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Original Article

AI-Enabled Breakthroughs in Orthodontic Care for Precision and Improved Clinical Results

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ABSTRACT

Artificial Intelligence (AI) is rapidly reshaping orthodontic practice by delivering customized treatment strategies that enhance both precision and workflow efficiency. This narrative review examines how AI is currently applied in orthodontics, emphasizing its contributions to predicting dental movement, developing patient-specific aligners, shortening treatment duration, and supporting real-time progress tracking. By processing extensive datasets composed of dental images, radiographs, and 3D digital models, AI systems generate individualized treatment solutions that improve therapeutic accuracy and patient outcomes. Intelligent aligner and bracket systems designed with AI assistance apply optimized mechanical forces, leading to faster and more comfortable treatments. Moreover, AI-based telemonitoring platforms allow patients to oversee their progress remotely, reducing in-office visits and increasing accessibility to orthodontic care. Future perspectives discussed in this review include integrating AI with robotic systems for procedural automation, utilizing predictive orthodontics for early diagnosis and intervention, and employing 3D printing for on-demand device fabrication. Despite its promise, AI adoption faces obstacles such as data protection issues, algorithmic bias, and high implementation costs. Nonetheless, continued advancements in AI are expected to further streamline orthodontic workflows, promoting treatments that are more patient-focused, efficient, and clinically effective. This review highlights AI's transformative influence on contemporary orthodontics and its potential to redefine the future of dental care.

Keywords: Artificial intelligence, Customized orthodontics, Tooth movement prediction, Aligner design, Remote supervision, Digital dentistry

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Introduction

Orthodontics, a specialized field within dentistry, is dedicated to identifying, preventing, and correcting irregularities in tooth alignment and jaw positioning [1, 2]. Such abnormalities, often described as malocclusions, not only impact facial appearance but also interfere with oral function, including mastication, speech, and hygiene maintenance [3]. Traditionally, orthodontic treatment planning has relied heavily on manual assessment by clinicians, who interpret diagnostic records, radiographs, and models to estimate tooth movement. Although effective, this conventional approach can produce variable outcomes and inconsistent treatment durations depending on clinical expertise [4].

Historically, orthodontic appliances such as braces and aligners have followed standardized treatment protocols applied across diverse patient populations. The drawback of this uniform method lies in biological variability—each individual's dental anatomy and tissue response differ—often leading to slower tooth movement, prolonged treatment times, and less predictable results [5, 6]. Additionally, accurately forecasting how teeth will respond to mechanical forces from orthodontic devices remains a complex challenge within traditional care models [7].

The advent of Artificial Intelligence (AI) in orthodontics is revolutionizing this landscape by introducing a more data-driven, personalized approach to treatment planning. Machine learning (ML) and computer vision–based AI tools can interpret patient-specific datasets—such as intraoral images, 3D scans, and radiographs—with precision that surpasses human capacity [8]. Through extensive training on large clinical datasets, AI algorithms can model tooth movement, determine optimal force application, and design individualized orthodontic strategies for each patient [9].

This transition toward AI-enabled personalization represents a major milestone in orthodontic innovation. Intelligent design platforms can generate patient-specific aligners and braces, incorporating unique anatomical and biomechanical variables. Consequently, treatments become more efficient, shorter, and require fewer manual adjustments [10, 11]. Moreover, AI enhances transparency by predicting treatment duration and outcomes, providing patients with greater clarity throughout their orthodontic journey. Remote monitoring tools driven by AI [12, 13] enable continuous supervision of progress using image-based analytics, ensuring that deviations from expected movement are detected early and corrective actions can be taken promptly [14].

The motivation for evaluating AI's role in orthodontic treatment planning stems from the need to improve both accuracy and operational efficiency. Conventional methods, although proven, depend heavily on subjective interpretation and standardized protocols that fail to accommodate individual variability. These limitations contribute to unpredictable results, extended treatment time, and higher overall costs [15].

This review addresses the constraints of traditional orthodontic approaches and explores how AI can overcome them by providing real-time, data-informed, patient-specific care. The objective is to assess the integration of AI into orthodontic practice, identify its clinical benefits and limitations, and propose pathways for future development in intelligent, personalized dental treatment.

AI in Orthodontic Treatment

Artificial intelligence (AI) is transforming orthodontic practice by introducing levels of accuracy and efficiency that surpass conventional approaches. Through the integration of machine learning (ML), neural network architectures, and computer vision, AI supports clinicians in formulating data-driven and highly individualized treatment strategies [7, 16]. These intelligent systems process extensive patient datasets—such as 3D digital impressions, radiographic images, and detailed jaw models—to forecast how teeth will react to various treatment modalities [17]. Consequently, orthodontists can fabricate patient-specific braces or aligners that yield faster, more predictable, and complication-free results [18].

Data collection: Building a comprehensive digital model

The foundation of AI-assisted orthodontic therapy lies in the precise acquisition of patient data used to construct a detailed digital representation of the dental anatomy. Advanced imaging tools such as 3D scanners, intraoral cameras, and radiographs capture the complete configuration of teeth and supporting bone structures [17]. These data inputs provide the essential framework for AI algorithms, enabling an in-depth evaluation of tooth positioning, alignment, and spacing patterns [19]. With recent innovations in imaging—particularly in high-resolution 3D scanning—orthodontists can now obtain datasets of exceptional accuracy and detail [20]. Moreover, AI-integrated imaging technologies can visualize subsurface bone contours and soft-tissue relationships, delivering a holistic understanding of a patient's oral environment [21]. This level of precision strengthens the accuracy of AI-generated simulations and recommendations, ensuring treatment is customized to each individual's dental morphology.

Figure 1 presents the standard AI-assisted orthodontic workflow, encompassing the processes of data acquisition, computational analysis, appliance manufacturing, clinical application, remote supervision, and final treatment completion.

