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Review Article

The role of artificial intelligence in modern orthodontics: Transforming diagnosis and treatment planning – A narrative review

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Abstract

Artificial Intelligence (AI) has emerged as a transformative force in Orthodontics, redefining traditional approaches to diagnosis, treatment planning, and patient management. This article explores the integration of AI into orthodontic practice, emphasizing how technologies like machine learning, deep learning, convolutional neural networks, and artificial neural networks have advanced the field. Early applications focused on automating cephalometric analyses and evolved to support predictive modelling for treatment outcomes and the development of clear aligner therapies. The article highlights AI's capabilities in diagnostic imaging, age and growth assessment, and managing complex cases through sophisticated algorithms and image analysis tools. It also examines cutting-edge applications such as DiagnoCat, transfer learning, and the integration of AI with 3D printing and robotics. Alongside benefits, the article addresses critical challenges, including data bias, ethical considerations, and workflow integration. The future promises AI-powered platforms that merge diagnostics, monitoring, and personalized care delivery, potentially enhancing accessibility through teledentistry. Ultimately, the synergy between AI and clinician expertise will define the next era of orthodontics, one marked by precision, efficiency, and improved patient outcomes. This comprehensive review provides valuable insights into how AI is reshaping modern orthodontic practice and its trajectory toward a more intelligent, patient-centric future.

Keywords: Orthodontics, Artificial intelligence, Diagnostic imaging, Neural network

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1. Introduction

AI is a science or technology by virtue of which machines inculcate human intelligence by implementing intelligent algorithms. It can be defined as science and engineering of building intelligent machines with the help of intelligent computer programs.[1] John McCarthy, a professor of computer science at Stanford who coined the term "artificial intelligence" in 1955 at Dartmouth Conference, the first artificial intelligence conference, very aptly echoed his voice on Artificial Intelligence (AI) through these words.[2]

Artificial Intelligence has emerged as a transformative force in healthcare, revolutionizing how professionals diagnose, treat, and manage various medical conditions. In orthodontics, a specialty deeply reliant on precise measurements, predictive modeling, and long-term treatment strategies, AI offers unprecedented opportunities to enhance both clinical outcomes and patient experiences.[3]

Orthodontics, traditionally seen as a meticulous blend of art and science, has long depended on the clinician's expertise, diagnostic acumen, and manual dexterity.[4] However, with the advent of AI technologies, the field is undergoing a paradigm shift. AI not only augments the orthodontist's capabilities but also introduces automation, precision, and predictive analytics into the core of orthodontic practice[5]. **(Figure 1)** This integration leads to more accurate diagnoses, efficient treatment planning, and improved monitoring of patient progress.[6]

The journey of AI in orthodontics mirrors its broader trajectory in medicine: from simple rule-based systems to sophisticated machine learning models capable of learning from vast datasets and making complex decisions. Today, AI applications in orthodontics range from automating cephalometric analyses to predicting treatment outcomes and optimizing aligner sequences for better patient adherence and satisfaction[5]. **(Figure 2)**

