A Review on the Role of Artificial Intelligence in Orthodontics: Current Trends and Prospective Advances

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Publication Date: 2025/10/09

Abstract: Artificial intelligence (AI) has emerged as a transformative force across healthcare, and orthodontics is no exception. By mimicking human intelligence and learning from large volumes of clinical data, AI technologies are increasingly being applied to diagnostic processes, treatment planning, and patient monitoring. In orthodontics, AI has shown particular promise in areas such as cephalometric landmark identification, malocclusion classification, growth prediction, and the customization of appliances like aligners and brackets. These tools not only enhance diagnostic accuracy but also streamline workflows, improve patient engagement, and allow for more personalized treatment strategies. Remote monitoring systems further extend orthodontic care beyond the clinic, increasing accessibility and convenience for patients. However, the integration of AI into orthodontics also presents challenges, including issues of data privacy, algorithmic transparency, and ethical responsibility. Despite these hurdles, ongoing innovations suggest that AI will continue to evolve as an essential partner in orthodontic practice, augmenting clinical expertise rather than replacing it. This review aims to provide a comprehensive overview of the applications, benefits, limitations, and future prospects of AI in orthodontics, highlighting its growing role in shaping the future of diagnosis, treatment, and patient-centered care.

Keywords: *Artificial Intelligence; Orthodontics; Cephalometric Analysis; Machine Learning; Teleorthodontics.*

How to Cite: Dr. Pachaiyappan G.; Dr. Madhusudhan V.; Dr. Shailaja A. M.; Dr. Chethan Kumar D.; Dr. Padmashri Narayanan (2025) A Review on the Role of Artificial Intelligence in Orthodontics: Current Trends and Prospective Advances. *International Journal of Innovative Science and Research Technology*, 10(10), 288-292. https://doi.org/10.38124/ijisrt/25oct240

I. INTRODUCTION

Artificial Intelligence (AI) has emerged as a transformative tool in modern healthcare and simulate human intelligence and decision-making. In orthodontics, the adoption of AI has accelerated due to the availability of digital records, radiographs, and three-dimensional imaging. AI models, particularly those based on machine learning and deep learning, are capable of analysing large datasets, identifying diagnostic patterns, and supporting treatment planning. These methods aim to complement the orthodontist's expertise by improving accuracy, reducing human error, and streamlining time-consuming diagnostic tasks [1].

A significant application of AI in orthodontics is automated cephalometric landmark detection. Convolutional neural networks have been trained to identify anatomical landmarks with accuracy comparable to expert orthodontists [2]. Deep learning algorithms applied to both two-dimensional and three-dimensional imaging modalities have improved the reliability of skeletal and dental assessments [3]. Commercially available AI platforms are now capable of assisting with cephalometric tracing, providing orthodontists with consistent and reproducible results that minimize inter-observer variability [4].

Beyond cephalometry, AI is increasingly applied to treatment planning and prediction models. Algorithms have been developed to forecast mandibular growth, determine extraction requirements, and classify skeletal malocclusions with high accuracy [5]. The ability to anticipate developmental changes provides orthodontists with additional guidance for personalized treatment planning. Furthermore, cervical vertebral maturation staging using AI tools allows more objective prediction of growth spurts, enhancing timing decisions for interceptive or corrective treatments [6].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25oct240

Despite its potential, challenges remain in applying AI universally in orthodontics. Variations in craniofacial morphology, image quality, and the presence of orthodontic appliances can reduce algorithm accuracy [7]. Ethical considerations, such as transparency, data privacy, and clinical accountability, also pose barriers to widespread adoption. Nevertheless, hybrid approaches that integrate imaging data with clinical, genetic, and demographic information are emerging as powerful tools for the future. These advances suggest that AI will continue to evolve as a critical adjunct in orthodontic diagnosis, treatment planning, and long-term monitoring [8].

II. AI TECHNOLOGIES IN ORTHODONTICS

➢ *Cephalometric Analysis*

Artificial Intelligence (AI) has significantly advanced the diagnostic capabilities in orthodontics by enabling objective, data-driven analysis of patient records. Traditional diagnostic processes, often dependent on the orthodontist's subjective judgment, are prone to inter-operator variability. With the integration of AI, especially machine learning models, clinicians can now classify malocclusion types, detect anomalies, and establish treatment needs with higher precision. AI algorithms trained on large imaging datasets are capable of differentiating between skeletal and dental discrepancies, thereby reducing diagnostic errors and assisting in accurate case classification [9].

Another important area of application is treatment planning**.** AI systems can simulate different treatment strategies, predict outcomes, and provide orthodontists with data-supported recommendations. In extraction decision-making, for example, models using cephalometric and clinical features have been shown to provide reliable predictions. Orthognathic surgery planning has also benefited from AI-driven three-dimensional modelling and virtual simulations, which help clinicians evaluate skeletal discrepancies and visualize corrective procedures before actual treatment. These applications contribute to creating individualized treatment plans tailored to patient-specific needs [10].

