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Precision-Driven Innovation in Orthodontics: A Systematic Review of Digital and Artificial Intelligence Applications

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ABSTRACT

Background and Objective: Digitalization encompasses a wide range of technologies, including Three-Dimensional (3D) Imaging, Intraoral Scanning, and Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM). These tools facilitate the creation of accurate digital dental models, which are critical for interventions that demand high precision. This systematic review aims to consolidate recent findings, identify critical gaps in current practices and provide a roadmap for future research in the application of digital technology and AI in orthodontics.

Methods: This systematic review was conducted using the keywords ''Digital Technology'', ''Artificial Intelligence'', ''Orthodontic Treatment'', ''Systematic Review'' and search was done on PubMed, Scopus, and Web of Science databases for articles published between 2004 and 2024. The inclusion criteria were evaluated and the Modified Newcastle-Ottawa Scale was employed to extract and evaluate data related to study design, sample size, and outcomes.

Findings: A total of 705 studies were initially identified through database search. After removing 85 duplicates, 620 unique studies were evaluated for title and abstract screening. 540 articles were excluded due to not meeting the inclusion criteria. The remaining 80 studies were assessed through full-text review. After a rigorous full-text review, 47 studies met the inclusion criteria and were incorporated into the qualitative analysis. With the help of digital technology and AI, diagnostic accuracy and treatment efficiency have significantly improved, particularly in complex cases. Digital models and AI-enhanced diagnostics have facilitated the development of tailored treatment plans. Despite these advances, issues such as data accuracy variability and the absence of standardized protocols remain.

Conclusion: The results showed that digital technology and AI significantly enhance orthodontic care and they possess the ability to significantly improve diagnostic accuracy, treatment planning, and clinical outcomes.

Keywords: *Digital Technology, Artificial Intelligence, Orthodontic Treatment, Systematic Review*.

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Introduction

Recent advancements in digital technology and artificial intelligence (AI) have transformed the field of orthodontics, enabling a shift from conventional manual techniques to more sophisticated, data-driven methodologies. These advancements address long-standing challenges in diagnosis, treatment planning, and patient care by introducing precision and efficiency previously unattainable with traditional approaches. Digitalization encompasses a wide range of technologies, including Three-Dimensional (3D) imaging, intraoral scanning, and Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM). These tools facilitate the creation of accurate digital dental models, which are critical for interventions that demand high precision. Recent studies have shown that these models not only enhance clinical workflows but also improve patient outcomes by reducing procedural errors and optimizing treatment efficiency (1, 2).

AI, on the other hand, is becoming increasingly integral to orthodontics due to its ability to process large datasets, recognize patterns, and automate complex tasks. For instance, deep learning algorithms have been employed to identify cephalometric landmarks, predict facial growth patterns, and optimize orthodontic treatment plans (3). These applications minimize human error, improve diagnostic accuracy, and provide personalized treatment strategies tailored to individual patient needs (4-6). Moreover, the integration of AI into orthodontic diagnostics and monitoring has paved the way for remote consultations and tele-orthodontics, particularly in post-pandemic healthcare environments. Recent innovations, such as AI-powered apps for tracking orthodontic tooth movement, highlight the growing role of technology in enhancing patient engagement and compliance (7). However, challenges remain in standardizing AI applications and ensuring interoperability across clinical settings (8).

Issues such as algorithm transparency, ethical considerations, and the need for comprehensive training programs for clinicians are also prominent areas of concern (9). The literature reflects a significant surge in research on these topics between 2022 and 2024, particularly in exploring AI's application in automated diagnostics and 3D imaging. Studies have demonstrated that AI-powered systems can achieve diagnostic accuracies comparable to experienced orthodontists, underscoring their potential as valuable tools in clinical decision-making (10, 11). Despite these promising developments, the lack of standardized protocols and the variability in data quality across different settings remain major barriers to widespread adoption. This systematic review aims to consolidate recent findings, identify critical gaps in current practices, and provide a roadmap for future research in the application of digital technology and AI in orthodontics. By addressing these challenges and opportunities, this study seeks to contribute to the evolving discourse on digital transformation in orthodontic care.

