber's roof, floor, and height, marginal enamel thickness, dentin thickness, tooth width, and crown length in both buccolingual and mesiodistal aspects. The classifier prediction was performed using Naïve Bayesian (NB), Random Forest (RF), and Support Vector Machine (SVM) analysis. Findings from the study revealed that NB emerged as the most effective tool for sex classification, indicating relatively high accuracy in determining sex based on first molar teeth (22).

A study on sex determination with the upper dental arcade parameters extracted from CBCT images using ML and ANN algorithm was performed by Erkartal et al. in 2023. The investigated parameters included the curvature length of the upper dental arcade (UDA-CL), intercanine width (IC-W), widths at the levels of first molars (M1-W), second molars (M2-W), and third molars (M3-W). ML and ANN modeling were performed using the Python 3.9 programming language and scikit-learn 1.1.1 framework. The study revealed an accuracy ratio of 0.86 with ML models, specifically linear discriminant analysis (LDA), quadratic discriminant analysis (QDA), and logistic regression (LR) algorithms, as well as with the random forest (RF) algorithm. Notably, the SHAP analyzer identified the width at the level of third molar teeth as the most significant contributor to gender determination within the RF algorithm. Additionally, training the multi-layer classifier perceptron (MLCP), an ANN model, 500 times resulted in an accuracy rate of 0.92 (23).

The utilization of AI for sex determination entailed several sequential stages. Initially, tooth size data was collected and annotated with corresponding gender labels. Subsequently, an iterative learning process commenced, involving the training of MLP models. After completing the training phase, a thorough testing procedure was conducted using the trained MLP models to analyze the results comprehensively (20,24).

Central to the learning phase was identifying latent patterns in the labeled attribute dataset. This methodical procedure led to the computation of optimal weight values customized for the classification model. Through a meticulous iterative approach, these weight values were systematically fine-tuned until reaching an optimal configuration that significantly enhanced the discriminatory power of the classification model. Consequently, a robust foundation for achieving precise sex classification was rigorously established (25).

The validation phase served as a fundamental mechanism for assessing the effectiveness of the classification model, utilizing a carefully curated collection of annotated data. Developed during the preceding learning phase, the classification model functioned as the cornerstone for sex attribution. The testing dataset provided a standard against which the performance of the Naive Bayes, decision tree, and MLP model was evaluated. This evaluation involved a systematic comparison of the testing dataset, enabling a comprehensive analysis of the performance of each model (26,27).

AI sex determination using maxillo-mandibular structures

Utilization of maxillo-mandibular structures for sex determination in forensic odontology involves the examination of various parameters, including craniofacial measurements. These features offer significant insights into sex determination, especially in situations where the maxillofacial features represent the sole evidence recovered at a scene (28–30).

Numerous studies have proposed various methods for sex determination utilizing maxillo-mandibular structures, including examinations of the mandible (31–35), sinuses (36–39), and lip prints (40–42). As automation gains traction in the medical field, computer science methodologies like machine learning (ML), artificial neural networks (ANN), and deep learning (DL) offer promising avenues for automating traditional approaches and improving reproducibility. Several research endeavors have been conducted, leveraging ML techniques for sex determination (4).

A study using mandibular morphometric parameters on panoramic radiographs was proposed by Patil et al. in 2020. Seven parameters, including maximum ramus breadth (MRB), bi-condylar width (BiCW), condylar height (CoH), coronoid height (CorH), bigonial width (BiGW), bimental width (BiMW), gonial angle (GoA) were selected for evaluation. In this investigation, Artificial Neural Networks (ANN) were employed for gender determination, with results compared against those obtained through logistic regression and discriminant analysis utilizing mandibular parameters as inputs. Findings from the study revealed an overall accuracy of 69.1% for discriminant analysis, 69.9% for logistic regression, and, notably, a higher accuracy of 75% for ANN (43).

Franco et al. (2022) conducted an investigation to assess the effectiveness of machine learning (ML) algorithms in discerning gender based on dentomaxillofacial features derived from a radiographic dataset. The dataset comprised 4003 panoramic radiographs collected from individuals aged between 6 and 22.9 years. Various convolutional neural network (CNN) models were evaluated to gauge their performance in sex determination. Results indicated that Transfer Learning (TL) outperformed training models from scratch (From Scratch), achieving 82% and 71% diagnostic accuracies, respectively. Correct classifications for females and males aged 15 years and above reached 87% and 84%, respectively. For

individuals under 15 years old, correct classifications were recorded at 80% for females and 83% for males. The study highlighted regions with heightened activation signals for machine-guided sexual dimorphism, predominantly observed around the crowns of both anterior and posterior teeth (44).