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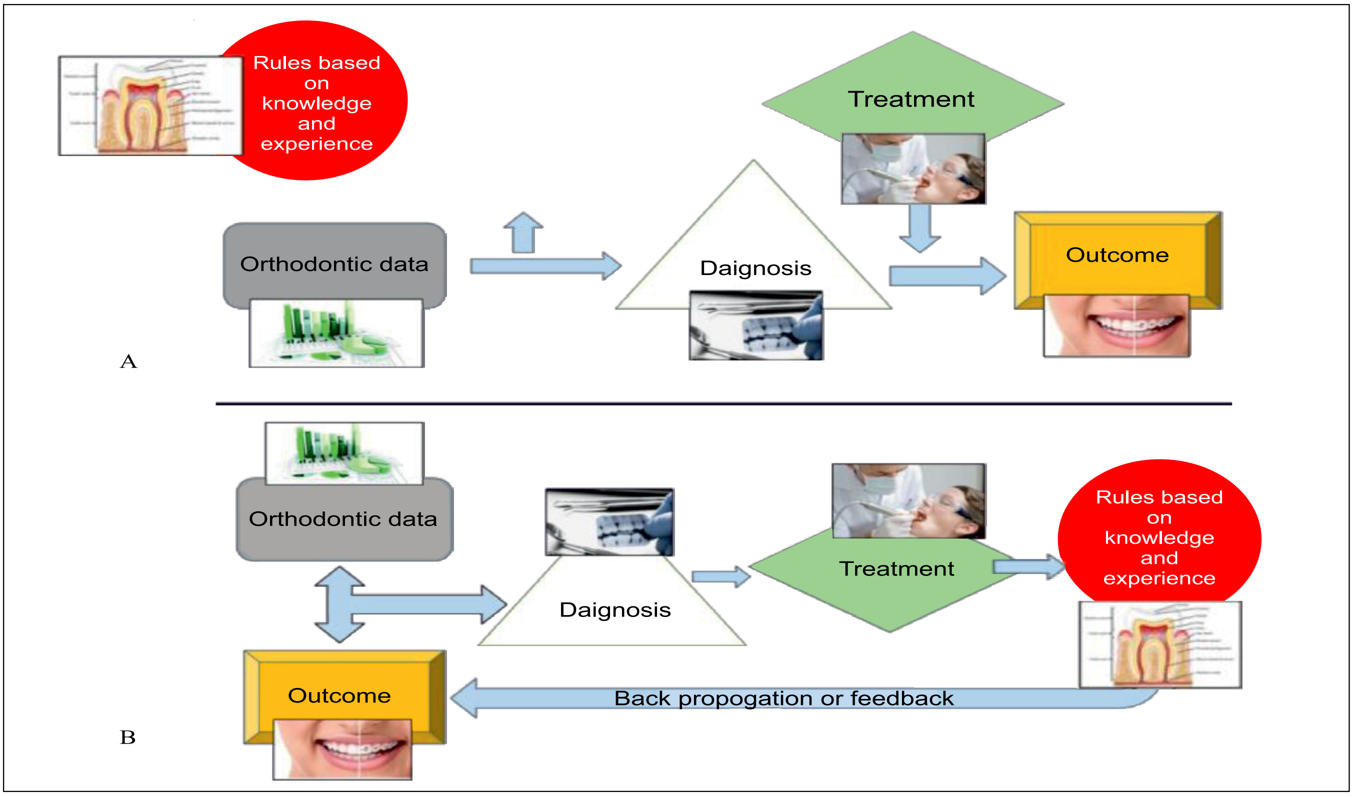

Figure 1: (A) Conventional workflow for orthodontic diagnosis and treatment planning, involving manual interpretation of clinical records, radiographs, and study models. (B) Artificial intelligence–assisted workflow, where AI algorithms support image analysis, cephalometric measurements, and decision-making to enhance efficiency and accuracy.

Table 1: Comparison of machine learning (ML) and deep learning (DL) approaches, highlighting their technical differences and implications for orthodontic applications such as image analysis, growth prediction, and treatment planning.

S. No	Machine Learning	Deep Learning
1	A subset of AI	A subset of ML
2	Can train on smaller data sets	Requires large amounts of data
3	Requires more human interventions to correct and learn	Learns on its own from environment and past mistakes
4	Shorter training and lower accuracy	Longer training and higher accuracy
5	Makes simple, linear correlations	Makes non-linear, complex correlations
6	Can train a CPU (Central Processing Unit)	Needs a specialized GPU (Graphic Processing Unit) to train

This article explores the historical development, current applications, challenges, and future directions of AI in orthodontics, offering a comprehensive overview of how technology is reshaping this critical field of dental medicine.

2. Evolution of AI and Machine Learning in Orthodontics

This section discusses the evolution of AI, machine learning and deep learning as its subsets and neural networks that formed the key components in its development.

2.1. Early developments in AI for Orthodontics

The integration of AI into orthodontics began with simple computer-assisted tools designed to automate repetitive tasks such as cephalometric tracing.[7] These early systems relied on pre-programmed algorithms and lacked the flexibility to adapt to new data or clinical variations.[4] Their utility was limited, often requiring significant manual input from clinicians.[8]

2.2. Emergence of Machine Learning and Deep Learning

The real breakthrough came with the rise of Machine Learning (ML), a subset of AI that enables systems to learn from data and improve over time without explicit programming.[2] Arthur Samuel, is credited for coining the term, “machine learning” in 1959 whereas Geoffrey Everest Hinton is a British-Canadian cognitive psychologist and computer scientist who is considered as the father of machine learning.[9,10] In orthodontics, ML models began to analyze vast datasets comprising radiographs, treatment outcomes, and patient demographics to identify patterns and make informed predictions.[4]

Deep Learning (DL), a more advanced form of ML, introduced neural networks capable of processing complex data structures. The differences between ML and DL have been enumerated in **Table 1** for better understanding.

