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Review Article

AI-Enabled Innovations in Orthodontics: Improving Treatment Precision and Clinical Results

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ABSTRACT

Artificial Intelligence (AI) is increasingly shaping modern orthodontics by enabling highly tailored treatment approaches that improve efficiency and accuracy. This review presents current applications of AI in the field, including predicting patterns of tooth movement, creating individualized aligners, shortening overall treatment timelines, and supporting remote patient monitoring. By leveraging extensive dental datasets such as 3D scans, radiographs, and clinical records, AI can generate treatment strategies specifically adapted to each patient, enhancing both clinical effectiveness and satisfaction. Devices guided by AI are designed to apply precise forces to teeth, reducing discomfort and therapy duration. Additionally, AI-enabled monitoring platforms allow patients to track progress remotely, lowering the need for frequent office visits and increasing accessibility to care. Emerging directions include the use of AI-integrated robotic systems for orthodontic procedures, predictive models for early interventions, and on-demand fabrication of appliances through 3D printing. Challenges such as safeguarding patient data, mitigating algorithmic bias, and managing the costs of AI implementation remain. Nonetheless, ongoing advancements in AI are expected to streamline orthodontic care, making treatments more precise, patient-centered, and efficient. This review highlights the transformative potential of AI in improving orthodontic outcomes.

Keywords: Artificial intelligence, Customized orthodontic treatment, Tooth movement prediction, Aligner design, Remote monitoring, Dental care

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Introduction

Orthodontics, a key discipline in dentistry, is dedicated to the identification, prevention, and correction of misaligned teeth and jaw structures [1, 2]. These malocclusions not only influence facial appearance but also affect essential oral functions, such as chewing, speech, and maintaining oral hygiene [3]. Traditionally, treatment planning has relied on the orthodontist's expertise, involving manual analysis of dental anatomy, interpretation of radiographs, and subjective predictions of tooth movement. While this approach has proven effective, it introduces variability in treatment outcomes, timing, and patient experience [4].

Conventional orthodontic methods, such as fixed braces or removable aligners, typically follow standardized treatment regimens applied across diverse patient populations. Because each patient's dental anatomy and physiological response differ, uniform treatment strategies can result in slower progress, extended durations, and occasionally less optimal results [5, 6]. Predicting how teeth respond to mechanical forces from orthodontic devices adds further uncertainty to traditional care [7].

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The emergence of Artificial Intelligence (AI) is transforming orthodontic treatment by enabling a personalized, data-driven approach. Machine learning (ML) and computer vision allow AI systems to process detailed patient data—including intraoral photographs, 3D scans, and X-ray images—at a level of precision beyond manual evaluation [8]. By leveraging extensive datasets from past orthodontic cases, AI models can forecast tooth movement, determine optimal force application, and develop individualized treatment plans [9].

This shift toward AI-assisted, patient-specific orthodontics has the potential to improve treatment efficiency and outcomes. Custom-designed braces and aligners, guided by AI, can apply targeted forces that minimize discomfort and reduce overall treatment time [10, 11]. Additionally, AI algorithms enable real-time progress tracking, allowing clinicians to detect deviations from the planned movement and adjust treatment accordingly [12, 13]. These predictive capabilities also provide patients with a clearer estimate of treatment duration, improving transparency and reducing uncertainty, which is often a limitation of traditional methods [14].

The rationale for integrating AI into orthodontic practice lies in overcoming the inefficiencies inherent in conventional treatment planning. Standardized approaches do not fully account for individual variability, leading to longer treatments, unpredictable results, and frequent adjustments—issues that increase both cost and inconvenience for patients [15]. By providing precise movement predictions, personalized device design, and continuous monitoring, AI offers a solution to these challenges. The objective of this review is to evaluate how AI can be effectively incorporated into orthodontic workflows to enhance both treatment efficiency and effectiveness, while outlining future directions for AI-driven innovations in patient-centered orthodontic care.

Artificial intelligence applications in orthodontics

AI is increasingly reshaping orthodontic practice by offering a level of accuracy and efficiency that traditional methods struggle to achieve. Leveraging technologies such as machine learning, deep neural networks, and computer vision, AI enables clinicians to develop treatment plans tailored to each patient's unique dental profile [7, 16]. These systems can examine extensive patient datasets—including 3D dental scans, radiographs, and detailed jaw models—to anticipate tooth movements and optimize treatment strategies [17]. Customized braces or aligners based on these predictions can reduce treatment duration, improve outcomes, and minimize complications [18].

Digital modeling through data collection

The foundation of AI-driven orthodontics lies in gathering comprehensive patient data to construct a precise digital model of the oral cavity. Using advanced 3D scanning, intraoral imaging, and X-ray technology, clinicians can capture detailed anatomical information about teeth and jaw structures [17]. This rich dataset allows AI algorithms to analyze tooth positions, spacing, and alignment in depth, providing insights that surpass conventional assessments [19]. Modern imaging tools even visualize the underlying bone and surrounding tissues, offering a thorough view of each patient's dental and skeletal characteristics [20, 21]. Such high-resolution data ensures that AI recommendations are closely aligned with the individual's anatomy, enhancing the accuracy and effectiveness of treatment planning.

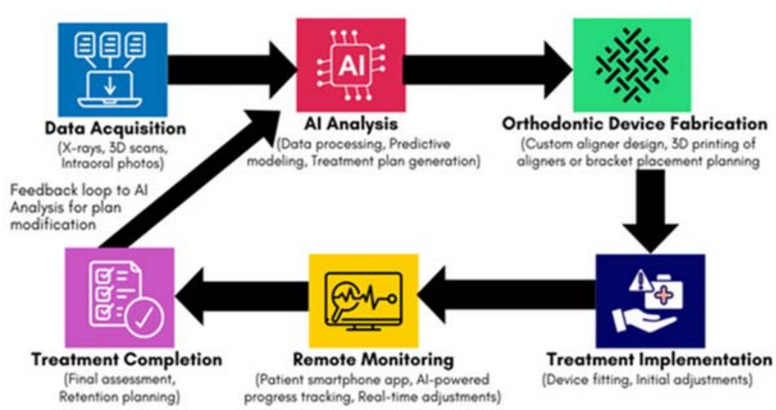

Figure 1. Conceptual workflow of AI-assisted orthodontics, illustrating the steps from digital data acquisition and AI analysis to appliance fabrication, treatment management, remote monitoring, and final outcomes.

