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Review Article **Orthodontics**

Artificial Intelligence & Digital Orthodontics

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Abstract

Artificial intelligence (AI) has emerged as a transformative technology in modern orthodontics, redefining conventional diagnostic and therapeutic workflows through digital integration and predictive analytics. The incorporation of machine learning, deep learning, convolutional neural networks, and computer vision into orthodontic practice has significantly improved the accuracy of cephalometric landmark identification, malocclusion classification, treatment simulation, aligner therapy planning, and remote patient monitoring. Digital orthodontics, supported by intraoral scanners, cone-beam computed tomography (CBCT), three-dimensional imaging, and cloud-based systems, has created a robust data-driven ecosystem that facilitates AI-assisted clinical decision-making. AI-based software systems are increasingly capable of reducing operator variability, minimizing human error, and improving clinical efficiency while enabling personalized orthodontic care. Furthermore, teleorthodontics and AI-enabled remote monitoring systems have expanded patient accessibility and compliance tracking. Despite these advancements, important concerns remain regarding algorithm transparency, ethical considerations, data privacy, medico-legal accountability, and clinician dependency on automated systems. Current evidence suggests that AI should function as an adjunctive clinical tool rather than a replacement for professional judgment. The present review comprehensively discusses the evolution, applications, advantages, limitations, ethical implications, and future prospects of artificial intelligence in digital orthodontics. The article highlights the growing role of AI in precision orthodontics and emphasizes the need for standardized validation and responsible clinical integration.

Keywords: Artificial intelligence, Digital orthodontics, Machine learning, Cephalometric analysis, Teleorthodontics.

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INTRODUCTION

Orthodontics has undergone a substantial transformation with the introduction of digital technologies and artificial intelligence (AI). Conventional orthodontic diagnosis traditionally relied on manual cephalometric tracing, clinical examination, study casts, and photographic analysis, all of which were time-consuming and susceptible to operator variability. The rapid evolution of digital dentistry has shifted orthodontic workflows toward more precise, efficient, and data-driven systems. Artificial intelligence now represents one of the most influential technological advancements in modern orthodontics, significantly impacting diagnosis, treatment planning, appliance fabrication, monitoring, and outcome prediction.[1]

Artificial intelligence refers to computational systems capable of performing tasks that typically require human intelligence, including pattern recognition, decision-making, data interpretation, and predictive analysis. In orthodontics, AI applications predominantly involve machine learning (ML), deep learning (DL), artificial neural networks (ANNs), and convolutional neural networks (CNNs), which can analyze extensive datasets obtained from radiographs, CBCT scans, intraoral scans, and facial photographs.[2]

The development of digital orthodontics has accelerated the implementation of AI technologies. Digital orthodontics encompasses the use of intraoral scanners, digital impressions, three-dimensional imaging, CAD/CAM systems, virtual treatment simulations, and telemonitoring platforms. These innovations have enhanced precision and improved patient-centered care by enabling customized treatment approaches.[3]

One of the earliest and most extensively researched applications of AI in orthodontics is automated cephalometric landmark detection. Deep learning algorithms can accurately identify craniofacial landmarks on lateral cephalograms and CBCT images with minimal human intervention, substantially reducing diagnostic time while maintaining high reproducibility.[4] AI systems have also demonstrated effectiveness in skeletal maturation assessment, impacted canine localization, airway evaluation, extraction decision-making, and orthognathic surgery planning.[5]

The emergence of clear aligner therapy has further accelerated the integration of AI into orthodontic practice. AI-assisted aligner software platforms can predict tooth movement patterns, optimize attachment placement, and simulate treatment outcomes with considerable precision.[6] Additionally, remote monitoring technologies employing AI algorithms allow clinicians to monitor patient compliance and treatment progress through smartphone-generated intraoral images, reducing unnecessary clinical visits.[7]

Despite the promising advantages, several challenges limit the widespread adoption of AI in orthodontics. These include concerns related to algorithm bias, inadequate training datasets, ethical considerations, patient privacy, explainability of AI models, and medico-legal accountability.[8] Furthermore, AI systems currently function primarily as decision-support tools rather than autonomous clinical entities, emphasizing the continued importance of clinician oversight.

