



Why does digitally predicted tooth movement fail? the biology-digital mismatch in orthodontics: a critical narrative review

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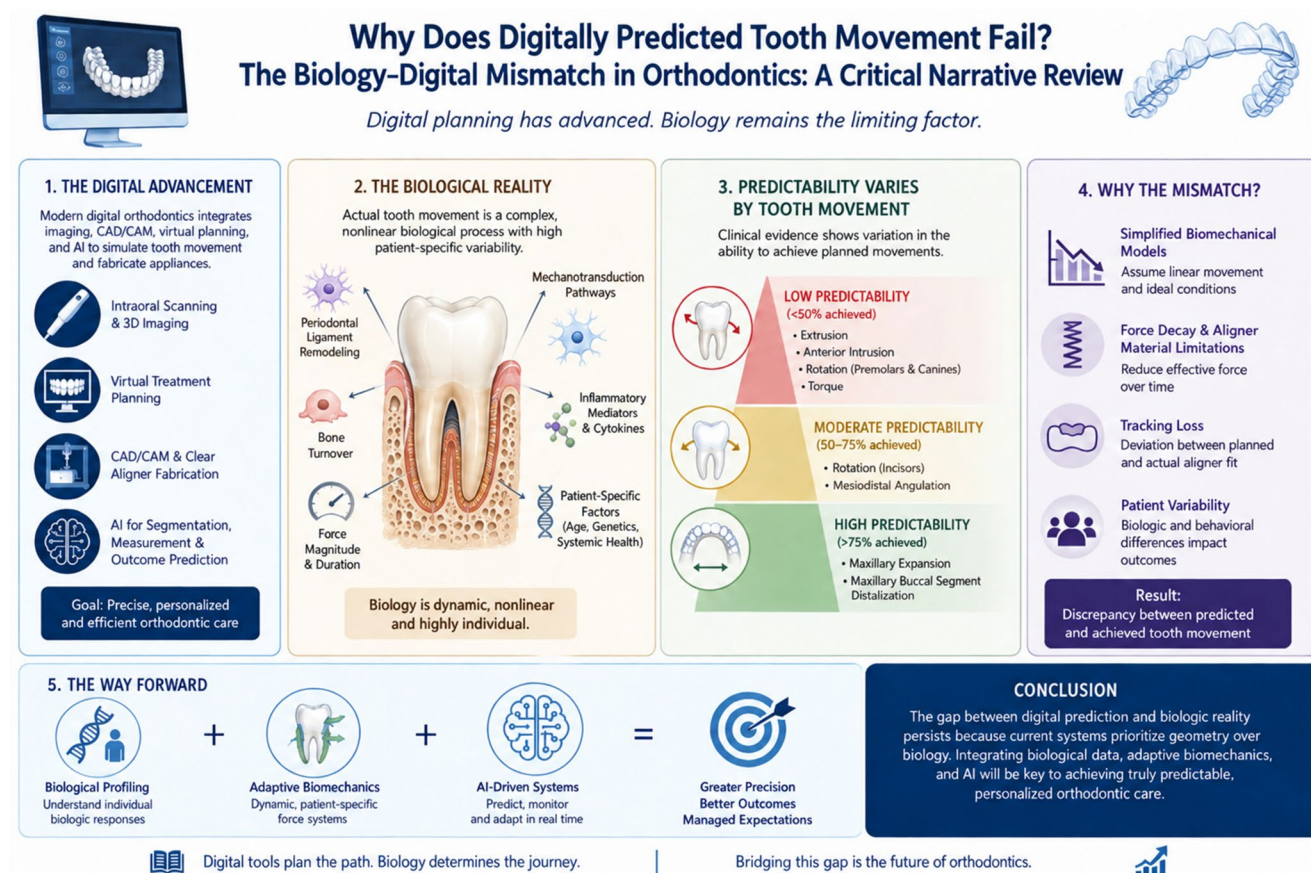
Abstract

Digital orthodontics has advanced through intraoral scanning, CAD/CAM, virtual planning, and clear aligners; however, discrepancies remain between predicted and actual tooth movements. This narrative review critically examined the biological and biomechanical factors underlying the limited predictability of digitally planned orthodontic treatment. A structured literature search of PubMed, Scopus, and Google Scholar was conducted and peer-reviewed articles were critically analyzed. Current digital systems primarily operate on geometric and algorithm-based models that assume linear and standardized tooth movements, whereas actual orthodontic tooth movements are governed by nonlinear biological processes, including periodontal ligament remodeling, bone turnover, mechanotransduction pathways, and substantial patient-specific variability. Clinical evidence shows a lower predictability for torque, extrusion, intrusion, and rotation than for tipping and expansion. The limitations of biomechanical models, force decay, and tracking loss are discussed along with AI applications in treatment planning. Future progress will require the integration of biological profiling, adaptive biomechanics, and AI-driven systems to enhance precision and manage patient expectations.

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Graphical Abstract



Keywords Digital orthodontics · Clear aligner therapy · Predictability · Artificial intelligence · Mechanobiology · Precision orthodontics · Personalized orthodontics

1 Introduction

1.1 Digital transformation in orthodontics

Orthodontic practice has undergone a fundamental transformation over the past two decades, driven by the convergence of three-dimensional imaging, computer-aided design and computer-aided manufacturing (CAD/CAM), and artificial intelligence (AI). Traditional workflows relying on alginate impressions and plaster models have been progressively replaced by intraoral scanning, virtual treatment planning, and digitally fabricated appliances. This evolution is propelled by the demand for precise diagnosis and treatment planning, with digital platforms encompassing digital radiography, cone beam computed tomography (CBCT), intraoral scanning, CAD, and computer-aided manufacturing systems that collectively enable customized treatment plans, appliance design, treatment simulation, and enhanced patient communication. Intraoral scanners offer clinically

acceptable accuracy and improve patient comfort (Mangano et al. 2017).

This transformation has been accelerated by the widespread adoption of clear aligner therapy (CAT). Contemporary CAT has evolved from its initial application in mild-to-moderate malocclusions to the management of more complex cases, including anterior open bites, Class II malocclusions requiring sequential molar distalization, and cases of crowding, and irregularity (Naoum and Lee 2026). The integration of AI into this workflow is accelerating; AI-based tooth segmentation has achieved 98% accuracy. AI effectively merges CBCT and intraoral scan data and supports digital measurements and outcome prediction (Ruiz et al. 2025).

