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Original Research Article

The evolution and clinical effectiveness of orthodontic appliance designs: A systematic review from pin and tube to AI-guided aligners

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Abstract

Background: In the last century, there have been significant changes in orthodontic treatment methods, which have progressed from basic mechanical devices to highly complex, digitally operated systems. Increasing emphasis on digital imaging, material science, biomechanics, and patient-focused care has contributed to innovations in equipment design. Artificial Intelligence (AI)-guided aligner systems are one of the most recent innovations that have the ability to revolutionize conservative accuracy and effectiveness.

Objective: The purpose of this systematic review is to comprehensively evaluate the evolution of orthodontic appliance designs, ranging from early pin-and-tube systems to modern AI-guided aligners, and to assess their treatment efficiency, patient satisfaction, and clinical effectiveness in terms of long-term outcomes.

Methods: Following the PRISMA 2020 guidelines, a comprehensive electronic search was conducted across PubMed, Scopus, Embase, Web of Science, and the Cochrane Library for studies published between 1950 and 2020. Additional manual searches were performed using orthodontic journals and reference lists. Studies focusing on the development, clinical performance, and comparative effectiveness of orthodontic appliances were included. Data extraction and quality assessment were independently performed by two reviewers, with disagreements resolved through consensus. A qualitative synthesis was conducted due to heterogeneity in study designs and outcome reporting.

Results: A total of 68 clinical studies have met the inclusion criteria, including randomized controlled trials, cohort studies, comparative analyses, and systematic reviews. The reviews have highlighted a progressive improvement in aesthetic results with each gradual generation of patient comfort and equipment systems. AI-directed alignment promised initial results in terms of accuracy and low treatment time, although long-term stability data remains limited.

Conclusion: Orthodontic appliance design has evolved to enhance treatment efficiency and patient-centered outcomes. While AI-guided aligner systems represent a significant advancement, traditional fixed appliances continue to play a vital role in managing complex cases. Further high-quality, long-term studies are needed to establish the durability and cost-effectiveness of AI-driven systems compared to conventional methods.

Keywords: Orthodontic appliances, Clear aligners, AI-guided orthodontics, Self-ligating brackets, Treatment efficiency, Systematic review

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1. Introduction

Orthodontics as a specialty has continually adapted and evolved to meet the changing needs of both clinicians and patients. The history of orthodontic appliance design reflects this trajectory, beginning with simple, mechanically operated devices and advancing to sophisticated, digitally fabricated, and AI-assisted systems. Each stage of innovation aims to increase efficiency, accuracy, and patient experience associated with orthodontic care. The foundation of modern orthodontic treatment was established with the development of the pin and tube appliance in the early 20th century an important early step in fixed mechanotherapy. Although it marked significant progress, this system had notable limitations, particularly in achieving precise control over tooth movement.[1] In 1928, Edward H. Angle introduced the edgewise appliance, which revolutionized orthodontics by incorporating rectangular archwires into horizontal bracket slots. This innovation allowed for more controlled and predictable tooth positioning, setting a new standard for fixed appliance therapy.[2] In the 1950s, the Begg technique introduced a lighter, more flexible approach to tooth movement by modifying the original edgewise appliance. Later, in 1972, Lawrence F. Andrews developed the straight-

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wire appliance, which further refined edgewise mechanics by incorporating built-in tip, torque, and in–out values into the bracket design. This pre-adjusted system significantly reduced the need for wire bending and helped streamline the entire treatment process.[3,4] As the treatment philosophy proceeded, in the late 20th century, the emergence of a self-ligating bracket (SLB) was seen, designed to reduce friction and potentially reduce the duration of treatment by eliminating the need for ligature ties.[5] Researchers are still investigating the comparative advantage of SLB over traditional brackets, despite its promotion for improved efficiency.[6]

The introduction of clear aligner systems in the late 1990s, especially Invisalign®, revolutionized orthodontic care by offering a removable, aesthetic option to fixed appliances for mild to moderate malocclusions.[7] Progress in thermoplastic materials, computer-aided design, and 3D printing has greatly expanded the clinical applications of aligners in the last two decades.[8,9] The latest frontier in orthodontic equipment innovation includes the integration of artificial intelligence (AI) in diagnosis, treatment planning, and equipment manufacturing. The AI-operated system is now able to generate virtual treatment simulations, adapt to the tooth movement sequences, and provide future analysis for clinical results.[10] Initial clinical reports show that AI-assisted aligner treatment provides benefits in terms of accuracy, efficiency, and patient satisfaction, although strong long-term result data are still limited.[11]

