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Review Article

Artificial intelligence in orthodontics: A comprehensive review of current applications and emerging trends

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Abstract

Artificial Intelligence (AI) is transforming the domain of orthodontics with improved diagnostic precision, treatment planning and clinical decision making. Machine learning, deep learning and computer vision have been integrated to automate cephalometric analysis, malocclusion assessment, extraction decision-making, orthognathic surgery planning, bracket positioning and prediction of tooth movement. AI advancements have fueled progress in clear aligner therapy, remote patient monitoring, treatment outcome prediction and tele dentistry resulting in greater efficiency and patient-centric care.

Additionally, progress has been made in the use of artificial intelligence not only in the diagnosis but also in the prediction of patient outcomes and personalized treatment approaches in orthodontic procedures. Artificial intelligence holds great promise in this particular field. However, there are some challenges that need to be considered, including data quality concerns and ethical issues.

In this review, the application of AI technologies in orthodontics is comprehensively analyzed, and trends such as intelligent aligners, robotics in orthodontics, digital twins, and real-time treatment are outlined. With continuous development in AI, there is a great possibility that it will have the capacity to enhance the precision of treatment, and with expertise, it will shape the future of intelligent orthodontic treatment.

Keywords: Artificial intelligence, Orthodontics, Machine learning, Digital orthodontics, Clinical decision-making, Predictive analytics.

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1. Introduction

The field of orthodontics has transformed significantly from traditional diagnostic and treatment methods to a technology-driven approach. Innovations in the areas of three-dimensional imaging, CBCT, intraoral scanning, and computer-aided design and manufacture (CAD/CAM) have improved diagnosis and treatment. This has produced vast amounts of clinical and imaging data, which in turn has provided possibilities for incorporating computational technologies into orthodontics.[1-3]

Artificial intelligence (AI) is a computer science discipline that permits machines to take actions that require intelligence, is changing the way healthcare operates. AI applies ML and DL techniques to process complex amounts of data and produce accurate outcomes.[4,5] This made it possible for many AI applications to be used in orthodontics, with data-supported solutions being made each step of the way.[3]

Recent researches revealed that the following abilities can be attributed to the Artificial Intelligence (AI): automated identification of cephalometric landmarks; classification of malocclusion; decision making on extraction; development of treatment plan; assessment of orthognathic surgical procedure; and prediction of tooth movement.[1-3] Furthermore, AI-based online monitoring system and tele-dentistry have improved monitoring of treatment of patients as well as have facilitated the interaction between the dental specialists and the patients reducing the necessity of frequent clinical appointments.[4]

Considering how quickly technology related to AI is being developed and how AI can be increasingly used in orthodontic practices, it is very important to comprehend how AI is being used today and what its potential in the near future is. Therefore, this review aims to summarize what is currently known about the utilization of AI in the field of orthodontics, outline some of the trends that are developing right now, and discuss possible future directions for its application in clinical practice.

2. Methodology

Various databases including PubMed, Scopus, and Google Scholar were searched using the terms "Artificial Intelligence", "Machine Learning", "Deep Learning" and "Orthodontics". Relevant articles, reviews, and research papers were selected for analysis to evaluate the present uses and future prospects of the use of AI in orthodontics.

3. Fundamentals of Artificial Intelligence in Orthodontics

Artificial Intelligence (AI) refers to a capability of computer programs to perform duties that require human intelligence, like learning, thinking, and decision making. In orthodontics, artificial intelligence can assist clinicians by processing large amounts of clinical and imaging data to improve diagnosis and treatment planning.[5,6]

Machine learning (ML) refers to the branch of AI technology where computers are able to learn from their experiences and improve on their performance without being specifically programmed. Machine learning algorithms have been widely applied in orthodontics.[5,7]

Deep learning (DL) is a part of machine learning where multiple layers of neural networks are designed to process huge amounts of data and recognize patterns in it accurately. The existence of DL has shown a great potential in some of the image-based orthodontic applications, such as cephalometric landmark detection and facial analysis.[6,7]

Convolutional Neural Networks (CNNs) are specialized deep learning architecture specifically designed for image recognition and analysis. The CNNs automatically learn the relevant features from the orthodontic images, which enable accurate classification, landmark detection, and diagnostic evaluation.[6,8]

4. Current Applications of Artificial Intelligence in Orthodontics

4.1. AI in orthodontic diagnosis

Artificial intelligence (AI) is a useful diagnostic instrument for orthodontics, specifically for cephalometric analyses and assessments of malocclusion.[9,10] Traditional diagnosis in orthodontics uses radiographs and patient records to perform the process manually, which may take time and be subjective.[11,12] AI-based systems aim to overcome these limitations by providing automated, objective, and efficient diagnostic support.[9]

