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Artificial Intelligence In Orthodontics- A Comprehensive Clinical Perspective

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ABSTRACT

Artificial intelligence (AI) is increasingly influencing modern orthodontic practice by facilitating more precise diagnosis, individualized treatment planning, and improved prediction of treatment outcomes. This review explores the clinical applications of AI in orthodontics, focusing on the contributions of machine learning and deep learning to contemporary diagnostic and therapeutic procedures. AI-driven technologies enable automated interpretation of radiographs, facial photographs, and digital dental models, supporting cephalometric analysis, cervical vertebral maturation assessment, and anatomical landmark identification. Their applications also encompass extraction decision-making, bracket positioning, fixed appliance therapy, clear aligner treatment, and orthognathic surgical planning. In clear aligner therapy, AI facilitates virtual treatment simulation, prediction of tooth movement, optimization of aligner staging, digital fabrication, and remote monitoring of treatment progress. Furthermore, predictive algorithms may assist in evaluating treatment complexity and anticipating postoperative soft tissue changes. Despite these advances, clinical implementation remains constrained by limitations in training data quality, algorithmic bias, generalizability, data security, regulatory frameworks, and implementation costs. Establishing the reliability of AI-based systems requires standardized assessment protocols and robust validation across diverse patient populations. Consequently, AI should currently be integrated as an adjunct to, rather than a substitute for, the clinical judgment and expertise of orthodontists. With continued technological development, rigorous clinical evaluation, and appropriate ethical safeguards, AI has the potential to strengthen evidence-based decision-making and advance efficient, predictable, and patient-centered orthodontic care.

Keywords: Artificial Intelligence; Orthodontics; Machine Learning; Deep Learning; Digital Dentistry; Treatment Planning.

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INTRODUCTION

Orthodontics is a specialized branch of dentistry focused on the diagnosis, prevention, and management of dental and skeletal irregularities. Malocclusions can negatively affect facial appearance, oral function, speech, mastication, and overall oral health. Traditionally, orthodontic treatment planning has relied on the clinician's experience and manual assessment of diagnostic records, including clinical examinations, radiographs, photographs, and dental models. While these methods have proven successful, they are often time-intensive and may be influenced by subjective judgment, leading to variations in treatment outcomes.

Conventional orthodontic approaches generally employ standardized treatment protocols using fixed appliances. However, every patient exhibits unique anatomical and biological characteristic that influence the rate and pattern of tooth movement. As a result, treatment duration, efficiency, and outcomes can vary considerably among individuals. Accurately predicting tooth movement and treatment response remains one of the major challenges in orthodontic practice.

Recent advances in Artificial Intelligence (AI) are reshaping orthodontic care by introducing highly personalized and data-driven treatment strategies. AI technologies, particularly machine learning and computer vision, can process and analyze complex patient data such as three-dimensional scans, cephalometric images, radiographs, and intraoral photographs with remarkable accuracy. By utilizing information from large datasets of previous orthodontic cases, AI systems can predict tooth movement, optimize force application, and assist in developing individualized treatment plans[1].

MACHINE LEARNING AND DEEP LEARNING IN ORTHODONTICS

Artificial Intelligence (AI) is an advanced branch of computer science that enables machines to perform tasks requiring human-like intelligence. It is primarily divided into machine learning (ML) and deep learning (DL), (Figure 1) which use algorithms and neural networks to learn from data, identify patterns, and generate accurate predictions. The integration of AI into dentistry and orthodontics has enhanced diagnostic accuracy, treatment planning, and personalized patient care through data-driven decision-making[2].

Key Applications and Advantages of AI in Orthodontics

Machine Learning (ML):

- Learns from existing datasets and continuously improves predictive accuracy.
- Assists in diagnosis, treatment planning, and outcome prediction.

Deep Learning (DL):

- Utilizes multilayered neural networks, particularly Convolutional Neural Networks (CNNs).
- Analyzes complex data such as radiographs, photographs, and 3D images.
- Provides highly accurate pattern recognition and predictive analysis.