The purpose of this review article is to comprehensively evaluate the role of artificial intelligence in digital orthodontics, focusing on its clinical applications, technological advancements, advantages, limitations, ethical concerns, and future perspectives.

EVOLUTION OF ARTIFICIAL INTELLIGENCE IN ORTHODONTICS

The concept of artificial intelligence in healthcare originated from advancements in computer science and data analytics. Initial AI applications in dentistry were limited to basic image analysis and computer-assisted diagnosis. However, improvements in computational power, cloud computing, and neural network architectures have enabled AI systems to process complex orthodontic datasets with remarkable efficiency.[9]

The transition from analog to digital orthodontics created an ideal environment for AI integration. Digital radiography, CBCT imaging, and intraoral scanning generated large volumes of structured clinical data suitable for machine learning training models. As a result, AI algorithms became increasingly capable of recognizing anatomical patterns and predicting treatment outcomes.[10]

Machine learning systems utilize training datasets to identify patterns and improve performance without explicit programming. Deep learning, a subset of machine learning, employs multilayer neural networks capable of analyzing highly complex image datasets. Convolutional neural networks are particularly valuable in orthodontics because of their superior image recognition abilities.[11]

Recent years have witnessed rapid commercialization of AI-driven orthodontic software. AI-based cephalometric tracing systems now provide automated landmark identification within seconds. Similarly, aligner planning platforms use predictive AI algorithms to simulate tooth movement and optimize treatment sequencing.[12]

The emergence of teleorthodontics further accelerated AI integration during the COVID-19 pandemic. Remote monitoring applications allowed orthodontists to evaluate patient progress using smartphone photographs analyzed by AI software, reducing the need for frequent chairside appointments.[13]

AI IN ORTHODONTIC DIAGNOSIS

Automated Cephalometric Analysis

Cephalometric analysis is a cornerstone of orthodontic diagnosis. Manual tracing methods are labor-intensive and prone to interobserver variability. AI-based systems have demonstrated high accuracy in identifying cephalometric landmarks using deep learning models.[4]

$SNA=\angle(S,N,A)$

Deep learning algorithms trained on thousands of radiographic images can identify skeletal and dental landmarks with precision comparable to experienced orthodontists. Studies have reported substantial reductions in analysis time while maintaining diagnostic reliability.[14]

Automated cephalometric systems also improve reproducibility and minimize human error. Furthermore, AI-assisted tracing can facilitate standardized diagnosis across multiple clinical settings.

Malocclusion Classification

AI systems are increasingly utilized for automated malocclusion classification based on cephalometric measurements, intraoral scans, and facial photographs.[15] Neural network models can classify skeletal discrepancies, dental crowding, and facial asymmetry with high diagnostic performance.

Machine learning algorithms have also shown promise in differentiating Class I, Class II, and Class III malocclusions while predicting growth patterns and treatment complexity.

Growth Prediction and Skeletal Maturity Assessment

Prediction of craniofacial growth remains one of the most challenging aspects of orthodontics. AI algorithms can analyze cervical vertebral maturation stages and hand-wrist radiographs to estimate skeletal maturity.[16]

Such predictive systems enhance treatment timing decisions, particularly in functional appliance therapy and orthognathic treatment planning. AI-assisted growth prediction may improve long-term treatment stability and efficiency.

Airway and TMJ Assessment

CBCT-based AI systems are increasingly employed for airway segmentation and temporomandibular joint analysis.[17] Automated airway volume assessment may facilitate the diagnosis of obstructive sleep apnea and craniofacial airway abnormalities.

Similarly, AI-based TMJ analysis can assist in identifying degenerative changes and morphological abnormalities, contributing to comprehensive orthodontic diagnosis.

AI IN ORTHODONTIC TREATMENT PLANNING

Extraction Decision-Making

Orthodontic extraction decisions are complex and multifactorial. AI algorithms trained on expert treatment records can predict extraction requirements based on skeletal relationships, crowding severity, and soft tissue parameters.[18]

Although AI models demonstrate promising accuracy, clinical judgment remains essential because extraction decisions involve esthetic, functional, and patient-specific considerations.