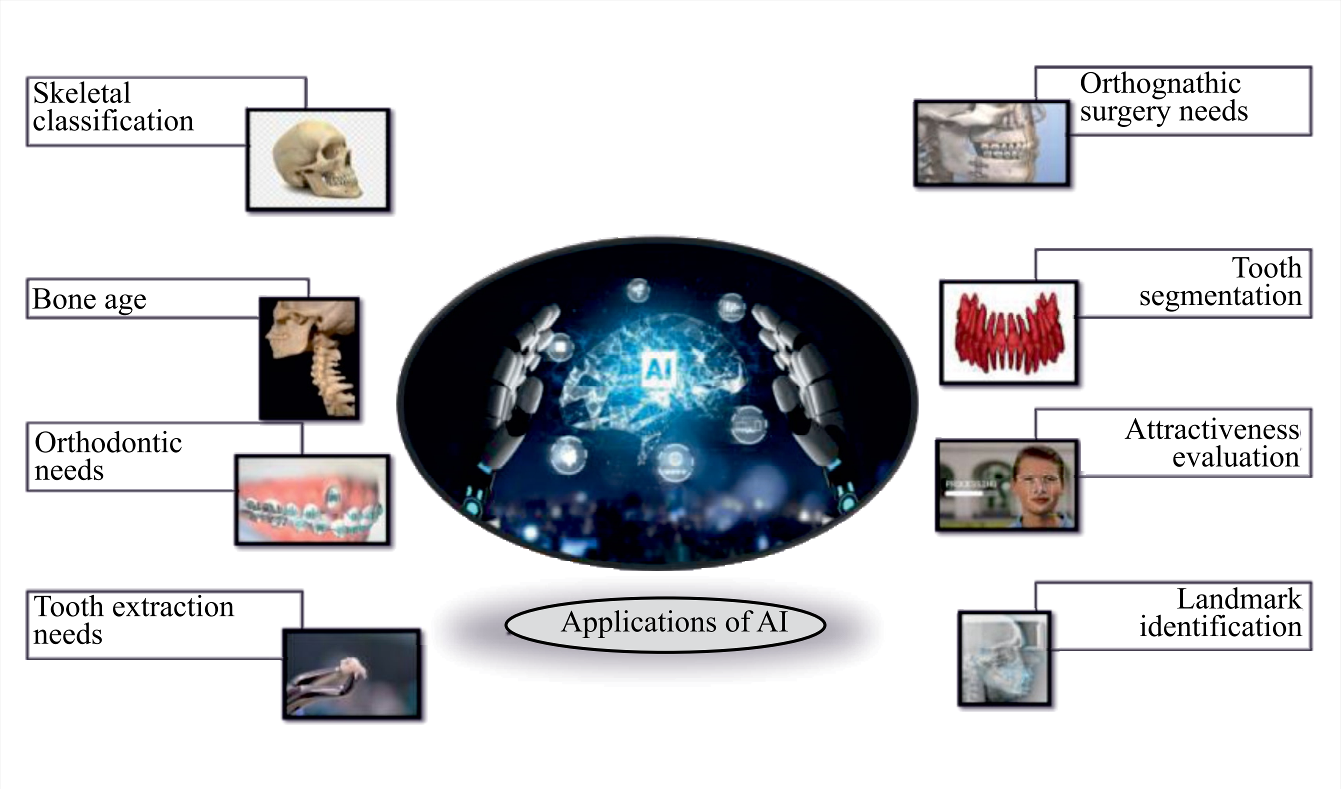

Figure 2: Schematic representation of the main applications of artificial intelligence in orthodontics, including automated cephalometric landmark detection, growth stage prediction, treatment simulation, and treatment outcome assessment.

Convolutional Neural Networks (CNNs), for instance, excel at analyzing images, making them ideal for interpreting cephalograms, panoramic radiographs, and 3D scans.[11] Amongst several DL-based artificial neural networks (ANNs), convolutional neural networks (CNNs), which have one or more layers of convolution units, have demonstrated the most optimal performance in the field of image analysis and are commonly being applied in the majority of dentomaxillofacial workflows for diagnostics, treatment planning and prognosis prediction.[12,13] These networks mimic the human brain's structure, enabling them to recognize patterns, classify anomalies, and assist in treatment planning with remarkable accuracy.[14]

3. The Role of Deep Learning and Advanced Algorithms

The state-of-the-art machine learning method 'deep learning' is based on artificial neural network (ANN)[10] which forms the backbone of AI. This section describes the three networks namely ANN, CNN and RNN.