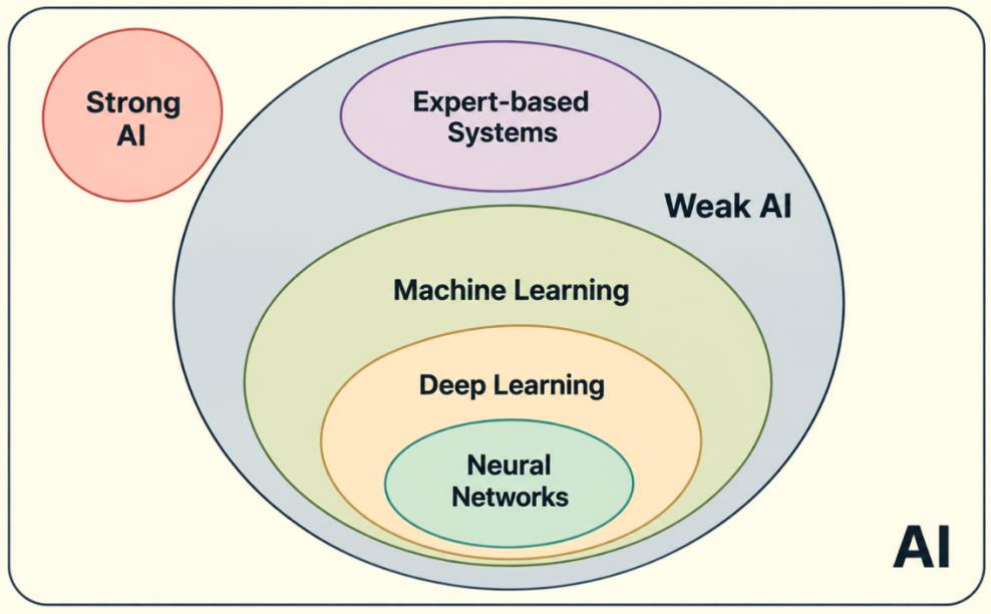


Figure 1: Schematic diagram of the relationship between AI, strong AI, weak AI, expert-based systems, machine learning, deep learning and neural network (NN).

APPLICATION OF AI IN ORTHODONTICS

AI IN DIAGNOSIS

Accurate orthodontic diagnosis forms the cornerstone of successful treatment planning and is based on the systematic collection and evaluation of comprehensive patient information. An orthodontic diagnostic database is typically compiled from patient history, clinical examination findings, dental casts or digital models, radiographs, photographs, and other relevant records. These data provide valuable insights into the patient's dental, skeletal, and soft tissue relationships, enabling clinicians to identify malocclusions and formulate appropriate treatment strategies.

Orthodontic diagnosis is a complex process that requires the simultaneous assessment of multiple craniofacial structures from different perspectives. Traditionally, clinicians must manually analyze large volumes of information, making the process both time-consuming and dependent on individual expertise. This can result in variations in diagnosis and treatment planning among practitioners.

Recent advances in digital dentistry have facilitated the transition from conventional records to digital databases, allowing more efficient storage, retrieval, and analysis of patient information. The integration of Artificial Intelligence (AI) and machine learning technologies

has further enhanced this process by automating diagnostic procedures and improving accuracy.

Key contributions of AI in orthodontic diagnosis include:

- Automated analysis of radiographs, photographs, and digital models.
- Identification of diagnostic patterns and anatomical landmarks with high precision.
- Reduction in the time required for patient evaluation and record analysis.
- Minimization of inter- and intra-examiner variability.
- Improved consistency and accuracy in diagnosis and treatment planning.
- Efficient management of large digital datasets for clinical decision-making.

By reducing the diagnostic burden on clinicians and enhancing the reliability of evaluations, AI has become an important tool in modern orthodontics. Its ability to process complex datasets rapidly and accurately supports more efficient, standardized, and patient-centered orthodontic care[3].