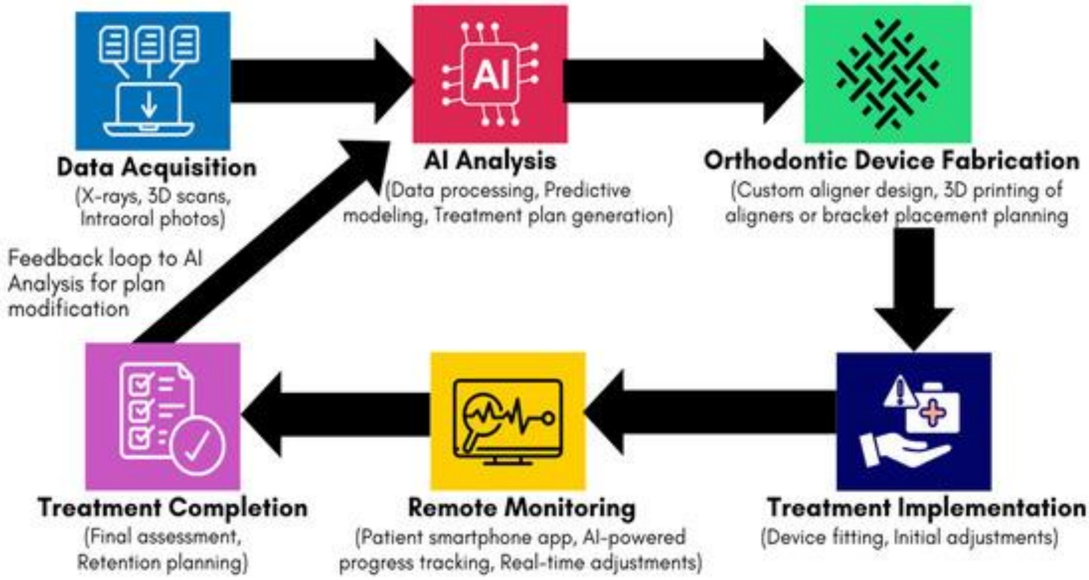

Figure 1. Conceptual diagram depicting the AI-supported orthodontic workflow, illustrating the sequential integration of data collection, AI processing, device creation, clinical execution, monitoring, and treatment conclusion

AI-Based prediction: Modeling tooth displacement dynamics

After data collection, AI algorithms are deployed to simulate and predict how teeth will move in response to distinct treatment protocols. Machine learning frameworks are trained using extensive orthodontic datasets that include thousands of clinical records featuring varied malocclusion types and intervention methods. Deep learning neural networks analyze these datasets to understand tooth displacement patterns over time under the influence of orthodontic forces such as braces, aligners, and auxiliary devices [22]. AI demonstrates exceptional capacity for modeling the biomechanics of tooth motion—specifically, the distribution and magnitude of force required for targeted movement.

For instance, predictive models can estimate tooth movement velocity, identify areas that demand greater mechanical input, and anticipate how specific teeth will respond to orthodontic appliances [12, 23]. This predictive functionality allows clinicians to design optimized, efficient treatment strategies that reduce overall duration and minimize errors [18].

Recent developments include the application of dynamic simulations, which enable clinicians to visualize progressive tooth movement across the entire treatment period. By testing multiple simulated treatment pathways, AI systems can determine the most effective and time-efficient approach for each patient, significantly decreasing reliance on trial-and-error and enhancing clinical precision [24].

Personalized treatment planning: Individualized therapeutic design

AI-driven orthodontic care redefines personalization by generating tailored treatment plans derived from the patient's anatomical and biomechanical data. Rather than adhering to standardized treatment templates, AI systems synthesize individual datasets to construct customized plans detailing appliance configuration, placement strategies, and optimized force application for devices such as braces or clear aligners [9, 25].

In the context of clear aligner therapy (e.g., Invisalign), AI platforms create a sequential series of aligners calibrated for each phase of tooth movement. These aligners apply targeted forces at precisely calculated intervals, guiding teeth incrementally toward their ideal alignment [26]. The objective is to achieve the intended tooth position in the shortest possible duration while maintaining patient comfort and minimizing the likelihood of complications.

For conventional braces

In the context of traditional orthodontic appliances, AI assists clinicians in determining the optimal positioning of brackets and archwires to ensure appropriate force distribution on each tooth. Additionally, AI algorithms can estimate the ideal timing for adjustments and identify when auxiliary components—such as elastics or headgear—are required, ultimately streamlining treatment and improving patient comfort [10]. The adaptability of AI-driven orthodontics extends well beyond the initial phase of care. These systems operate dynamically, continuously updating treatment strategies in response to real-time tooth movement. This ongoing adaptability enhances precision, reducing the need for mid-course corrections or frequent clinical visits [27].

Continuous monitoring and adjustment: Real-time progress tracking

Among the most impactful contributions of AI to orthodontics is its capacity for continuous assessment of treatment progress. Using advanced data comparison methods, AI systems monitor how teeth are shifting and contrast the observed movements with predicted trajectories [28]. This enables orthodontists to verify that the treatment remains on schedule and make necessary refinements before deviations become problematic [10, 29].

Patients are also increasingly integrated into this monitoring process. Through tele-orthodontic solutions and mobile applications, individuals can upload photos of their teeth from home. AI-based software analyzes these images, providing automated progress evaluations and alerting both patient and clinician if movement patterns deviate from expectations [30]. This form of remote supervision is particularly advantageous for clear aligner users, who may not require frequent in-person appointments but still need consistent oversight to maintain treatment accuracy [31].

AI-powered monitoring supports timely clinical decisions. For instance, if a tooth fails to progress as predicted, the system may recommend modifications to aligner geometry or bracket configuration to realign progress. This proactive approach minimizes treatment delays and prevents the need for extensive later corrections. In certain cases, AI platforms can even forecast when treatment completion is near and suggest early appliance removal, enhancing both efficiency and patient satisfaction.

Applications in Orthodontic Care

The integration of AI into orthodontics has expanded rapidly, offering sophisticated computational tools that enhance personalized treatment planning. By leveraging complex algorithms and machine learning (ML) models, AI facilitates more precise tooth movement prediction, customized appliance design, optimized treatment durations, real-time progress evaluation, and advanced 3D visualization—all contributing to improved efficiency and superior clinical outcomes [32-34].

Numerous studies highlight AI's measurable benefits in diagnostic precision, treatment speed, patient experience, appointment frequency, and predictive modeling performance. AI-assisted diagnostic methods demonstrate significantly higher accuracy in clinical planning than traditional techniques ($p < 0.05$) [35]. Predictive AI models for orthodontic outcomes achieved 73% accuracy, although performance remains limited in highly complex cases [36]. A meta-analysis reported an overall treatment planning accuracy of 95.47% using AI systems [15].

In terms of efficiency, AI-guided planning shortened treatment duration by an average of 4.3 months compared with conventional methods (mean ± SD: 14.6 ± 3.2 months vs. 18.9 ± 4.5 months, $p < 0.001$) [35]. Furthermore, ML models produced more accurate duration estimates, achieving a mean absolute error of 7.27 months [4]. Patient satisfaction was also significantly higher under AI-assisted care (mean ± SD: 9.2 ± 0.6 vs. 8.1 ± 0.8, $p < 0.001$) [35]. Another investigation found that laypersons rated AI-predicted post-treatment results more favorably, while orthodontists tended to evaluate them more critically [37].