Methods

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and consistency throughout the study selection process. A comprehensive search was performed in PubMed, Scopus, and Web of Science databases to identify relevant studies published between 2004 and 2024. The search was conducted using keywords such as "orthodontics," "digitalization," "AI," "3D imaging," "treatment planning," and "accuracy." The study selection process involved the following steps:

Identification: A total of 705 studies were initially identified through database searches. After removing 85 duplicates, 620 unique studies were retained for title and abstract screening.

Screening: During the title and abstract screening stage, 540 articles were excluded for not meeting the inclusion criteria. The remaining 80 studies were assessed through full-text review.
Eligibility and Inclusion: Following a rigorous full-text review, 45 studies met the inclusion criteria and were incorporated into the qualitative analysis. Additionally, 2 studies were identified from references in the selected articles, resulting in a final total of 47 studies included in the analysis.

To assess the quality of the included studies, a Modified Newcastle-Ottawa Scale was employed, focusing on study design, sample size, technologies utilized, and primary outcomes. Data extraction emphasized both qualitative and quantitative aspects to identify trends and evaluate the efficacy of digital and AI technologies in orthodontics.

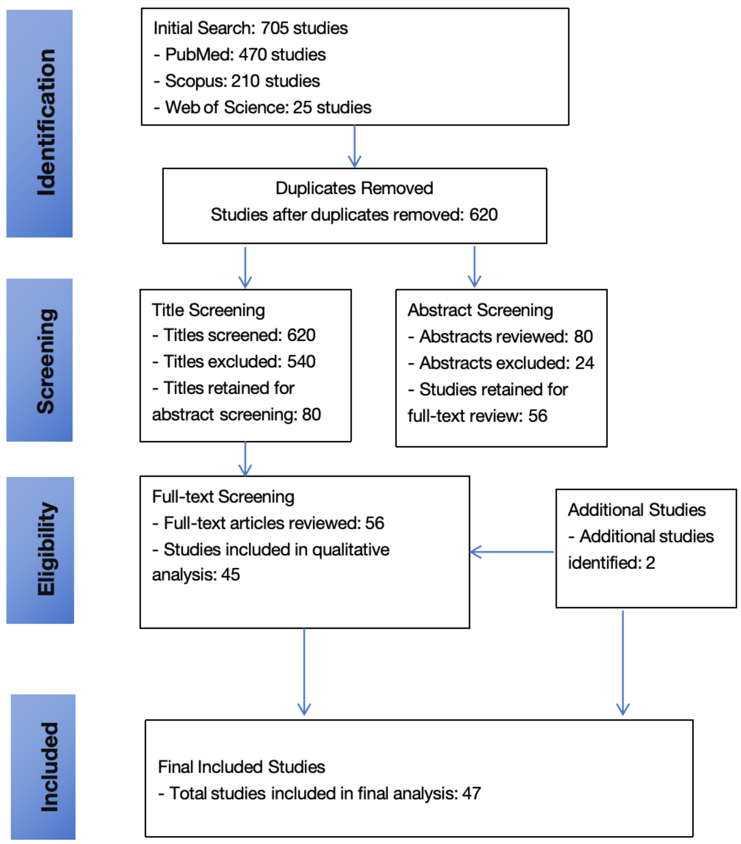

Figure 1. PRISMA Flow Diagram. (This flow diagram illustrates the study selection process based on PRISMA guidelines, including stages of identification, screening, eligibility, and inclusion of studies)

Overview of Key Studies on Digitalization and AI in Orthodontics: A methodological selection for the most relevant 20 studies out of the initial 47 that significantly contribute to the use of both digital technology and AI in orthodontic practice is carried out according to the following criteria: methodological rigor, relevance to clinical practice, and contribution to furthering the state-of-art understanding of both applications in orthodontics. These include works related to 3D imaging and printing, AI-driven diagnostics, and treatment planning.

Figure 2 below illustrates the trend in research publications related to the use of digital technology and AI in orthodontics over recent years, highlighting the growing interest and research output in this field.

Figure 2. Trends in research publications

Table 1 summarizes the focus areas and findings of these representative studies, highlighting their impact on the field and potential for future clinical applications.