Predicting tooth movement using AI

Once patient data are gathered, AI tools can estimate how teeth will shift in response to different orthodontic strategies. These systems rely on machine learning models trained on thousands of prior orthodontic cases, spanning diverse malocclusions and treatment methods. By leveraging deep neural networks, AI can interpret the biomechanical behavior of teeth under forces applied by braces, aligners, or other devices [22]. This includes determining which teeth may need additional pressure, predicting the pace of movement, and evaluating how specific teeth are likely to react to various interventions [12, 23]. Such predictive insights allow orthodontists to design treatments that are more efficient and precise, potentially shortening therapy duration and minimizing complications [18].

Modern AI approaches also incorporate dynamic simulations, allowing clinicians to visualize predicted tooth movements over the course of treatment. By simulating different scenarios, the system can identify the most effective strategy for each patient, reducing reliance on trial-and-error and improving both speed and accuracy of treatment outcomes [24].

Customizing treatment plans for individual patients

AI enhances orthodontic care by producing individualized treatment plans that consider a patient's unique dental and jaw anatomy. Instead of relying on generic protocols, AI systems process detailed patient data to outline optimal appliance designs, placement, and force application for braces or clear aligners [9, 25].

For clear aligner therapy, AI generates a sequence of aligners that deliver controlled forces at each stage, gradually repositioning teeth into the intended alignment [26]. This approach aims to complete treatment efficiently while maintaining patient comfort.

In traditional braces, AI supports precise placement of brackets and wires, guides the need for auxiliary tools like rubber bands or headgear, and helps determine adjustment frequency [10].

A significant advantage of AI is its adaptability: as treatment progresses, the system updates the plan in real time according to actual tooth movement. This ensures greater precision, reduces the need for mid-treatment adjustments, and can limit the number of follow-up visits required [27].

Continuous oversight and adaptive management of orthodontic treatment

One of the key advantages of artificial intelligence in orthodontics is its capacity to continuously monitor a patient's treatment progress. These systems can track the movement of teeth in real time and compare it with expected patterns derived from predictive models [28]. This continuous oversight allows clinicians to verify that treatment is following the planned trajectory and make adjustments proactively, before any complications develop [10, 29].

Patients can also actively contribute to this process. With the growth of tele-orthodontics and dedicated mobile applications, individuals can upload images of their teeth remotely. AI platforms evaluate these images, producing detailed progress reports and alerting both the patient and the orthodontist if the treatment deviates from expectations [30]. Such remote supervision is particularly beneficial for patients using clear aligners, who require fewer in-office appointments but still need close observation to ensure proper alignment [31].

The adaptive capabilities of AI also allow for timely modifications. If certain teeth are not shifting as intended, the system can recommend adjustments to aligner sequencing or bracket positioning, helping maintain the planned treatment timeline and preventing extended therapy or additional corrections. In some cases, AI can even forecast when the treatment is nearing its endpoint, suggesting an earlier removal of appliances to streamline the overall process and improve efficiency.

AI applications in orthodontic practice

In recent years, artificial intelligence has emerged as a transformative force in orthodontics, enabling highly personalized and efficient treatment strategies. By leveraging machine learning algorithms and computational models, AI can analyze individual patient data—including 3D scans, radiographs, and dental models—to forecast tooth movements, design custom appliances, optimize overall treatment duration, and monitor progress continuously in three dimensions [32–34]. These innovations enhance treatment effectiveness while simultaneously improving patient satisfaction.

Empirical studies demonstrate measurable improvements in multiple aspects of care. AI-based diagnostic systems provide higher precision in treatment planning than traditional approaches ($p < 0.05$) [35], with predictive models achieving roughly 73% accuracy for outcome forecasts, though they may encounter limitations with complex malocclusions [36]. A meta-analysis indicated that AI-assisted planning can reach a 95.47% overall accuracy [15]. Regarding treatment timelines, patients guided by AI-based planning completed therapy on average 4.3 months faster than those using conventional methods (mean ± SD: 14.6 ± 3.2 months vs. 18.9 ± 4.5 months, $p < 0.001$) [35]. Machine learning also refines the estimation of treatment duration, with a mean absolute error of 7.27 months [4].

Patient-reported satisfaction is consistently higher under AI-driven care (mean ± SD: 9.2 ± 0.6 vs. 8.1 ± 0.8, $p < 0.001$) [35], while lay evaluations of predicted outcomes are more favorable than professional assessments [37]. Additionally, AI reduces the number of required visits (10.2 ± 2.1 vs. 12.8 ± 3.4, $p < 0.001$) [35], and in predictive modeling, it outperformed traditional linear regression in 6 of 32 soft-tissue landmarks [38]. Post-treatment facial predictions are highly reliable, although estimates for lip-to-teeth relationships remain less precise [39]. Collectively, these findings underscore AI's pivotal role in advancing more accurate, efficient, and patient-focused orthodontic care.

Table 1 organizes patients by age and malocclusion type, demonstrating the diverse benefits of AI-assisted treatment. Applications range from early detection in pediatric patients to individualized aligner design for adults, and predictive surgical modeling for severe cases. While AI enhances treatment precision, duration, and monitoring, practitioners must account for individual variables such as craniofacial growth in children, adherence in teenagers, and periodontal health in older adults. This classification framework highlights the tailored and patient-centered approach made possible through AI in orthodontics.

Table 1. Personalized orthodontic treatment improvements enabled by AI across patient subgroups.

