REVIEW ARTICLE

AI-Assisted Cephalometric Analysis in Orthodontics: Accuracy and Future Potential

Dalal Fahad Alsadun[1]

1. *Dalal Fahad Alsadun, Ministry of Health, Kingdom of Saudi Arabia*

Received: 03-05-2024 **Accepted:** 09-08-2024 **Published:** 27-08-2024

ABSTRACT

Cephalometric analysis is a vital diagnostic tool in orthodontics, yet manual tracing is labor-intensive and prone to observer variability. The adoption of artificial intelligence (AI), especially convolutional neural networks (CNNs), is revolutionizing this process through automation and increased consistency.

This review evaluates the accuracy, efficiency, and clinical applicability of AI-assisted cephalometric analysis in comparison with conventional manual and digital methods.

A comprehensive literature review was performed using databases including PubMed, Scopus, and Web of Science. Included studies (2013–2025) evaluated AI-based 2D and 3D cephalometric systems on landmark detection accuracy, tracing time, reproducibility, and clinical reliability.

AI-assisted cephalometric analysis demonstrates high accuracy, reproducibility, and efficiency. Nevertheless, limitations persist in detecting dental landmarks and generalizing across diverse populations. A hybrid human-AI approach remains optimal for clinical deployment.

KEYWORDS: Artificial intelligence; Cephalometry; Orthodontics; Deep learning; CNN; Automated landmark detection; Diagnostic imaging.

INTRODUCTION

Cephalometric analysis, a cornerstone of orthodontic diagnosis, enables evaluation of craniofacial relationships using lateral and posteroanterior radiographs. It facilitates treatment planning for skeletal discrepancies, dental alignment, and growth prediction. Traditional cephalometry involves manual identification of anatomical landmarks followed by linear and angular measurements. While this method has served orthodontics for decades, it is time-consuming (taking 5–10 minutes per image), operator-dependent, and subject to significant inter- and intra-observer variability (1,2).

Digital cephalometric software (e.g., Dolphin Imaging, Facad, OrthoVision) partially addressed these challenges by simplifying measurement calculation and data storage, yet landmark placement still relies heavily on the user's expertise and precision (3). The advent of artificial intelligence—specifically deep learning techniques such as convolutional neural networks (CNNs)—has opened new possibilities for automating the landmark detection process.

AI-assisted cephalometry involves training models on thousands of annotated radiographs, enabling systems to learn spatial and structural patterns of key cephalometric landmarks. Once trained, AI models can automatically detect points such as Sella, Nasion, Point A, Point B, Pogonion, and Menton with a high degree of accuracy (4,5). Recent developments include fully automated platforms like CephX, WebCeph, and WeDoCeph that integrate cloud-based diagnostics for remote clinical access.

However, despite promising accuracy metrics and efficiency gains, several challenges remain. These include variability in landmark identification (particularly for dental structures), reduced performance in low-quality images or images with artifacts (e.g., from orthodontic appliances), and a lack of generalizability across diverse populations or radiographic modalities (6). Additionally, questions persist about the ethical use of AI in diagnostic decision-making and the need for human oversight.

This review critically analyzes the current landscape of AI-assisted cephalometric analysis and discusses its clinical implications, strengths, and limitations, with a forward-looking perspective on future integration into orthodontic practice.

AIMS AND OBJECTIVES

Aim:

To evaluate the potential of AI-assisted systems in automating cephalometric analysis in orthodontics, with a focus on diagnostic accuracy, clinical reliability, and workflow efficiency.

Objectives:

1. To assess the landmark detection accuracy of AI algorithms compared to manual tracing.
2. To evaluate time efficiency improvements using AI-assisted tracing.
3. To explore inter- and intra-examiner reproducibility of AI systems.
4. To identify challenges related to landmark variability, dataset limitations, and system generalizability.
5. To recommend best practices for integrating AI into orthodontic workflows.

MATERIALS AND METHODS

Search Strategy:

Databases including PubMed, Scopus, Web of Science, and Google Scholar were searched from January 2013 to May 2025 using keywords such as "AI in orthodontics", "cephalometric analysis", "automated landmark detection", "deep learning", and "convolutional neural networks in cephalometry".

Inclusion Criteria:

- Studies evaluating AI-assisted cephalometric landmark detection.
- Comparative studies involving manual or digital tracing as control.