The detection of cephalometric landmarks is one of the most extensively studied uses of artificial intelligence in orthodontics. Deep learning algorithms, especially CNNs, are trained on radiographs with annotations indicating cephalometric landmarks determined by an expert.[6,13] Radiographs are analyzed via multiple convolutional layers of CNNs extracting the features of images and their structural relations.[6] Kim et al. designed a two-stage deep learning algorithm based on a region of interest detection module and a landmark localization module allowing the automatic detection of 13 cephalometric landmarks.[13] Several research groups have proved that the use of artificial intelligence in detecting cephalometric landmarks can provide clinically satisfactory results, decrease the duration of tracing and potentially be as accurate as an expert orthodontist.[9,12,13] The CEPHA29 competition highlighted the need for large datasets in order to increase the robustness of automated systems of cephalometric landmarks.[12]

Aside from cephalometric analysis, artificial intelligence has also found its way into the field of malocclusion assessment through clinical photographs and radiographic images. The deep learning algorithms learn characteristic image features from the labeled database and then classify the orthodontic condition based on the features learned during the training process.[6,12] As a result of the successive convolutional layers, the CNN automatically analyzes the features that help classify different types of orthodontic conditions

without having to select any features manually.[6] There are a number of reports that show how deep learning systems can reliably classify orthodontic conditions based on clinical photographs.[10]

The overall current evidence indicates that AI has the potential to improve orthodontic diagnosis by improving the accuracy, consistency and efficiency of cephalometric analysis and malocclusion assessment and reducing the dependence on manual interpretation.

4.2. AI in orthodontic treatment planning

The application of artificial intelligence in orthodontic treatment planning has grown in recent years to support clinical decision-making, especially in the choice between extraction and non-extraction treatment options.[14,15] AI systems are trained on clinical records, cephalometric measurements and diagnostic data of previously treated patients, allowing them to identify patterns associated with specific treatment outcomes.[15] The decision making in orthodontic treatment planning and extraction has been investigated by using Artificial Neural Networks (ANNs), Convolutional Neural Networks (CNNs), Random Forest (RF), Multilayer Perceptron (MLP), Support Vector Machines (SVM) and Decision Tree (DT).[14,15]

AI models can learn the relationship between diagnostic variables and treatment plans selected by clinicians to predict if tooth extraction may be necessary for a specific mal-occlusion.[2] Recent evidence has shown the diagnostic accuracy of AI systems to predict orthodontic extraction choices to be moderate to high. In a meta-analysis, the pooled sensitivity and specificity of AI models were 70% and 90%, respectively, showing good performance in cases that required and did not require extractions. Among the models considered, CNN-based architectures such as ResNet and VGG showed the highest and most consistent diagnostic performance.[14]

However, despite the encouraging results, considerable heterogeneity was found between the different studies as a result of varying designs, patient samples, databases, and AI techniques employed. Thus, AI can only be considered as a supplement to clinical judgment, as opposed to an alternative, at the present time, with the need for additional standardization of the research required.[15]

4.3. AI in orthognathic surgery

The use of artificial intelligence (AI) technology in the planning of orthognathic surgery has been applied to enable the selection of those patients who may require surgery as compared to orthodontic treatment. First, cephalometric radiographs of the patient were taken, and data regarding the skeleton of the patient was extracted.[16,17] In one of the methods adopted, data about soft and hard tissue measurements of the cephalometrics that were made from lateral radiographs were fed as the input variable to machine learning. Patients were grouped as training, validation, and testing groups, and the decisions made by expert orthodontists and surgeons were used as reference for the development of the models. Ten different algorithms of machine learning, including neural network, random forest, support vector machines, and XG Boost, were employed in a combined predictive model.[16]

An alternative strategy involved the use of a deep learning technique involving convolutional neural networks trained using posteroanterior and lateral cephalogram images. Independent extraction of features from each image was done using the ResNet34 backbone network, and the features were then joined together to be processed by the classifier for prediction of the need for surgery. The analysis of feature maps revealed that the network considered the teeth and maxillofacial areas in its decision-making process.[17] The machine learning ensemble model attained accuracies of 0.707, 0.759, and 0.822 in the overall, Class II, and Class III data sets, respectively,[16] while the convolutional neural network classified correctly 394 out of 413 images, an accuracy of 0.954.

These findings highlight the potential of AI-assisted approaches in the diagnostic and treatment-planning stages of orthognathic care.