In 2023, Fei Fan et al. proposed an automatic dental age and sex estimation from orthopantomograms (OPGs) and compared it to manual methods. A hybrid deep learning model, combining CNN and transformer models, was trained and tested using a substantial dataset of 15,195 OPGs. The study focused on analyzing teeth and surrounding bone as observed on the OPGs. Results revealed a remarkable accuracy of 95.54% and an area under the receiver operating characteristic curve (AUC) of 0.984 for sex estimation. Notably, the heatmap analysis emphasized that premolars and molars' crown and pulp chamberontain the most age-related information (45).

Wen-qing Bu et al. (2023) presented an automated sex determination approach utilizing OPGs among Chinese subjects. Their study encompassed a dataset of 10,703 OPGs, partitioned into training (80%), validation (10%), and test (10%) subsets. The research focused on developing a CNN model to evaluate diverse parameters related to sex determination, including dental features, maxillary sinus characteristics, and mandibular morphology. Results indicated a higher accuracy in sex estimation using the CNN model for adults (90.97%) compared to minors (82.64%). This investigation underscores the potential of the proposed model, trained on a large dataset, for automatic morphological sex-related identification, offering promising implications for forensic science (46).

Various parameters, including craniofacial measurements, have proven valuable in this regard. Numerous studies have explored different methods for sex determination using maxillofacial structures, such as examinations of the mandible, sinuses, and lip prints. With the growing influence of automation in the medical field, computer science methodologies like machine learning (ML), artificial neural networks (ANN), and deep learning (DL) offer promising avenues for automating traditional approaches and improving reproducibility. Studies employing ML techniques, such as ANN and convolutional neural networks (CNN), have shown promising results in accurately discerning gender based on dentomaxillofacial features derived from radiographic datasets. For instance, a hybrid deep learning model achieved remarkable accuracy in automatic dental age and sex estimation from orthopantomograms (OPGs), highlighting the potential of such models for enhancing sex-related identification in forensic science.

Conclusion

The use of AI in forensic odontology for determining sex based on dental features and facial structures shows great promise for improving the accuracy and efficiency of identification methods. Studies have shown that AI algorithms, like machine learning and deep learning models, effectively identify sex differences using dental characteristics. By employing AI technology, forensic professionals can automate tasks, improve accuracy, and make identification processes more efficient. Moreover, AI has potential applications beyond sex determination, including estimating age, analyzing bite marks, and examining lip impressions. These developments highlight the transformative impact of AI on forensic dentistry and emphasize the need for ongoing research and innovation to advance investigative techniques and enhance forensic science.

Declaration of Interest

None

Author Contributions

AK, AC, BNR, and MSM contributed to the study's conceptualization. AK, FAA, MH, MFSS, and XS contributed to data curation and writing the original draft of manuscript. AK and AM are the study supervisors. All authors have contributed and approved the final draft of the manuscript.

References

1. Bush MA, Delattre VF. Science and Forensic Odontology. In: Senn DR, Weems RA, editors. Manual of Forensic Odontology 5th ed. Boca Raton: CRC Press; 2013. p. 61.
2. Kurniawan A, Sosiawan A, Nurrahman TF, Chusida A, Rizky BN, Prakoeswa BFWR, et al. Predicting sex from panoramic radiographs using mandibular morphometric analysis in Surabaya, Indonesia. Bull Int Assoc Paleodont. 2023;17(1):32–40.
3. Marini MI, Angrosidy H, Kurniawan A, Margaretha MS. The anthropological analysis of the nasal morphology of Dayak Kenyah population in