However, this transformation has introduced a critical clinical question: To what extent do digitally simulated tooth movements correspond to the actual biological tooth displacement achieved in the patient? The answer defines the predictability of orthodontic treatment, which has

emerged as a significant challenge in contemporary digital orthodontics.

1.2 The concept of predictability

In orthodontic treatment, predictability refers to the concordance between the tooth movement prescribed in a digital treatment plan and the actual movement achieved in the patient's dentition. It is expressed as a percentage; an achieved movement equal to 100% of the planned movement represents perfect predictability, while lower percentages indicate a discrepancy. Contemporary literature has established a clinically useful three-tier classification: tooth movements with low predictability are those where achieved movement is less than 50% of planned movement, including extrusion, anterior intrusion, rotation of premolars and canines, and torque; movements of moderate predictability are those where 50% to 75% of planned movement is achieved, including rotation of incisors and mesiodistal angulation; and movements of high predictability are those where achieved movement exceeds 75% of planned movement, including maxillary expansion and maxillary buccal segment distalization (Naoum and Lee 2026).

The distinction between predicted and achieved tooth movements has profound clinical implications. When the predicted and achieved movements diverge, the consequences include prolonged treatment duration, the need for refinement phases, increased patient discomfort, and potentially compromised final occlusion. Haouili et al. (2020) reported that the overall accuracy of all tooth movements with clear aligners was approximately 50% and that significant differences between predicted and actual tooth movements were expected (Haouili et al. 2020). More recent prospective studies have confirmed that the lack of correction is significant for all movements and groups of teeth, with the greatest discrepancies found for angular movements and rotation of teeth characterized by round crowns at a ratio of approximately 0.4° achieved per 1° prescribed (Castroflorio et al. 2023).

1.3 The biology–digital mismatch

At the core of the predictability problem is a fundamental mismatch between the geometric precision of digital simulations and the biological complexity of orthodontic tooth movement. Current digital treatment planning software operates on a predominantly geometric paradigm: teeth are treated as rigid bodies that are translated and rotated along prescribed vectors, with movement staged in linear increments. The underlying assumption is that a given aligner geometry will produce a corresponding tooth displacement,

and that sequential aligners will produce cumulative, additive movements.

The orthodontic tooth movement (OTM), however, is not a linear geometric event. It is a complex biological process involving the transduction of mechanical forces into cellular signals, recruitment and differentiation of osteoclasts and osteoblasts, and coordinated remodeling of the periodontal ligament (PDL) and alveolar bone. This process is governed by mechanobiological pathways that include the RANKL/RANK/OPG signaling axis, the TGF- β pathway, and mechanosensitive ion channels such as Piezo1 and Piezo2, which collectively regulate the rate and extent of bone resorption and apposition in response to applied forces (Tang and Yang 2026). The biological response is inherently nonlinear and is characterized by lag phases, inter-individual variability, and adaptive tissue changes that cannot be fully captured by a geometric staging algorithm.

Therefore, it is critical to distinguish between geometric and biological predictability. Modern intraoral scanners and CAD software achieve remarkable geometric precision, with trueness and precision errors in the range of approximately 0.02 mm for orthodontic applications (Mangano et al. 2017). By contrast, biological predictability refers to the fidelity with which the living periodontium responds to applied forces in a manner that mirrors the prescribed tooth movement. However, the latter form of prediction remains unclear. Mechanobiological research has shown that individual genetic makeup significantly influences biological responses to orthodontic forces, with variations in the genes involved in bone remodeling contributing to interpatient variability (Tang and Yang 2026).

This review is based on the central thesis that the predictability gap observed in contemporary digital orthodontics is not primarily a failure of technology but rather a consequence of the incomplete integration of biological and biomechanical principles into digital treatment planning systems. Until digital planning platforms evolve to account for patient-specific biological variables and the nonlinear dynamics of tissue response, the discrepancy between the predicted and achieved tooth movement remains an inherent feature of simulation-driven orthodontics. The conceptual relationship between digital simulation, biological variability, and the resulting predictability gap is illustrated in Fig. 1.

This conceptual framework illustrates how contemporary digital orthodontic systems rely on geometric simulations and idealized biomechanical assumptions, whereas actual orthodontic tooth movement is governed by nonlinear biological responses, tissue remodeling dynamics, force decay, patient-specific variability, and clinical factors such as tracking loss and compliance. The interaction of these biological and biomechanical variables contributes to the

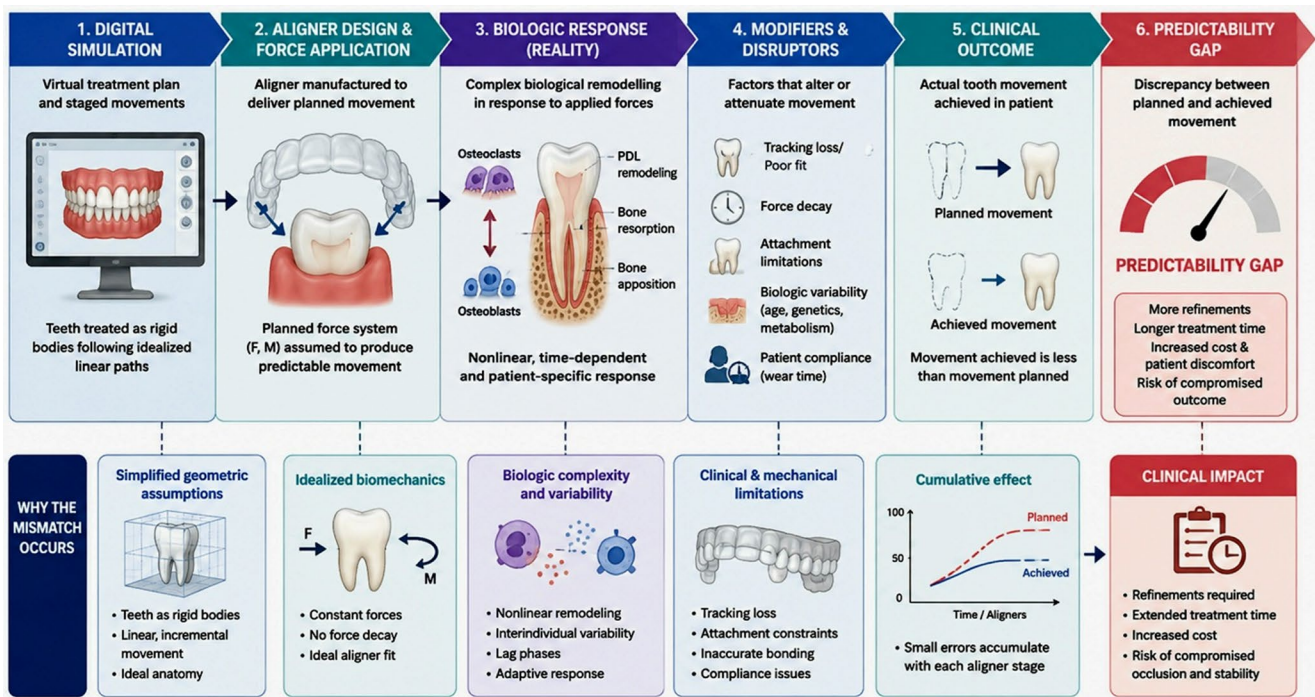


Fig. 1 The biology–digital mismatch in orthodontics: From digital simulation to clinical reality. The figures were created using Mind the Graph

