THE EVOLVING ROLE OF ARTIFICIAL INTELLIGENCE IN ORTHODONTIC DIAGNOSIS AND TREATMENT PLANNING

Ewolucyjna rola sztucznej inteligencji w diagnostyce i planowaniu leczenia ortodontycznego

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Abstract

Artificial intelligence is increasingly transforming the field of orthodontics by enhancing diagnostic precision, optimising treatment planning, and improving patient outcomes. This review explores current applications, benefits, limitations, and future prospects of artificial intelligence in orthodontic practice. By examining recent technological advancements and clinical implementations, this article aims to provide a comprehensive understanding of how artificial intelligence is reshaping contemporary orthodontics.

Streszczenie

Sztuczna inteligencja coraz bardziej rewolucjonizuje dziedzinę ortodoncji, zwiększając precyzję diagnostyczną, optymalizując planowanie leczenia i poprawiając wyniki terapeutyczne. Niniejsza praca przeglądowa przedstawia aktualne zastosowania, korzyści, ograniczenia oraz przyszłe perspektywy wykorzystania sztucznej inteligencji w praktyce ortodontycznej. Artykuł ma na celu wyjaśnienie, na podstawie analizy najnowszych osiągnięć technologicznych i zastosowań klinicznych, w jaki sposób sztuczna inteligencja zmienia współczesną ortodoncję.

Introduction

The integration of artificial intelligence (AI) into healthcare represents one of the most significant technological achievements of the 21st century. Across various medical specialties, AI enhances diagnostic accuracy, streamlines workflows, and supports more informed clinical decision-making [1]. In orthodontics, the adoption of AI has been gaining momentum due to the central role of imaging, pattern analysis, and personalised treatment planning [2]. The digital transformation of orthodontic records, including the widespread use of cone beam computed tomography (CBCT), intraoral scans, and cephalometric radiographs, has created favourable conditions for the introduction and application of AI algorithms.

AI encompasses a broad range of technologies, including machine learning (ML), deep learning (DL), and convolutional neural networks (CNNs), which are capable of analysing large and complex datasets to identify patterns

that may be imperceptible to clinicians [2, 3]. These technologies are used to automate time-consuming tasks such as outlining anatomical structures in cephalometry [4], improving the accuracy of skeletal assessment [5], and generating insights that support treatment planning.

Neural network learning involves a multi-stage optimisation process in which the model learns by analysing vast datasets. In deep networks, each layer transforms data into increasingly abstract representations, ultimately producing a diagnostic output. A key stage of this process is the training phase, during which the model adjusts its parameters in response to errors.

In this context, the role of specialist clinicians is crucial. In addition to supplying high-quality training data (e.g. manually annotated cephalometric landmarks, clinical case descriptions), they act as validators and reviewers of algorithm performance. Expert clinical knowledge is essential at every stage of developing AI systems: from preparing datasets to evaluating the accuracy and practical utility of models. Specialist clinicians also play a key role in identifying model limitations, improving result interpretability, and ensuring that AI tools align with real clinical needs [6].

As orthodontics continues to evolve, AI offers promising opportunities to enhance the quality of patient care, shorten appointment times, and achieve better treatment outcomes [1]. However, effective integration into orthodontic practice also requires consideration of ethical, regulatory, and practical challenges [7].

Aim of study

The aim of this article is to review the available literature on the evolving role of artificial intelligence in orthodontics, with particular emphasis on its current applications, benefits, limitations, and future development prospects.

Evolution and fundamental concepts of artificial intelligence in orthodontics

Artificial intelligence in healthcare refers to the simulation of human intelligence by machines, particularly computer systems capable of learning from data, recognising patterns, and making decisions. In orthodontics, AI relies primarily on machine learning, which enables systems to learn from experience without explicit programming, and on deep learning, which uses artificial neural networks to model complex patterns in data. Convolutional neural networks, in particular, have proven highly effective in image analysis and are widely used in orthodontic diagnostics based on radiographic imaging [2].

These technologies have enabled a shift from manual, time-consuming procedures to digitally assisted, automated systems. From predicting malocclusions to designing customised orthodontic appliances, AI supports orthodontists in making more informed and precise decisions [2, 3].

Applications in diagnostic imaging

Orthodontics relies heavily on imaging techniques such as cephalometric radiographs, panoramic radiographs, and CBCT scans. AI plays a crucial role in streamlining the analysis of these modalities.

Cephalometric analysis is the cornerstone of orthodontic diagnostics and treatment planning. Traditionally, the identification of anatomic landmarks on cephalometric radiographs has been a manual process, characterised by variability both between different clinicians and within the same clinician at different times. AI, particularly deep learning models such as convolutional neural networks, can automate this process with high precision and reproducibility [4]. These systems can detect and annotate landmarks faster than experts, increasing workflow efficiency and diagnostic consistency while maintaining accuracy. A controlled study showed that AI was 2.12% more accurate and 95% faster than specialists [8].