Patient Group	Typical Orthodontic Requirements	AI's Role in Treatment	Primary Advantages	Potential Challenges
Young Children (6–12 years)	Early correction of emerging bite issues, space retention devices, tracking jaw development.	AI supports early identification via predictive analytics, pinpoints jaw irregularities, and streamlines cephalometric evaluations.	Minimizes future extensive treatments, promotes healthy jaw growth, boosts treatment precision.	Needs ongoing observation; AI predictions must adjust for skeletal growth changes.
Adolescents (13–18 years)	Full orthodontic care (braces or aligners), addressing bite misalignments, ensuring treatment adherence.	AI enhances aligner/bracket positioning, forecasts treatment progression, and supports compliance via remote tracking tools.	Shortens treatment duration, improves adherence with AI reminders, enhances smile aesthetics and confidence.	Adherence varies among teens; AI remote monitoring relies on patient participation.
Adults (19–40 years)	Cosmetic-focused orthodontics, minor-to-moderate bite corrections, preference for clear aligners, fixing relapsed teeth.	AI tailors aligner designs for precise movements, reduces treatment duration, and integrates with virtual smile planning tools.	Offers less invasive options, improves efficiency, provides digital previews for informed patient choices.	AI must consider gum health and bone density differences in adults.
Older Adults (40+ years)	Orthodontics factoring in gum health, pre-restorative alignment, addressing jaw misalignments.	AI evaluates bone loss risks, customizes treatment plans, and monitors gum-related factors during planning.	Enables complex case management, prevents gum health deterioration, supports multi-disciplinary dental care.	AI accuracy depends on dental history, bone density variations, and other oral health conditions.
Severe Skeletal Misalignments	Major jaw discrepancies needing surgical intervention, severe overbites/underbites, or facial asymmetry corrections.	AI simulates treatment outcomes, predicts surgical-orthodontic requirements, and aids in digital surgical planning.	Enhances surgical accuracy, improves pre-treatment visualization, offers clear outcome previews for patients.	AI cannot substitute for surgical expertise; requires high-quality 3D imaging for accuracy.
Mild to Moderate Misalignments	Tooth crowding, gaps, or minor bite issues suitable for aligners or short-term braces.	AI optimizes aligner force systems, predicts shorter treatment times, and automates case suitability assessments.	Decreases treatment time, increases comfort, reduces refinement needs.	AI effectiveness depends on case complexity and patient compliance.
Post-Treatment Relapse Cases	Tooth shifting after prior treatment, requiring retainers or minor aligner corrections.	AI identifies subtle tooth movements, suggests retainer modifications, and optimizes minor corrective adjustments.	Prevents further tooth shifting, ensures long-term alignment stability, minimizes extensive re-treatment.	Demands precise post-treatment monitoring and consistent retainer use by patients.

Predicting tooth movement

A major advancement in orthodontics is the use of AI to forecast the movement of teeth with high precision.

Historically, clinicians estimated tooth responses to braces or aligners based on experience and biomechanical principles [40]. In contrast, AI utilizes extensive historical treatment records and computational models to simulate tooth trajectories over time, producing predictions that exceed conventional methods.

Training data for these AI systems include thousands of previous cases, covering diverse malocclusion types, individualized dental anatomies, and appliance variations. Such datasets allow AI to model not just the ultimate position of each tooth but also the duration of movements required to reach those positions [41]. Studies have shown that AI can accurately simulate forces applied via braces, clear aligners, or other devices, supporting more precise bracket placement and aligner design for optimal efficiency [42, 43].

Recent analyses indicate that AI-driven predictions are superior to traditional techniques in both accuracy and treatment planning speed. For instance, the AI component of Invisalign has demonstrated an overall prediction accuracy of 50%, with specific movements like buccal-lingual crown tipping reaching 56% accuracy [44]. Furthermore, AI-based planning has been shown to reduce treatment time by several months in complex cases by enabling targeted, real-time adjustments [45].

Custom aligner production

Clear aligners, particularly those in systems such as Invisalign, are popular due to their discreet appearance and convenience. However, their success is strongly dependent on precise design [26]. AI plays a critical role by analyzing 3D dental scans to produce aligners tailored to each patient's anatomy. This allows the application of calculated forces to each tooth, guiding accurate and predictable movements [17, 26, 46].

Unlike standard templates used in traditional aligners, AI-driven designs fully adapt to individual dental characteristics, improving treatment effectiveness and patient comfort [47]. The aligners exert continuous, gentle pressure, ensuring smooth, controlled tooth movement [48]. This approach reduces the need for mid-treatment modifications and supports more consistent progress across all stages of therapy.

AI technologies are transforming aligner production by increasing both precision and speed. Traditional aligner manufacturing often involves multiple manual steps and can take several weeks. In contrast, AI-enabled systems automate key stages of design and fabrication, allowing patients to receive customized aligners more quickly [46]. This faster production is particularly useful for incremental aligner therapies, ensuring patients obtain each successive set without delay, which helps maintain treatment continuity [31]. Research has shown that AI-generated aligners can reduce the total number of aligners required by roughly 20%, as fewer mid-treatment corrections are needed [40]. Furthermore, patients experience less discomfort because the AI designs aligners that fit closely to the natural contours of teeth and gums, enhancing comfort and effectiveness.

Reducing treatment duration

AI also significantly shortens the length of orthodontic treatment, which can typically span 18–24 months depending on case complexity [6]. By simulating tooth movement and adjusting force application, AI systems ensure that teeth shift efficiently in the intended direction [10, 15, 49]. When deviations from expected movement occur, AI can suggest treatment modifications to maintain progress, preventing stagnation or unnecessary delays [50]. Continuous updates based on real-time patient data allow orthodontists to dynamically refine treatment, helping patients finish therapy faster than traditional methods [11, 32].