3.1. Artificial Neural Networks (ANNs)

Artificial Neural Network was inspired by biological neural network. The basic unit of ANN is called an artificial neuron (nodes). ANN can be described as a function with both input and output value as a vector. ANN, is a group of multiple perceptrons or neurons at each layer. ANN is also known as a Feed-Forward Neural network because inputs are processed only in the forward direction.[14] This type of neural networks is one of the simplest variants of neural networks. They pass information in one direction, through various input nodes, until it makes it to the output node.[14]

3.2. Convolutional Neural Networks (CNNs)

Convolutional Neural Networks are one of the most popular models used today.[10] This neural network computational model uses a variation of multilayer perceptrons and contains one or more convolutional layers that can be either entirely connected or pooled.[15] These are pivotal in AI-driven orthodontics, excelling in image-based tasks.[11] They analyze 2D and 3D dental images, identifying anatomical landmarks, assessing bone structures, and detecting anomalies.[16] CNNs' layered architecture allows them to capture complex patterns, making them indispensable for diagnostic imaging.[17]

3.3. Recurrent Neural Networks (RNNs)

Recurrent Neural Networks, are more complex. They save the output of processing nodes and feed the result back into the model (they did not pass the information in one direction only). This is how the model is said to learn to predict the outcome of a layer.[15] RNNs, especially Long Short-Term Memory (LSTM) networks, process sequential data, making them suitable for modeling growth patterns and treatment progress.[18] These networks consider temporal dependencies, enhancing their predictive capabilities in dynamic clinical scenarios.[17] **Table 2** summarizes all 3 networks.

Table 2: Summary of three major neural network architectures, Artificial Neural Networks (ANNs), Convolutional Neural Networks (CNNs), and Recurrent Neural Networks (RNNs), with typical data types, strengths, limitations, and examples of orthodontic tasks suited to each.

Feature	ANN	CNN	RNN
Type of data	Tabular data, text data	Image data	Sequence data
Performance	ANN is considered to be less powerful than CNN, RNN	CNN is considered to be more powerful than ANN, RNN	RNN includes less feature compatibility when compared to CNN
Application	Computer vision	Facial recognition, text digitization and natural language processing	Text-to-speech conversions
Advantages	Having fault tolerance, ability to work with incomplete knowledge	High accuracy in image recognition problems, weight sharing	Remembers each and every information, time series prediction.
Disadvantages	Hardware dependence, unexplained behaviour of network	Large training data needed, don’t encode the position and orientation of object	Gradient vanishing, exploding gradient.

3.4. Attention mechanisms

Attention mechanisms within neural networks focus computational resources on the most relevant image regions, improving accuracy while reducing processing demands.[17] This is particularly beneficial in orthodontics, where certain anatomical features are more critical for diagnosis and treatment planning.[17]

3.5. Transfer learning

Transfer learning leverages pre-trained models on large datasets like ImageNet, refining them with domain-specific orthodontic data.[17] This approach accelerates model development, enhances accuracy, and reduces the need for extensive domain-specific data.

3.6. Key milestones

The following milestones underscore AI’s growing role in enhancing precision, efficiency, and predictability in orthodontic care.

1. **Automated cephalometric analysis:** Early AI applications focused on automating the identification of anatomical landmarks on radiographic images, a task prone to human error.
2. **Predictive modelling for treatment outcomes:** Machine learning models started predicting treatment duration, success rates, and potential complications based on historical data.
3. **Integration with CAD/CAM systems:** AI-enhanced computer-aided design and manufacturing (CAD/CAM) tools facilitated the creation of customized orthodontic appliances.
4. **Development of clear aligner technologies:** AI-driven platforms like Invisalign leveraged AI to design sequential aligners, optimizing tooth movement and treatment efficiency.

4. Applications of AI in Orthodontics

Artificial intelligence has expanded its horizon in each and every component of orthodontic practice, be it diagnosis, cephalometric analysis, caries detection, skeletal maturity and growth predictions, treatment planning among a few to name.

4.1. Diagnostic imaging and cephalometric analysis

Diagnostic imaging forms the backbone of orthodontic assessment.[4,19] In this regard, adequately trained neural networks like DiagnoCat (Moscow, Russia) can be a boon to diagnosis, especially in conditions having multifactorial etiology.[20] The software proposes a differential diagnosis in its generated description.[20] This limits the time spent for analysis and provides hints to possible pathological processes, even if those where not primarily indicated.[17] DiagnoCat identifies various conditions and disorders by assessing 50 signs (normal appearance, filling, crown, treated root canal, implant, sign of periapical lesion, etc) and selects dedicated images to support an individualized therapeutic planning.