Indonesia as a basic data for forensic identification. Transl Res Anat. 2020;19:100064.
4. Mohammad N, Ahmad R, Kurniawan A, Mohd Yusof MYP. Applications of contemporary artificial intelligence technology in forensic odontology as primary forensic identifier: A scoping review. Front Artif Intell. 2022;5.
5. Albernaz Neves J, Antunes-Ferreira N, Machado V, Botelho J, Proença L, Quintas A, et al. An Umbrella Review of the Evidence of Sex Determination Procedures in Forensic Dentistry. J Pers Med. 2022;12(5):787.
6. White TD, Black MT, Folkens PA. Assessment of Age, Sex, Stature, Ancestry, and Identity of the Individual. In: Human Osteology. Elsevier; 2012. p. 379–427.
7. Capitaneanu C, Willems G, Thevissen P. A systematic review of odontological sex estimation methods. J Forensic Odontostomatol. 2017;35(2):1–19.
8. Ramakrishnan K, Sharma S, Sreeja C, Pratima DB, Aesha I, Vijayabanu B. Sex determination in forensic odontology: A review. J Pharm Bioallied Sci. 2015;7(Suppl 2):S398–402.
9. G V, Gowri S R M, J A. Sex determination of human mandible using metrical parameters. J Clin Diagn Res. 2013;7(12):2671–3.
10. Akhlaghi M, Khalighi Z, Vasigh S, Yousefinejad V. Sex determination using mandibular anthropometric parameters in subadult Iranian samples. J Forensic Leg Med. 2014;22:150–3.
11. Vodanović M, Subašić M, Milošević DP, Galić I, Brkić H. Artificial intelligence in forensic medicine and forensic dentistry. J Forensic Odontostomatol. 2023;41(2):30–41.
12. Khanagar SB, Vishwanathaiah S, Naik S, A. Al-Kheraif A, Devang Divakar D, Sarode SC, et al. Application and performance of artificial intelligence technology in forensic odontology – A systematic review. Leg Med. 2021;48:101826.
13. Ahmed O, Saleem SA, Khan AA, Daruwala S, Pettiwala A. Artificial intelligence in forensic odontology – A review. Int Dent J Stud Res. 2023;11(2):54–60.
14. Agrawal P, Nikhade P. Artificial Intelligence in Dentistry: Past, Present, and Future. Cureus. 2022;14(7):e27405.
15. Reddy V, Saxena S, Bansal P. Mandibular canine index as a sex determinant: A study on the population of western Uttar Pradesh. J Oral Maxillofac Pathol. 2008;12(2):56.
16. Kazmi S, Mânica S, Revie G, Shepherd S, Hector M. Age estimation using canine pulp volumes in adults: a CBCT image analysis. Int J Legal Med. 2019;133(6):1967–76.
17. Krishnan RP, Thangavelu R, Rathnavelu V, Narasimhan M. Gender determination: Role of lip prints, finger prints and mandibular canine index. Exp Ther Med. 2016;11(6):2329–32.
18. Prakoeswa BFWR, Kurniawan A, Chusida A, Marini MI, Rizky BN, Margaretha MS, et al. Children and Adolescent Dental Age Estimation by the Willems and Al Qahtani Methods in Surabaya, Indonesia. Biomed Res Int. 2022;2022:1–4.
19. Fidya F, Priyambadha B. Automation of gender determination in human canines using artificial intelligence. Dent J. 2018;50(3):116.
20. Anic-Milosevic S, Medancic N, Calusic-Sarac M, Dumancic J, Brkic H. Artificial neural network model for predicting sex using dental and orthodontic measurements. Korean J Orthod. 2023;53(3):194–204.
21. Senol D, Secgin Y, Duman BS, Toy S, Oner Z. Sex and age estimation with machine learning algorithms with parameters obtained from cone beam computed tomography images of maxillary first molar and canine teeth. Egypt J Forensic Sci. 2023;13(1):27.
22. Esmaeilyfard R, Paknahad M, Dokohaki S. Sex classification of first molar teeth in cone beam computed tomography images using data mining. Forensic Sci Int. 2021;318:110633.
23. Erkartal HŞ, Tatlı M, Secgin Y, Toy S, Duman BS. Gender Estimation with Parameters Obtained From the Upper Dental Arcade by Using Machine Learning Algorithms and Artificial Neural Networks. Eur J Ther. 2023;29(3):352–8.
24. Thurzo A, Kosnáčová HS, Kurilová V, Kosmeľ S, Beňuš R, Moravanský N, et al. Use of Advanced Artificial Intelligence in Forensic Medicine, Forensic Anthropology and Clinical Anatomy. Healthcare. 2021;9(11):1545.
25. Putra RH, Doi C, Yoda N, Astuti ER, Sasaki K. Current applications and development of artificial intelligence for digital dental radiography. Dentomaxillofac Radiol. 2022;51(1).
26. Nikita E, Nikitas P. Sex estimation: a comparison of techniques based on binary logistic, probit and cumulative probit regression, linear and quadratic discriminant analysis, neural networks, and naïve Bayes classification using ordinal variables. Int J Legal Med. 2020;134(3):1213–25.
27. Kumagai A, Jeong S, Kim D, Kong H-J, Oh S, Lee S-S. Validation of data mining models by comparing with conventional methods for dental age estimation in Korean juveniles and young adults. Sci Rep. 2023;13(1):726.
28. Okkesim A, Sezen Erhamza T. Assessment of mandibular ramus for sex determination: Retrospective study. J Oral Biol Craniofac Res. 2020;10(4):569–72.