AI IN TREATMENT PLANNING

Orthodontic diagnosis and treatment planning involve predicting the most appropriate course of action to achieve optimal treatment outcomes while minimizing potential risks. Effective treatment planning requires careful clinical decision-making, including determining the need for tooth extraction and assessing the necessity of orthognathic surgical intervention. Artificial intelligence (AI) has the potential to support orthodontists by enhancing diagnostic accuracy and assisting in complex treatment decisions, particularly for clinicians with limited experience [4]

AI IN CEPHALOMETRICS AND CVMI ASSESSMENT

AI-based cephalometric software has demonstrated high reliability while substantially reducing the time required for cephalometric tracing. Although statistically significant differences have been reported between AI-assisted and conventional manual tracing methods, these variations are generally not clinically significant and have minimal impact on treatment decisions. Semi-automatic AI systems offer the optimal balance between efficiency and accuracy, as they allow clinicians to manually verify and correct landmark identification when necessary. Therefore, AI should currently be regarded as a valuable clinical decision-support tool that enhances diagnostic efficiency, while the expertise and supervision of the orthodontist remain essential for ensuring accurate diagnosis and treatment planning[4].

- Artificial intelligence (AI) has demonstrated high accuracy and reliability in cervical vertebral maturation (CVM) assessment.
- Deep learning models, particularly convolutional neural networks (CNNs), achieve excellent performance in automatic CVM stage classification.

- AI enables rapid and automated identification of cervical vertebrae from lateral cephalometric radiographs.
- AI improves the consistency and reproducibility of CVM assessment by minimizing inter- and intra-observer variability.
- Automated CVM analysis reduces diagnostic time and increases clinical efficiency.
- AI-assisted skeletal maturity assessment supports accurate timing of growth modification and orthodontic intervention.
- AI provides objective and standardized evaluation, reducing subjective interpretation during growth assessment.
- Integration of AI into digital orthodontic workflows facilitates streamlined diagnosis and treatment planning.
- AI functions as a valuable clinical decision-support tool by assisting orthodontists in skeletal maturity evaluation.
- Orthodontist supervision remains essential, particularly in complex or borderline cases, to ensure appropriate clinical decision-making.
- The accuracy of AI models depends on the quality and diversity of training datasets and imaging standards.
- Large-scale multicenter validation studies are needed to improve the robustness, generalizability, and clinical applicability of AI-based CVM assessment before routine clinical implementation.[5].

AI IN FIXED APPLIANCE THERAPY

Artificial intelligence is transforming fixed appliance therapy by improving the precision, efficiency, and predictability of bracket-based orthodontic treatment. By integrating data from intraoral scans, CBCT images, lateral cephalograms, and digital models, AI supports personalized treatment planning, optimized bracket placement, force application, and treatment monitoring.

AI-Assisted Bracket Positioning

Accurate bracket placement is essential for effective orthodontic treatment. AI-powered computer vision algorithms, particularly convolutional neural networks (CNNs), automatically identify optimal bracket positions based on tooth morphology and treatment objectives. This improves placement consistency, reduces operator-dependent errors, minimizes bracket repositioning, and enhances treatment efficiency, although orthodontist supervision remains essential in complex cases.[1]

Prediction of Tooth Movement

Machine learning models predict the direction, magnitude, and rate of tooth movement by analyzing large clinical datasets and biomechanical principles. These predictions help clinicians optimize force systems, anticipate challenging movements, and visualize treatment progression, resulting in more efficient treatment with fewer adjustments.[1]

Clinical Benefits and Limitations

AI-assisted fixed appliance therapy has been associated with improved treatment accuracy, shorter treatment duration, reduced chairside time, and enhanced patient satisfaction. However, its performance depends on high-quality imaging, comprehensive training datasets, and biological variability. Therefore, AI should currently be regarded as a clinical decision-support tool, with orthodontist expertise remaining indispensable for diagnosis, treatment planning, and management of complex cases[1].

AI IN BRACKET PLACEMENT

- AI-assisted digital indirect bonding demonstrates bracket positioning accuracy comparable to conventional indirect bonding for mesiodistal and occlusogingival placement.
- AI improves bracket angulation accuracy, enhancing the precision of bracket positioning.
- Clinicians can transition from conventional to AI-assisted digital indirect bonding without compromising placement accuracy while benefiting from a more efficient digital workflow.
- AI reduces operator-dependent variability and streamlines the indirect bonding process.
- AI serves as a clinical decision-support tool and complements, rather than replaces, the orthodontist's expertise.
- Continued technological advancements and robust clinical validation are expected to further expand the role of AI in fixed appliance therapy[6].