Table 1. Representative Studies on the Application of Digitalization and AI in Orthodontic Treatment

	Title	Authors and Year	Main Focus	IF
1	A fully automatic AI system for tooth and alveolar bone segmentation from cone-beam CT images	Cui Z, et al. 2022	AI-based dental imaging analysis	14.7
2	Fully automatic AI segmentation of oral surgery-related tissues based on cone beam computed tomography images	Yu Liu, et al. 2024	AI-based automatic oral tissue segmentation	10.8
3	Cascaded convolutional networks for automatic cephalometric landmark detection	Zeng M, et al. 2021	Automated cephalometric landmark detection	10.7
4	3D and 4D printing in dentistry and maxillofacial surgery: Printing techniques, materials, and applications	Khorsandi D, et al. 2021	3D and 4D printing	9.4
5	Deep Multi-Scale Mesh Feature Learning for Automated Labeling of Raw Dental Surfaces From 3D Intraoral Scanners	Lian C, et al. 2020	3D Intraoral Scanning	8.9
6	A digital orthodontic arch wire design system with interactive adjustment and intelligent optimization	Song Z, et al. 2023	Orthodontic Arch Wire Design	7.0
7	A cross-temporal multimodal fusion system based on deep learning for orthodontic monitoring	Chen H, et al. 2024	AI-based multimodal orthodontic monitoring	7.0
8	Evolution of the Orthodontic Diagnosis in	John Kim, A.I.	AI in orthodontic	6.0

	the Age of Artificial Intelligence	Mazza. 2022	diagnostics	
9	Multiclass CBCT Image Segmentation for Orthodontics with Deep Learning	Wang H, et al. 2021	Deep Learning	5.7
10	Deep learning–based prediction of the 3D post orthodontic facial changes	Park YS, et al. 2022	AI-driven 3D facial change prediction	5.7
11	Can smartphones be used for routine dental clinical application? A validation study for using smartphone-generated 3D facial images	Singh P, et al. 2023	3D facial images	4.8
12	Evaluation of artificial intelligence model for crowding categorization and extraction diagnosis using intraoral photographs	Ryu, J, et al. 2023	AI-based crowding and extraction diagnosis	3.8
13	Effectiveness of cone-beam computed tomography-generated cephalograms using artificial intelligence cephalometric analysis	Chung EJ, et al. 2022	AI-driven CBCT cephalometric analysis	3.8
14	Accuracy of 3D facial scans: a comparison of three different scanning system in an in vivo study	Pellitteri, F, et al. 2023	3D facial scans	3.5
15	Orthodontic treatment quality evaluated by partially automated digital IOTN and PAR index determination: a retrospective multicenter study	Coenen FA, et al. 2023	Digital Orthodontic Assessment	2.8
16	Machine learning-based decision support system for orthognathic diagnosis and treatment planning	Du W, et al. 2024	AI in orthognathic treatment planning	2.6
17	Deep convolutional neural network-based automated segmentation and classification of teeth with orthodontic brackets on cone-beam computed-tomographic images: a validation study	Ayidh Alqahtani K, et al. 2023	AI in Automated Dental Imaging Analysis	2.8
18	Evaluation of digital and manual orthodontic diagnostic setups in non-extraction cases using ABO model grading system: an in-vitro study	Shakr S, et al. 2024	Digital vs. Manual Orthodontic Diagnostics	2.6
19	Effectiveness of AI-driven remote monitoring technology in improving oral hygiene during orthodontic treatment	Snider V, et al. 2024	AI-driven remote monitoring	2.4
20	Divergence between CBCT and Optical Scans for Soft Tissue Analysis and Cephalometry in Facial Imaging: A cross-sectional study on healthy adults	Farronato M, et al. 2024	CBCT vs. Optical Scans in AI Imaging	1.8

Results

In a nutshell, this study has focused on the influence of digital technology and AI on orthodontics, explained the development of AI is evolving continuously for diagnostic imaging and treatment planning. Furthermore, they have emphasized integrating 3D imaging and printing for precision and efficiency in outcomes that would introduce the transformation of classic orthodontic practices through improvement in diagnosis, facilitated treatment plans, and personalized solutions for care.