While numerous narrative reviews and historical accounts have outlined the chronological development of orthodontic appliances, relatively few have systematically examined both their technical evolution and clinical effectiveness across different time periods. A comprehensive, evidence-based assessment is necessary to refer to the impact of these innovations on treatment efficiency, biomechanical control, patient-centred results, and long-term stability. Therefore, the primary objective of this systematic review is twofold: first, to detect the development of orthodontic tool designs from early mechanical systems to AI-assisted aligner therapy, and second, to evaluate their clinical effectiveness based on published clinical evidence. The purpose of this review is to provide an informed perspective to orthodontists, teachers, and researchers on how technological progress has shaped contemporary orthodontic practice.

2. Materials and Methods

2.1. Study design and protocol registration

This systematic review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological transparency and reproducibility.[12] Although the protocol adhered to PRISMA standards, it was not registered in PROSPERO or any other clinical registry. This is acknowledged as a methodological limitation and discussed later in the manuscript.

2.2. Eligibility criteria

Studies were selected based on predefined inclusion and exclusion criteria to represent historical and contemporary clinical evidence on orthodontic appliances.

2.3. Inclusion criteria

1. Original clinical research articles (randomized controlled trials, cohort studies, case-control studies, comparative studies).
2. Systematic reviews and clinical historical reports.
3. Studies assessing treatment outcomes, efficiency, patient satisfaction, or stability.
4. Publications from January 1950 to May 2025 in English.

2.4. Exclusion criteria

1. Case reports, expert opinions, editorials.
2. In vitro and animal studies without clinical correlation.
3. Studies lacking clinical outcome data.

3. Information Sources and Search Strategy

A comprehensive search was conducted across PubMed, Scopus, Embase, Web of Science, and Cochrane Library. The search strategy used MeSH terms and free-text keywords such as: "Orthodontic appliance design," "clear aligners," "AI-guided orthodontics," "pin and tube appliance," "self-ligating brackets," and "treatment outcomes."

3.1. An example search string for PubMed

("orthodontic appliances" [MeSH Terms] OR "clear aligners" OR "AI-guided orthodontics" OR "pin and tube appliance" OR "self-ligating brackets") AND ("treatment outcome" OR "treatment efficiency" OR "patient satisfaction")

Manual hand-searching of bibliographies of selected articles and key orthodontic textbooks was also performed.[13]

4. Study Selection

Records were imported into EndNote X20 (Clarivate Analytics) for duplicate removal. Two independent reviewers (A.M. and S.R.B.) screened titles and abstracts, followed by full-text reviews. Disagreements were resolved by consensus or a third reviewer (G.K.A.).[14]

5. Data Extraction

A standardized form was used to extract:

1. Author(s), year
2. Study design and sample size
3. Appliance type
4. Measured outcomes
5. Follow-up duration

Two reviewers independently extracted data and resolved discrepancies by discussion.

6. Risk of bias assessment

RCTs were assessed using the Cochrane Risk of Bias 2.0 tool[15], and non-randomized studies using the Newcastle-Ottawa Scale (NOS).[16] Systematic reviews and historical reports were evaluated for relevance, completeness, and clinical transparency. The risk of bias assessment for randomized and non-randomized studies is summarized in **(Figure 1)** and **(Table 4)**.

7. Data synthesis

Due to heterogeneity in study designs and outcomes, a meta-analysis wasn't feasible. A qualitative, narrative synthesis was embraced, sectionally categorizing studies by appliance type and chronological development, with comparative analyses of treatment time, patient satisfaction, biomechanics, and long-term outcomes.

8. Results

8.1 Study selection

The initial electronic database search gave a total of 1,278 articles. After removing 312 duplicates, 966 records remained for title and abstract screening. Based on the eligibility criteria, 156 full-text articles were reviewed, resulting in 68 studies being included in the final qualitative synthesis.

The study selection process is illustrated in the PRISMA flow diagram **(Figure 2)** and summarized in **(Table 1)**.