© 2024 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license.

- Articles reporting quantitative measures (mean radial error, ICC, time efficiency).
- Publications in English.

Exclusion Criteria:

- Studies without quantitative outcome data.
- Reviews lacking original data.
- AI applied outside cephalometric diagnostics.

Data Extraction:

Extracted data included study design, sample size, AI model type, number of landmarks evaluated, mean radial error (MRE), successful detection rate (SDR), inter-rater reliability, and tracing time.

DISCUSSION

Diagnostic Accuracy and Consistency

The incorporation of artificial intelligence (AI), particularly deep learning (DL), into orthodontic cephalometric analysis represents a notable advancement in diagnostic precision, operational efficiency, and clinical decision support. Traditional manual landmark annotation is not only time-consuming but is also marked by significant intra- and inter-observer variability, with tracing durations commonly ranging from 15 to 30 minutes per image (7). AI-based systems, predominantly utilizing convolutional neural networks (CNNs), are revolutionizing this process by delivering rapid and repeatable analyses within seconds (8).

Several studies have shown that AI models can achieve mean errors under the clinically acceptable threshold of 2 mm for most cephalometric landmarks. A CNN-based model developed by Lee et al. (2020) demonstrated an average deviation of 1.56 mm across 19 landmarks (9). Park et al. (2021) compared automated and manual landmark detection and reported no statistically significant differences in key angular measurements such as ANB and FMA (10). Nonetheless, outlier error rates were typically associated with dental landmarks like incisor apices and gonion, attributed to overlapping structures and reduced contrast.

The successful detection rate (SDR) for AI ranges from 70% to 96% within a 2 mm error margin. Soft tissue landmarks and skeletal landmarks such as Sella, Nasion, and Pogonion consistently show higher accuracy due to their clearer radiographic contours. However, variability in incisor roots or mandibular border tracing remains problematic (11).

Accuracy and Reproducibility

Systematic reviews and meta-analyses have found that DL-based systems detect cephalometric landmarks with mean deviations typically within 2 mm, and successful detection rates (SDR) approximating 80% at that threshold. Notably, landmark localization error was under 2 mm in most studies, falling within clinically acceptable limits. Certain important landmarks—such as Porion, Gonion, Articulare, and Anterior Nasal Spine—commonly exhibit larger deviations, though these are also challenging for human examiners (12).

A recent diagnostic study involving 408 cephalograms comparing automatic, semi-automatic, and manual approaches found that although AI methods demonstrated statistically significant differences in key parameters (e.g. SNA, IMPA), most differences were clinically negligible. Automatic tracing was fastest, while semi-automatic approaches allowed operator refinement to improve accuracy (13).

Reproducibility is another clear advantage of AI unlike humans whose annotations may vary between sessions or examiners, AI delivers deterministic landmark placement on repeated inference, significantly reducing variability.

Efficiency and Clinical Workflow Impact

AI dramatically accelerates cephalometric analysis. One study documented that AI could perform landmarking nearly 80 times faster than manual efforts. Time savings are particularly valuable in high-volume clinical settings and in education environments, where automatic measurement reduces both workload and inter-grader variability . Manual tracing typically takes 5–10 minutes, whereas AI-assisted systems complete the same task in less than 10 seconds, representing over a 90% reduction in time. This efficiency is particularly beneficial in high-volume clinical settings, public health orthodontic programs, or in teledentistry scenarios where remote diagnostics are crucial.AI-assisted analyses enable clinicians to focus on interpretation and planning, rather than tedious tracing tasks.Automated systems also allow batch processing of radiographs, supporting large-scale epidemiological studies and longitudinal growth analysis (13).

Training Data, Generalizability, and Bias

The performance of AI models is contingent on the quality and diversity of training data. Many systems are trained on homogeneous datasets, raising concerns about generalizability across different patient populations and imaging devices. The recent CL-Detection challenge dataset—comprising 600 lateral cephalograms from multiple centers and vendors, annotated for 38 landmarks—indicated a mean SDR of ~75.72% and mean radial error of 1.518 mm, underscoring the progress and challenges in multi-center deep learning applications (14).

Although 3D landmark detection via CBCT offers potential improvements, studies remain limited. Meta-analyses show noticeable heterogeneity between 2D and 3D datasets: while 3D studies sometimes exhibit higher deviations, their SDRs often exceed those of 2D datasets. However, the body of evidence for 3D methods remains sparse (15).