Beyond landmark detection, AI models can perform segmentation, i.e. identification and extraction of specific anatomical structures such as teeth, the maxilla, the mandible, or the airway. This enables automated measurements, anomaly detection, and morphological classification. For example, CNNs are effectively applied to the segmentation of CBCT scans and the detection of dental caries or root resorption, increasing the objectivity and efficiency of image interpretation [9].

Enhancing treatment planning and monitoring

The integration of AI into orthodontic workflows has revolutionised the way clinicians plan, execute, and oversee treatment. Thanks to the use of large datasets and advanced algorithms, AI-based tools can enhance the precision, efficiency, and individualisation of orthodontic care.

One of the most groundbreaking applications of AI in orthodontics is predictive modelling. Machine learning algorithms, trained on large datasets from historical cases, are capable of forecasting treatment outcomes based on variables such as skeletal structure, the specific type of malocclusion, and the patient's age. Predictive tools enable orthodontists to:
- simulate multiple possible treatment pathways, helping select the most effective strategy;
- estimate treatment duration and the probability of complications;
- predict skeletal and dental growth in younger patients.

Such solutions are particularly valuable in complex cases requiring orthognathic surgery or interdisciplinary collaboration (e.g. with a periodontist or prosthodontist), where AI-based simulations can support planning by forecasting post-treatment occlusion and facial aesthetics [10].

AI has significantly streamlined the orthodontic appliance design process through integration with CAD/CAM systems. By utilising intraoral scans or CBCT (Cone Beam Computed Tomography), AI-based platforms can automatically:
- analyse tooth morphology and alignment;
- design custom-fitted archwires, brackets, and aligners;
- simulate optimal force vectors and tooth movements.

In the case of aligner therapy, AI can determine the optimal sequence and magnitude of movements necessary to achieve therapeutic goals, while minimising patient discomfort and the risk of material fatigue. Automation of appliance design not only increases the precision of orthodontic appliances but also shortens chair time and reduces human error – an important advantage in high-volume clinical settings [11].

Continuous treatment monitoring is vital for success. AI-based tools now allow for the assessment of treatment progress in real-time or at regular intervals through:
- sequential photographic analysis – AI compares facial or intraoral images taken at different treatment stages;
- cephalometric superimposition – AI automatically overlays anatomical landmarks from radiographs to evaluate skeletal and dental changes;
- 3D model comparison – periodic intraoral scans can be analysed for accuracy of tooth positioning and arch movements.

These tools are especially useful in aligner therapy, where patient compliance is critical. AI algorithms can detect and flag insufficient aligner wear or unexpected tooth movements, enabling early intervention and reducing the risk of relapse [12].

Applications of AI in orthodontic diagnostics

Artificial intelligence has significantly improved cephalometric analysis by automating the identification of anatomical landmarks on radiographic images. This has reduced human error and enhanced diagnostic efficiency. Platforms such as WeDoCeph, WebCeph, and CephX use deep-learning algorithms, particularly CNNs, to detect cephalometric landmarks with high accuracy [11, 13].

Studies have shown that these systems generate results comparable to those of experienced clinicians – often within seconds of image upload. The integration of these tools into orthodontic practice allows for faster diagnosis and reproducible landmark identification, which is crucial for precise treatment planning [11, 13, 14].

AI is increasingly used to assess skeletal maturity, which is essential for determining the optimal timing of intervention in growing patients. AI models trained on radiographic images, such as lateral cephalograms or hand-wrist radiographs, can estimate cervical vertebral maturation (CVM) stages and Fishman's skeletal maturity indicators (SMI).

Studies have demonstrated that AI systems achieve high levels of agreement with expert assessments in CVM classification. These tools assist clinicians in selecting the appropriate window for treatment commencement, particularly in growth-modification therapies [15–17].

Artificial intelligence is also applied in the analysis of the upper airway and temporomandibular joint (TMJ) structures using CBCT and magnetic resonance imaging (MRI). These systems support the diagnosis of airway obstruction, such as obstructive sleep apnoea, by segmenting and measuring the volume of the nasopharyngeal and oropharyngeal spaces [18, 19].

In TMJ diagnostics, AI systems classify disc displacement, identify degenerative changes, and analyse the morphology of the mandibular condyle based on imaging data, providing a faster and more standardised assessment than manual methods [20].

Clinical outcomes and effectiveness

Artificial intelligence has significantly improved the accuracy of orthodontic diagnosis and treatment planning. Using machine learning algorithms and deep learning models, AI systems are able to analyse complex datasets, resulting in more accurate identification of cephalometric landmarks and improved assessment of malocclusions. A randomised controlled trial demonstrated that AI-assisted diagnostics achieved higher precision in treatment planning compared with traditional methods, with a statistically significant improvement ($p < 0.05$) [10]. The integration of AI into orthodontic practice has also led to shorter treatment durations and a reduced number of appointments. In the study, the mean treatment duration for patients in the AI-assisted group was 14.6 ± 3.2 months, compared to 18.9 ± 4.5 months in the group without AI support ($p < 0.001$). Additionally, the AI group required fewer appointments (10.2 ± 2.1) than the traditional group (12.8 ± 3.4) [21].