4.4. AI in fixed orthodontics

AI has been integrated into fixed orthodontic therapy to make possible the correct placement of brackets and the manufacture of appliances, as well as digital treatment planning.[18-20] The process involving artificial intelligence technology makes use of intraoral scanning, radiographs, and 3D models of teeth to design an individual treatment plan for bracket placement.[18] The system of software predictions is applied during indirect bonding procedures and involves analysis of the morphology of teeth and computer-generated models to position the brackets, which further can be corrected by the specialist.[20]

There are many artificial intelligence (AI)-based platforms that facilitate tooth movement and bracket placement virtually in a digital workflow.[18,20] In addition, AI can be employed in designing three-dimensional (3D) printed transfer trays, in which tray designs and their internal structures can be created automatically based on the tooth morphology in order to unify appliance designs.

During clinical practice, intraoral scans after bracket bonding will be compared with planned scans to analyze the accuracy of bracket transfer. AI-assisted tray designs, either in groups or individually, were shown to be clinically accurate in most linear and angular measurements except for torque transfer.[19]

Furthermore, AI-assisted digital indirect bonding exhibited comparable linear accuracy to conventional methods while providing improved bracket angulation accuracy and enabling a streamlined digital workflow.

4.5. AI in clear aligner therapy

Artificial intelligence (AI) has opened new horizons for clear aligner therapy via enhanced treatment planning, workflow automation, treatment monitoring and patient compliance. AI-based treatment planning software relies on machine learning algorithms together with three-dimensional (3D) imaging and modeling to estimate root movements and to visualize the surrounding alveolar bone structures, giving clinicians the opportunity to assess whether the proposed tooth movements are within the biological limits. This enables the design of personalized treatment plans considering tooth morphology, periodontal health and the severity of malocclusion, thus enhancing the predictability of orthodontic outcomes.[21]

Recent advances in AI have also made it possible to automate several parts of the digital orthodontic workflow (eg, tooth segmentation, digital model registration, digital setup creation). A scoping review identified several AI integrated aligner software systems, showing the increasing role of automation in treatment planning and aligner design.[22] Furthermore, computer-aided design and manufacturing (CAD/CAM) technologies and remote assessment platforms have improved diagnostic accuracy and treatment monitoring using artificial intelligence and machine learning.[23]

AI-based monitoring systems utilize image analysis algorithms, decision tree models, and real-time feedback to evaluate the progress of treatment and enhance patient compliance.[24] Dental Monitoring™ provides AI-based image analysis to assess aligner fit, identify treatment divergences and provide remote advice on aligner change intervals for efficient clinical decision making.[25] These technologies have been shown to improve patient engagement, compliance and efficiency of monitoring. In brief, the data available indicates that AI is transforming clear aligner therapy from a primarily clinician-dependent procedure to a data-driven and more automated treatment approach.

4.6. AI in remote monitoring and teledentistry

Artificial intelligence (AI) has improved tele-dentistry by allowing constant remote monitoring of orthodontic treatment through smartphone apps. AI software employs the techniques of machine learning, deep learning, and convolutional neural networks (CNNs) to analyze photo, video, and digital scans uploaded by the patient. This helps in evaluating the condition of tooth movement, aligner fitting, device condition, and oral hygiene. The use of remote follow-up by the doctors allows them to monitor the treatment process and receive alerts about losing track of the treatment, appliance problems and hygiene issues.[26,27]

For instance, AI-driven programs such as Dental Monitoring can help increase patient compliance through automated reminders, tracking of progress, and feedback based on patient's specific requirements. Research shows that using AI-based remote monitoring can decrease the need for office visits by about 23–33% without compromising the effectiveness of treatments and promoting timely improvements. In addition to this, improved communication between the clinician and the patient ensures efficiency and increased access to treatment. However, inconsistent AI decision-making and lack of transparency of algorithms indicate that continuous supervision is required, thus making AI suitable only as an additional tool.[26-28]

5. Advantages of AI in Orthodontics[1,5,6,8,29]

1. **Enhanced diagnostic precision:** The advanced AI algorithms increase the accuracy and consistency of radiographic, photographic, and virtual model analysis for diagnosis.
2. **Rapid cephalometric analysis:** Cephalometric and automated landmarks help in reducing the analysis time without compromising on its accuracy.
3. **Optimized treatment planning**: The use of data analysis helps in the determination of suitable treatment approaches.
4. **Personalized treatment approaches:** Using patient data will aid in formulating treatment methods that will be specific to each individual.
5. **Prediction of treatment outcomes:** Prediction models will enable one to predict tooth movement, treatment duration, and post-treatment stability.
6. **Improved clinical efficiency:** Automating some of the tasks in orthodontics will decrease the burden of work in the clinic.
7. **Continuous monitoring of treatment progress:** The use of an AI-based remote monitoring system

makes it possible to assess real-time tooth movements as well as patient compliance.