discrepancy between predicted and clinically achieved tooth movement, resulting in the predictability gap observed in digital orthodontics.

1.4 Aim and scope of the review

This narrative review aims to provide a comprehensive and conceptually structured examination of the predictability of orthodontic tooth movement in the digital era, focusing on the interplay between digital simulation, biomechanics, and the underlying biology. This review is organized around three intersecting themes: the capabilities and limitations of contemporary digital orthodontic systems, the biological determinants that govern individual variability in tooth movement response, and the biomechanical principles underlying force delivery in aligner-based mechanotherapy.

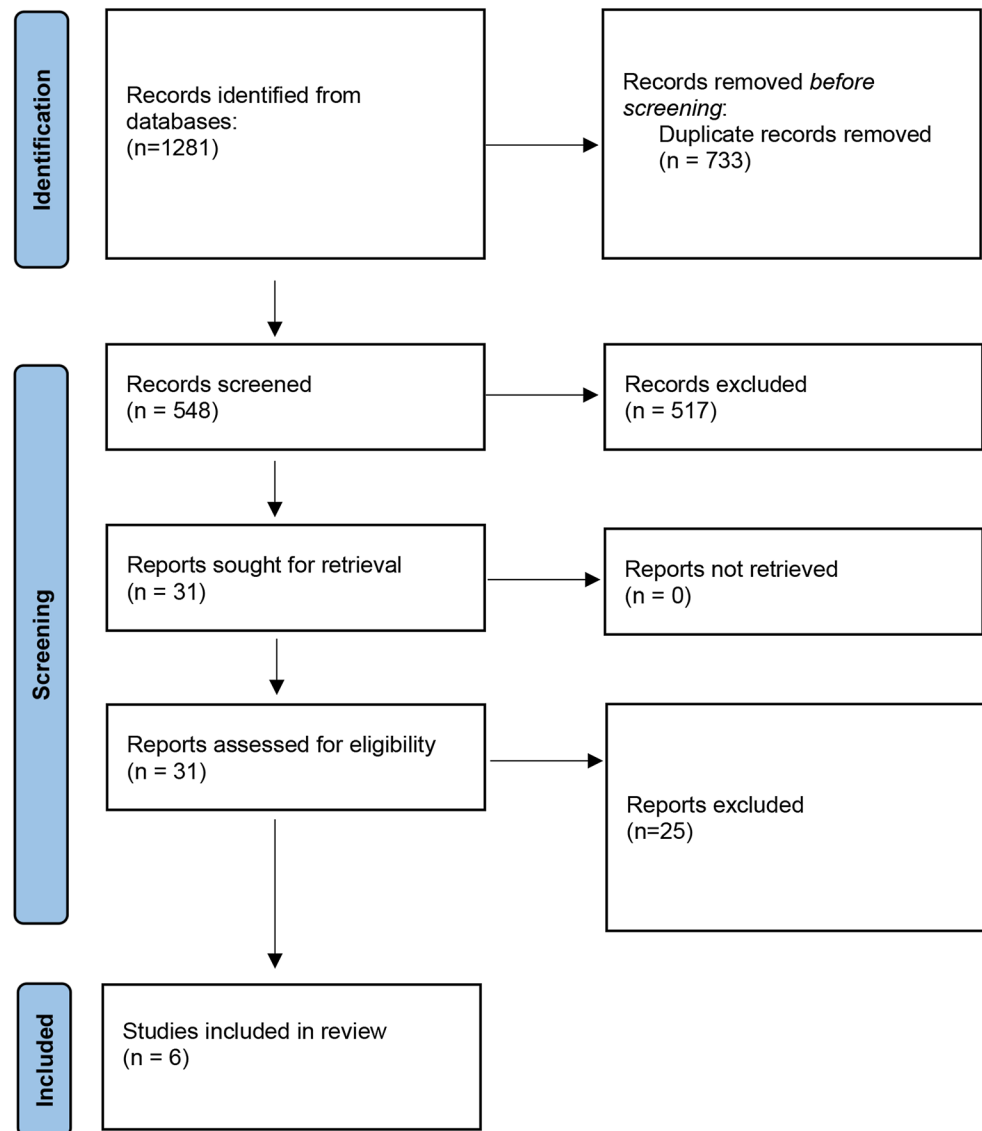
This review adopts a critical narrative, evidence-informed approach rather than a systematic review methodology. The objective was not only to summarize the existing literature, but also to compare the available evidence, analyze the biomechanical and biological reasons underlying inconsistent clinical findings, and propose a conceptual explanatory framework for the mismatch between digitally predicted and clinically achieved orthodontic tooth movement. This review further seeks to identify recurring patterns across the literature and construct a coherent framework to understand why digital simulations frequently fail to translate into clinical reality. The scope encompasses both fixed and removable digital orthodontic systems, although emphasis

is placed on clear aligner therapy, given its inherent dependence on virtual treatment planning and its dominant role in the contemporary digital orthodontic landscape.

Several recent reviews have addressed clear aligner predictability. Naoum and Lee (2026) provided a comprehensive three-tier classification (Naoum and Lee 2026), Alwafi et al. (2023) published an overview of systematic reviews (Alwafi et al. 2023), and a 2026 AJODO article explored strategies to enhance predictability (Long and Park 2026). Unlike previous narrative and systematic reviews that have catalogued movement-specific accuracy rates, this review proposes an integrative explanatory framework, the Biology-Digital Mismatch, which holds that the predictability gap arises from the collision of two fundamentally different systems: geometrically precise but biologically naïve software and the nonlinear, patient-specific biologic response of the periodontal tissues.