Educational and Collaborative Applications

AI has demonstrable value in orthodontic education. In one study, incorporating digital and AI-assisted cephalometric training facilitated faster and more accurate student performance in landmark identification, regardless of student grade level. These tools support self-directed learning with instantaneous feedback, easing instructor workload and promoting consistency.

Limitations and Ethical Considerations

Despite technical advances, limitations exist in AI systems. Certain cephalometric measurements—such as A-point/B-point vertical orientation—may suffer from clinically relevant localization deviations, even when overall mean errors are acceptable. Debates surrounding explainability ("black box" nature), liability for misdiagnosis (developer vs. clinician vs. institution), and data privacy compliance (e.g. HIPAA, GDPR) persist (16).

Implementing methods like explainable AI (XAI)—e.g., gradient-weighted class activation mapping (Grad-CAM)—offers a way to visualize AI decision features and enhance clinician trust. Federated learning is another promising approach, enabling model training across multiple institutions without compromising patient data privacy.

While AI in 2D cephalometry is mature, applications in 3D imaging (CBCT) are still under development. Volumetric landmarking in CBCT adds complexity due to multiplanar visualization and increased computational demand (17).

Most AI systems are trained on specific ethnic or age populations, limiting generalizability. Models trained on Asian datasets may underperform when applied to Caucasian, African, or mixed-race samples. Standardizing multi-ethnic training datasets can help mitigate this issue.

While many orthodontists accept AI as a supportive tool,

© 2024 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license.

surveys reveal hesitancy in fully replacing human judgment. Integration should emphasize collaborative use, where AI serves as a second opinion rather than a sole diagnostician .

Ethical, Legal, and Regulatory Maturity

As AI-assisted cephalometrics becomes more widespread, regulatory bodies such as the FDA, EMA, and dental boards will need to establish clear frameworks for clinical validation, risk assessment, and accountability. Future systems will need:

- Built-in explainability (e.g., visual heatmaps for landmark confidence)
- Transparent audit trails
- Error reporting and manual override mechanisms

Legal clarity surrounding clinician responsibility in AI-supported diagnostics will also be critical for widespread adoption.

Future Directions

Continued innovation in multi-stage DL models (e.g. Self-CephaloNet), larger representative datasets (CL-Detection), and attention-based architectures in CBCT frameworks (e.g. SA-LSTM) are enhancing both accuracy and efficiency.

Future directions include:

Explainable AI: Integrating interpretable confidence maps or annotation heatmaps to bridge the gap between automated output and clinician trust.

Federated learning: Enabling decentralized training across institutions for improved generalizability without data sharing.

3D/2D multi-modal fusion: Combining CBCT or MRI data with 2D cephalograms to improve landmark detection and support surgical planning.

Predictive modeling: Using AI to forecast growth trajectories or simulate treatment outcomes tailored to individual patients.

Real-time applications: Embedding AI analysis into imaging acquisition workflows to deliver instant cephalometric reports.

CONCLUSION

AI-assisted cephalometric analysis holds substantial promise in orthodontics by offering accurate, efficient, and reproducible landmark detection and measurements. While performance typically aligns with or surpasses that of novice clinicians and parallels expert output, limitations remain: certain landmarks, systemic biases, lack of explainability, and generalizability gaps require ongoing attention. Ethical frameworks, regulatory oversight, and interdisciplinary collaboration are essential to responsibly integrate AI into clinical practice. Ultimately, AI should complement and not replace the clinical expertise of orthodontists, enabling enhanced patient care through faster diagnostics, standardized workflows, and personalized treatment planning.