EXTRACTION DECISION MAKING

Artificial intelligence (AI) is increasingly being explored as a valuable aid in orthodontic extraction decision-making by integrating clinical findings with radiographic and cephalometric information to facilitate evidence-based treatment planning. Advanced deep learning architectures, particularly convolutional neural networks (CNNs) such as ResNet and VGG, have consistently demonstrated greater predictive performance than conventional machine learning approaches. By detecting complex relationships within multidimensional patient data, these models can accurately predict extraction requirements and serve as effective clinical decision-support systems[7].

Although the available evidence highlights the promising role of AI in improving extraction decision-making, its routine use in clinical orthodontics remains premature. Limitations such as heterogeneous study designs, variability in datasets, and insufficient external validation restrict the generalizability of current findings. Therefore, AI should be considered an adjunctive tool that enhances, rather than replaces, the orthodontist's clinical judgment and comprehensive patient assessment. Future large-scale, multicenter studies employing standardized methodologies and rigorous validation are required to establish the reliability, reproducibility, and clinical applicability of AI-assisted extraction decision-making[7]. AI can aid orthodontic extraction planning but should complement, not replace, clinical judgment. Standardized validation is required before routine clinical use.

AI IN CLEAR ALIGNER THERAPY

Artificial intelligence (AI) has revolutionized clear aligner therapy by improving diagnosis, treatment planning, aligner fabrication, and treatment monitoring. Through the integration of machine learning (ML), deep learning (DL), computer vision, and computer-aided design/computer-aided manufacturing (CAD/CAM), AI enables more precise, personalized, and efficient orthodontic care. AI-based platforms process digital intraoral scans, cone-beam computed tomography (CBCT), cephalometric radiographs, facial photographs, and patient-specific clinical data to create customized tooth movement simulations, optimize aligner staging, and track treatment progress. These innovations have enhanced the accuracy, predictability, and efficiency of clear aligner therapy while reducing the need for manual intervention in treatment planning[8]

AI-driven treatment planning starts with the automated segmentation of dental arches and detection of anatomical landmarks from digital models. Advanced deep learning algorithms identify tooth morphology, estimate three-dimensional tooth movements, and generate virtual treatment setups with minimal clinician intervention. These systems optimize aligner staging, attachment positioning, force delivery, and treatment duration prediction, resulting in more accurate, consistent, and efficient treatment planning while minimizing operator-dependent variability[9]

AI offers a significant advantage in clear aligner therapy by improving the prediction of treatment complexity and duration. Lee et al. reported that deep learning algorithms can automatically segment teeth and quantify six degrees of freedom of tooth movement, including translation, intrusion/extrusion, tipping, rotation, and torque. Although individual tooth movements were not reliable predictors of treatment duration, a composite movement score demonstrated a significant correlation with the number of aligner trays required. Additionally, pretreatment anterior malalignment was identified as a strong predictor of

treatment duration, highlighting the value of AI-based comprehensive assessments in estimating treatment complexity.[9]

AI also enhances the biomechanical efficiency of clear aligners by optimizing staging protocols and force application. Modern algorithms analyze previous treatment outcomes to determine optimal sequential tooth movements, reducing unnecessary refinement stages and improving treatment predictability. Machine learning models continuously learn from large clinical datasets, allowing treatment protocols to evolve as additional clinical evidence becomes available[8]

AI also plays a pivotal role in the digital manufacturing workflow of clear aligners. By integrating with CAD/CAM systems and three-dimensional (3D) printing technologies, AI enables the efficient fabrication of patient-specific aligners from digital treatment plans. (Figure 2) AI-assisted manufacturing enhances aligner fit, minimizes production errors, reduces fabrication time, and allows rapid modification of treatment plans when actual tooth movement deviates from the planned outcome. Furthermore, the integration of AI with additive manufacturing facilitates mass customization, improves production efficiency, and reduces material waste[8,10]

Recent advances have expanded the role of AI in treatment monitoring, enabling automated evaluation of digital scans and smartphone-based intraoral images to compare actual tooth movement with the planned virtual setup. AI algorithms can detect tracking loss, delayed tooth movement, poor aligner adaptation, and patient non-compliance at an early stage, allowing timely clinical intervention before significant deviations occur. This continuous monitoring supports prompt refinements, reduces unnecessary appointments, and facilitates remote orthodontic care through virtual follow-up.