1.5 Search strategy and evidence selection

A structured literature search of PubMed, Scopus, and Google Scholar was conducted for publications up to May 2026 using the following keyword groups and Boolean operators: (a) “clear aligner” OR “digital orthodontics” OR “aligner therapy” AND (b) “predictability” OR “tooth movement accuracy” OR “treatment outcome” AND (c) “biomechanics” OR “biologic response” OR “periodontal ligament” OR “bone remodeling.” Systematic reviews, meta-analyses, and clinical studies that quantified or classified the discrepancy

Fig. 2 Summary of Study Selection process

between predicted and achieved tooth movement with clear aligners were eligible for the core evidence synthesis. No language restrictions were applied; however, only peer-reviewed publications were considered.

The database search identified 1281 records. After the removal of 733 duplicates, 548 records were screened by title and abstract, and 517 were excluded. Thirty-one full-text reports were retrieved and assessed for eligibility; 25 were excluded, and six studies were included in the core evidence synthesis. The study selection process is shown in Fig. 2. In addition, 23 publications were identified through targeted subtopic searches (e.g., “mechanobiology AND orthodontic tooth movement,” “artificial intelligence AND orthodontic treatment planning,” “attachment design AND clear aligner,” and “overcorrection AND aligner therapy”) and manual screening of reference lists; these were used as supporting literature for the digital, biological,

biomechanical, and AI sections, giving a total of 29 cited references. Given the narrative design of this review, no formal quality-assessment tool was applied; instead, studies were critically appraised for methodological rigor, sample size, and relevance to the central thesis.

2 Contemporary digital orthodontics: current capabilities and limitations

2.1 Digital treatment planning and virtual staging

Intraoral scanners offer clinically acceptable accuracy and improve patient comfort (Mangano et al. 2017). Once acquired, the digital model is imported into treatment-planning software, in which individual teeth are segmented, a virtual setup is performed, and tooth movements are staged

in increments of approximately 0.2 mm of linear or 2° of angular movement per aligner (Naoum and Lee 2026). The staged models are 3D-printed and aligners are thermoformed over them, a CAD/CAM pipeline that allows a degree of customization that is difficult to achieve with conventional laboratory techniques (Mangano et al. 2017).

2.2 Advantages of digital orthodontics

Digital workflows provide three-dimensional visualization of the malocclusion and the proposed treatment sequence, and the integration of intraoral scans with CBCT volumes allows root positions to be visualized relative to the alveolar bone (Mangano et al. 2017). Digital platforms enable substantial customization; attachment placement, aligner trimline design, and staging velocity can be tailored to the specific requirements of each case (Bichu et al. 2024). Presenting a virtual treatment simulation to patients before commencing therapy improves case acceptance and patient engagement (Mangano et al. 2017). AI-driven remote monitoring systems, which use smartphone-based photographic evaluations to assess aligner tracking and patient compliance, have the potential to reduce the number of in-office visits and enable earlier detection of treatment deviations (Ruiz et al. 2025).

2.3 Limitations of simulation-based orthodontics

Despite these advantages, digital platforms have fundamental limitations. First, virtual staging presents tooth movements as independent, isolated events, whereas, in clinical reality, forces are transmitted through the aligner and across interproximal contacts, and every planned movement generates reactive forces elsewhere in the dentition (Bichu et al. 2024).

Second, digital treatment planning is static. The entire sequence is predetermined, and each aligner is designed on the tooth position expected at the previous stage; if a tooth fails to track, the error propagates through the remaining aligners, a major contributor to high refinement rates (Bichu et al. 2024).

Third, and most critically for the thesis of this review, the software stages movement using geometric algorithms and preset velocities without accounting for bone density, periodontal condition, age, genetic polymorphisms affecting bone remodeling, or concomitant medications (Bichu et al. 2024). Therefore, two patients with identical malocclusions treated with identical aligner sequences may exhibit markedly different clinical responses.

2.4 Clinical implication

Orthodontists should view the digital setup as a treatment template rather than a guaranteed outcome and routinely plan for refinement from the outset.

3 The Predictability paradox in orthodontics

3.1 Predicted vs. achieved tooth movement

The predictability of orthodontic tooth movement refers to the degree of concordance between the tooth displacement prescribed in a digital treatment plan and the displacement achieved by the patient. The literature has established a clinically useful classification system that categorizes tooth movement into three tiers. As described in Sect. 1.2, tooth movements are classified into low (<50%), moderate (50–75%), or high (>75%) predictability tiers (Naoum and Lee 2026).

The mechanisms underlying differential predictability are rooted in biology and biomechanics. Extrusion is poorly achieved because aligners rely on the elastic recovery of thermoplastic material to generate forces; when the aligner is stretched over a tooth programmed to be extruded, the material tends to separate from the tooth surface, resulting in incomplete force delivery (Castroflorio et al. 2023). The rotation of teeth with round clinical crowns, such as premolars and canines, presents a mechanical challenge because the aligner cannot adequately grasp the tooth surface to deliver the force couple necessary for pure rotation. Torque requires a force couple that is difficult to generate with a removable thermoplastic appliance that primarily engages the clinical crown (D'Antò et al. 2024).

3.2 Clinical evidence on movement accuracy

A growing body of clinical evidence has quantified the discrepancy between predicted and achieved tooth movements. Haouili et al. (2020) reported that the overall accuracy of all tooth movements with clear aligners was approximately 50% (Haouili et al. 2020). Castroflorio et al. (2023) found that rotational movements of canines and premolars were achieved at a rate of approximately 0.4° per 1° prescribed, representing only 40% predictability (Castroflorio et al. 2023). A 2025 systematic review of rotational movements confirmed this hierarchy, reporting a mean accuracy of approximately 65% across studies, with incisors and molars demonstrating consistently higher predictability than maxillary canines and premolars (Benedetti et al. 2025).