AI integration has also reduced clinical workload. Studies indicate a marked decrease in the average number of orthodontic appointments (10.2 ± 2.1 vs. 12.8 ± 3.4, $p < 0.001$) [35]. Regarding predictive capacity, AI models surpassed traditional linear regression in 6 of 32 evaluated soft-tissue landmarks when forecasting orthodontic results [38]. Additionally, AI demonstrated strong predictive accuracy for post-treatment facial modifications, though estimations involving lip–tooth relationships showed slightly reduced reliability [39].

Collectively, these results underscore AI's expanding influence in orthodontic optimization—enhancing treatment precision, efficiency, and patient-centered care.

Table 1 categorizes patients according to age and malocclusion type, illustrating the distinct advantages AI-powered orthodontics provides across demographics. Its applications range from early anomaly detection in pediatric patients to AI-assisted aligner fabrication for adults and surgical outcome prediction in severe cases. While AI enhances accuracy, monitoring, and overall workflow, certain factors—such as craniofacial growth in younger patients, compliance challenges in adolescents, and periodontal considerations in older individuals—must still be factored into clinical decision-making. This framework supports a more systematic and individualized approach to integrating AI within orthodontic treatment.

Table 1. Summary of AI-enabled personalized orthodontic treatment benefits across various patient groups

Demographic Group	Typical Orthodontic Requirements	AI Contributions to Care	Primary Advantages	Potential Obstacles
Young Children (6–12 years) [36, 40]	Early correction of emerging bite issues, space maintainers, tracking developmental patterns	AI supports early identification via predictive analytics, detects jaw misalignments, and streamlines cephalometric evaluations	Minimizes future complex treatments, promotes optimal facial development, boosts care efficiency	Demands ongoing observation; AI forecasts must consider evolving skeletal structures
Adolescents (13–18 years) [10, 40]	Full orthodontic interventions (braces, aligners), bite correction, adherence monitoring	AI refines bracket/aligner positioning, forecasts treatment progression, and enhances remote adherence tracking	Shortens treatment duration, improves compliance with AI-driven notifications, enhances aesthetics and self-esteem	Adherence varies among teens; AI remote monitoring relies on patient participation
Adults (19–40 years) [37, 41]	Aesthetics-driven orthodontics, mild-to-moderate bite issues, clear aligners, relapse correction	AI tailors aligners for precise tooth adjustments, accelerates treatment, integrates with virtual smile planning	Offers less invasive options, increases efficiency, provides digital previews for informed patient choices	AI must address gum health and bone density variations in adults
Older Adults (40+ years) [42, 43]	Orthodontics with gum health considerations, pre-restorative alignment, jaw positioning issues	AI evaluates bone loss, proposes adaptive care plans, and monitors gum-related risks during planning	Improves feasibility in complex cases, prevents gum health deterioration, supports multidisciplinary treatment	AI accuracy depends on dental history, bone density fluctuations, and concurrent oral conditions
Severe Skeletal Misalignment Cases [36, 44]	Major skeletal issues needing surgical intervention, severe overbites/underbites, facial asymmetry	AI simulations project treatment results, predict surgical-orthodontic requirements, and aid in digital surgical planning	Enhances surgical accuracy, improves pre-treatment preparation, offers visual outcome previews for patients	AI cannot substitute surgical expertise; precision relies on high-quality 3D imaging integration
Mild to Moderate Misalignment Cases [40, 45]	Crowding, spacing, minor bite corrections suitable for aligners or short-term braces	AI-optimized aligner designs enhance force distribution, predict shorter treatment timelines, and automate case suitability	Reduces treatment time, improves patient comfort, minimizes adjustment needs	AI effectiveness varies with misalignment complexity and patient adherence
Relapse Cases [10, 46]	Post-treatment tooth movement, retainer needs, minor corrective aligner treatments	AI identifies subtle tooth shifts, suggests retainer modifications, and optimizes minor corrective adjustments	Prevents further misalignment, ensures long-term stability, reduces extensive re-treatment needs	Requires precise post-treatment monitoring and consistent retainer use by patients

Prediction of tooth movement

A fundamental use of artificial intelligence (AI) in orthodontics lies in its capability to forecast tooth displacement with remarkable precision. In conventional orthodontic care, anticipating how teeth respond to braces or aligners largely depends on clinical experience and an understanding of applied biomechanical forces [41]. In contrast, AI utilizes extensive treatment databases and advanced computational biomechanical modeling to simulate and predict dental movements over time.

By training on large, diverse datasets encompassing various malocclusion patterns, individual dental anatomies, and different orthodontic appliances, AI algorithms can build highly refined movement models. These systems can estimate both the eventual tooth positions and the expected progression timeline [47]. Research confirms that AI-guided biomechanics can replicate the effects of varying force applications from braces, clear aligners, and other corrective devices. This accuracy allows practitioners to determine the optimal bracket configuration or aligner design required to reach desired outcomes in a shorter period [48, 49].

Recent evidence indicates that AI-based predictive systems exceed conventional approaches in both precision and computational speed. For instance, one investigation reported that Invisalign's AI-powered prediction platform achieved an average tooth movement accuracy of 50%, with specific actions—such as buccal-lingual crown tipping—reaching 56% [50]. Another study revealed that AI-assisted forecasts could shorten treatment timelines by several months in complex cases by enabling more targeted and timely clinical adjustments [51].

Custom aligner fabrication

Clear aligners, exemplified by systems such as Invisalign, have grown increasingly popular due to their discretion and user comfort. Their therapeutic success, however, depends heavily on the accuracy of their design [26]. AI technologies play a crucial role in producing aligners uniquely adapted to each patient's dental profile. Using 3D digital scans of the dentition and jaw, AI algorithms compute aligners that deliver precise, controlled forces to guide tooth movement [17, 26, 52].

Unlike conventional aligners created from standardized templates, AI-derived aligners are fully individualized, aligning with each patient's dental morphology to maximize both comfort and treatment efficiency [53]. These aligners maintain continuous, gentle pressure, ensuring balanced force distribution and predictable movement throughout the treatment course [54].

In addition to improving design precision, AI significantly accelerates the fabrication process. Traditional aligner production can span several weeks and requires multiple manual steps. In contrast, AI-based manufacturing automates much of this workflow, reducing turnaround time and expediting delivery to patients [52]. This acceleration benefits those undergoing staged aligner therapies, as subsequent sets can be provided sooner to maintain treatment continuity [31]. One study documented a 20% reduction in the number of aligners required per case due to fewer mid-treatment corrections [41]. Moreover, patients experienced less discomfort, as AI-generated aligners offered a closer anatomical fit to the teeth and gingival contours.