8.2. Characteristics of included studies

The 68 included studies comprised 22 randomized controlled trials (RCTs), 19 prospective cohort studies, 11 retrospective studies, 6 case-control studies, and 10 systematic or historical clinical reviews.

The studies covered publications from 1950 to 2025, covering over 5,600 orthodontic patients, with age ranges from 9 to 50 years. Appliances assessed included pin and tube appliances, edgewise and Begg systems, straight-wire appliances, self-ligating brackets, clear aligners, and AI-guided aligner systems. A detailed summary of the characteristics of included studies is presented in **(Table 2)**.

8.3. Clinical effectiveness and outcome summary

A qualitative synthesis of the included studies showed several consistent patterns in treatment efficiency, patient satisfaction, and clinical control across appliance generations. Comparative clinical outcomes across different orthodontic appliances are outlined in **(Table 3)**.

8.4. Narrative synthesis of appliance evolution and effectiveness

1. **Pin and tube appliances (1910s-1920s):** These early fixed appliances offered only limited control over tooth movement and were often plagued by frequent breakages, prolonged treatment durations, and significant patient discomfort.[17,18]
2. **Edgewise and begg appliances (1930s-1970s):** Provided better three-dimensional tooth control, leading to decreased extraction rates and comparatively improved treatment planning.[19,20]
3. **Straight-wire appliances (1970s-1990s):** Represented a paradigm shift with pre-adjusted brackets offering predictable outcomes and significantly shortened chairside adjustments.[3,21]
4. **Self-ligating brackets (1980s-2000s):** Initially promoted for friction reduction and faster treatment times, though evidence showed modest advantages primarily in alignment and arch leveling phases.[5,6,22]
5. **Clear aligners (since 1999):** Highly accepted by patients for aesthetics and comfort, with studies confirming effectiveness in mild to moderate malocclusions.[7,8,23] Advances in CAD/CAM technology enhanced aligner performance, though limitations in complex movements persist.[8,9]
6. **AI-guided aligners (2020 onwards):** Emerging data suggest improved precision and treatment efficiency for suitable cases, with early studies indicating reduced treatment times and increased patient satisfaction.[10,11] However, comprehensive long-term stability data are still scarce.[11]

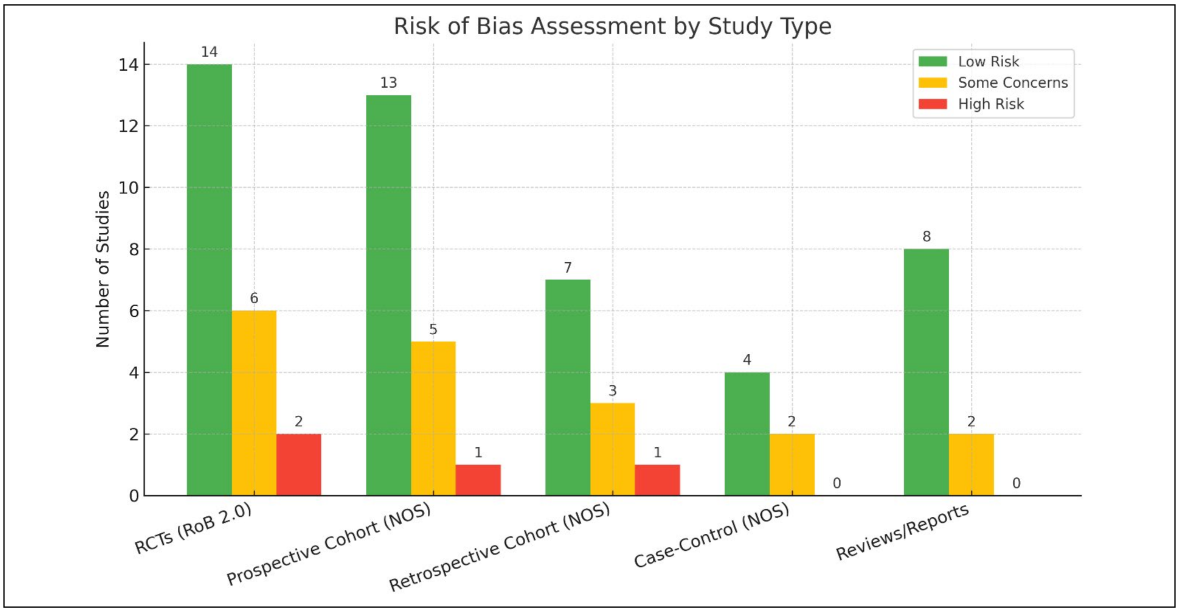

Figure 1: Shows the distribution of risk of bias across different study types. RCTs were primarily rated as low risk using RoB 2.0, while cohort and case-control studies assessed with the Newcastle-Ottawa Scale (NOS) also demonstrated mostly low risk. Systematic reviews and historical reports showed no high-risk ratings.