Diagnostic imaging system, for example, Expert System (ES) simulates the decision making and working processes of experts and solves actual problems.[21] Shihao Li et al used deep learning models to effectively classify and monitor orthodontic images using a set of annotated photographs; the model tested demonstrated excellent classification.[22] Image classification was based on CNN model of DeepID.[23] The lateral cephalogram and the panoramic radiograph are typical grayscale images.[11] Grayscale images are “one-channel”, and other images are RGB image with “three-channel”.[24] The deep learning model was trained using facial regions observed in intraoral photographs corresponding to 12 categories; these images were annotated by an orthodontist.[22]

Cephalometric analyses, essential for evaluating craniofacial relationships, historically required manual landmark identification- a process both time-consuming and susceptible to variability.[25]

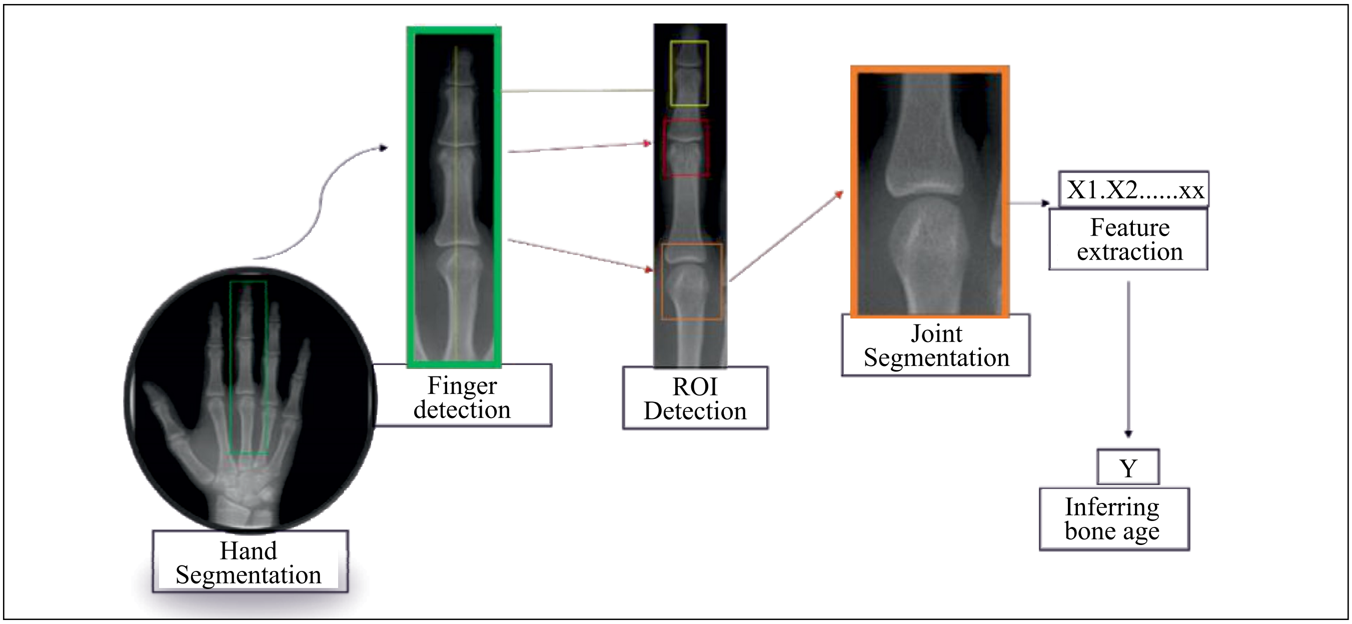

Figure 3: Illustration of an AI-assisted image analysis pipeline for orthodontic applications. The example shows the complete process from raw image acquisition through preprocessing, feature extraction by a neural network, prediction output (e.g., skeletal maturity classification), and clinical interpretation.

Artificial Intelligence, particularly CNNs, has revolutionized this process.[11] Automated systems now accurately identify cephalometric points, calculate measurements, and generate diagnostic reports.[16] Tools like the Fully Automatic Landmark Annotation (FALA) system utilize Random Forest regression combined with constrained local models to ensure high accuracy despite variations in patient anatomy or image quality.[8] Similarly, paraconsistent artificial neural network (PANN) introduced in the Bulletin of Symbolic Logic, derives its diagnosis based on all three units of antero-posterior, vertical and dental discrepancies.[26] Here standardization and data modelling rules out any differences between the data from the patient radiographs and its relative norms.[26] Another major application is the superimposition of deformation analysis with the ICPROX algorithm.[27] The main task of the 'Iterative closest proximity algorithm' (ICProx) is to detect deformations.[27]