Application of Digitalization and AI in Orthodontics: Building on the insights presented above, specific applications of digital technology and AI in orthodontics are discussed in this section. A number of the ways in which these technologies have reshaped treatment at every level, from diagnostics to personalized care, by integrating advanced digital solutions into treatments.

Figure 3 illustrates the various areas of orthodontic research where digitalization and AI have been applied, highlighting the concentration of research in fields such as diagnosis and treatment planning, automated cephalometric landmark identification, and 3D imaging and reconstruction. The figure also suggests the potential for further research in patient-specific treatment optimization and predictive analytics for treatment outcomes.

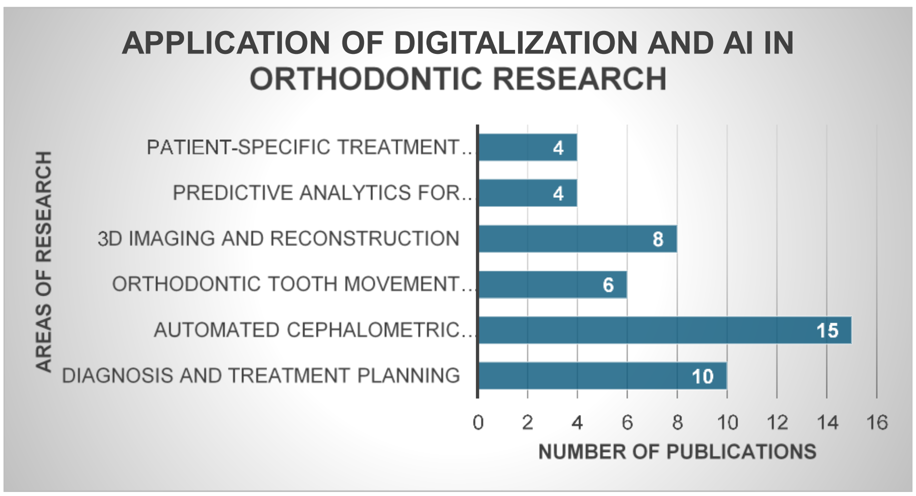

Figure 3. Application of Digitalization and AI in Orthodontic Research

Acquisition of Orthodontic Case Data:

Acquisition of Dental and Jaw Models: Digital models have revolutionized dental and jaw modeling since the 1980s, achieving widespread adoption by the 1990s (12). Sourced from various scanning methods, including model scans, intraoral scans, and cone beam computed tomography (CBCT), these digital models offer convenience, spatial efficiency, and durability, while maintaining measurement reliability comparable to that of traditional plaster models (5). However, optical scans, especially intraoral, may distort the morphology of long arches. The lack of standardized accuracy in orthodontics highlights the need for precise digital model standards. AI enhances diagnostic modeling, particularly in tooth marker and CBCT segmentation. Traditional algorithms often require manual input and are complex (13). Although convolutional neural network (CNN)-based methods have seen improvements, tooth count and segmentation accuracy are still constrained. CBCT segmentation, including region of interest (ROI) localization and alveolar bone segmentation, encounters automation challenges, especially under varying imaging protocols (14).

Facial Soft Tissue Morphology Capture: Facial soft tissue plays a critical role in orthodontic outcomes and patient satisfaction. Digital technology has superseded two-dimensional (2D) images with 3D facial data, enhancing virtual patient modeling and analysis. Stereoscopic photography, 3D laser scanning, and structured light scanning are prevalent methods, with stereoscopic photography being preferred for its accuracy (15). Despite submillimeter accuracy, challenges persist in areas of high curvature, scan duration, and patient movement. AI focuses on aesthetic assessments and feature recognition in orthodontics and orthognathic treatments (16). Subjectivity in evaluations and ethical considerations regarding the use of 3D data remain as challenges. Research focuses on improving algorithms, but practical application demands robust aesthetic standards and ethical frameworks for optimized AI-based diagnosis and treatment (15, 17).