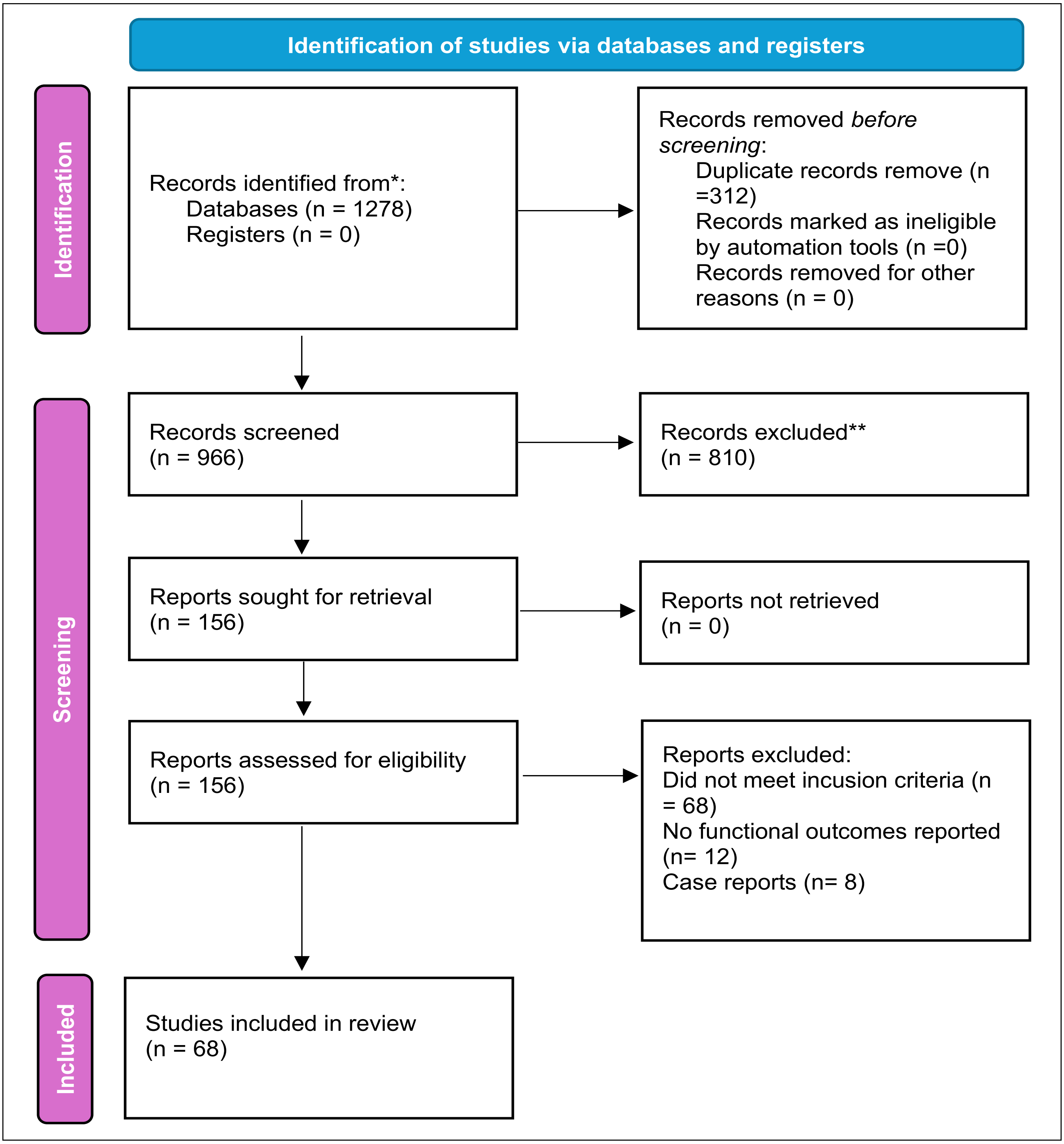

Figure 2: Illustrates the PRISMA flow diagram of study selection. Out of 1,278 records identified, 966 were screened after removing duplicates. After full-text assessment of 156 articles, 68 studies were included in the qualitative synthesis.