29. Nagare SP, Chaudhari RS, Birangane RS, Parkarwar PC. Sex determination in forensic identification, a review. J Forensic Dent Sci. 2018;10(2):61–6.
30. Samatha K, Byahatti S, Ammanagi R, Tantradi P, Sarang C, Shivpuje P. Sex determination by mandibular ramus: A digital orthopantomographic study. J Forensic Dent Sci. 2016;8(2):95.
31. Saini V, Srivastava R, Rai RK, Shamal SN, Singh TB, Tripathi SK. Mandibular Ramus: An Indicator for Sex in Fragmentary Mandible. J Forensic Sci. 2011 Jan;56(S1):S13–6.
32. Alias A, Ibrahim AN, Abu Bakar SN, Swarhib Shafie M, Das S, Abdullah N, et al. Anthropometric analysis of mandible: an important step for sex determination. Clin Ter. 2018;169(5):e217–23.
33. Gupta P, Bharati N, Hussein M, Singh AB. Clinical implications of variations in the position of mandibular foramen in North Indian mandibles. J Anat Soc India. 2016;65(2):132–5.
34. Álvarez VE, Menéndez GA, Torres G, Sánchez-Mejorada G, Gómez-Valdés JA. Gender assessment using the mandible in the Mexican population. Span J Leg Med. 2017;43(4):146–54.
35. Hu K-S, Koh K-S, Han S-H, Shin K-J, Kim H-J. Sex determination using nonmetric characteristics of the mandible in Koreans. J Forensic Sci. 2006;51(6):1376–82.
36. Leão de Queiroz C, Sayuri SDTA, Uenoyama DT, Gomes de Araújo L, Galo R, Oliveira-Santos C, et al. Sex Determination of Adult Human Maxillary Sinuses on Panoramic Radiographs. Acta Stomatol Croat. 2016;50(3):215–21.
37. Teke HY, Duran S, Canturk N, Canturk G. Determination of gender by measuring the size of the maxillary sinuses in computerized tomography scans. Surg Radiol Anat. 2007;29(1):9–13.
38. Tambawala SS, Karjodkar FR, Sansare K, Prakash N. Sexual dimorphism of maxillary sinus using cone beam computed tomography. Egypt J Forensic Sci. 2016;6(2):120–5.
39. Uthman AT, Al-Rawi NH, Al-Naaimi AS, Al-Timimi JF. Evaluation of Maxillary Sinus Dimensions in Gender Determination Using Helical CT Scanning. J Forensic Sci. 2011;56(2):403–8.
40. Sharma P, Saxena S, Rathod V. Cheiloscopy: The study of lip prints in sex identification. J Forensic Dent Sci. 2009;1(1):24
41. Patel S, IshPaul, Madhusudan AS, Gayathri RSGV. A study of lip prints in relation to gender, family and blood group. Int J Oral Maxillofac Pathol. 2010;1(1):4–7.
42. Kapoor N, Badiye A. A study of distribution, sex differences and stability of lip print patterns in an Indian population. Saudi J Biol Sci. 2017;24(6):1149–54.
43. Patil V, Vineetha R, Vatsa S, Shetty DK, Raju A, Naik N, et al. Artificial neural network for gender determination using mandibular morphometric parameters: A comparative retrospective study. Cogent Eng. 2020 Jan 1;7(1):1723783.
44. Franco A, Porto L, Heng D, Murray J, Lygate A, Franco R, et al. Diagnostic performance of convolutional neural networks for dental sexual dimorphism. Sci Rep. 2022;12(1):17279.
45. Fan F, Ke W, Dai X, Shi L, Liu Y, Lin Y, et al. Semi-supervised automatic dental age and sex estimation using a hybrid transformer model. Int J Legal Med. 2023;137(3):721–31.
46. Bu W, Guo Y, Zhang D, Du S, Han M, Wu Z, et al. Automatic sex estimation using deep convolutional neural network based on orthopantomogram images. Forensic Sci Int. 2023;348:111704.