Virtual Patient Construction: Virtual patient construction involves soft and hard tissue data acquired from teeth, jaws, and facial structures. This information may be acquired independently; however, it must be combined in a manner that would result in the correct formation of a virtual model of the patient's anatomy (18). The ideal model, therefore, should encompass both static and dynamic changes in the anatomy-such as occlusal movements and facial muscle actions-for perfect alignment within a unified system (7, 18). Data from jaws, facial soft tissues, and dentition are combined; orthognathic surgery data are often included. Traditional approaches rely on anatomical markers or manually selected surfaces, but more accurate surface alignments are nowadays delivered by novel algorithms like Iterative Closest Point (ICP) and Simultaneous Pose and Correspondence (SPC) (19). Some of these techniques are indispensable steps of the orthodontic diagnostics and surgery. Virtual patients will continue to assist in remote consultations, treatment planning, and navigation, since dynamic data capture is continuously improving (20).

Orthodontic Case Diagnosis:

Model Analysis: Digital dental models are increasingly recognized as the new gold standard in orthodontics, providing more precise and comprehensive 3D data than traditional plaster models (21). These models improve diagnostics and treatment planning by facilitating detailed analyses of tooth position, occlusal pressure, and maxillofacial morphology. Additionally, they enable the simulation of treatment scenarios, enhance data storage, and boost reproducibility, offering significant advantages over traditional methods. However, the assessment of digital models often adheres to outdated plaster model standards, constraining the potential of these advanced tools (5). Challenges such as rigid segmentation and insufficient consideration of 3D dental structures call for enhanced accuracy standards in digital modeling (14, 22).

Diagnostic Imaging and Analysis: CBCT is an essential tool for orthodontic diagnosis, treatment planning, and monitoring, offering superior 3D insights over traditional imaging, with a slight increase in radiation (23). It enhances craniofacial analysis, facilitating impacted tooth localization, airway visualization, jaw asymmetry identification, and periodontal assessments (24, 25). AI has advanced cephalometric analysis by automating marker point calibration, cervical spine maturity assessment, and orthognathic surgery evaluation. While AI improves efficiency and accuracy, it cannot replace clinical expertise, and it faces challenges such as image overlap, marker precision, and algorithm robustness (13, 26).

Soft Tissue Aesthetic Analysis: As facial soft tissue changes have become central to orthodontics, evaluations have shifted from photographs to 3D modeling, providing comprehensive, reproducible analyses (4). 3D assessments enable precise evaluation of facial changes, especially in orthognathic surgery, where jaw movement significantly affects soft tissue (16, 27). AI in soft tissue diagnostics focuses on facial aesthetics, closely mimicking physician assessments. Studies show AI’s ability to predict postoperative profiles and assist in aesthetic decision-making (28).

Orthodontic Treatment Design and Implementation:

Diagnostic Alignment of Teeth: Dr. Haas's Diagnostic Alignment Test initially employed plaster models for simulating post-treatment tooth alignment, hindered by manual processes (29). Digital dental models have revolutionized this process, enabling more precise and efficient simulation of tooth and jaw movements. Although these digital simulations provide clearer understanding of the orthodontic process for both doctors and patients, the biomechanical execution ultimately relies on the orthodontist's expertise (30). In this context, AI primarily automates teeth marking and segmentation on digital models. Current AI applications are better suited for full denture restorations and often fall short in clinical orthodontics. Continued research is essential to improve AI's utility in orthodontic applications, despite its potential (31).

Clinical Decision-Making in Orthodontic Treatment Planning: Orthodontic treatment planning, guided by clinician expertise and data, benefits from AI model support (16). Although AI assists in decision-making, it cannot replace the judgment of experienced clinicians. Studies reveal that AI models, such as CNN and machine learning (ML), effectively learn from expert decisions regarding extractions and surgery, demonstrating high accuracy. Bayesian networks accurately predict treatment needs (kappa=0.894) (32). AI models facilitate irreversible decisions like tooth extraction with accuracy on par with expert orthodontists. Additionally, AI precisely identifies the need for orthognathic surgery, particularly in complex cases. Machine learning further refines these models' predictive accuracy, offering detailed analysis in challenging diagnostic contexts (33).