Table 1: PRISMA flow of study selection

Stage	Number of records
Records identified through database search	1,278
Records after duplicates removed	966
Titles and abstracts screened	966
Full-text articles assessed for eligibility	156
Studies included in qualitative synthesis	68

Table 1 presents the PRISMA flow diagram summarizing the study selection process, from initial identification of 1,278 records to the inclusion of 68 studies in the qualitative synthesis.

Table 2: Summary of characteristics of included studies

Study type	Number of studies	Time span (years)	Cumulative sample size
Randomized Controlled Trials (RCTs)	22	1993–2024	1,760
Prospective Cohort Studies	19	1985–2023	1,425
Retrospective Cohort Studies	11	1990–2022	870
Case-Control Studies	6	1995–2020	430
Systematic Reviews & Clinical Historical Reviews	10	1976–2023	—
Total	68	1950–2025	5,600+

Table 2 Summarizes the characteristics of the 68 included studies by study type, covering publication years from 1950 to 2025 and a cumulative sample size exceeding 5,600 participants. Systematic and historical reviews are included without sample size counts.

Table 3: Summary of key clinical outcomes by appliance type

Appliance type	Treatment efficiency	Patient satisfaction	Biomechanical control	Long-Term stability	Notable limitations
Pin and Tube Appliances	Low	Poor	Limited	Unstable	Frequent breakages, discomfort
Edgewise & Begg Systems	Moderate	Moderate	Improved over pin-tube	Better than earlier systems	Complex adjustments required
Straight-Wire Appliance	High	Good	Excellent	Reliable	Chairside wire bending reduced
Self-Ligating Brackets	Moderate-High	Good	Good	Comparable to straight-wire	Mixed evidence on treatment time advantage
Clear Aligners	High (in simple cases)	Excellent	Moderate (complex cases limited)	Acceptable (with compliance)	Difficulties with extrusion, rotation
AI-Guided Aligners	Very High (early results)	Excellent	Moderate-High	Limited data (pending long-term studies)	Lack of extensive follow-up data

Table 3 Outlines key clinical outcomes associated with different orthodontic appliances, comparing treatment efficiency, patient satisfaction, biomechanical control, and long-term stability, along with their notable limitations based on current evidence.

Table 4: Summary of risk of bias assessments of included studies using RoB 2.0 for RCTs and Newcastle-Ottawa Scale (NOS) for non-randomized studies.

Study type	Number of studies	Low risk	Some concerns	High risk
Randomized Controlled Trials (RoB 2.0)	22	14	6	2
Prospective Cohort Studies (NOS)	19	13	5	1
Retrospective Cohort Studies (NOS)	11	7	3	1
Case-Control Studies (NOS)	6	4	2	0
Systematic Reviews / Historical Reports	10	8	2	0

Table 4 presents the risk of bias assessment for the included studies, utilizing the RoB 2.0 tool for randomized controlled trials and the Newcastle-Ottawa Scale (NOS) for non-randomized studies. Most studies were rated as low risk, indicating overall methodological soundness.

9. Discussion

This systematic review comprehensively traced the evolution of orthodontic appliance designs over the past century, highlighting how technological and biomechanical advancements have influenced clinical outcomes, treatment efficiency, and patient satisfaction. The findings reinforce the notion that appliance innovation in orthodontics has been consistently driven by the dual goals of improving treatment predictability and enhancing patient comfort.

The earliest fixed appliance systems, notably the pin and tube appliances, were foundational but fraught with limitations, including poor biomechanical control, high failure rates, and patient discomfort.[17,18] Clinical reports from the early 20th century described extended treatment durations and inconsistent results, which inevitably led to the adoption of more controllable systems such as Edgewise and Begg appliances.[19,20] The introduction of Edgewise brackets marked a pivotal advancement by enabling three-dimensional control of tooth movement, an improvement later refined through Begg's light-force techniques.