A systematic review of mesiodistal molar movements reported that upper molar distalization demonstrated a mean predictability of 61.1% for movements ranging from

0.45 to 3.2 mm, while molar mesial movement exhibited substantially higher median predictability of 85.6% (García-Marín et al. 2025). More recently, Alulyan et al. (2026) demonstrated in a retrospective cohort of 44 patients that all mandibular anterior teeth exhibited significant discrepancies between predicted and achieved movements, with rotational discrepancies of canines being the largest (mean difference 3.46 ± 3.25). A novel finding was the positive association between crowding severity and movement inaccuracy; a one-unit increase in crowding corresponded to a 0.49 increase in lower canine rotational difference (Alulyan et al. 2025). For rotational movements, D'Antò et al. (2024) reported overall predictability rates of 78.6% for the mandibular arch and 75.0% for the maxillary arch, with the lowest accuracy consistently observed for second molars in both arches (D'Antò et al. 2024). A systematic review of lower incisor intrusion found that achieved intrusion represented approximately 35–65% of the planned movement (Fracchia et al. 2025). The clinical consequences of this predictability gap are highly dependent on refinement, with a substantial proportion of clear aligners requiring at least one additional series of aligners (Bichu et al. 2024). Comparison of these studies revealed patterns of differential movement expressions that cannot be explained by appliance design alone, pointing to the interplay between force delivery characteristics and individual biological responsiveness. Table 1 summarizes the key studies that quantified the discrepancy between predicted and achieved tooth movements.

3.3 Clinical implication

Clinicians should inform patients that movements such as extrusion and canine rotation are likely to be less accurate and should incorporate overcorrection strategies during initial planning.

4 Biological determinants of orthodontic tooth movement

4.1 Periodontal ligament and bone remodeling

Orthodontic tooth movement is a biological phenomenon that occurs through coordinated remodeling of the periodontal ligament and alveolar bone in response to applied mechanical forces. When orthodontic force is applied, compression and tension regions are created within the periodontal ligament. On the compression side, reduced blood flow and local hypoxia lead to release of proinflammatory mediators, including interleukin-1 beta (IL-1 β), prostaglandin E2 (PGE2), and tumor necrosis factor alpha (TNF- α), which collectively promote recruitment and differentiation of osteoclast precursors. On the tension side, increased vascular perfusion and mechanical strain stimulate osteoblast differentiation and the deposition of new bone matrix.

At the molecular level, receptor activator of nuclear factor kappa-B ligand (RANKL), its receptor RANK, and its

Table 1 Studies evaluating predicted vs. achieved tooth movement with clear aligners

Study	Year	Design	Sample	Movement Type(s)	Key Findings on Predictability	Study Design Hierarchy	Limitations
Castroflorio et al. (Castroflorio et al. 2023)	2023	Prospective Clinical	$n = 79$	Rotations, angulations, linear	0.4°/1° prescribed for canine/pre-molar rotations; lack of correction significant for all movements	II	Single-centre; short observation
D'Antò et al. (D'Antò et al., 2024)	2024	Retrospective	$n = 45$	Rotations	78.6% mandibular, 75.0% maxillary; lowest for second molars	III	Retrospective; no attachment analysis
García-Marín et al. (García-Marín et al. 2025)	2025	Systematic Review	Systematic review (6 studies)	Mesiodistal molar	Upper distalization $61.1\% \pm 9.1\%$; mesial movement $85.6\% \pm 1.1\%$	I	Moderate heterogeneity
Naoum & Lee (Naoum and Lee 2026)	2026	Narrative Review	Narrative review	Multiple	Low: extrusion, intrusion, canine/premolar rotation, torque; Moderate: incisor rotation, tip; High: expansion, maxillary distalization	V	Author opinion
Alulyan et al. (Alulyan et al. 2025)	2026	Retrospective	$N = 44$	Linear, vertical, rotational (mandibular anterior)	All anterior teeth showed significant discrepancies (mean 3.46 ± 3.25); rotational canines least accurate; crowding positively associated with inaccuracy	III	Small sample; single aligner system
Benedetti et al. (Benedetti et al. 2025)	2025	Systematic Review	Systematic review (12 studies)	Rotations (all tooth types)	Accuracy range 36–85%, averaging around 65%; incisors/molars more predictable than canines/premolars	I	Low-moderate certainty of evidence

*Study design hierarchy was assigned according to the methodological characteristics of each included study: Level I, systematic reviews/meta-analyses; Level II, prospective clinical studies; Level III, retrospective observational studies; Level IV, case series and other observational studies; and Level V, narrative reviews and expert opinion

decoy receptor osteoprotegerin (OPG) constitute the principal signaling axis governing bone resorption. Mechanical compression upregulates RANKL expression while simultaneously downregulating OPG and shifting the RANKL/OPG ratio to favor osteoclastogenesis. Concurrently, mechanosensitive ion channels of the Piezo family, particularly Piezo1 and Piezo2, have been identified as critical molecular translators that convert physical forces into biochemical signals, initiating the intracellular calcium signaling cascades underlying osteoclast differentiation and activation (Tang and Yang 2026).

The biological response is inherently nonlinear. Following force application, a lag phase occurs before osteoclast recruitment reaches sufficient levels to initiate bone resorption (Li et al. 2021). The rate of movement then accelerates as the remodeling process becomes established before gradually decelerating as the periodontal tissues adapt. This temporal pattern, which includes lag, acceleration, and plateau phases, contrasts sharply with the linear constant-velocity movement assumed by digital staging algorithms.

4.2 Patient-specific biological variability

Orthodontic tooth movement is subject to substantial inter-individual variability arising from multiple patient-specific factors. Age is among the most significant determinants, with younger patients consistently exhibiting faster and more pronounced biological responses to orthodontic forces, with biomarker levels, including RANKL, OPG, IL-1 β , IL-6, PGE2, and alkaline phosphatase, peaking within the first 72 h of force application (Kapoor et al. 2014). In adults, the tissue response is characteristically slower, with reduced cellularity of the periodontal ligament and decreased vascularity of the alveolar bone, contributing to a longer lag phase and diminished rate of movement.

Sex has also been shown to significantly influence the biological response to orthodontic forces; transcriptomic analysis of periodontal ligament and pulp tissue gene expression demonstrated that females exhibit more active osteoclastic responses during the early phase of orthodontic loading, whereas age primarily affects calcium homeostasis and regenerative capacity during later phases (Zhao et al. 2025). Genetic factors represent another critical source of variability, with polymorphisms in genes encoding components of the RANKL/RANK/OPG pathway, interleukins, matrix metalloproteinases, and collagen types associated with differences in the rate of tooth movement and susceptibility to root resorption (Tang and Yang 2026).

Systemic conditions and concomitant medications further modulate the biological responses. Patients with diabetes mellitus, hypothyroidism, or osteoporosis may exhibit altered bone turnover rates that affect the tooth movement velocity.