8. **Increased treatment predictability:** Analyzing a huge amount of clinical data ensures that there is more consistency and predictability in the results of the treatment.
9. **Support for complex clinical decisions:** Pattern recognition and data integration skills help in dealing with difficult cases.
10. **Advancement of digital orthodontic workflows:** Integration with digital imaging, intraoral scanning, virtual setup, and aligner systems helps make the orthodontic practice more efficient and technology-based.

6. Limitations and Challenges of AI in Orthodontics[1,6,30,31]

6.1. Data quality and availability

Inconsistencies in the way data is acquired, formatted, and documented by different entities may affect the consistency of data used for AI model training, impacting its ability to generalize beyond the training environment.

6.2. Algorithmic bias and limited generalizability

Under-representation of certain demographic groups in the training data set can be a source of bias in the use of algorithms.

It can influence the process of diagnoses and treatments, thus bringing problems with inequalities in healthcare services.

6.3. Lack of explainability

Various machine learning models, particularly those that include artificial neural networks, give predictions without any obvious explanation behind them.

This ambiguity can be a barrier to clinicians trusting the system and getting consent from the patients.

6.4. Risk of diagnostic and treatment errors

Mistaken output could be generated by AI technologies owing to the potential for errors in processing, landmarks localization, image recognition, or unexpected deviations of the clinical case from known norms.

In cephalometric analysis, incorrect output could be caused by anatomical differences, distortions of the image, or anatomical overlap.

6.5. Ethical, privacy, and security concerns

The more patients whose data is stored and collected, the more chances there are of their privacy being violated. There are some ethical considerations when it comes to data ownership, confidentiality, and use of patient data.

6.6. Dependence on human oversight

It will always need human intervention because AI cannot replace it at any cost. It becomes imperative to have professional oversight for ensuring the validity of advice given by AI-based systems.

6.7. Legal and accountability issues

Accountability in cases where harm results from the use of artificial intelligence in diagnosis and treatment presents a significant challenge. Existing laws provide minimal guidance regarding liability in AI-based clinical decisions.

6.8. Economic and implementation barriers

The adoption of advanced AI technologies requires substantial investment in software, infrastructure, maintenance and clinicians' training. These costs may further increase the divide between well-resourced and poorly resourced orthodontic practices.

7. Emerging Trends and Future Perspectives of AI in Orthodontics

The future of orthodontic treatments is becoming more oriented towards intelligent, data-driven, and personalized strategies. 5D Orthodontics utilizes artificial intelligence with multiple modalities of imaging and prediction in order to achieve complete craniofacial structures analysis and more accurate forecasting of treatments.[32] Digital twins are the next step on this road that allows one to create dynamic digital models of patients that can process clinical data in real time, provide biomechanical analysis, and predict adaptive treatment during the course of treatment.[33] The development of deep learning, reinforcement learning, and explainable artificial intelligence will help to increase the clarity, precision, and acceptance of such systems.[33] The generative artificial intelligence becomes a valuable tool for automated documentation, simulations of treatment, patient education, and professional training.[34] In addition, future practice of orthodontics will be more focused on collaborative intelligence, when the AI will serve as the decision support system, which works in collaboration with the expert and provides ethically acceptable and patient-centered results.[35]

8. Conclusion

Artificial intelligence has emerged as a transformative technology in the field of orthodontics with applications ranging from diagnosis and treatment planning to

prediction of tooth movement, clear aligner therapy and remote patient monitoring. Cephalometric landmarks detection, assessment of malocclusion and decisions on tooth extraction have proved to be quite accurate due to the application of AI technology. This led to the increase in diagnostic precision and effectiveness of the treatment process. Nonetheless, these advancements are still limited by the issues such as low data quality, insufficient generalization of models, ethics and lack of transparency, which do not allow to apply these techniques widely in the clinic. In the current reality, AI can only be seen as an additional tool for assistance of orthodontists.

List of Abbreviations

AI: Artificial Intelligence;
ML: Machine Learning;
DL: Deep Learning;
CNN: Convolutional Neural Network;
CBCT: Cone-Beam Computed Tomography;
CAD/CAM: Computer-Aided Design and Computer-Aided Manufacturing;
ANN: Artificial Neural Network;
RF: Random Forest;
MLP: Multilayer Perceptron;
SVM: Support Vector Machine;
DT: Decision Tree;
3D: Three-Dimensional;
XGBoost: Extreme Gradient Boosting

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Kavya BR: Conceptualization, literature review, methodology, data curation, investigation, writing—original draft preparation, and writing—review and editing.
Jansiya Thangavelu: Literature review, data curation, investigation, and writing—original draft preparation.
Bhavana BA: Methodology, data curation, writing - review and editing.

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Conflict of Interest

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