AI can additionally evaluate hybrid strategies, such as combining braces with clear aligners, to identify the most time-efficient approach. For instance, severe misalignments may initially be addressed with braces, followed by aligners for precise adjustment. These simulations enable orthodontists to select evidence-based strategies tailored to the patient. Clinical studies confirm that AI can drastically improve workflow efficiency, with some reports noting up to an 80-fold reduction in analysis time compared to conventional manual planning [51-54].

Advanced patient oversight and adaptive adjustments

AI-enabled orthodontic platforms provide sophisticated monitoring, allowing practitioners to observe treatment progress continuously. This capability is particularly advantageous for individuals using clear aligners, as it ensures the devices are functioning correctly without frequent office appointments [49, 55]. Through AI-powered smartphone apps, patients can upload images of their teeth remotely. These images are processed by AI algorithms, which evaluate whether tooth movement aligns with the intended plan [56]. When deviations are detected, the system notifies the orthodontist, who can then recommend modifications or refine the treatment strategy. Remote monitoring is especially useful for patients living at a distance from the clinic or with tight schedules, reducing unnecessary in-person visits [31, 57].

Real-time progress tracking allows orthodontists to intervene proactively. For instance, if a tooth does not move as expected, AI can suggest adjustments to the aligner or bracket positioning, helping maintain the treatment timeline and preventing delays [40, 58]. This personalized approach enhances treatment efficiency and minimizes the likelihood of complications [49]. Research by Sosiawan *et al*. demonstrated that remote AI-based systems, such as Dental Monitoring, can significantly cut down the number of required office visits while maintaining successful outcomes [57]. Patients report high satisfaction with AI-assisted monitoring due to the convenience and accessibility of the system. Orthodontists also benefit from the timely insights, enabling quicker interventions that improve overall treatment effectiveness [10, 57].

3D modeling for treatment planning

AI-driven software allows orthodontists to generate detailed three-dimensional models of the teeth and jaw, which serve as a foundation for comprehensive treatment planning [59]. These 3D reconstructions give a complete representation of the patient's current dental anatomy and allow simulation of anticipated tooth movements over time [43]. By leveraging AI-based 3D models, practitioners can virtually simulate the entire treatment journey—from initial alignment to final positioning. These simulations help identify potential obstacles early, allowing adjustments to the plan before problems arise. Furthermore, visualizing the expected outcomes enhances communication with patients, providing clarity about the treatment process and setting realistic expectations [59].

AI-based 3D visualization platforms give patients a tangible preview of their orthodontic journey. By displaying a stepwise simulation of expected tooth movements, these systems enhance patient comprehension and encourage adherence to treatment. Evidence suggests that visualizing the projected outcomes increases compliance with the orthodontist's instructions [60]. One study reported that patients who reviewed AI-generated 3D treatment simulations prior to starting therapy expressed greater satisfaction and followed treatment guidelines more reliably [9, 59]. Another investigation found that access to these visual tools corresponded with fewer missed visits and more consistent aligner use [30].

Reliability and precision of AI-powered tracing systems

AI-assisted cephalometric tracing has streamlined landmark identification and measurement, reducing the time needed for orthodontic analysis. Utilizing deep learning algorithms, these systems automatically detect key anatomical points on radiographs, facilitating faster and more structured treatment planning [61]. Despite these advantages, challenges remain: AI tracing can occasionally mislabel landmarks, especially in cases with complex craniofacial anatomy, overlapping structures, or low-quality images, highlighting the need for expert oversight [10].

Manual vs. AI-based cephalometric tracing

Traditional cephalometric tracing, conducted manually by orthodontists, has historically been considered the standard method because it allows for nuanced interpretation of complex anatomical landmarks, accommodates individual variations, and integrates clinical judgment [49]. While this approach is labor-intensive, it remains highly dependable, particularly in cases involving image distortion, pathological features, or atypical skeletal structures, where automated detection may fail.

In contrast, AI-driven tracing systems offer considerable speed and automation, but they are not entirely free from limitations. Research indicates that AI tools can often replicate manual tracings within a 1–2 mm margin of error; however, certain points—such as the orbitale, condylion, and gonion—are more susceptible to misidentification [62]. Comparative studies report AI error rates ranging from 2% to 10%, influenced by the algorithm's sophistication and the training dataset. For well-defined landmarks, AI systems can reach 90–95% accuracy, yet performance declines when anatomical structures are partially hidden or display unusual variability [63].

Hybrid systems and manual refinements

Because AI tracing is not flawless, orthodontists often need to perform manual corrections to ensure clinical precision. Many contemporary AI platforms employ a hybrid workflow, where the software initially identifies landmarks, and the clinician subsequently reviews and fine-tunes the results [64]. This approach strikes a balance between efficiency and diagnostic reliability, preventing misidentified landmarks from compromising treatment planning. Furthermore, adaptive learning algorithms are enhancing AI performance by incorporating expert corrections into future predictions [65, 66]. Over time, these systems "learn" from human adjustments, steadily reducing errors and improving the accuracy of subsequent cephalometric analyses.

Advantages of AI-enhanced personalized orthodontics

Integrating artificial intelligence into orthodontic care introduces a range of benefits that improve both treatment effectiveness and the patient experience. AI enables highly individualized, precise, and efficient interventions that were difficult to achieve with traditional methods. **Figure 2** presents a summary of the primary advantages of AI-assisted orthodontic care and their key components.

The use of AI shortens treatment timelines by accelerating tooth movement while reducing the overall duration of therapy. Remote monitoring and instant feedback capabilities allow patients to track their progress without frequent office visits, promoting convenience and adherence. AI improves treatment precision by optimizing the application of forces and reliably predicting tooth displacement, leading to more accurate outcomes. These efficiencies also help lower costs by reducing the number of aligners needed, minimizing in-clinic adjustments, and streamlining overall treatment management. Patient engagement is enhanced through 3D visualizations of treatment progress and individualized reports that offer insights at every stage of therapy.