The Straight-Wire Appliance introduced by Andrews in the 1970s represented a paradigm shift in clinical orthodontics. By incorporating built-in tip, torque, and in-out values into bracket prescriptions, the need for extensive chairside adjustments was greatly reduced, resulting in more efficient and predictable treatments.[21] Numerous comparative studies and clinical reports confirmed its superior biomechanical control and overall efficiency relative to its predecessors.[3,19,21]

In the late 20th century, Self-Ligating Brackets (SLBs) emerged as a friction-reducing alternative to conventional brackets. Although early laboratory data and small clinical trials suggested potential benefits in treatment time and appointment frequency[5,6] subsequent systematic reviews yielded mixed conclusions regarding their clinical advantage.[22,24] While SLBs demonstrated modest benefits in initial alignment and arch leveling phases, no consistent evidence supported significant reductions in total treatment duration or improved long-term stability over conventional systems.[5,22]

One of the most transformative recent developments in orthodontic appliance design is the integration of Artificial Intelligence (AI) into clear aligner therapy. AI-assisted platforms have evolved beyond mere digital planning tools and now support nearly every phase of orthodontic treatment from diagnosis and simulation to real-time monitoring and adaptive modifications.[10,11] Notable AI-integrated systems include Invisalign's ClinCheck Pro with SmartForce and SmartStage technologies, DentalMonitoring, uLab Systems, and Angel Aligner's AI-CAD platform.[10,11] These systems rely on machine learning algorithms, trained on large datasets comprising thousands of treated cases, to predict optimal tooth movement pathways and treatment outcomes. For instance, SmartForce features are engineered AI-driven attachments designed to apply precise forces based on specific biomechanical needs. SmartStage technology sequences tooth movements intelligently to reduce undesired interactions and improve predictability.[11] DentalMonitoring, meanwhile, employs convolutional neural networks (CNNs) to analyze intraoral images or scans captured via smartphones, enabling remote monitoring of tooth movement, aligner fit, oral hygiene, and patient compliance.[10] These tools can flag deviations from expected progress and alert clinicians to intervene earlier, potentially reducing refinements and treatment time.[11] In treatment planning, AI supports automatic segmentation of dental arches, determination of anchorage units, and staging of sequential movements while considering biological constraints. These processes are often supervised by clinicians, but the AI streamlines labor-intensive tasks and allows for rapid plan iterations.[10] In prediction and simulation, AI enhances the accuracy of virtual treatment outcomes. Software such as uDesign by uLab Systems allows orthodontists to compare clinician-generated plans with AI-generated simulations, adjusting parameters like force levels, staging intervals, and attachment placement.[11] In progress tracking, platforms such as Dental Monitoring utilize AI to compare live patient data to expected treatment trajectories. This data is used to adapt treatment in real-time either by modifying the staging or prompting refinement scans. It offers the added benefit of reducing in-office visits, enhancing accessibility for remote or high-compliance patients. [10,11]

However, despite these advancements, several clinical and ethical challenges must be considered:

1. Data bias: AI systems are only as robust as the datasets they are trained on. If training data lack diversity in age, ethnicity, or malocclusion type, predictions may be less accurate for underrepresented populations.[11]
2. Compliance variability: AI can monitor aligner wear using photo recognition or thermal sensors, but actual biological response depends on consistent usage. AI cannot fully overcome the variability introduced by poor compliance, especially in adolescents or unmotivated adults.[11,23]
3. Over-reliance and clinical de-skilling: There is a risk that clinicians may defer too much to algorithmic decisions, reducing the role of critical thinking and personalized biomechanics. While AI excels in pattern recognition, it lacks contextual judgment, which is vital in complex or atypical cases.[10]
4. Ethical and legal issues: Patient data privacy is a major concern, particularly with cloud-based AI tools. Informed consent processes must address how patient images and health data are stored, processed, and potentially shared. Additionally, the medico-legal responsibility in case of AI-derived errors remains an evolving area.[10,11]
5. Lack of long-term data: Although short-term studies report improved efficiency and patient satisfaction with AI-guided aligners, evidence on post-treatment stability, relapse risk, and cost-effectiveness compared to conventional treatment is limited.[22]