Optimization of treatment time

A key advantage of AI integration in orthodontics is its ability to minimize overall treatment duration. Traditional orthodontic interventions often extend between 18 and 24 months or longer, depending on case complexity [6]. AI reduces this timeline by refining each treatment phase to operate at peak efficiency [10, 15, 42]. AI-driven systems model and optimize the mechanical forces applied by orthodontic appliances, ensuring that teeth shift along the intended trajectories without unnecessary delays. When discrepancies arise—such as when teeth fail to move as forecasted—the algorithms can recommend modifications to sustain steady progress [55]. Through continuous real-time evaluation and plan adjustment, AI prevents stagnation in tooth movement and supports faster case completion than manual treatment approaches [11, 32].

Furthermore, AI can assess whether hybrid treatment strategies—such as initiating therapy with fixed braces and transitioning to aligners for fine-tuning—offer better time efficiency. By simulating multiple intervention paths, AI empowers orthodontists to identify the most expedient and evidence-based approach for each case. Clinical data reinforce these time-saving capabilities [56-58]; one study demonstrated that AI improved orthodontic workflow efficiency dramatically, reducing analysis time by nearly 80-fold compared to traditional manual assessment methods [59].

Enhanced patient monitoring and adjustments

Artificial intelligence (AI)-integrated orthodontic systems have greatly improved patient monitoring by enabling practitioners to oversee treatment progress in real time. This capability is especially advantageous for patients using clear aligners, as it allows orthodontists to verify treatment effectiveness without requiring frequent office appointments [42, 60]. Through AI-supported mobile applications, patients can regularly upload photos of their teeth from home, which are automatically analyzed by machine learning models to determine whether tooth movements align with the planned progression [61]. When discrepancies between predicted and actual movement patterns are detected, the AI system alerts the orthodontist, who can then modify the treatment strategy accordingly. Such remote monitoring is particularly beneficial for individuals living far from clinics or managing demanding schedules, as it minimizes unnecessary in-person consultations [31, 62].

Because AI tracks progress continuously, orthodontists can make timely adjustments to ensure treatment accuracy and efficiency. For example, if a tooth's movement deviates from expectations, the system may recommend refining the aligner design or altering bracket positions, thereby preventing treatment delays and maintaining consistent progress [41, 63]. This adaptability enhances both precision and patient outcomes [42]. A study by Sosiawan *et al.* demonstrated that AI-based remote platforms, such as

Dental Monitoring, substantially reduced the number of required in-office visits without compromising treatment success [62]. Patients reported high satisfaction with AI-assisted systems, emphasizing convenience and accessibility, while orthodontists appreciated the ability to intervene earlier, improving overall clinical results [10, 62].

3D visualization for treatment planning

AI-driven visualization software enables orthodontists to construct detailed three-dimensional (3D) digital models of the patient's dentition and jaw, forming the foundation of modern treatment planning [64]. These 3D simulations provide a complete view of the patient's oral anatomy and predict how the teeth are expected to shift over time [49]. By utilizing AI-generated models, clinicians can simulate the entire treatment course—from the initial configuration to the final result—allowing for early identification of potential obstacles and proactive modification of treatment plans. Furthermore, the ability to visualize projected outcomes enhances communication between orthodontist and patient, making the treatment process more transparent and comprehensible [64].

AI-based 3D visualization tools also enrich patient engagement by offering an interactive view of their anticipated treatment progression. Patients can observe how their teeth are expected to move step by step, which increases motivation and adherence. Research indicates that individuals who are shown 3D treatment projections are more likely to comply with instructions and follow their orthodontist's guidance [65]. One study found that patients presented with AI-generated 3D visualizations prior to treatment reported greater satisfaction and cooperation levels [9, 64]. Another investigation revealed that these patients had fewer missed appointments and higher commitment to aligner wear schedules [30].

Accuracy and reliability of AI-Assisted tracing systems in orthodontics

AI-enabled automatic tracing systems have markedly improved the efficiency of cephalometric analysis by reducing the time required for identifying and measuring anatomical landmarks. Utilizing deep learning-based image recognition, these tools can automatically detect skeletal points on radiographs, expediting both diagnosis and treatment planning [40]. However, concerns remain regarding their precision, as AI tracing tools may occasionally misidentify landmarks—especially in complex cases with overlapping anatomy, irregular structures, or low-quality images [10].

Comparison of manual tracing vs. AI-Assisted tracing

Manual cephalometric tracing, traditionally performed by experienced orthodontists, has long been regarded as the gold standard due to its ability to accommodate anatomical variation and account for image distortions or skeletal asymmetries [42]. Although it requires more time, manual tracing maintains exceptional reliability, particularly in cases involving pathology or radiographic distortion.

Conversely, AI-assisted tracing delivers automation and speed but comes with certain limitations. Studies indicate that AI tools can reach accuracy levels within 1–2 mm of manual tracings; however, landmarks such as the *orbitale*, *condylion*, and *gonion* are still more prone to errors [66]. Comparative research between AI and manual approaches has reported error margins ranging from 2% to 10%**,** influenced by algorithmic robustness and dataset diversity. Some investigations suggest that AI can achieve 90–95% accuracy for distinct landmarks, though reliability decreases when dealing with obscured or anatomically atypical regions [67].

Need for manual corrections and hybrid approaches

Given these limitations, AI tracing outputs often require orthodontic review and refinement to maintain diagnostic validity. Many contemporary AI tools now employ hybrid workflows—where initial landmark detection is automated, followed by orthodontist verification—to balance efficiency with precision [68]. This collaborative approach mitigates misidentification risks and preserves the integrity of diagnostic measurements. Additionally, advances in adaptive learning systems are progressively enhancing AI accuracy. Through continuous feedback from expert corrections, AI models are able to learn iteratively and improve their future predictions, thereby reducing errors in landmark detection over time [69, 70].

Benefits of AI-Powered Personalized Orthodontic Treatment

The integration of artificial intelligence (AI) into orthodontic workflows has introduced substantial improvements in both clinical precision and patient satisfaction. These advantages arise from AI's capacity to deliver data-driven, adaptive, and individualized treatment strategies. **Figure 2** summarizes the key benefits and corresponding aspects of AI-assisted personalized orthodontic therapy.

By leveraging predictive algorithms, AI enhances overall treatment efficiency through accelerated tooth movement and reduced treatment duration. Remote progress tracking and automated feedback mechanisms further minimize the need for frequent in-person consultations. The precision of AI-guided care stems from optimized force calibration and accurate modeling of tooth movement, ensuring consistency and reproducibility in outcomes. Moreover, these advancements contribute to cost-effectiveness by shortening treatment timelines, refining aligner fabrication, and decreasing procedural expenses. Patient engagement is also improved through 3D visualization tools and dynamic progress updates, which support customized treatment experiences.