Medications such as nonsteroidal anti-inflammatory drugs reduce prostaglandin synthesis and diminish the rate of tooth movement, whereas bisphosphonates profoundly suppress osteoclast activity. Corticosteroids, parathyroid hormone, and thyroxine may accelerate tooth movement, whereas estrogen may reduce it (Diravidamani et al. 2012).

4.3 Biological responsiveness and movement variability

The cumulative effect of these biological variables means that OTM cannot be fully standardized across patients. Even within a single individual, different teeth may exhibit different rates and extents of movement depending on local factors, such as root morphology, bone density, and periodontal ligament thickness. Given the significant individual variability in biological responses, personalized treatment approaches utilizing optimized force regimens and targeted interventions are essential to balance treatment efficiency with periodontal safety (Tang and Yang 2026). This fundamental biological heterogeneity is in direct contrast to the standardization inherent in digital treatment planning, where identical movement velocities and aligner activation patterns are applied across all patients regardless of their biological profiles.

5 Biomechanics in the digital era

5.1 Fundamentals of orthodontic biomechanics

Orthodontic biomechanics is based on an analysis of force systems and their effects on tooth displacement. An orthodontic force system comprises both forces and moments. The key factor influencing the type of tooth movement produced is the center of resistance, which represents the point within a tooth or group of teeth through which the line of action of an applied force must pass to induce pure bodily translation. If the line of action of the applied force deviates from the center of resistance, a moment is generated that rotates the tooth, resulting in tipping rather than bodily movement. To achieve controlled bodily movement, a counterbalancing moment must be applied, and the ratio of the applied moment to the applied force, termed the moment-to-force ratio, determines the center of rotation and thus the characteristics of the resulting tooth movement (Liaw et al. 2024).

5.2 Biomechanics of clear aligners

Clear aligners generate orthodontic forces through elastic deformation of a thermoplastic shell fabricated with a shape mismatch relative to the current tooth position. When the

aligner is seated over the dentition, the material is strained, and its elastic recovery generates forces and moments that are transmitted to the teeth. The aligner engages the clinical crown, which is typically located 8–12 mm from the center of resistance. This substantial distance indicates that the forces generated by the aligner inherently tend to produce tipping rather than bodily movements (Naoum and Lee 2026).

To mitigate this limitation, clear aligner systems employ composite resin attachments that are bonded to the tooth surface. Attachments serve three principal functions: increasing the surface area available for aligner engagement, providing undercuts that improve aligner retention, and creating leverage points that enable the generation of force couples necessary for controlled rotational and torque movements. Recent finite element analysis studies compared different attachment designs for specific movements and found that certain configurations enhance buccolingual stability during molar mesialization (Vatansever et al. 2025).

The aligner material properties are critical for force delivery. Thermoplastic materials exhibit viscoelastic behavior, characterized by stress relaxation over time. When an aligner is first seated, the initial force magnitude is the highest. Over subsequent hours and days, the force decays as the polymer chains gradually rearrange to accommodate the strain, reducing the orthodontic activation delivered to the periodontium. Recent evidence suggests that aligners with variable moduli of elasticity may offer the potential for improved treatment outcomes, with simple alignment achievable using softer materials, whereas more complex movements may benefit from higher-modulus materials (Weir and Meade 2026).

5.3 Limitations of current digital biomechanical models

Current digital treatment planning software operates on biomechanical models that are substantially simplified relative to the clinical reality. The primary limitation is the assumption of linear additive tooth movement. The software calculates the position of each tooth at each stage based on the premise that the aligner geometry will produce a proportional and predictable tooth displacement and that the cumulative effect of sequential aligners is the arithmetic sum of individual stage movements. This assumption neglects the viscoelastic behavior of the aligner material, the time-dependent nature of stress relaxation, and the variability of force delivery across different tooth types and movement directions.

The second limitation relates to the static nature of the treatment planning. Once the aligner series is manufactured, the biomechanical environment is fixed for the duration of the series. If a tooth does not track as planned, the force

system cannot be adjusted in real time, and maladaptation propagates through the remainder of the aligner series, producing cumulative errors that necessitate refinement (Bichu et al. 2024). This contrasts with fixed-appliance therapy, in which the orthodontist can adjust the archwire dimensions, bracket positions, and auxiliary mechanics at each appointment to adapt to the observed tissue response.

Third, current digital biomechanical models lack the integration of patient-specific anatomic variables. The location of the center of resistance varies among individuals, depending on root length, root morphology, alveolar bone height, and periodontal attachment level. Digital planning software does not routinely incorporate cone beam computed tomography (CBCT)-derived data on root dimensions and bone morphology when calculating force systems and staging sequences. Consequently, the same aligner geometry may produce different force systems and movement responses in different patients, which is a source of variability for which the planning software was not designed.

6 The illusion of linear tooth movement

6.1 Nonlinear nature of orthodontic movement

Contemporary digital treatment planning is built on an implicit assumption of linearity: each aligner delivers a prescribed increment in tooth displacement, and the sequential accumulation of these increments produces the final tooth position in a predictable and additive manner. However, OTM is nonlinear. At the tissue level, the response to the applied force follows a characteristic temporal pattern, beginning with a lag phase, during which osteoclast precursors are recruited to the compression sites. In humans, this lag phase can extend up to approximately 21 days before clinically detectable tooth movement begins (Iwasaki et al. 2000). Once bone resorption is established, the rate of movement accelerates, plateaus, and eventually decelerates as the tissues adapt. Furthermore, the biological response to the orthodontic force exhibits a saturation phenomenon; beyond a certain force magnitude, further increases do not produce corresponding increases in the rate of tooth movement (Alikhani et al. 2015).

6.2 Sources of clinical inaccuracy

The divergence between the simulated and actual tooth movements arises from multiple interacting sources. Tracking loss is the most visible manifestation; a progressive gap develops between the aligner and the tooth surface as the tooth fails to maintain its programmed position. This loss compounds with each successive aligner as a poorly fitting

tray reduces the force delivery further (Bichu et al. 2024). Force decay represents a second source: thermoplastic materials exhibit viscoelastic stress relaxation, losing a substantial proportion of their initial force within the first 24–48 h of wear (Weir and Meade 2026). Cumulative staging errors also contribute. If a movement prescribed for a single stage exceeds the biological or biomechanical capacity of the system, the residual discrepancy propagates through the subsequent stages.