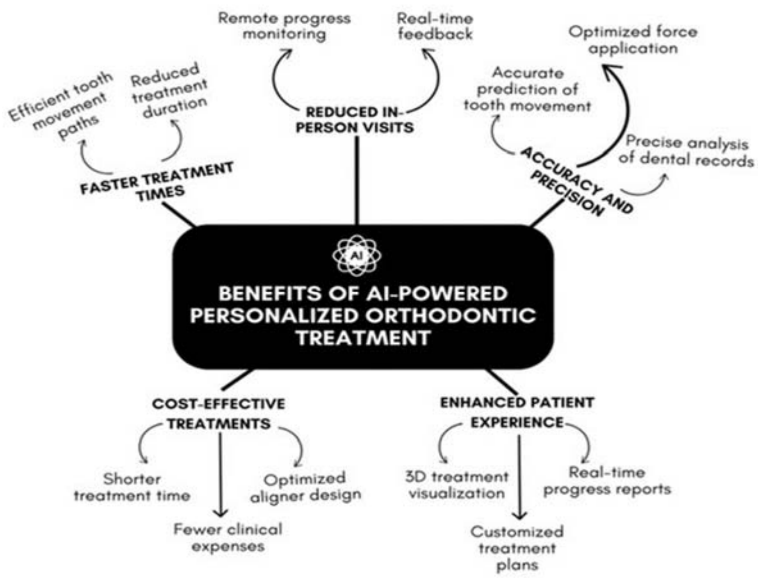

Figure 2. Summary of major benefits and key features of AI-driven personalized orthodontic treatment.

Table 2 details the use of AI across orthodontic procedures, specifying the machine learning models employed and their respective clinical roles. AI has modernized orthodontics in several areas, including cephalometric landmark identification via convolutional neural networks (CNNs), tooth movement forecasting with recurrent neural networks (RNNs), and the production of custom aligners using generative adversarial networks (GANs). Object detection frameworks like Faster R-CNN are applied to automate bracket placement. Collectively, these AI technologies improve treatment accuracy, efficiency, and patient-centered care.

Table 2. Machine learning approaches and their specific applications in AI-assisted orthodontic treatment.

AI Application in Orthodontics	Machine Learning Model	Role in Clinical Orthodontics	Benefits	Limitations
Cephalometric Landmark Identification [10, 61]	CNNs, Deep Learning	Automatically detects anatomical landmarks on cephalometric X-rays to guide diagnosis and treatment planning.	Speeds up tracing, improves measurement consistency, reduces variability between clinicians.	May incorrectly label landmarks in images with distortions or unusual anatomy; manual review is often needed.
3D Segmentation of Teeth and Jaw [65]	U-Net, R-CNN	Separates dental and jaw structures in CBCT, panoramic, and intraoral scans for precise modeling.	Produces detailed 3D models for better aligner and bracket placement; enhances treatment planning.	Accuracy depends on training data; unusual dental cases (e.g., extra teeth) can cause errors.
Tooth Movement Prediction [35]	RNNs, LSTM Networks	Estimates how teeth respond to orthodontic forces using patient-	Personalizes treatment, minimizes mid-	Biological variations may limit prediction accuracy;

		specific biomechanical information.	course corrections, optimizes applied forces.	ongoing clinical supervision is required.
AI-Based Treatment Plan Optimization [35, 61]	SVM, Gradient Boosting (XGBoost)	Generates patient-specific plans for braces and aligners.	Accelerates case review, allows evaluation of multiple treatment simulations quickly.	Orthodontist oversight is essential; may not fully consider patient preferences or lifestyle.
Customized Aligner Production [26, 46]	GANs, Reinforcement Learning	Designs patient-specific clear aligners using 3D scans to deliver precise forces.	Improves accuracy, reduces production time and costs, shortens overall treatment duration.	Requires 3D printing integration; errors in force calculation may require mid-treatment adjustments.
AI-Assisted Bracket Placement [55]	CNN Object Detection (YOLO, Faster R-CNN)	Suggests optimal bracket positioning for fixed appliances.	Improves placement consistency and precision; reduces human error.	Complex cases may need manual corrections; models need regular updates.
Early Detection of Caries and Periodontal Disease [10, 35]	Deep CNNs, Transfer Learning	Identifies early decay, bone loss, and periodontal disease from intraoral scans.	Enables earlier interventions, reducing complications and improving oral health.	Artifacts in images may cause false positives/negatives; requires clinician confirmation.
Remote Monitoring of Orthodontic Treatment [10, 35]	Vision Transformers (ViTs), Deep CNNs	Tracks patient progress using photos or videos submitted remotely.	Reduces in-office visits; improves adherence through real-time feedback.	Patient compliance and image quality are critical; poor submissions reduce accuracy.
AI-Enhanced 3D Printing for Orthodontics [26, 46]	Generative Design Algorithms, Evolutionary AI	Produces customized orthodontic appliances (aligners, retainers) using 3D printing.	Speeds production, allows tailored devices for each patient.	Requires clinical supervision; AI integration in design is still evolving.
Robotic Assistance in Orthodontics [67]	Reinforcement Learning, Motion Planning Algorithms	Supports robotic wire bending, bracket placement, and appliance customization.	Increases precision, reduces manual effort, ensures consistent treatment results.	High costs; robotics in orthodontics is still in early development stages.

AI-enabled tools are transforming orthodontic practice by improving diagnostic accuracy, streamlining workflow, and supporting ongoing patient monitoring, which reduces reliance on manual labor and decreases human error. Despite these benefits, limitations remain: AI depends heavily on high-quality training datasets, may produce errors in complex or atypical cases, and still requires orthodontist oversight to validate treatment recommendations. Integrating AI with technologies like 3D printing, robotics, and remote monitoring expands its capabilities, though hurdles such as cost, patient compliance, and variability in AI performance across different populations must be addressed.

This technical overview underscores that AI functions as an assistive resource rather than a replacement for clinical judgment. Through iterative improvements in algorithms and thoughtful integration into orthodontic workflows, AI can enhance treatment precision, efficiency, and accessibility while preserving the essential role of human expertise.