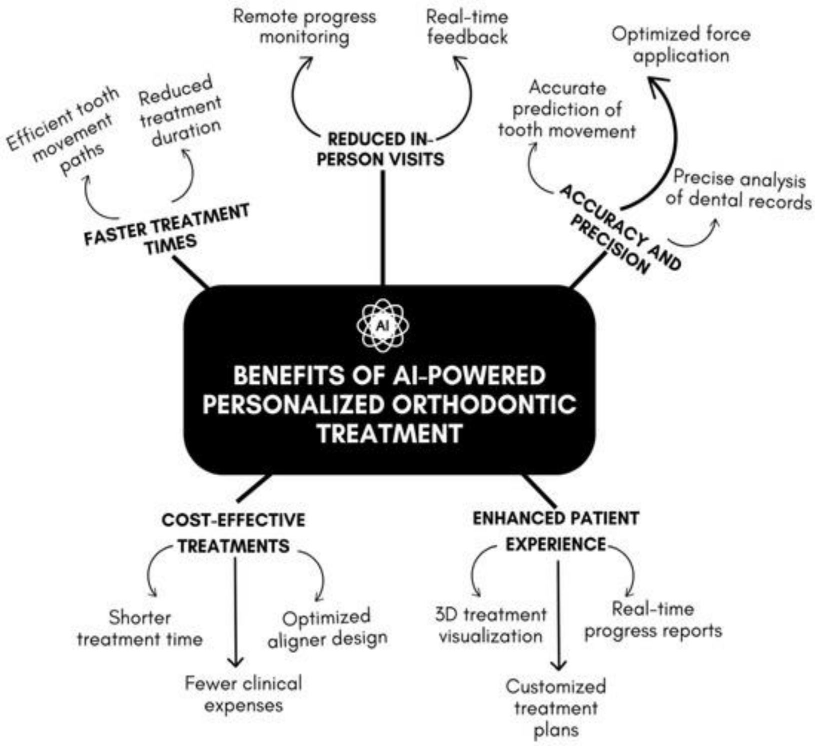

Figure 2. Overview of the benefits of AI-powered personalized orthodontic treatment

Table 2 provides a detailed summary of AI's clinical applications, linking specific machine learning models to their roles in orthodontic care. Within the field, convolutional neural networks (CNNs) are used for automated cephalometric landmark detection, recurrent neural networks (RNNs) assist in predicting tooth movement, and generative adversarial networks (GANs) facilitate the creation of personalized aligners. In addition, object detection algorithms such as Faster R-CNN enhance the precision of automated bracket placement.

Table 2. Machine learning models and their applications in AI-driven orthodontic treatment

AI Implementation in Orthodontics	Algorithm Type Employed	Purpose and Application in Orthodontics	Key Benefits	Potential Constraints
Craniofacial Landmark Identification [10, 40]	Neural Networks with Convolution (CNNs), Advanced Deep Learning Models	Streamlines detection of anatomical points on cephalometric radiographs, supporting diagnostics and treatment design	Cuts down on manual outlining time, boosts precision, reduces variability among operators	May misread landmarks in low-quality images or with anatomical anomalies, needing orthodontist correction
3D Tooth and Bone Delineation [69]	U-Net Architecture, Region-Focused CNN (R-CNN)	Facilitates segmentation of teeth and jaw structures in CBCT, intraoral scans, and panoramic images	Delivers accurate 3D models for diagnostics and treatment planning, optimizes aligner/bracket placement	Relies on high-quality training data; complex cases like extra teeth can challenge accuracy
Tooth Movement Forecasting [35]	Sequential Neural Networks (RNNs), Long Short-Term	Predicts tooth displacement under orthodontic forces	Supports tailored treatment strategies, minimizes mid-treatment	May not fully capture biological variations in tooth movement,

	Memory (LSTM) Systems	using patient-specific biomechanical data	adjustments, enhances force distribution	requiring clinical verification
Automated Treatment Design [35, 40]	Support Vector Models (SVM), Gradient Boosting Systems (e.g., XGBoost)	Optimizes treatment strategies for braces and aligners based on individual patient profiles	Speeds up case evaluation, enables rapid review of multiple treatment scenarios	Needs orthodontist review; may overlook patient lifestyle or preferences
Precision Aligner Production [26, 52]	Generative Adversarial Systems (GANs), Reinforcement Learning Frameworks	Designs clear aligners with precision using 3D scans, ensuring effective force application	Enhances aligner staging accuracy, lowers production costs, shortens treatment duration	Requires 3D printing integration; errors in force calculations may necessitate adjustments
Bracket Placement Optimization [60]	CNN-Based Detection Models (YOLO, Faster R-CNN)	Recommends ideal bracket positions for fixed appliances, streamlining treatment processes	Improves placement consistency, reduces manual errors	Complex cases may need manual tweaks; models require ongoing refinement
Caries and Gum Disease Detection [10, 35]	Deep Convolutional Networks, Transfer Learning Frameworks	Identifies early caries, periodontal issues, and bone loss in scans and radiographs	Promotes early treatment, reduces complications, enhances oral health outcomes	May misinterpret imaging artifacts; human validation needed for false positives/negatives
Remote Treatment Monitoring [10, 35]	Vision Transformer Models (ViTs), Deep CNN Frameworks	Analyzes patient-provided images/videos to monitor treatment progress remotely	Decreases office visits, boosts adherence with real-time tracking	Accuracy hinges on image quality and patient compliance with imaging protocols
3D Printing Customization [26, 52]	Generative Design Systems, Evolutionary Algorithms	Customizes orthodontic devices like aligners, retainers, and splints via 3D printing	Speeds up device fabrication, enables tailored solutions	Integration with AI design is developing; requires orthodontist oversight
Robotic Orthodontic Applications [71]	Reinforcement Learning Systems, Motion Planning Frameworks	Supports robotic systems for wire shaping, bracket positioning, and device customization	Enhances precision, reduces manual labor, ensures procedural consistency	High setup costs; robotic applications remain in early development stages

These AI-based innovations improve diagnostic reliability, operational efficiency, and patient oversight while minimizing human error and streamlining clinical workflows. Nonetheless, certain challenges persist, including dependence on robust training datasets, occasional inaccuracies in complex cases, and the continued necessity of orthodontist supervision in AI-generated plans. As AI increasingly integrates with technologies such as robotics, remote monitoring, and 3D printing, its capabilities continue to expand. However, obstacles such as high implementation costs, patient compliance variability, and inconsistent model performance across populations remain to be addressed.

This structured comparison highlights AI's supportive role as an augmentation tool rather than a substitute for clinical expertise. Continued refinement of algorithmic frameworks and seamless integration into orthodontic procedures will enable greater precision, efficiency, and accessibility—while preserving the orthodontist's critical role in clinical judgment and decision-making.