Clear Aligner Therapy

Clear aligner therapy has become one of the most AI-integrated orthodontic modalities. AI-assisted software predicts tooth movement, optimizes staging, and customizes aligner fabrication.[19]

Digital workflows involving intraoral scanners, CAD/CAM technology, and AI-driven movement simulation have improved treatment precision and efficiency. AI systems can also identify attachment placement requirements and estimate treatment duration.

Orthognathic Surgery Planning

Artificial intelligence is increasingly applied in orthognathic surgery planning through three-dimensional virtual simulations.[20] AI-assisted planning improves surgical prediction accuracy and enhances interdisciplinary collaboration between orthodontists and maxillofacial surgeons.

CBCT-based AI software can automate segmentation and facilitate virtual surgical planning, reducing treatment complexity and planning time.

TELEORTHODONTICS AND REMOTE MONITORING

Teleorthodontics has emerged as a significant component of digital orthodontics. AI-enabled remote monitoring systems utilize smartphone-generated intraoral photographs to evaluate treatment progress.[7]

These systems can identify aligner fit discrepancies, bracket failures, oral hygiene concerns, and patient compliance issues. Remote monitoring reduces unnecessary clinical visits and enhances treatment accessibility, especially for patients in remote locations.

AI-driven telemonitoring also improves communication between clinicians and patients. However, concerns remain regarding data security, patient confidentiality, and overreliance on automated decision-making.[21]

ADVANTAGES OF AI IN DIGITAL ORTHODONTICS

Artificial intelligence offers several advantages in orthodontic practice:

1. Improved diagnostic accuracy
2. Reduced operator variability
3. Faster treatment planning
4. Enhanced workflow efficiency
5. Personalized treatment approaches
6. Better patient communication
7. Reduced clinical chairside time
8. Improved treatment monitoring
9. Enhanced data management
10. Predictive analytics for treatment outcomes

AI systems can process large datasets rapidly, allowing clinicians to make evidence-based decisions more efficiently. Additionally, digital workflows improve patient experience by enabling virtual simulations and enhanced visualization of treatment outcomes.[22]

LIMITATIONS AND CHALLENGES

Despite substantial progress, AI in orthodontics faces multiple limitations.

Data Quality and Bias

AI systems require large, high-quality datasets for accurate training. Inadequate or biased datasets may compromise algorithm performance and reduce generalizability across diverse populations.[23]

Ethical and Legal Concerns

The use of AI raises ethical issues related to patient privacy, informed consent, and accountability.

Questions regarding liability in cases of AI-related diagnostic errors remain unresolved.[24]

Lack of Explainability

Many AI systems function as "black box" models, limiting clinician understanding of the decision-making process. Explainable AI remains a major research priority in healthcare applications.[25]

Dependence on Human Oversight

Current AI technologies cannot replace orthodontic expertise. Clinical judgment remains indispensable for comprehensive diagnosis and individualized treatment planning.

FUTURE DIRECTIONS

The future of digital orthodontics is closely linked to advancements in artificial intelligence, big data analytics, and cloud-based healthcare systems. Emerging technologies such as digital twins, augmented reality, and AI-driven robotic orthodontics may further transform orthodontic practice.[26-30]

Integration of AI with genomics and personalized medicine could facilitate individualized orthodontic therapies tailored to genetic and skeletal characteristics. Additionally, explainable AI models may improve clinician trust and regulatory acceptance.

Future research should focus on multicenter validation studies, ethical frameworks, and standardized clinical protocols to ensure safe and effective AI implementation in orthodontics.

CONCLUSION

Artificial intelligence has revolutionized digital orthodontics by enhancing diagnostic precision, treatment planning, workflow efficiency, and patient monitoring. AI applications such as automated cephalometric analysis, malocclusion classification, aligner therapy optimization, and teleorthodontics have significantly transformed contemporary orthodontic practice. Despite these advancements, current AI systems remain adjunctive tools requiring continuous clinician oversight. Challenges related to ethical considerations, data privacy, algorithm transparency, and medico-legal accountability continue to limit complete clinical integration. Future developments in explainable AI, predictive analytics, and personalized digital workflows are expected to further refine orthodontic care. The successful incorporation of artificial intelligence into orthodontics will depend on evidence-based validation, responsible implementation, and maintenance of clinician-centered decision-making.

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