Implementation of Personalized Treatment: Digital technology and AI significantly enhance orthodontic treatment, especially in the creation of personalized appliances using 3D printing (6). This technology improves the precision of orthodontic tools, ensuring optimal fit, enhancing comfort, and increasing treatment effectiveness. Personalized features, including custom grooves and precise bonding, enhance the performance of devices such as lingual and labial brackets and clear aligners (8). CAD and 3D printing contribute to accurate bracket placement, streamlining procedures (34). Clear aligners achieve their intended tooth movements through specific design features; however, optimal treatment outcomes are ultimately contingent upon a high degree of patient adherence throughout the course of therapy (3).

Orthodontic Monitoring:

Orthodontic Tooth Movement Monitoring: Orthodontic tooth movement (OTM) is induced by mechanical forces and depends on coordinated remodeling of the periodontal ligament and alveolar bone through bone resorption and apposition (35). AI-powered remote systems like Dental Monitoring (DM) enable patients to take intraoral images with smartphones, producing 3D models with accuracy comparable to traditional intraoral scans. These technologies decrease the need for in-office visits, thereby enhancing patient satisfaction (32, 36). In invisible orthodontics, AI supports treatment adjustments through 3D model analysis, despite challenges such as marker selection. The DM Go Live system employs deep learning to track progress but still integrates traditional methods for comprehensive evaluation. Combined use of CBCT and intraoral scans monitors the root-bone interface with reduced radiation exposure (37).

Orthodontic-related Complication Monitoring: Research indicates a higher presence of cariogenic and periodontopathogen bacteria in patients with fixed orthodontic appliances compared to those with invisible aligners (38). Orthodontists must prioritize hygiene monitoring and manage complications through education and preventive measures. Fixed treatments are associated with enamel demineralization; early detection is crucial to minimize caries risk (39). Tools like Digital Plaque Image Analysis (DPIA) and Quantitative Light-Induced Fluorescence-Digital (QLF) evaluate plaque accumulation and demineralization, providing valuable insights into oral hygiene (40, 41). Remote monitoring improves plaque control and decreases caries risk but can increase costs. Smartphone applications for oral health diagnosis are becoming more prevalent (37).

Orthodontic Patient Compliance Monitoring: Removable orthodontic appliances are effective when worn consistently; however, insufficient usage prolongs treatment and compromises outcomes (42). Orthodontists utilize follow-up visits and apps for self-assessment and data sharing. Advanced applications that use decision tree algorithms can detect poor patient compliance and generate alerts (32). Studies indicate that actual aligner wear times frequently differ from patient-reported durations. Temperature-sensitive sensors embedded in aligners can accurately track wear time and supply valuable data to inform clinical decisions. When combined with regular monitoring, this technology has been shown to improve patient compliance (20, 43).

Discussion

Digital technology and AI have revolutionized orthodontics field, significantly enhancing diagnostic accuracy, treatment planning, and overall clinical outcomes. This study underscores the profound impact these technologies have in elevating the precision and efficiency of orthodontic practices.

Digital Technology in Orthodontics: Digital technologies, particularly CBCT and digital models, has transformed orthodontics by providing 3D images that enable more accurate assessments of complex structures than 2D methods (13). CBCT precisely localizes impacted teeth and evaluates the temporomandibular joint for early diagnosis and intervention (25). Digital models, replacing traditional plaster models, enhance accuracy, storage, and data sharing, and have become the standard in clinics for personalized treatment planning (44). While advancing digital technology and AI offer greater precision and efficiency in orthodontics, they also demand significant technical training and clinical integration from professionals (27, 45). Future research should focus on developing training programs for these technologies and establishing guidelines for standardization and data security.

Artificial Intelligence in Orthodontics: AI has transformed orthodontic diagnostics and treatment planning. CNNs and ANNs (Artificial Neural Networks) deliver high accuracy in cephalometric analysis, cervical spine assessments, and surgery predictions (26, 46, 47). AI not only enhances diagnostic precision but also reduces analysis time, improving the efficiency of patient care. However, challenges persist concerning the robustness of algorithms and their generalizability across clinical settings. AI supports critical decisions such as extractions and surgical interventions, often matching the accuracy of orthodontists (9, 36). Nevertheless, AI is not a substitute for the refined clinical judgment required in complex orthodontic cases, where decision-making depends heavily on individual patient characteristics and practitioner expertise (48). Furthermore, the reliability of AI-driven tools is inherently linked to the quality of their training datasets, highlighting the importance of ethical frameworks and comprehensive clinician education for effective implementation (49).