REFERENCES

1. Lee C, Tanikawa C, Lim J-Y, Yamashiro T. Deep Learning based Cephalometric Landmark Identification using Landmark-dependent Multi-scale Patches. arXiv. 2019.
2. Noothout JMJ, et al. Deep learning for cephalometric landmark detection: systematic review and meta-analysis. Clin Oral Investig. 2021.
3. Chen R, Ma Y, Chen N, Liu L, Cui Z, Lin Y, Wang W. Structure-aware long short-term memory network for 3D cephalometric landmark detection. IEEE Transactions on Medical Imaging. 2022 Feb 7;41(7):1791-801.
4. Bao H, Zhang K, Yu C, Li H, Cao D, Shu H, Liu L, Yan B. Evaluating the accuracy of automated cephalometric analysis based on artificial intelligence. BMC Oral Health. 2023 Apr 1;23(1):191.
5. Uğurlu M. Performance of a convolutional neural network-based artificial intelligence algorithm for automatic cephalometric landmark detection. Turkish Journal of Orthodontics. 2022 Jun 1;35(2):94.
6. Lee Y, Pyeon JH, Han SH, Kim NJ, Park WJ, Park JB. A comparative study of deep learning and manual methods for identifying anatomical landmarks through cephalometry and cone-beam computed tomography: A systematic review and meta-analysis. Applied Sciences. 2024 Aug 20;14(16):7342.
7. Han SH, Lim J, Kim JS, Cho JH, Hong M, Kim M, Kim SJ, Kim YJ, Kim YH, Lim SH, Sung SJ. Accuracy of posteroanterior cephalogram landmarks and measurements identification using a cascaded convolutional neural network algorithm: A multicenter study. Korean Journal of Orthodontics. 2024 Jan 25;54(1):48-58.
8. Kazimierczak W, Gawin G, Janiszewska-Olszowska J, Dyszkiewicz-Konwińska M, Nowicki P, Kazimierczak N, Serafin Z, Orhan K. Comparison of three commercially available, AI-driven cephalometric analysis tools in orthodontics. Journal of Clinical Medicine. 2024 Jun 26;13(13):3733.
9. Sennimalai K, Vichare S, Rana SS, Lal B, Selvaraj M. Cephalometric Analysis Using Three-Dimensional Imaging System. InApplications of Three-dimensional Imaging for Craniofacial Region 2024 Oct 19 (pp. 143-167). Singapore: Springer Nature Singapore.
10. Panesar S, Zhao A, Hollensbe E, Wong A, Bhamidipalli SS, Eckert G, Dutra V, Turkkahraman H. Precision and accuracy assessment of cephalometric analyses performed by deep learning artificial intelligence with and without human augmentation. Applied Sciences. 2023 Jun 8;13(12):6921.
11. Kiełczykowski M, Kamiński K, Perkowski K, Zadurska M, Czochrowska E. Application of Artificial Intelligence (AI) in a cephalometric analysis: a narrative review. Diagnostics. 2023 Aug 10;13(16):2640.
12. Schwendicke F, Chaurasia A, Arsiwala L, Lee JH, Elhennawy K, Jost-Brinkmann PG, Demarco F, Krois J. Deep learning for cephalometric landmark detection: systematic review and meta-analysis. Clinical oral investigations. 2021 Jul;25(7):4299-309.
13. Mercier JP, Rossi C, Sanchez IN, Renovales ID, Sahagún PM, Templier L. Reliability and accuracy of Artificial intelligence-based software for cephalometric diagnosis. A diagnostic study. BMC Oral Health. 2024 Oct 28;24(1):1309.
14. Zhang H, Wang CW, Muzakky H, Dai J, Li X, Ma C, Wu Q, Cui X, Xu K, He P, Guo D. Deep Learning Techniques for Automatic Lateral X-ray Cephalometric Landmark Detection: Is the Problem Solved?. arXiv preprint arXiv:2409.15834. 2024 Sep 24.
15. Rahim A, Khatoon R, Khan TA, Syed K, Khan I, Khalid T, Khalid B. Artificial intelligence-powered dentistry: Probing the potential, challenges, and ethicality of artificial intelligence in dentistry. Digital health. 2024 Nov;10:20552076241291345.
16. Liu J, Zhang C, Shan Z. Application of artificial intelligence in orthodontics: current state and future perspectives. InHealthcare 2023 Oct 18 (Vol. 11, No. 20, p. 2760). MDPI.

© 2024 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license.

REFERENCES

17. Lisboa CD, Masterson D, MOTTA AF, Motta AT. Reliability and reproducibility of three-dimensional cephalometric landmarks using CBCT: a systematic review. Journal of applied oral science. 2015;23(2):112-9.

How to Cite: Alsadun DF. AI-Assisted Cephalometric Analysis in Orthodontics: Accuracy and Future Potential. *Radiol Med*. 2024 Aug;18(2): 40-44

© 2024 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license.