Despite these benefits, AI-assisted clear aligner therapy has several limitations. The accuracy of AI models depends largely on the quality and diversity of training datasets, and their performance may be reduced when applied to populations outside those used for model development. In addition, high implementation costs, regulatory challenges, data privacy concerns, and the lack of standardized validation protocols continue to limit widespread clinical adoption. Therefore, AI should be regarded as a clinical decision-support tool that complements, rather than replaces, the orthodontist's expertise and clinical judgment.

Future advancements are expected to integrate AI with predictive analytics, finite element analysis (FEA), digital twin technology, and real-time adaptive treatment planning. These innovations may enable dynamic modification of treatment protocols based on individual patient response, further improving treatment efficiency and advancing personalized orthodontic care[8]

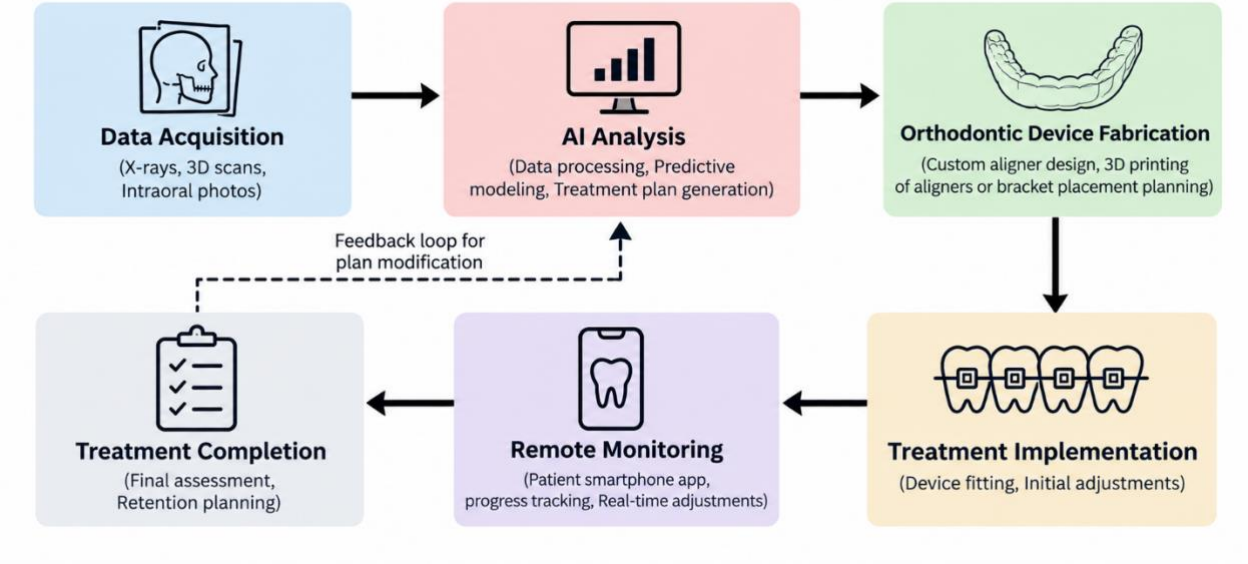


Figure 2: Schematic diagram of the AI-assisted orthodontic workflow, demonstrating the integration of data acquisition, AI analysis, device fabrication, treatment implementation, remote monitoring, and treatment completion.