Furthermore, AI tools are enhancing patient–clinician communication by providing visual simulations of potential treatment outcomes. Such predictive visualization improves patient understanding, compliance, and satisfaction. At the same time, AI-powered systems are being incorporated into digital orthodontic platforms that centralize diagnostic data, cephalometric tracings, and case simulations into one integrated workflow. Although these systems cannot replace clinical expertise, they serve as valuable adjuncts, enabling orthodontists to optimize efficiency and ensure more consistent treatment planning outcomes [11].

➢ *Cephalometric Analysis*

Artificial intelligence in orthodontics is underpinned by a suite of technologies including machine learning (ML), deep learning (DL), convolutional neural networks (CNNs), and hybrid/ensemble models. Machine learning often uses hand-crafted features (e.g., distances, angles) and classical models such as support vector machines or decision trees to classify malocclusions or decide extractions. Deep learning advances, particularly CNNs, allow for automatic feature extraction directly from images, reducing the need for manual preprocessing. In some systems, hybrid models combine CNNs with traditional ML layers to refine predictions [12,13].

In cephalometric landmark detection, fully automatic deep learning models have been developed that can localize anatomical points with minimal human intervention. For example, a fully deep learning model using real clinical data showed competitive accuracy relative to human examiners in landmark identification. Two-step models that first isolate regions of interest and then apply CNNs for fine localization have been applied successfully to lateral cephalometric images ("Automatic Cephalometric Landmark Detection on X-ray Images", Respective Journal) [14]. Extension to three dimensions is also progressing: volumetric CNNs and U-Net architectures have been trialed for CBCT-based landmark localization, though accuracy still varies with data quality and image artifacts.

Another technological advance is in confidence estimation and Bayesian deep networks, which provide not just point predictions but also maps of uncertainty for each landmark. In one study, Bayesian CNN models allowed the calculation of confidence regions around predicted landmarks, aiding clinicians to weigh model outputs more prudently [15]. Such probabilistic frameworks can flag predictions with low confidence, prompting human review. Additionally, ensemble approaches—where multiple models' outputs are aggregated—have been used to reduce individual model bias and improve robustness across varied datasets.

Recent challenges and competitions (such as the CL-Detection challenge) have spurred state-of-the-art algorithm development. Benchmark datasets combining multi-center and multi-vendor cephalometric images allow comparative evaluation of methods [16]. Studies report that top models now approach clinical error thresholds (e.g. < 2 mm mean error). Nevertheless, discrepancies across landmarks persist, especially in concave anatomical areas. The evolving technology landscape in AI for orthodontics is thus advancing rapidly, pushing toward robust, generalizable solutions across imaging modalities and populations.

➢ *Aligners & Biomechanics*

Clear aligner therapy has benefited significantly from AI-driven tools that enhance precision in treatment planning and execution. AI algorithms can analyze intraoral scans and CBCT data to segment teeth, predict tooth movement trajectories, and plan optimal staging sequences. A recent scoping review noted that AI-based tooth segmentation reached ~98% accuracy, and AI helps merge imaging modalities and predict treatment outcomes, although many commercial aligner platforms remain unevaluated [17]. Moreover, force-sensing aligners embedded with sensors allow continuous monitoring of occlusal pressure and tooth movement, offering real-time feedback that can be

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25oct240

integrated into AI models to adjust force application dynamically [18].

Biomechanics within orthodontics—especially the relationship between applied force systems and resulting tooth movement—has become more interpretable with AI coupled with finite element modelling (FEM). Deep learning models have been combined with FE simulations to reduce computational cost and enhance prediction accuracy of stress-strain distributions in bone and periodontal ligament tissues. For example, a hybrid model using ML to approximate FE results improved efficiency while maintaining predictive fidelity [19]. Such integration promises to personalize aligner force design based on individual anatomical variability and optimize biomechanical planning beyond generic assumptions.

However, challenges remain in translating AI predictions into clinical biomechanics. Data heterogeneity, sensor noise, discrepancies between invitro models and biological response, and limited training samples constrain generalizability. Ethical and safety considerations also warrant that AI-suggested force patterns be validated by clinicians before application. Future research must focus on large multicenter datasets, real-world trials, and interpretability of AI biomechanical models to fully harness their potential in aligner biomechanics.

- *Growth Prediction*

Predicting craniofacial growth is one of the most complex areas in orthodontics, as it influences the timing and selection of treatment strategies. Artificial intelligence (AI) has recently been applied to growth forecasting, offering more objective alternatives to traditional manual methods. Deep learning models trained on cephalograms have been used to classify skeletal maturation stages and predict future growth patterns with high accuracy. By automating these analyses, AI reduces the variability associated with manual interpretation and provides orthodontists with consistent diagnostic tools [20].

AI has also been applied to the assessment of cervical vertebral maturation (CVM), which is critical for identifying growth spurts in adolescents. Convolutional neural networks can automatically stage CVM on lateral cephalograms, producing results comparable to expert orthodontists. In one large dataset study, a CNN achieved >90% accuracy for CVM classification, demonstrating its clinical potential in identifying optimal intervention periods [21]. These predictive capabilities enhance treatment timing decisions, especially for functional appliances or growth-modification therapies.