Accuracy and precision

A key advantage of AI in orthodontics lies in its exceptional ability to enhance the accuracy and precision of treatment planning. Conventional orthodontic assessment relies heavily on manual analysis and clinical interpretation, often introducing variability between practitioners. In contrast, AI systems can process vast collections of dental records, radiographs, and 3D scans to construct highly detailed virtual models of each patient's dentition [34].

By accurately predicting the trajectory of tooth movement, AI enables a truly personalized approach to treatment. Machine learning algorithms simulate different force applications to identify the most effective and controlled movement patterns, leading to fewer mid-course modifications and more reliable outcomes. Empirical data indicate that AI-assisted predictions significantly reduce error margins compared with manual evaluations, producing a higher rate of successful treatment completion [10].

A comparative study further confirmed that AI-based 3D modeling systems deliver superior accuracy and efficiency relative to traditional plaster model analysis. Results demonstrated that AI-assisted scanning improved precision and reduced measurement time by more than **60%**, underscoring the technology's value in enhancing diagnostic and procedural workflows [72].

Faster treatment times

AI also contributes significantly to shortening the duration of orthodontic treatments by optimizing tooth movement pathways. Through analysis of individualized anatomical data and application of advanced biomechanical modeling, AI systems determine the most efficient vectors of motion for each tooth. This ensures that forces are distributed appropriately and movements occur without unnecessary deviations or delays [11, 73].

Traditional orthodontic interventions, such as braces or clear aligners, typically require 18 to 24 months or longer to complete [74]. However, AI-enhanced systems can substantially reduce this timeframe by tailoring strategies to the patient's specific dental structure and response patterns. These optimizations not only expedite results but also improve treatment comfort and predictability [29].

Clinical findings suggest that AI-supported orthodontic planning can decrease overall treatment time by up to 26%, primarily by eliminating redundant or inefficient movement phases [73]. Consequently, patients experience quicker, more comfortable treatments while orthodontists benefit from improved workflow efficiency and more consistent outcomes.

Reduced number of In-Person visits

A key advantage of incorporating artificial intelligence into orthodontic care is the substantial reduction in required in-office appointments. Traditionally, patients undergoing orthodontic treatment must attend frequent follow-up sessions for progress evaluation and appliance adjustments. With the advent of AI-driven systems, however, remote monitoring technologies enable patients to oversee their own progress from home [62]. Using smartphone-based applications or other digital tools, individuals can upload periodic photos or intraoral scans, which AI software then analyzes to verify treatment alignment with projected outcomes. When deviations or concerns are detected, the system notifies the orthodontist, who can make recommendations or modify the plan without an in-person consultation [61]. This capability is especially beneficial for patients in geographically isolated or underserved communities, where travel to clinics may be challenging. Consequently, AI-assisted orthodontic treatments markedly decrease the frequency of physical appointments, conserving both time and financial resources for patients and providers alike [62].

Cost-Effective treatments

AI-based personalized orthodontic systems also contribute to greater cost efficiency for both clinics and patients. One of the principal economic advantages stems from reduced overall treatment time, which lowers the number of required aligners or adjustments. By automating various aspects of diagnosis and planning, AI streamlines the treatment process and minimizes resource utilization. Moreover, AI-supported customization of aligners optimizes their fabrication, cutting down on the number of revisions typically needed during therapy. This improvement translates to reduced material consumption and labor input, thereby lowering production costs and making aligner treatments more financially accessible [26, 75]. Additionally, fewer on-site visits equate to lower clinical expenses and increased practice efficiency. As AI continues to mature, its role in providing high-quality, individualized orthodontic care at a lower cost will expand, improving affordability and accessibility for a wider patient population.

Enhanced patient experience

The integration of AI into orthodontic care profoundly elevates patient comfort and satisfaction. Because treatment plans are generated using individualized anatomical data, aligners and braces can be tailored precisely to a patient's dentition, resulting in better fit, reduced irritation, and greater comfort throughout the process. Optimized tooth movement guided by AI shortens overall treatment duration and improves procedural efficiency, contributing to higher satisfaction levels [76]. Additionally, AI platforms deliver real-time updates and progress tracking, keeping patients informed about ongoing results and anticipated outcomes. This transparency fosters engagement and trust, as individuals gain clear insight into their progress.

Remote monitoring capabilities further enhance convenience—particularly for patients with demanding schedules—by reducing the need for frequent clinical appointments [10, 62]. Furthermore, AI-generated 3D simulations allow patients to visualize the expected end results before treatment begins, helping set realistic expectations and motivating adherence to prescribed regimens [77]. Such visualization tools not only reinforce compliance but also strengthen patient confidence and participation in their care.

Technologies, tools, and workflow

Implementing AI in orthodontic practice relies on the integration of digital imaging systems, specialized analytical software, and structured data workflows. For clinicians seeking to incorporate AI into daily operations, a systematic approach that combines AI-driven diagnostics, treatment modeling, and real-time monitoring is essential [44]. The process begins with data acquisition, utilizing advanced imaging technologies such as Cone Beam Computed Tomography (CBCT), intraoral scanning, and digital radiography. These modalities generate precise anatomical information that AI algorithms use to perform highly accurate diagnostic assessments and develop customized treatment strategies. AI-powered image analysis can detect malocclusions, assess tooth inclinations, and identify skeletal discrepancies with a degree of precision surpassing manual evaluation [40].

Following image capture, orthodontists employ AI-supported planning software—such as ClinCheck (Align Technology, Invisalign), Dental Monitoring, OrthoAnalyzer, and 3Shape Ortho System—to construct predictive models of tooth movement [35]. These platforms simulate numerous treatment scenarios, allowing clinicians to choose the most efficient sequence tailored to the patient's needs. AI also refines aligner progression by forecasting tooth displacement patterns, reducing the number of mid-course adjustments required. Additionally, the combined use of AI and 3D printing facilitates in-house fabrication of aligners, retainers, and appliances, significantly accelerating production and improving convenience for patients [78].

During the active treatment phase, AI-enabled monitoring tools ensure consistent and accurate progress evaluation with minimal physical checkups. Systems such as Dental Monitoring and Grin Remote Monitoring employ smartphone-based intraoral scanning, allowing patients to upload images that AI software reviews for deviations from predicted movements [31]. When discrepancies occur, the orthodontist is automatically notified to revise the treatment plan remotely.

Emerging AI-integrated robotic orthodontics also offers potential for precise bracket placement and automated wire bending, reducing manual variability and improving efficiency [40]. For seamless adoption, interoperability between AI applications and existing Electronic Health Records (EHRs) is essential. Compatibility with established orthodontic software—including Dolphin Imaging, OrthoCAD, and SureSmile—enables smooth data exchange and workflow optimization [40, 79].