Accuracy and precision

A primary advantage of AI in orthodontics is its ability to achieve highly precise treatment planning. Traditional approaches rely largely on manual assessments and subjective interpretations, which can lead to inconsistent outcomes. AI, by contrast, leverages large-scale datasets—including dental records, X-rays, 3D scans, and previous treatment outcomes—to generate detailed, patient-specific dental models [34].

This predictive capability allows orthodontists to anticipate tooth movement with high accuracy. By running simulations of various treatment scenarios, AI can optimize the forces applied to teeth, ensuring movement is controlled and effective. This results in more predictable outcomes, fewer complications, and reduced need for mid-course adjustments. Evidence suggests that AI-based predictions markedly reduce errors compared with conventional manual assessments, increasing the likelihood of achieving the intended treatment objectives [10].

For instance, studies comparing traditional plaster models with AI-assisted virtual 3D models found that AI not only improved accuracy but also shortened the time required for measurements by more than 60% relative to manual methods [68].

Shortened treatment duration

Artificial intelligence can notably reduce the overall timeframe of orthodontic care by determining the most efficient sequence of tooth movements. By analyzing individualized dental data and applying complex biomechanical models, AI ensures that each tooth is guided with the correct force and direction, avoiding unnecessary shifts that could lengthen therapy [11, 69]. Conventional approaches with braces or clear aligners often span 18–24 months or longer [70]. AI-driven planning, however, tailors the treatment pathway to each patient's unique dental anatomy, enabling quicker progression and improved comfort [29]. Studies indicate that AI-assisted treatment can shorten total duration by as much as 26%, helping patients reach their desired results faster while eliminating redundant movements [69].

Reduced in-office appointments

Another key advantage of AI in orthodontics is the reduced dependence on frequent clinic visits. Traditionally, patients must attend regular check-ups to evaluate progress and adjust appliances. With AI-supported monitoring, real-time evaluation of treatment progress is possible [57]. Patients can submit images or scans from home using smartphone applications, which the AI analyzes to detect deviations from the planned trajectory [56]. When discrepancies are identified, the system notifies the orthodontist, who can remotely advise on necessary modifications, minimizing the need for physical appointments. This approach is especially useful for patients in remote locations or those with limited access to care, making orthodontic treatment more convenient and accessible. By decreasing the frequency of visits, AI-assisted care conserves both patient and practitioner time [57].

Cost-effective care

AI-based personalized orthodontics can also lower treatment costs for patients and providers. Shortened treatment timelines reduce the total number of aligners or braces needed, as well as the frequency of adjustments [71-73]. AI optimizes the design and production of custom aligners, reducing material waste and labor requirements [26, 74]. Additionally, fewer in-office visits translate into lower clinical expenses. As AI technology continues to mature, it has the potential to make personalized, high-quality orthodontic care more affordable and widely available.

Elevating the patient experience

Artificial intelligence has the potential to transform the patient journey in orthodontics by making care more personalized and comfortable. Treatments powered by AI create braces or aligners specifically adapted to each patient's dental anatomy, which reduces discomfort and improves fit during the treatment period. By optimizing tooth movements and shortening overall treatment duration, AI contributes to a smoother and more satisfying experience [75].

Patients also benefit from AI's real-time feedback capabilities. Progress updates and interactive reports allow individuals to track their treatment closely, enhancing understanding, engagement, and trust in the process. Remote monitoring adds convenience, especially for those who cannot attend frequent in-office appointments [10, 57]. Moreover, AI-generated 3D visualizations provide a preview of expected outcomes, helping patients set realistic expectations and motivating adherence to aligner or brace schedules [76].

Tools, technologies, and workflow integration

Implementing AI in orthodontics relies on a combination of advanced imaging tools, specialized software, and structured workflows. The first step involves gathering detailed patient data through high-resolution imaging methods such as Cone Beam Computed Tomography (CBCT), intraoral scans, and digital X-rays. These data provide precise anatomical information, which AI algorithms analyze to identify malocclusions, jaw discrepancies, and tooth angulations with greater accuracy than traditional assessments [61].

Once data collection is complete, orthodontists employ AI-based planning platforms—including ClinCheck (Invisalign), Dental Monitoring, OrthoAnalyzer, and 3 Shape Ortho System—to simulate tooth movements across multiple treatment scenarios. These simulations allow practitioners to select the most efficient approach tailored to each patient [35]. AI optimizes the sequence of aligners by predicting tooth shifts at each stage, minimizing mid-treatment refinements. When combined with 3D printing, AI enables the rapid in-house fabrication of custom aligners, retainers, and other orthodontic appliances, significantly reducing production time while improving patient convenience [77].

During orthodontic therapy, AI-enabled monitoring tools allow clinicians to track treatment progression in real time while minimizing the need for routine office visits. Systems like Dental Monitoring and Grin Remote Monitoring utilize smartphone-based intraoral scans to continuously assess tooth movement. Patients upload images via mobile applications, which are processed by AI to identify any deviations from the expected alignment trajectory [31]. When discrepancies are detected, the platform notifies the orthodontist, who can adjust the treatment remotely without requiring the patient to attend additional appointments. Emerging AI-integrated robotic systems are also being developed for tasks such as precise bracket placement and wire shaping, which reduce manual errors and improve overall treatment efficiency [61].

For practitioners implementing AI-assisted workflows, interoperability with existing digital tools and electronic health records (EHRs) is critical. AI software must function seamlessly with established orthodontic platforms such as Dolphin Imaging, OrthoCAD, and SureSmile, enabling effective data exchange and workflow optimization [61, 78]. Cloud-based AI solutions further allow orthodontists to access patient treatment plans remotely, collaborate with colleagues, and maintain detailed documentation. Although these technologies require upfront investment in digital infrastructure, the long-term improvements in precision, workflow efficiency, and patient convenience make them highly valuable in modern orthodontic practice.