Challenges and Future Directions: Despite the considerable benefits of digital technology and AI in orthodontic practice, a number of challenges must still be overcome. Inconsistent accuracy in digital models and AI-generated predictions across different clinical scenarios contributes to outcome variability (50), which in turn affects their overall reliability. Furthermore, the continuous need for clinicians to update their training and adapt to evolving digital tools adds additional complexity to the integration process (51). Future research should be directed at improving the robustness of AI and developing standardized protocols for the digital models to ensure reproducibility of diagnostic and therapeutic outcomes in all circumstances (2, 36). Systematic reviews of digital applications and AI is necessary to determine their long-term effectiveness and safety, and thereby provide a sound basis for wider dissemination in orthodontics. Data security and patient privacy is an issue of growing importance with the continuous development of digitalization and AI. Security protocols need to be enhanced in order to protect patient information. Once these are overcome, complete digitalization with AI will be enabled in personalized and effective orthodontic care.

This study highlights the transformative impact of digital technology and AI on the field of orthodontics, emphasizing their ability to significantly improve diagnostic accuracy, treatment planning, and clinical outcomes. Through the integration of advanced tools such as digital models, cone-beam computed tomography (CBCT), and AI-driven algorithms, the practice of orthodontics has witnessed a paradigm shift towards greater precision and efficiency. These technologies have not only streamlined workflows but also facilitated the development of personalized and adaptive treatment plans, addressing patient-specific needs with unparalleled accuracy.

The systematic review confirms that digital technologies and AI are making substantial contributions to orthodontic practice across multiple domains. Their strengths are most evident in three areas: the enhancement of diagnostic imaging through high-resolution 3D visualization and AI-assisted interpretation; the optimization of appliance design via computer-aided modeling and simulation; and the enablement of real-time, remote treatment monitoring. Notably, the integration of 3D imaging and AI diagnostics has elevated the precision of case analysis, while the proliferation of remote monitoring tools has significantly improved patient access to orthodontic care—an advancement that has proven especially valuable in the shifting healthcare landscape following the pandemic.

While the benefits of digital and AI technologies are evident, significant challenges must still be overcome before their full potential can be realized in clinical orthodontics. Chief among these is the absence of standardized protocols governing digital model accuracy and the clinical validation of AI applications, which can result in inconsistent treatment outcomes. Additionally, the applicability of AI algorithms to diverse patient populations and varied clinical settings remains uncertain, and important ethical and legal concerns persist regarding data privacy and security. A concerted effort to address these gaps—through collaborative research, policy development, and continuous education—will be critical to achieving the seamless and responsible integration of these technologies into everyday orthodontic care.

The findings of this study contribute to a deeper understanding of the ongoing digital transformation in orthodontics and highlight several promising avenues for future inquiry. To fully harness the potential of digital and AI technologies, concerted efforts are needed across multiple fronts: the development of internationally accepted guidelines and quality standards, the creation of robust training curricula for both current practitioners and trainees, and the careful navigation of ethical, legal, and social implications. By addressing these priorities, the orthodontic community can continue to advance toward its ultimate goal—delivering care that is not only technologically sophisticated but also highly personalized, efficient, and responsive to the needs of each individual patient.

In conclusion, there is little doubt that digital and AI technologies have elevated the quality and precision of orthodontic care in recent years. Nevertheless, the process of integrating these tools into everyday clinical practice is far from complete and will require sustained effort across multiple fronts. Future research must focus on addressing the challenges identified in this review—including issues of standardization, generalizability, ethics, and training—to ensure that these innovations contribute meaningfully to clinical efficiency, patient satisfaction, and the long-term sustainability of orthodontic services in an evolving healthcare landscape.

Conflicts of Interest: The authors declare no conflicts of interest.

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