4.2. Age and growth estimation

Accurate assessment of skeletal maturity is crucial for determining the optimal timing of orthodontic interventions.[28] Traditionally, the gold standard of determining the growth and development periods of individuals was achieved by hand-wrist radiographs, which has higher degree of intra- and inter-observer errors due to the subjectivity in the stage evaluation.[29] Guo et al.,[30] applied deep learning techniques for age estimation but it was lacking performance comparison between manual and machine learning methods based on a large sample of dental orthopantomograms (OPGs).[30] They went on to conclude that CNN models can surpass humans in age classification.[30] AI models trained on large datasets of dental and skeletal images can predict biological age with high precision[31]. **(Figure 3)** These models analyze morphological features of cervical vertebrae or dental development stages, assisting clinicians in planning treatments aligned with the patient's growth potential.[28]

4.3. Treatment planning optimization

Artificial Intelligence enhances treatment planning by simulating tooth movements, forecasting outcomes, and optimizing intervention strategies.[4] The ANN has the advantage of excavating features from massive medical data and the past decade has witnessed the rapid development of this approach[32]. **(Figure 4)** In clear aligner therapy, AI models generate precise aligner sequences that guide teeth through incremental adjustments, reducing treatment duration and minimizing the need for refinements.[33]

These systems incorporate biological constraints, such as bone density and tissue response, factors traditionally challenging to model accurately.[15] By integrating these variables, AI-driven planning tools offer more predictable and efficient treatment pathways.[4] One such tool is Learning-based multisource IntegratioN frameworK for Segmentation (LINKS).[34] LINKS, based on advanced machine learning imaging techniques by Wang et al.[34] was utilized to auto-segment the maxilla.

4.4. Management of complex cases

Artificial Intelligence significantly aids in managing complex orthodontic cases, including those requiring surgical interventions.[35] By analyzing cephalometric data and historical case outcomes, AI assists in identifying candidates for orthognathic surgery and predicting postoperative results.[36] This enhances clinical decision-making and facilitates clearer communication with patients through visualized treatment outcomes.[4]

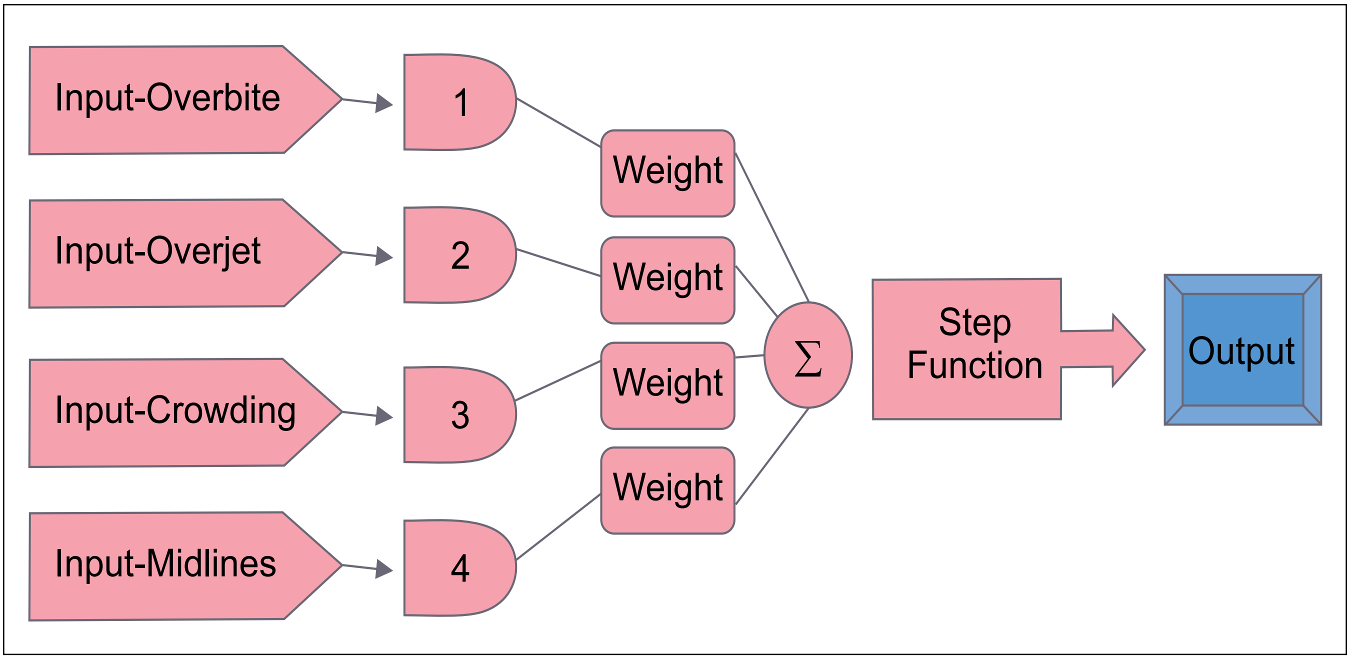

Figure 4: Treatment planning optimisation using artificial intelligence: integration of patient data, predicted treatment outcomes, and automated setup adjustments to achieve the most efficient biomechanical plan.