6.3 Why simulated movement fails clinically

The failure of simulated tooth movements to translate into clinical reality is the product of an interaction between biology and biomechanics, which is not captured by current digital paradigms. The nonlinear tissue response, interindividual variability in bone remodeling, and saturation of the biological response ensure that the movement rate varies in ways that are unpredictable from geometry alone. Simultaneously, viscoelastic force decay and cumulative error propagation limit the biomechanical fidelity. The dynamic nature of treatment response further compounds the problem: in aligner therapy, the entire force sequence is predetermined at the outset, and the system lacks the capacity to adapt in real time to deviations from the planned trajectory (Bichu et al. 2024). This rigidity renders aligner therapy inherently more susceptible to cumulative variability than fixed-appliance therapy.

7 Evidence synthesis and analytical perspective

7.1 Comparative analysis of movement predictability

Accumulated clinical evidence permits a comparative analysis of the predictability of different orthodontic tooth movements with clear aligners. Thus, a consistent hierarchy emerges. Maxillary expansion and maxillary buccal segment distalization consistently demonstrated the highest predictability, with movements exceeding 75% of those planned. Mesiodistal angulation changes and incisor rotations occupied an intermediate tier (50–75% achieved). The lowest predictability was observed for extrusion, intrusion, torque of anterior teeth, and rotation of canines and premolars, where the achieved displacement was consistently less than 50% of planned (Castroflorio et al. 2023; Naoum and Lee 2026). A recent study further demonstrated that the severity of the lower anterior crowding independently exacerbates this discrepancy, with each unit increase in crowding producing measurable increases in rotational and

Table 2 Predictability of different orthodontic movements with clear aligners

Movement Type	Predictability Tier	Approximate Achievement	Key Primary Studies
Maxillary expansion	High (> 75%)	80–90%	(Naoum and Lee 2026)
Molar distalization	High (> 75%)	61–86%	(García-Marín et al. 2025)
Incisor rotation	Moderate (50–75%)	75–79%	(D'Antò et al. 2024)
Mesiodistal angulation	Moderate (50–75%)	60–75%	(Castroflorio et al. 2023)
Torque (anterior)	Low (< 50%)	30–45%	(Naoum and Lee 2026)
Canine/premolar rotation	Low (< 50%)	40%	(Castroflorio et al. 2023)
Extrusion	Low (< 50%)	30–40%	(Naoum and Lee 2026)
Intrusion (anterior)	Low (< 50%)	35–65%	(Fracchia et al. 2025)

linear movement errors (Alulyan et al. 2025). This hierarchy reflects the biomechanical capacity of aligners to deliver controlled forces; movements accomplished through crown tipping are more predictably expressed than those requiring root movement, and teeth with favorable crown morphology for aligner engagement are more predictable than those with round clinical crowns. Table 2 categorizes the common orthodontic movements according to their reported predictive tiers and approximate clinical achievement rates.

7.2 Patterns and causes of treatment inaccuracy

The analysis revealed four principal categories of factors underlying the treatment inaccuracies. Biological variability is the most fundamental factor; even with identical force systems, the rate and extent of tooth movement can vary by a factor of three or more between individuals (Iwasaki et al. 2000). Poor force expressions represent the second category. Aligners are inherently limited in generating the force couples required for controlled root movement, and complex movements, such as extrusion and torque, are consistently more prone to tracking challenges. Material limitations constitute the third category. Stress relaxation reduces the orthodontic force over each wear interval. Patient compliance is the fourth category, and insufficient wear time is one of the most common causes of tracking failures (Bichu et al. 2024). A tooth-level analysis of 696 maxillary anterior teeth further identified that rotation and inclination of the lateral incisors independently increased the likelihood of requiring refinement, whereas planned extrusion surprisingly reduced it (Özkan 2025).

7.3 Analytical interpretation of current evidence

Several trends have emerged from the accumulated evidence. First, the overall accuracy of tooth movement with clear aligners consistently converges to a mean of approximately 50–60% when all movement types are aggregated, although this obscures substantial heterogeneity. Among the conflicting findings, the studies by Castroflorio et al. (2023) and Benedetti et al. (2025) are particularly informative because they reported both mean accuracy and its variability, and they used contemporary aligner materials. Therefore, the lower end of the range (approximately 40% for canines) is considered more clinically realistic for challenging rotations, whereas the higher end reflects well-planned cases with optimized attachments (Benedetti et al. 2025; Castroflorio et al. 2023). Second, the refinement rate has become a de facto indicator of predictability, with the majority of cases requiring at least one additional aligner series. Third, the predictability gap has not narrowed substantially over time, despite advances in materials and attachment design, supporting the thesis that meaningful improvement requires the integration of biological variables into planning rather than the continued refinement of geometric approaches.

8 Artificial intelligence and the future of precision orthodontics

8.1 Current applications of AI in orthodontics

Artificial intelligence is being rapidly integrated into the orthodontic workflow across the treatment pathway. In the diagnostic phase, AI-assisted cephalometric landmark detection achieved a clinically acceptable accuracy comparable to that of expert manual tracing (Polizzi et al. 2026). AI models also assist in extraction decision-making, anchorage prediction, and treatment duration forecasting. In treatment planning, AI-based tooth segmentation has achieved approximately 98% accuracy, and deep-learning algorithms support automated measurements and outcome predictions (Ruiz et al. 2025). Emerging neuroscientific frameworks, such as OrthoAI, combine 3D dental segmentation with automated biomechanical analysis, encoding evidence-based per-stage limits as constraints to help identify plans that are geometrically feasible but biomechanically problematic (Lansiaux et al. 2026).

8.2 Limitations of current AI models

The current AI models in orthodontics are limited by their predominant use of geometric datasets. They lack access to the biological data required to predict individual tissue

responses, meaning that AI can optimize the geometric sequence but cannot forecast whether a given sequence is biologically achievable in a specific patient. Additional limitations include dataset bias, limited generalizability across diverse populations, and the “black box” nature of many deep learning models, which raises concerns regarding clinical accountability and transparency (Nordblom et al. 2024). Moreover, most current AI algorithms are trained on datasets from single-ethnic populations and lack cross-population validation. Federated learning approaches that allow model training across institutions without sharing patient data can address this issue while maintaining data privacy. Additionally, the implementation of AI-guided orthodontics raises unresolved ethical and legal questions, including the liability for treatment decisions, data security, and the need for explainable AI frameworks that make algorithmic recommendations transparent to clinicians.