Beyond skeletal maturity, machine learning approaches have been developed to forecast mandibular growth, predict facial changes, and estimate orthodontic treatment duration. Algorithms using cephalometric, demographic, and clinical features have demonstrated predictive accuracies exceeding traditional regression methods. Such models are valuable for long-term treatment planning and patient counselling, although their performance depends on training data quality and diversity [22]. While limitations exist, especially regarding generalizability across populations, AI-based growth prediction represents a promising advancement toward precision orthodontics.

III. ADVANTAGES AND LIMITATIONS

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Artificial Intelligence (AI) has introduced clear advantages in orthodontics by increasing diagnostic efficiency and precision. Automated cephalometric landmark detection, malocclusion classification, and growth prediction models reduce operator variability and save valuable clinical time. These systems provide orthodontists with objective data that enhance the accuracy of treatment planning. AI can also simulate multiple treatment pathways, allowing clinicians to choose optimal strategies with improved predictability. The ability to analyze large amounts of clinical and imaging data supports evidence-based decision-making and promotes personalized care tailored to individual patients [24].

Another advantage is improved patient engagement and accessibility. By visualizing possible treatment outcomes, AI applications enhance patient understanding and compliance. Teleorthodontics, supported by AI monitoring platforms, allows remote follow-up of patients through smartphone images or smart intraoral devices. This improves accessibility for patients in underserved areas and helps clinicians identify issues such as poor aligner fit or bracket failure at an early stage. Additionally, AI-integrated software reduces repetitive manual tasks, enabling orthodontists to focus on complex decision-making and patient communication [24].

Despite these benefits, limitations remain significant. A key concern is the “black-box” nature of many AI algorithms, which makes interpretation difficult for clinicians and raises accountability issues. The accuracy of predictions depends heavily on the quality and diversity of training datasets, and models trained on limited populations may not generalize across ethnic or age groups. Data privacy, cybersecurity risks, and ethical concerns about patient consent are also barriers to widespread adoption. Moreover, AI systems are not yet fully validated for all orthodontic applications, emphasizing the need for rigorous clinical trials before integration into everyday practice. Therefore, while AI holds transformative potential, orthodontists must apply it cautiously as an adjunct rather than a replacement for clinical expertise [25].

IV. FUTURE PERSPECTIVES

The future of artificial intelligence (AI) in orthodontics is strongly linked to the development of more advanced, interpretable, and clinically integrated systems. Current algorithms focus largely on landmark detection and treatment planning, but future models are expected to incorporate multi-modal data, including genetic, demographic, and lifestyle information. This integration could enable truly personalized treatment approaches, where predictive models account not only for skeletal and dental characteristics but also for biological variability. By combining radiographic, clinical, and biological data, AI has the potential to deliver highly accurate and individualized orthodontic care [26].

Another key direction lies in the use of explainable AI (XAI)**,** which aims to address the “black-box” problem. For clinicians to trust and rely on AI recommendations, models must provide transparent reasoning for their predictions. Explainable systems will allow orthodontists to understand which features most influence diagnostic and treatment outcomes, thereby fostering accountability and ethical practice. In addition, the integration of AI into robotic and 3D-printing technologies could revolutionize appliance design, enabling fully automated workflows for the fabrication of aligners, retainers, and customized fixed appliances [27].

In the coming years, AI is also expected to play a significant role in remote and preventive orthodontics. Smart intraoral devices and wearable sensors, connected with AI platforms, may allow continuous monitoring of tooth movement and oral health parameters, alerting clinicians to potential complications before they become clinically evident. Large multi-centre collaborations will be essential to train robust models and validate their performance across diverse populations. While challenges remain regarding ethics, regulation, and data privacy, the integration of AI into orthodontic care promises to improve efficiency, precision, and patient experience, paving the way for a new era of digital orthodontics [28].

V. CONCLUSION

Artificial intelligence (AI) is rapidly transforming orthodontics by enhancing diagnostic precision, optimizing treatment planning, and improving patient monitoring. With applications ranging from automated cephalometric analysis and growth prediction to aligner biomechanics and Teleorthodontics, AI has demonstrated its ability to streamline workflows, reduce human error, and support evidence-based clinical decisions. These innovations improve efficiency and patient engagement, offering more personalized and accessible care. However, limitations remain, including concerns about data quality, algorithm transparency, generalizability across populations, and ethical issues such as privacy and accountability. Rather than replacing orthodontists, AI should be regarded as a valuable adjunct that complements clinical expertise. The future of orthodontics will likely involve the integration of explainable AI, multimodal data fusion, and real-time adaptive monitoring, paving the way toward precision treatment and digitally driven care. With continued validation and ethical safeguards, AI has the potential to become a cornerstone in shaping the future of orthodontic practice.

ACKNOWLEDGMENT

The study was self-funded with no financial interests.

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ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25oct240

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