By adopting these AI-driven approaches, orthodontists can transition from conventional methods to fully optimized digital workflows, improving predictability while reducing treatment duration and patient discomfort. The integration of AI in orthodontics is therefore a paradigm shift, enhancing decision-making, streamlining clinical operations, and supporting more individualized patient care [79].

Orthodontist's role in AI-supported treatment

The rise of AI in orthodontics is intended to assist rather than replace professional expertise. While AI tools can facilitate diagnostics, simulate treatment plans, and monitor progress remotely, the clinician's judgment remains indispensable, particularly for complex cases. Considerations such as facial aesthetics, patient-specific preferences, and individualized biomechanics cannot be fully captured by AI alone. Orthodontists must evaluate and, when necessary, modify AI-generated treatment plans to ensure clinical accuracy and patient-specific customization. Emphasizing the supportive role of AI prevents the misconception that it functions independently; instead, AI serves as a complementary tool, enhancing efficiency while preserving the clinician's central role in delivering high-quality orthodontic care [49].

AI as an assistive tool: learning and time considerations

AI improves efficiency in treatment planning but does not replace the clinician's expertise [61]. Instead, it changes how orthodontists interact with patient data, requiring a period of adjustment to fully utilize AI systems. Traditional orthodontic planning often demands multiple hours or appointments, due to manual review of imaging, diagnosis, and iterative adjustments. AI systems can accelerate this by quickly processing scans and producing predictive treatment models, potentially halving the time required for the initial plan. Nevertheless, orthodontists must still verify AI outputs, interpret the results, and modify the plan as necessary. Therefore, while repetitive tasks are reduced, human oversight remains essential to ensure treatments are individualized. Balancing automation with professional judgment is critical for maintaining efficiency without compromising quality [15].

Influence on patient trust, engagement, and personalized care

The introduction of AI into orthodontic care brings considerations regarding patient confidence and the personal clinician–patient relationship [10]. Automated planning and remote monitoring can reduce in-office visits, but direct interactions remain vital for establishing trust and ensuring patients feel heard. Patients may be hesitant to rely solely on AI recommendations, concerned that personal nuances or complex cases may not be fully addressed. AI should be positioned as a support tool rather than a replacement, complementing the clinician's expertise. Overreliance on AI could weaken clinical judgment, as practitioners might depend too heavily on system outputs. To maintain patient engagement, orthodontists should clearly explain AI's role, supervise treatment decisions, and continue regular face-to-face appointments, ensuring care remains both personalized and trustworthy [15].

Future prospects of AI in orthodontics

AI technology is poised to bring transformative changes to orthodontics, offering opportunities to enhance treatment precision, efficiency, and accessibility. These innovations promise benefits for both patients and orthodontic practitioners. **Figure 3** summarizes the key future directions for AI in orthodontics, including AI-guided robotics, predictive modeling, real-time 3D printing, and tele-orthodontic integration, along with their principal features [80-86].

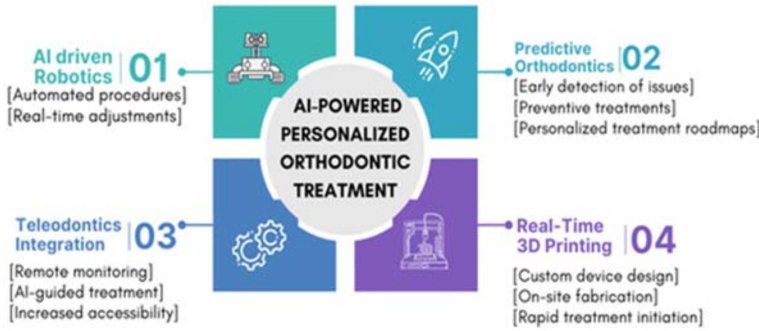

Figure 3. Anticipated developments in AI-driven orthodontics.

Robotics guided by AI in orthodontic care

One of the most promising areas is combining AI with robotic systems to perform orthodontic procedures with higher accuracy. While robotics is already used in dentistry for operations like implant placement, integrating AI can enable automated execution of tasks such as bracket positioning, archwire shaping, or taking dental impressions with minimal human error [87]. AI-equipped robots can adjust their actions in real time based on patient-specific feedback, allowing for more consistent and precise treatment outcomes [88]. This approach could shorten treatment times, standardize procedures across patients, and make advanced orthodontic care more widely available by reducing dependence on manual skill.

AI in predictive orthodontics

Advances in AI are making it increasingly possible to anticipate orthodontic needs earlier in life. By examining childhood dental records, 3D imaging, genetic data, and other health information, AI could detect potential misalignments or malocclusions before they become pronounced [17]. Early identification allows for preventive interventions during growth stages, potentially decreasing or even avoiding the need for extensive treatments like braces or aligners in the future. In this predictive approach, AI can offer orthodontists a detailed roadmap for guiding dental and jaw development, enabling subtle, non-invasive adjustments that prevent more serious issues later on. This proactive strategy not only enhances long-term oral health but also reduces overall treatment costs and duration [1, 34].

Real-time 3D printing of orthodontic appliances

AI's integration with 3D printing represents another transformative potential in orthodontics. Currently, producing custom braces and aligners requires significant time due to design and manufacturing steps. AI could accelerate this by rapidly processing patient-specific data and generating individualized designs ready for 3D printing, either in-clinic or even remotely [11, 26]. For instance, a patient could have a 3D scan during an initial visit, and within minutes, an AI system could create a treatment plan and produce the first set of custom aligners or braces. This approach would minimize delays between consultation and treatment start, improve patient convenience, and allow for more frequent adjustments as treatment progresses, with AI generating updated devices in real time [11, 46].