Cloud-based AI platforms further enhance collaboration by allowing practitioners to access cases remotely, share insights with peers, and maintain comprehensive documentation. Although implementing AI-based orthodontics requires initial investment in digital infrastructure, the long-term benefits—such as higher diagnostic accuracy, greater efficiency, and improved patient satisfaction—make it a transformative development in the field.

Through the integration of these technologies, orthodontic professionals can transition from traditional methodologies to fully AI-optimized systems, achieving superior predictability, shorter treatment durations, and enhanced patient comfort. The adoption of AI marks not merely an incremental advancement but a fundamental shift in modern orthodontic care, redefining clinical precision, workflow efficiency, and the overall personalization of treatment [80].

The Role of the Orthodontist in AI-Driven Treatment and Its Impact on Clinical Practice

The rising implementation of artificial intelligence in orthodontics does not diminish the importance of professional expertise; rather, it enhances clinical precision and supports more efficient decision-making. AI-based platforms can assist in diagnosis, automate aspects of treatment design, and facilitate remote progress evaluation. Nevertheless, the orthodontist's judgment remains indispensable—particularly in complex or atypical cases where experience, intuition, and an understanding of facial balance, patient preferences, and biomechanical nuances are essential. These human factors cannot be entirely replicated by algorithms. Orthodontists must critically assess AI-generated recommendations to verify their clinical feasibility, accuracy, and suitability for individual patients. Maintaining this oversight ensures that AI remains a complementary tool rather than an independent operator in the clinical process. Thus, in everyday practice, AI should be regarded as a supportive system that improves workflow efficiency while preserving the orthodontist's central role in patient care [42].

AI as a tool, not a replacement: The learning curve and time considerations

While AI simplifies and accelerates treatment planning, it does not eliminate the need for orthodontic interpretation and expertise. Instead, it transforms the practitioner's interaction with diagnostic data, requiring new technical competencies and adaptation to AI-integrated workflows [40]. In traditional orthodontics, developing a treatment plan often demands several hours or multiple consultations, as clinicians manually assess radiographs, models, and diagnostic records. In contrast, AI-driven software can rapidly process scans and produce predictive treatment simulations, potentially reducing the initial planning phase by nearly half. Even so, orthodontists must review these outputs, interpret algorithmic predictions, and adjust treatment details to meet clinical standards. This introduces a different kind of time investment—focused on verification rather than manual computation. Although AI automates repetitive and data-heavy tasks, it cannot substitute for professional reasoning or patient-specific customization. Achieving an effective balance between automation and human oversight will be crucial to maintaining time efficiency without compromising the precision or quality of patient care [15].

The impact of AI on patient trust, engagement, and personalized care

The integration of AI into orthodontic care raises important considerations regarding patient trust and the preservation of personalized treatment. While remote monitoring and automated analysis can reduce the need for frequent visits, the interpersonal relationship between the orthodontist and patient remains vital to successful outcomes. Many patients still place high value on direct human interaction, particularly when discussing concerns or verifying treatment progress. Overreliance on AI-generated assessments may create apprehension about reduced personal attention or algorithmic errors that a human clinician would otherwise identify [10].

To maintain patient confidence, AI must function as a supportive aid rather than a replacement for human expertise. Excessive dependence on automated systems could also diminish clinical intuition, as practitioners might become less attuned to subtle diagnostic cues. To counteract this, orthodontists should continue fostering transparent communication, clarifying AI's supportive role, and maintaining direct oversight of treatment decisions. Consistent personal engagement and regular follow-ups reinforce trust, adherence, and satisfaction, ensuring that technology enhances rather than disrupts the human dimension of orthodontic care [15].

Future prospects of AI in orthodontics

As artificial intelligence continues to advance, its role in orthodontics is expected to expand dramatically, paving the way for greater precision, efficiency, and accessibility in clinical practice. These technological innovations promise to redefine both patient experience and professional workflows, enabling orthodontists to deliver more individualized and predictive care. **Figure 3** highlights the key domains of future progress in AI-driven orthodontics, encompassing robotic automation, predictive modeling, real-time 3D printing, and integration with tele-orthodontic platforms—each contributing to a more interconnected and adaptive treatment ecosystem.

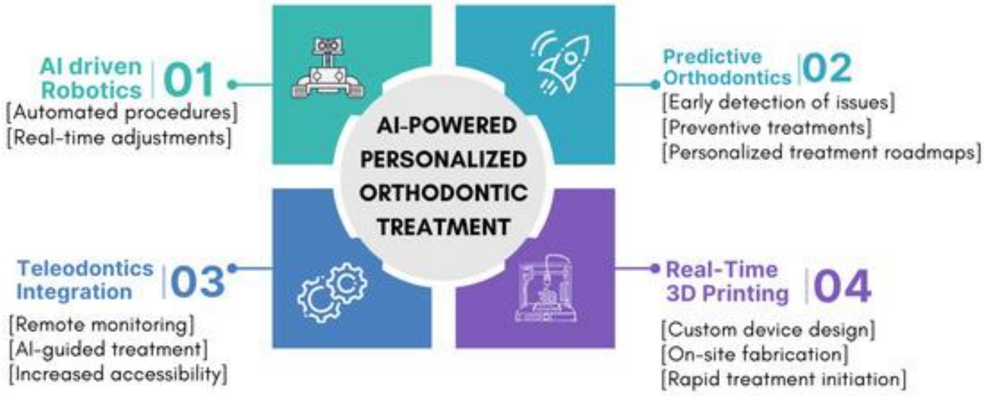

Figure 3. Future prospects of AI in orthodontics

AI-Driven robotics in orthodontic procedures

A major forthcoming innovation in orthodontics lies in merging artificial intelligence with robotic technologies. While robotics has already transformed areas such as dental implantology, its integration with AI's analytical and predictive capabilities could automate several orthodontic processes. In this context, AI-guided robotic systems may execute tasks like precise bracket placement, archwire modification, and digital impressions with exceptional accuracy, minimizing manual errors and improving procedural consistency [81]. Through real-time AI feedback, robotic systems could perform orthodontic adjustments autonomously, standardizing clinical outcomes and improving reproducibility. Moreover, AI-enabled robots could continuously monitor treatment progress, making on-the-spot modifications to enhance accuracy and reduce overall treatment duration [82]. This combination of automation and intelligence promises not only greater precision but also improved accessibility, allowing high-quality orthodontic care to reach a wider population.

AI in predictive orthodontics

Advancements in AI's predictive modeling are paving the way for early detection and prevention in orthodontics. By analyzing comprehensive datasets—including pediatric dental scans, genetic markers, medical histories, and 3D imaging—AI systems may soon identify potential malocclusions or alignment issues before they fully emerge [17]. Such early detection would enable preemptive and minimally invasive interventions during childhood, potentially reducing or eliminating the need for braces or aligners later in life. In predictive orthodontics, AI could provide clinicians with data-driven guidance to influence jaw and dental development proactively. This proactive approach not only improves long-term oral health outcomes but also significantly lowers treatment costs and duration for patients [1, 34].