AI in Orthognathic Surgery

Artificial intelligence (AI) is increasingly being integrated into orthognathic surgery to improve diagnosis, surgical planning, treatment outcome prediction, and patient communication. By analyzing cephalometric radiographs, cone-beam computed tomography (CBCT), facial photographs, and clinical records, AI generates patient-specific predictions of skeletal and soft tissue changes, enabling more accurate surgical treatment planning and visualization of postoperative outcomes.

One of the most valuable applications of AI is the prediction of postoperative soft tissue response. Deep learning models outperform conventional prediction methods by learning complex relationships between skeletal movements and soft tissue adaptations, resulting in more precise and individualized outcome predictions.

The performance of AI models is strongly influenced by the quality and size of training datasets. Large, diverse, and well-validated datasets improve prediction accuracy, reduce variability, and enhance the reliability of AI-assisted surgical planning. Although AI significantly improves treatment planning and interdisciplinary communication, it should currently serve as a clinical decision-support tool rather than replacing the expertise of orthodontists and maxillofacial surgeons[11](Figure 3).

Future developments integrating AI with three-dimensional facial imaging, virtual surgical planning, finite element analysis (FEA), digital twin technology, and augmented reality are expected to further improve surgical precision, treatment predictability, and personalized patient care.



Figure 3: Overview of the benefits of AI-powered personalized orthodontic treatment

Ethical Considerations of Artificial Intelligence in Orthodontics

Artificial intelligence (AI) has the potential to improve orthodontic diagnosis, treatment planning, and patient monitoring. However, its integration into clinical practice raises important ethical, legal, and professional concerns. Responsible implementation requires protecting patient rights while ensuring that AI complements, rather than replaces, clinical expertise.

- **Patient Privacy and Data Security:** AI relies on large volumes of patient data, making secure storage, data encryption, anonymization, and compliance with privacy regulations essential to protect patient confidentiality.[12,13]
- **Informed Consent:** Patients should be informed about the use of AI in diagnosis and treatment planning, including its benefits, limitations, and role in clinical decision-making[13]
- **Algorithmic Bias and Fairness:** AI models should be trained using diverse and representative datasets to minimize bias and ensure accurate and equitable treatment recommendations across different populations.[12,13]
- **Transparency and Explainability:** Explainable AI (XAI) is necessary to improve clinician understanding, increase patient trust, and facilitate informed clinical decisions.
- **Accountability:** AI should function as a clinical decision-support tool, while orthodontists remain responsible for diagnosis, treatment planning, and final clinical decisions.

- **Regulatory and Legal Challenges:** Standardized validation protocols, regulatory oversight, and clear legal frameworks are essential to ensure the safe and ethical use of AI in orthodontics.[12]
- **Equity and Accessibility:** The high cost of AI technologies may limit their availability; therefore, affordable and accessible AI solutions should be developed to reduce disparities in orthodontic care.[13]
- **Future Perspectives:** Continued clinical validation, multidisciplinary collaboration, and ethical governance will promote the responsible integration of AI, improving patient care while maintaining clinician oversight and patient-centered practice.

CONCLUSION

Artificial intelligence is rapidly transforming orthodontics by enhancing diagnostic accuracy, treatment planning, biomechanical analysis, appliance design, treatment monitoring, and outcome prediction. The integration of machine learning and deep learning algorithms into digital orthodontic workflows has improved the precision, efficiency, and predictability of treatment while supporting personalized patient care. Applications in cephalometric analysis, cervical vertebral maturation assessment, extraction decision-making, fixed appliance therapy, clear aligner treatment, and orthognathic surgery demonstrate the broad potential of AI to improve clinical outcomes and streamline orthodontic practice.

Despite these advances, AI should be regarded as a clinical decision-support tool rather than a replacement for the orthodontist. Limitations related to data quality, algorithmic bias, explainability, ethical concerns, patient privacy, and the need for robust clinical validation must be addressed before its widespread implementation. Future research should focus on developing standardized datasets, transparent and explainable AI models, and comprehensive regulatory frameworks. As these challenges are overcome, AI is expected to become an indispensable component of modern orthodontics, complementing clinical expertise and enabling more accurate, efficient, and patient-centered orthodontic care.

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