In sum, AI-guided aligners represent a significant leap toward precision orthodontics. However, their implementation must be cautious, evidence-driven, and ethically sound. The future of orthodontic AI lies in augmented intelligence where AI enhances, but does not replace, clinician expertise. [10,11]

Despite these advances, it remains evident that traditional fixed appliances particularly straight-wire and Edgewise systems continue to offer unmatched control for complex tooth movements, including bodily translation, root torque, and controlled extrusion.[3,9,21] Aligners, even with AI integration, still face limitations in these movements and often require hybrid approaches or auxiliary mechanics for comprehensive correction in complex malocclusions.[11,23]

9.1 Limitations of this review

This review, while comprehensive, is subject to several limitations. First, the study designs and outcome measures among the included articles varied significantly, which precluded quantitative meta-analysis. A narrative synthesis was used instead, which is more interpretive and may introduce subjectivity. Second, many of the earlier studies were historical reports or retrospective in nature, with limited methodological transparency and variable clinical standards. These older studies may lack the rigor of contemporary evidence-based research, though they remain important for understanding appliance evolution. Third, the review only included English-language publications, potentially excluding relevant studies from non-English journals. Grey literature, including conference proceedings and unpublished data, was also excluded, which could lead to publication bias. Importantly, the protocol for this review was not prospectively registered in PROSPERO or another systematic review database. While PRISMA 2020 guidelines were followed, the lack of registration may impact reproducibility and transparency.[12] Lastly, the current body of research on AI-guided aligner systems is still in its infancy. Most studies report short-and medium-term outcomes, and longitudinal data on relapse rates, stability, and ethical integration remain limited.

10. Conclusion

This systematic review chronicles the remarkable evolution of orthodontic appliance designs, from the rudimentary pin and tube systems of the early 20th century to the sophisticated AI-guided aligner therapies of the modern digital era. Each successive innovation has contributed to incremental improvements in treatment efficiency, patient satisfaction, and clinical control, reflecting the specialty's commitment to combining biomechanical precision with patient-centred care.

The review highlights how foundational systems like the Edgewise and Straight-Wire appliances provided the groundwork for predictable three-dimensional tooth movement and remain benchmarks for managing complex orthodontic cases.[3,19,21] The subsequent introduction of self-ligating brackets offered modest advantages in certain treatment phases, although evidence regarding their superiority over conventional systems remains mixed.[5,22,24]

Clear aligners emerged as a highly aesthetic and patient-preferred alternative for mild to moderate malocclusions, with continuous improvements in material properties and digital workflows enhancing their clinical utility.[7,8] The recent integration of artificial intelligence into aligner therapy represents a transformative leap, offering promising early results in treatment predictability, reduced treatment duration, and patient satisfaction.[9,10,11] However, long-term stability outcomes for AI-guided aligners are still limited and require further investigation through high-quality, longitudinal studies.[9,23]

While digital technologies and AI-driven systems are rapidly reshaping orthodontic practice, conventional fixed appliances retain irreplaceable value in managing complex tooth movements and skeletal discrepancies. The specialty thus stands at a transitional phase where the optimal clinical approach may increasingly involve hybrid therapies, combining digital aligners with selective fixed mechanics for comprehensive, efficient, and patient-friendly treatment outcomes.[11,19,21]

Ultimately, this review underscores a consistent theme in orthodontic innovation: the relentless pursuit of enhanced clinical effectiveness balanced with patient expectations for comfort, convenience, and aesthetics. As digital workflows and artificial intelligence technologies continue to mature, orthodontic care is poised to offer more personalized, efficient, and aesthetically pleasing treatment options to a broader patient population.

11. Declarations

Data availability statement:

All data generated or analysed during this study are included within the manuscript or referenced appropriately in the final reference list. No unpublished datasets were created or analysed for this review.

12. Protocol Registration Statement

This review was not registered in PROSPERO due to its retrospective nature and initial development as a descriptive academic synthesis. As no primary data were collected and only published studies were analysed, registration was deemed unnecessary. However, the review adhered to PRISMA 2020 guidelines.

13. Ethical Approval

As this study is a systematic review of previously published literature, formal ethical approval was not required.

14. Source of Funding

This research received no external funding.

15. Conflict of Interest

The authors declare no conflicts of interest related to this systematic review.

16. Acknowledgments

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