8.3 Toward biologically adaptive orthodontics

The future of precision orthodontics lies in treatment-planning systems that integrate biological and biomechanical data with geometric models. Such systems would incorporate patient-specific biomarkers of bone-remodeling activity, genetic polymorphisms, bone density from CBCT, age, and periodontal status. Treatment plans are dynamically adjusted based on the monitored tissue response, with AI algorithms analyzing remote monitoring data to detect deviations and recommend midcourse corrections. Concurrently, innovations in aligner materials, such as shape-memory polymers that deliver sustained forces and direct 3D printing that eliminates geometric distortion, may improve biomechanical fidelity (Eliades 2026; Weir and Meade 2026). The convergence of mechanobiological understanding, material science, and computational capability creates conditions for a paradigm shift from geometric to biologically informed personalized care.

9 Clinical implications

9.1 Implications for orthodontic practice

The recognition that digital treatment simulations represent idealized projections has several practical implications. First, systematic overcorrection strategies should be adopted for low-predictability movements. Incorporating approximately 20% overcorrection into the initial digital setup for challenging movements such as inclination and rotation can substantially reduce the residual discrepancy and the need for refinement phases (Palone et al. 2023). Second, refinement should be anticipated as an integral component of

clear aligner therapy rather than a failure. Proactive planning for refinement, including strategic sequencing of complex movements, can minimize the total treatment duration. Third, case selection must account for the predictability hierarchy; malocclusions with substantial torque, extrusion, or rotation of round-crowned teeth may be more predictably managed with fixed appliances.

9.2 Patient communication and expectations

Effective communication regarding predictability is both an ethical obligation and a practical necessity. Visually compelling simulations generated using digital software may create unrealistic patient expectations regarding treatment certainty and timelines. Clinicians should contextualize these simulations as treatment goals rather than guaranteed outcomes and explicitly address the likelihood of refinement and factors influencing treatment duration. Setting realistic expectations at the outset reduces the risk of dissatisfaction and facilitates the collaborative management of inevitable deviations.

9.3 Clinical decision-making in digital orthodontics

This evidence supports a model of clinical decision-making in which digital simulations serve as a valuable planning tool but do not replace clinician judgment based on biological and biomechanical understanding. Digital treatment planning software determines where teeth can be moved geometrically but does not indicate whether these movements are biologically or biomechanically realistic (Bichu et al. 2024). Orthodontists must critically evaluate digital plans, identify movements that are likely to be poorly expressed, and incorporate compensatory strategies. The digital treatment plan is best understood as a starting point for clinician-guided optimization, a framework refined through the application of principles the software does not yet incorporate.

Key Clinical Take-home Messages.

1. Digital setups are templates, not guarantees — anticipate refinement.
2. Movements with low predictability (extrusion, torque, and canine rotation) require routine overcorrection.
3. Patient compliance and force decay are major modifiable contributors to tracking loss.
4. Case selection should consider the predictability hierarchy, because complex cases may benefit from fixed appliances.
5. AI currently improves geometric planning but cannot yet predict individual biologic response.

6. Biomarker-guided orthodontics is a promising but unvalidated strategy.
7. Effective communication of realistic expectations reduces dissatisfaction.

10 Future directions and research gaps

The predictability gap is a structural consequence of treatment-planning systems that neglect biological realities. Addressing this issue requires a coordinated research across several domains.

- **Biologically integrated predictive models.** Computational models that couple finite element biomechanical analysis with bone-remodeling algorithms must be translated from research environments into clinical treatment planning tools to enable patient-specific probabilistic predictions of tooth movement trajectories (Van Schepdael et al. 2013).
- **Longitudinal studies on movement variability.** Repeated digital scans throughout the treatment, combined with monitoring of biological and behavioral covariates, are needed to characterize the temporal dynamics of predictability loss and inform adaptive intervention strategies.
- **Biomarker-guided orthodontics.** Gingival crevicular fluid and salivary biomarkers (RANKL, OPG, IL-1 β , IL-6, PGE2) correlate with movement rate and could be developed into point-of-care monitoring systems to stratify patients and guide force regimens (Kapoor et al. 2014; Tang and Yang 2026).
- **Smart aligners and adaptive systems.** Shape-memory polymers and integrated microsensors enable aligners to monitor force delivery and wear time, thereby providing data for real-time closed-loop treatment adaptation (Eliades2026).
- **AI-driven precision orthodontics.** Future AI must evolve to incorporate multimodal data, including biomarkers, genetics, and CBCT-derived bone information, using explainable algorithms that articulate reasoning and undergo rigorous prospective validation across diverse populations (Ruiz et al. 2025).
- **Multicenter prospective trials.** Large-scale, multicenter clinical trials with standardized protocols are needed to validate patient-specific finite element models and digital twin technologies and to determine whether biomarker-guided force modulation improves predictability in everyday practice.

11 Limitations

This study had some limitations. First, this was a narrative synthesis; study selection and interpretation were performed by a single author, introducing possible selection bias. Second, formal quality-assessment instruments were not applied; therefore, the strengths of the individual studies were judged qualitatively. Third, gray literature and unpublished works were excluded, which may have biased the evidence toward studies with positive or significant findings. Fourth, the rapid evolution of aligner materials and AI algorithms means that some of the included data, particularly from pre-2020 studies, may not fully reflect current technology. Finally, the heavy reliance on very recent in-press publications, while ensuring contemporaneity, means that some cited works have not yet been replicated. Readers should weigh these factors when interpreting conclusions.

12 Conclusion

This narrative review addresses the predictability gap in orthodontic tooth movement arising from the fundamental mismatch between the geometric precision of digital simulations and the biological complexity of the periodontal tissue response. Digital orthodontic systems model teeth as rigid bodies following idealized trajectories, whereas actual tooth movement is a nonlinear biological process influenced by mechanobiological pathways and significant inter-individual variability, including age, genetics, bone density, health status, and medication. This gap manifests clinically as an incomplete expression of the prescribed movements, cumulative tracking loss, and a frequent need for refinement. Movements requiring controlled root displacement exhibit notably lower accuracy than crown tipping, with an overall clear aligner accuracy averaging 50–60%. Bridging this gap requires the integration of biomechanical and biological insights into digital planning through mechanobiological predictive models, longitudinal research, biomarker-guided protocols, smart materials, and explainable AI capable of multimodal data reasoning. Until such advances are realized, clinicians must critically interpret digital treatment plans as geometric templates rather than literal prescriptions, applying judgments grounded in biomechanics and tissue physiology to adapt and overcorrect treatments based on individual biological responses. The proposed Biology–Digital Mismatch framework elucidates the persistent unpredictability of certain tooth movements and offers a roadmap for incorporating biological intelligence into orthodontic treatment planning.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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