AI integration with tele-orthodontics

Tele-orthodontics is expanding rapidly, and combining it with AI technologies could make orthodontic services far more accessible. Currently, AI-powered remote monitoring systems allow patients to upload dental images and receive guidance from orthodontists without attending in-person appointments [89]. Looking ahead, AI could enable a largely home-based orthodontic experience, where the treatment process is guided automatically, and human oversight is only needed for complex cases [90]. Orthodontists could oversee multiple patients simultaneously from a single location, providing consultations, tracking progress, and making plan adjustments remotely. This model would be particularly advantageous for patients in regions with limited access to orthodontic care due to geographic or economic constraints [57, 91]. By reducing routine clinic visits, tele-orthodontics also minimizes travel and improves convenience for patients, while lessening the operational load on clinics [92]. Future AI developments may allow seamless coordination between remote and in-office care, creating a hybrid system that maximizes both efficiency and patient convenience.

Ethical considerations, data privacy, and AI limitations in orthodontics

The adoption of AI in orthodontics offers notable improvements in precision, workflow efficiency, and individualized treatment. Nonetheless, its implementation raises ethical and privacy concerns, as well as technical limitations that require attention. Key challenges include potential biases in training datasets, algorithmic inaccuracies, overdependence on AI-generated outputs, and safeguarding sensitive patient information [93, 94]. Careful oversight and responsible integration are essential to ensure that AI serves as a beneficial adjunct to human clinical expertise rather than introducing new risks.

Ethical aspects of AI in orthodontics

Orthodontic AI systems rely heavily on extensive patient information, including 3D dental images, X-rays, intraoral photographs, and medical records. Handling this volume of sensitive data introduces significant privacy and security risks [95]. Among the primary concerns are unauthorized access or data breaches that could compromise patient confidentiality [96]. Since AI requires large datasets for training and continuous improvement, developers must enforce strong data protection protocols.

Adherence to global data protection laws, such as HIPAA in the U.S. and GDPR in Europe, is crucial [97]. These regulations mandate secure storage, encryption, and controlled access to patient records. Additionally, anonymization methods can remove personal identifiers from datasets before they are used in AI training, safeguarding confidentiality.

Data ownership represents another important ethical consideration. When AI developers collect patient datasets, questions arise about who holds the rights to the data and how it is managed. Patients and orthodontic professionals need clarity regarding whether their data is stored locally, in the cloud, or shared with third parties [98]. Ethical AI deployment demands transparent data governance, offering patients the choice to share or withhold their data, and ensuring its use is confined to improving clinical care rather than commercial exploitation.

Data privacy and security in AI-orthodontics

AI systems in orthodontics depend heavily on extensive patient information, such as 3D dental scans, X-rays, intraoral photos, and medical records. Managing this data presents significant security and privacy challenges. One key concern is the risk of unauthorized access, which could expose sensitive personal information. Because AI algorithms require large datasets for learning and improvement, providers must implement strict safeguards to protect patient confidentiality.

Compliance with international privacy regulations is essential. In the United States, systems must follow HIPAA guidelines, while in Europe, GDPR rules apply [97]. These frameworks require data to be encrypted, securely stored, and only accessible by authorized personnel. Furthermore, anonymization techniques can remove identifiable information before data is used for AI model training, ensuring patients' privacy is preserved.

Data ownership also raises important ethical questions. When AI platforms collect and process patient datasets, clarity is needed regarding who holds rights to the data and how it may be utilized. Patients and clinicians must know whether data is stored locally, on cloud servers, or shared with third parties [98]. To implement AI responsibly, clear governance and opt-in/opt-out options must be provided, guaranteeing that patient information is used exclusively to enhance clinical care rather than for commercial purposes.

Limitations and challenges of AI in orthodontics

Although AI offers significant advantages in orthodontics, several limitations must be acknowledged. A primary challenge lies in potential inaccuracies during automated diagnoses, which largely depend on the quality and scope of the AI's training data [93]. If the dataset lacks representation of certain dental conditions, the AI may misidentify or overlook rare malocclusions, leading to inappropriate or suboptimal treatment suggestions. This underscores the importance of regularly updating AI systems with comprehensive, high-quality datasets to improve diagnostic reliability.

AI performance can also vary across different patient groups. Models trained on existing datasets may not generalize well for all ages, ethnicities, or unique dental anatomies. Research indicates that AI-based imaging tools occasionally demonstrate reduced accuracy for underrepresented populations [99]. Ensuring diverse and inclusive training data is therefore essential for consistent performance across all patient demographics.

Another risk is over-reliance on AI without professional oversight. Treatment plans generated by AI should always be reviewed by an orthodontist to verify their clinical feasibility. Relying solely on AI recommendations without expert evaluation could compromise care, especially if the system does not fully account for biomechanical nuances or patient-specific factors [100]. AI should be regarded as an aid, providing guidance that orthodontists refine using their professional judgment.

Cost is an additional barrier to adoption. Implementing AI technologies, including sophisticated imaging, treatment planning software, and cloud-based AI services, often requires significant investment [79]. Smaller practices may find these costs restrictive. For broader adoption, AI tools need to become more affordable, with scalable pricing options that allow clinics of all sizes to integrate AI into their workflows without excessive financial burden.

Conclusion

The adoption of AI for individualized orthodontic planning signifies a transformative step in modern dental care, bringing greater accuracy, speed, and personalization to treatment. Leveraging AI's advanced predictive modeling, orthodontists can design plans that are specifically adapted to each patient's dental characteristics, improving treatment results while reducing the total duration. AI tools enable precise forecasting of tooth movements, fine-tuning of aligner and brace designs, and continuous monitoring, which together streamline the treatment process and minimize inefficiencies.

Nonetheless, implementing AI comes with challenges. Issues such as protecting patient data, mitigating potential biases in algorithms, and ensuring widespread access across practices must be addressed to use these technologies responsibly. As AI continues to evolve and integrates with complementary systems like robotic assistance and real-time 3D printing, orthodontic care is poised to become more patient-centered, cost-effective, and widely available. The ongoing refinement of AI in this field has the potential to reshape how treatments are delivered globally, improving overall dental health outcomes and enhancing the patient experience.

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