Artificial Intelligence also contributes to diagnosing and planning for conditions like temporomandibular joint disorders (TMD) and craniofacial anomalies such as cleft lip and palate, where treatment involves multifaceted considerations.[34] The Data science spectrum includes data capture/acquisition, data processing with optimized web based storage and management, data analytics involving in-depth statistical analysis, machine learning approaches, and data communication.[17]

4.5. Image classification and monitoring

Beyond diagnostics, AI supports treatment monitoring through advanced image classification systems.[33] These systems analyze intraoral photographs and radiographs over time, detecting deviations from expected progress and alerting clinicians to potential issues early.[11] This proactive approach enhances treatment efficiency and minimizes complications.[37]

4.6. Predictive modeling for outcomes

Artificial Intelligence models trained on extensive datasets predict treatment outcomes with remarkable accuracy.[38] They consider variables such as initial malocclusion severity, patient compliance, and anatomical limitations, providing clinicians with data-driven forecasts that inform treatment planning and patient education.[4,32]

5. Overcoming Challenges in AI Integration

Artificial Intelligence effectiveness hinges on the quality and diversity of its training data.[22] In orthodontics, datasets must encompass a wide range of ages, ethnicities, and malocclusion types to ensure models are robust and generalizable.[39] Bias in datasets can lead to inaccurate predictions and suboptimal treatment recommendations.[17] Seamless integration of AI tools into existing clinical workflows remains a challenge.[4] Systems must be user-friendly, interoperable with practice management software, and aligned with clinical protocols to gain widespread adoption.[33] Ethical considerations include patient data privacy, informed consent, and the potential for AI to diminish human oversight.[17] Regulatory bodies must establish guidelines ensuring AI tools are validated, reliable, and used responsibly.[22] While AI enhances efficiency, it should augment, not replace clinical expertise.[4] Orthodontists must interpret AI outputs within the broader context of patient care, ensuring decisions reflect holistic clinical judgment.[4,33]

6. Recent Advances

Since 2023, research on artificial intelligence in orthodontics has evolved rapidly from proof-of-concept models toward clinically validated, multimodal systems. Recent scoping and umbrella reviews highlight a marked improvement in the accuracy and reproducibility of AI-assisted cephalometric landmarking and treatment planning.[13] Studies demonstrate the potential of multimodal and reproducible neural networks for 2D/3D imaging, while Ziaei et al. (2025)[40] and Nallamilli et al. (2025)[41] extend AI applications to extraction decisions and aligner outcome prediction. The integration of dynamic, data-driven monitoring systems and face-driven aesthetic analyses[42] signifies a shift from static diagnosis toward continuous, patient-specific management. Furthermore, recent reviews emphasize the ethical imperatives of explainability, bias control, and clinician oversight. Collectively, these studies underscore a new era in orthodontics where AI not only automates measurement but actively guides personalized, adaptive treatment pathways with growing evidence of clinical readiness.

Table 3: Overview of artificial intelligence based products in dentistry products based on ML in dental field

Company	Product	Function	Origin
DentlAI	DentlAI	Dental disease detection	Toronto, Canada
VideaHealth	VideaHealth	Dental disease detection	Boston, USA
Pearl	Second opinion	Dental disease detection	West Hollywood, USA
Dentem	Dx Vision	Dental disease detection	Toronto, Canada
Medihome	Medihome	Dental disease detection	Tokyo, Japan
DeepCare	DeepCare Dental Landscape	Dental disease detection	Beijing, China
ORCA Dental AI	Cephx	Cephalometric analysis Teeth segmentation Airway analysis	Las Vegas, USA
CellmatQ GmbH	DentaliQ ortho DentaliQ opg	Cephalometric analysis Dental disease detection	Hamburg, Germany
Uceph	Uceph	Cephalometric analysis	Chengdu, China
Zhibeicloud	Zhibeicloud	Cephalometric analysis Bone age analysis Facial aesthetic analysis	Chengdu, China