Real-Time 3D printing of orthodontic devices

The integration of AI with 3D printing technology is set to revolutionize orthodontic device fabrication. Currently, creating custom aligners or braces involves design, verification, and production stages that can take several days or weeks. AI-driven systems could dramatically shorten this process by instantly analyzing a patient's scans and generating optimized 3D printable designs [11, 26]. For instance, after a single consultation, an AI system could formulate a treatment plan and fabricate the initial set of aligners or appliances in real time using an in-office 3D printer. This rapid production capability would reduce waiting periods, allowing treatments to begin immediately while improving convenience and patient satisfaction. Furthermore, AI could continuously generate new device iterations as tooth positions change, supporting dynamic and responsive orthodontic care [11, 52].

Integration with tele-orthodontics

Tele-orthodontics is already transforming patient care through digital communication tools, and its fusion with AI will likely expand remote treatment capabilities. Existing AI-based monitoring platforms enable patients to upload images or videos of their teeth for automated analysis and feedback, minimizing the need for routine in-office appointments [83]. Future systems may enable fully remote orthodontic workflows, where AI independently tracks treatment progression, provides automated adjustments, and alerts clinicians only in complex scenarios [84]. Such systems would allow orthodontists to manage multiple patients simultaneously, offering real-time consultations and treatment modifications from a centralized platform. This model holds particular promise for patients in remote or resource-limited regions, significantly improving access to care while reducing travel time and clinic congestion [62, 85]. As AI-enhanced tele-orthodontics evolves, it is expected to create hybrid care models that blend virtual and in-person consultations for optimal efficiency and convenience [86].

Ethical Considerations, Data Privacy, and Limitations of AI in Orthodontics

The application of artificial intelligence in orthodontic care introduces significant improvements in diagnostic precision, workflow automation, and treatment personalization. However, it also presents ethical, technical, and privacy-related challenges that must be carefully managed. Core concerns include algorithmic bias, inaccuracies in AI-generated outputs, overdependence on automated systems, and risks associated with handling sensitive health data [87, 88]. Addressing these issues is essential to ensure that AI technologies remain safe, transparent, and clinically reliable.

Ethical considerations in ai-driven orthodontics

AI-based orthodontic platforms depend on extensive patient datasets—ranging from X-rays and intraoral images to 3D scans and medical histories—which raises substantial data protection and confidentiality concerns [89]. Unauthorized access or data breaches could expose sensitive personal information, compromising patient trust and security [90]. To prevent such risks, developers and practitioners must adhere to international privacy regulations, including the Health Insurance Portability and Accountability Act (HIPAA) in the United States and the General Data Protection Regulation (GDPR) in Europe [91]. These frameworks mandate encryption, restricted access, and secure storage of medical data. Additionally, anonymization techniques are vital to remove identifiable information from training datasets, ensuring privacy during AI development.

Another important ethical issue involves data ownership—specifically, determining who controls and benefits from patient information used to train AI systems. Patients and clinicians must be informed about whether data are stored locally, in the cloud, or shared with external entities [92]. Ethical deployment of AI requires transparent data governance, including explicit consent mechanisms, opt-in or opt-out options, and restrictions on the commercial use of patient data. Upholding these principles ensures that AI serves healthcare advancement without compromising individual privacy or autonomy.

Data privacy and security in AI-orthodontic applications

AI-driven orthodontic platforms rely on extensive patient datasets, including X-rays, 3D dental scans, intraoral photographs, and medical histories. Collecting, storing, and processing such data introduces significant privacy and security concerns. One major threat is unauthorized access, where confidential patient information could be exposed. Because AI systems require large datasets for training and optimization, companies offering AI orthodontic solutions must implement strong data protection mechanisms.

To protect sensitive information, AI-powered orthodontic systems must comply with global privacy regulations such as the Health Insurance Portability and Accountability Act (HIPAA) in the U.S. and the General Data Protection Regulation (GDPR) in Europe [91]. These regulations mandate encryption, secure storage, and restricted access to authorized personnel. Additionally, anonymization techniques can remove personally identifiable information (PII) from datasets before AI training, further safeguarding patient confidentiality.

Data ownership is another key issue. When AI companies collect large datasets, it is critical to define who owns the data and how it can be used. Patients and providers must understand whether their data is stored locally, in the cloud, or shared with third-party services [92]. Ethical AI implementation requires transparent governance policies, allowing patients to opt in or out of data-sharing agreements, and ensuring that the data is used solely to improve healthcare outcomes rather than commercial exploitation.

Limitations and challenges of AI in orthodontics

Despite its advantages, AI in orthodontics has several limitations. Automated diagnostics are prone to errors if training data is incomplete or lacks diversity [87]. Rare malocclusions or unusual dental structures may be misinterpreted by AI, potentially leading to incorrect or suboptimal treatment suggestions. Continuous updates and training on diverse, high-quality datasets are essential to maintain reliability.

Performance can also vary among patient groups. AI models trained on specific populations may perform less accurately for different ages, ethnicities, or atypical dental conditions. Research indicates that AI diagnostic tools sometimes underperform for underrepresented groups [93]. Using inclusive datasets helps ensure consistent accuracy across all patient demographics.

Another concern is excessive reliance on AI without orthodontist oversight. AI-generated treatment plans should be verified by qualified orthodontists to ensure clinical appropriateness. Blindly following AI outputs could compromise care, especially if unique biomechanical or patient-specific factors are overlooked [94]. AI should be regarded as a decision-support tool, not a replacement for professional judgment.

Cost is an additional barrier. Implementing AI-based systems—including advanced imaging, cloud-based software, and treatment planning tools—requires considerable investment [80]. Smaller clinics may struggle to adopt such technologies. To encourage broader use, AI platforms must become more affordable, possibly through flexible pricing or subscription-based models.

Conclusions

AI-powered personalized orthodontic treatment represents a major advancement in dentistry, offering unprecedented precision, efficiency, and customization. AI enables orthodontists to predict tooth movement more accurately, optimize the design of braces and aligners, and monitor treatment progress continuously. This leads to shorter treatment durations, better clinical outcomes, and a more streamlined experience for patients.

Nevertheless, challenges remain, including data privacy, algorithmic bias, and barriers to widespread adoption. These must be addressed to ensure that AI is applied ethically and effectively across diverse patient populations. As AI continues to evolve and integrates with robotics, 3D printing, and other emerging technologies, orthodontic care is expected to become more accessible, cost-effective, and patient-centered. The ongoing development of AI promises not only to improve individual treatment outcomes but also to advance orthodontic care globally.

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