Patients undergoing AI-assisted orthodontic treatment reported higher levels of satisfaction. A randomised controlled trial showed that the AI group achieved a mean satisfaction score of 9.2 ± 0.6, compared with 8.1 ± 0.8 in the traditional group ($p < 0.001$). Factors contributing to the increased satisfaction included shorter treatment duration, fewer appointments, and improved treatment outcomes [21].

Challenges and limitations

Despite the growing potential of AI in orthodontics, several significant challenges remain. The integration of AI into orthodontic practice necessitates the collection and analysis of extensive documentation and patient data, including radiographs, 3D intraoral scans, and clinical treatment records. This raises serious concerns regarding patient privacy and data security. It is essential to comply with strict regulatory frameworks, such as the General Data Protection Regulation (GDPR) in Europe and the Health Insurance Portability and Accountability Act (HIPAA) in the United States. Orthodontic practices must implement advanced cybersecurity measures and data anonymisation techniques to protect sensitive information [22].

The use of AI in orthodontic diagnostics also raises questions regarding the determination of liability for the results obtained. Despite the increasing autonomy of algorithms, there is still a lack of clear legal regulations concerning liability for potential diagnostic errors or incorrect clinical decisions made based on AI suggestions. In practice, the specialist remains responsible for the entire course of treatment, regardless of whether AI-assist-

ed tools were used. This legal framework reflects the view that AI serves a supportive rather than a decision-making role, and that the final interpretation of data and therapeutic decisions rests with the clinician. Nevertheless, as technology continues to advance, it will be necessary to refine the legal and ethical frameworks to account for the specific nature of algorithmic recommendations and their impact on the treatment process [23].

AI models are only as unbiased as the data on which they were trained. If training datasets lack diversity or exhibit bias toward specific demographic groups, the resulting AI systems may perpetuate existing prejudices, leading to disparities in treatment outcomes. For example, the underrepresentation of certain ethnic groups in training datasets can result in reduced AI efficacy for these populations, thereby exacerbating health disparities. Addressing algorithmic bias requires the inclusion of diverse and representative datasets in the development of AI systems [24].

Despite significant advances of AI in orthodontics, this technology cannot replace the clinical experience of orthodontists. While AI systems excel at pattern recognition and data analysis, they are unable to account for patient preferences, psychosocial factors, or ethical considerations. Therefore, human oversight remains indispensable to interpret AI recommendations, make informed clinical decisions, and provide personalised care [25].

Future and perspectives

The integration of AI with other cutting-edge technologies, such as 3D printing and Virtual Reality (VR), has the potential to further personalise orthodontic treatment. AI algorithms can analyse vast amounts of data from previous cases to predict the most effective treatment plans for new patients. 3D printing enables the rapid production of customised orthodontic appliances, reducing manufacturing time while improving fit and comfort [26]. Moreover, VR technology can be used in patient education, in increasing patient awareness, and in treatment planning. The visualisation of tooth movements and anticipated treatment outcomes allows patients to better understand the course of therapy, which enhances satisfaction and cooperation. For clinicians, VR offers immersive simulations for training and planning complex procedures, which may improve clinical outcomes [27].

The development of AI systems capable of continuous learning is essential for increasing their clinical usefulness. Traditional AI models are static, meaning they are trained on fixed datasets and may not adapt well to new information or evolving clinical practices. Systems capable of continuous learning can adapt to new data in real time, improving their performance and relevance in dynamic clinical environments [12].

Implementing such systems requires rigorous quality-control mechanisms to monitor algorithm behaviour and prevent the incorporation of erroneous data. Moreover, their integration demands careful planning to ensure patient safety and data integrity [25].

Conclusions

Artificial intelligence is redefining orthodontics by providing tools that enhance diagnostic accuracy, streamline treatment planning, and support personalised patient care. Through innovations such as automated cephalometric analysis, predictive modelling, and intelligent orthodontic appliance design, AI enables clinicians to make faster and more informed decisions, ultimately improving efficiency and treatment outcomes.

Integration with complementary technologies such as 3D printing and virtual reality may further revolutionise workflow organisation in orthodontics, enhancing treatment precision and supporting a more personalised approach to patient care.

However, to fully harness the potential of AI in orthodontic practice, the existing challenges must be addressed. Data-privacy concerns must be resolved through strict adherence to regulations such as GDPR and HIPAA, as well as the implementation of advanced cybersecurity protocols. Also, algorithmic bias remains a significant concern, underscoring the need for diverse and representative training datasets to ensure equitable care for all patient groups. Equally important is continuous human oversight, as AI systems are not yet capable of replacing the clinical experience, ethical reasoning, and individualised patient approach provided by skilled orthodontists.

As AI technologies continue to advance, fostering interdisciplinary collaboration among clinicians, data scientists, and regulatory experts will be essential. Such collaboration will be key to integrating AI in an ethical, safe, and effective manner, opening the door to a new era of precise, personalised orthodontic care.

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