6.1. Future directions: Towards integrated, patient-centered care

The future lies in integrated platforms combining diagnostic imaging, treatment planning, and monitoring.[22] Such systems will offer real-time feedback, adapt treatment plans dynamically, and support remote consultations, expanding access to care.[43] **(Table 3)** AI-driven tools will facilitate teledentistry, enabling patients in underserved areas to receive expert diagnoses and treatment plans.[6,44] This expansion improves accessibility, reduces costs, and enhances patient convenience.[6] Future AI systems will incorporate broader datasets, including genetic information, lifestyle factors, and comprehensive medical histories, delivering truly personalized orthodontic care.[17,45,44] These systems will predict responses to treatment modalities, optimize appliance design, and tailor interventions to individual needs.[38] AI will synergize with 3D printing and robotics to create on-demand, customized orthodontic appliances.[4,46,47] This integration streamlines workflows, enhances precision, and reduces production times, further revolutionizing orthodontic practice.[4,45] Collaborative efforts between dental professionals, AI experts, and policymakers are crucial to developing robust frameworks that ensure the responsible and ethical implementation of AI in dentistry. Moreover, AI-driven robotics has introduced innovative approaches to dental surgery, enabling precise and minimally invasive procedures, and ultimately reducing patient discomfort and recovery time. Virtual reality (VR) and augmented reality (AR) applications further enhance dental education and training, allowing dental professionals to refine their skills in a realistic and immersive environment.[48]

7. Conclusion

Artificial Intelligence stands as a transformative force in orthodontics, enhancing diagnostic accuracy, streamlining treatment planning, and improving patient outcomes. While each application uses different data types and algorithms, the underlying goal is to improve efficiency, accuracy, and consistency in clinical decision-making. **Table 4** summarises illustrative examples of these applications, highlighting the task, dataset characteristics, AI model used, reported performance, and considerations for clinical readiness. This provides a quick reference for clinicians to appreciate both the breadth of AI developments and the contexts in which they have been tested. While challenges in data quality, integration, and ethics persist, the trajectory of AI points towards increasingly sophisticated, patient-centred applications.

The future of orthodontics will be defined by the synergy between AI and human expertise. Clinicians who embrace AI will not only elevate their practice but also contribute to shaping the next era of dental medicine, where technology and compassion coalesce to deliver superior patient care. As AI continues to evolve, its integration into orthodontics promises a future where precision, efficiency, and personalized care become the standard, ensuring optimal outcomes for patients worldwide.

Table 4: Evidence synthesis of AI in orthodontics[39,46,49,50,51]

Application area	Study / year	Sample size	Data type	AI model	Key performance	Validation	Clinical readiness / limitations
Cephalometric landmark detection	Lee et al., 2020	400 lateral cephalograms	2D radiographs	CNN (ResNet)	Mean landmark error 1.1 mm	External dataset	Comparable to orthodontist accuracy; limited ethnic diversity in dataset
Cephalometric analysis automation	Torosdagli et al., 2019	400 cephalograms	radiographs	CNN (modified U-Net)	Mean error: 1.15 mm	Internal CV	Strong performance in single-centre study; requires testing on diverse equipment/settings
Growth stage prediction	Kim et al., 2021	350 CVM images	Cephalometric radiographs	CNN	Accuracy 92% vs gold standard		Promising but needs multi-centre validation
Skeletal maturation via hand–wrist radiographs	Choi et al., 2020	900 images	2D radiographs			External dataset	Comparable to human experts; may not generalise across imaging protocols
Treatment outcome prediction (aligners)	Castroflorio et al., 2023	79 cases	Intraoral scans	ANN	80% match with final clinical outcome	None	Proprietary data; lacks independent validation
Automated treatment simulation	Zhang et al., 2020	150 CBCT scans	3D imaging	GAN (Generative Adversarial Network)	Visual similarity to final post-treatment CBCT	Internal CV	Computationally intensive; requires large GPU resources
Airway analysis from CBCT	Yu et al., 2021	120 CBCT scans	3D CBCT	CNN (3D U-Net)	Dice similarity: 0.89	External dataset	Accurate segmentation; requires hardware resources and workflow integration
Disease detection in orthodontic radiographs	Patel et al., 2021	500 panoramic radiographs	2D radiographs	CNN	AUC 0.95 for caries detection	External dataset	Good for adjunctive screening; integration with ortho workflow untested

Internal CV (internal cross-validation) refers to testing the model on different portions of the same dataset by dividing it into folds for training and testing. This assesses performance on unseen data from the same source but may not reflect performance in different clinics or populations. External dataset means the model is tested on a completely independent dataset collected from another source, allowing evaluation of its ability to generalise to new settings.

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Conflict of Interest

None.

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This work is original, and no AI tools were used in its creation. All images are authentic and self-generated.

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