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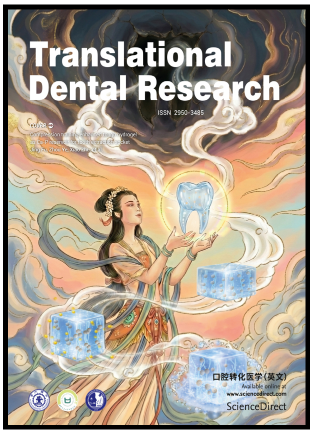

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Advancing Orthodontic Care Through Digital Twin Technology

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Abstract

Digital twin technology represents a transformative innovation in healthcare, creating virtual replicas that enable real-time monitoring, simulation, and predictive analytics. At its core, a digital twin is a comprehensive virtual representation of a physical entity that continuously synchronizes with real-world data, enabling dynamic simulation and predictive capabilities that distinguish it from static digital models or digital shadows. In orthodontics, digital twins integrate patient-specific anatomical data, treatment parameters, and biomechanical simulations to enhance clinical decision-making. Advances in three-dimensional imaging, artificial intelligence, and computational modelling have accelerated adoption, offering unprecedented opportunities for personalised planning. This narrative review aims to examine the current applications of digital twin technology in orthodontics, evaluate its clinical benefits and limitations, and explore future directions for research and implementation. A narrative review methodology was employed, synthesising peer-reviewed literature, clinical reports, and technological assessments published between 2018 and 2025. Electronic databases were searched to identify relevant studies on digital twin applications in orthodontic diagnosis, treatment planning, and biomechanical simulation. Digital twin technology demonstrates significant potential in orthodontics across multiple domains, including enhanced treatment planning accuracy, improved prediction of tooth movement, personalised biomechanical analysis, and adaptive treatment monitoring. Integration of artificial intelligence with digital twin models enables sophisticated outcome predictions and adaptive protocols. However, challenges persist, including high computational requirements, data integration complexities, the distinction between true digital twins and static digital workflows, and the need for standardised protocols. Digital twin technology represents a paradigm shift in orthodontic practice, offering transformative potential for precision diagnosis and individualised treatment. Future developments should focus on improving accessibility, establishing validation protocols, and integrating real-world evidence to support widespread adoption.

Keywords: Digital twin, orthodontics, treatment planning, biomechanical simulation, artificial intelligence

1 Introduction

The evolution of orthodontic practice has been characterised by continuous technological advancement, from the introduction of fixed appliances to the development of digital treatment planning systems [1]. In recent years, digital twin technology has emerged as a revolutionary approach in healthcare, creating virtual representations of physical entities that mirror their real-world counterparts in structure, behaviour, and response to interventions [2]. Digital twins represent a significant evolution beyond traditional digital models through their defining characteristics: bidirectional data flow enabling continuous synchronization between physical and virtual entities, real-time or near-real-time updating capabilities that reflect current state, predictive and prescriptive analytics for scenario simulation, integration of multi-source data streams including imaging, biomechanical parameters, and temporal progression, and adaptive learning mechanisms that refine predictions based on observed outcomes [3,4]. This conceptual framework distinguishes digital twins from static digital representations or digital shadows that lack continuous data exchange and predictive capabilities. Originally developed in aerospace and manufacturing industries, digital twin technology has found compelling applications in medicine and dentistry, where its capacity for personalised simulation and predictive modelling aligns perfectly with the growing emphasis on individualised patient care. The orthodontic specialty, with its inherent reliance on precise three-dimensional analysis and biomechanical principles, presents an ideal environment for digital twin implementation [5].

The conceptual origins of digital twin technology can be traced to 2002, when Michael Grieves first articulated the idea of a virtual, digital equivalent of a physical product, initially termed the 'mirrored spaced model' before the phrase 'digital twin' gained wider currency [6,7] Early practical implementations emerged through NASA's Apollo programme and subsequent aerospace engineering, where virtual models of spacecraft were used to simulate and diagnose in-flight anomalies in real time. The United States Department of Defense subsequently formalised digital twin frameworks for structural life-cycle management of military aircraft, marking the first large-scale adoption of continuous bidirectional physical-virtual synchronisation outside the laboratory setting. The advent of Industry 4.0 in the 2010s catalysed the expansion of digital twin technology into smart manufacturing, energy infrastructure, and civil engineering, driven by concurrent advances in the Internet of Things, cloud computing, and edge analytics that made persistent data streaming economically viable [8]. Healthcare adopted digital twin principles from approximately 2015 onwards, initially in hospital facility management, pharmacokinetic modelling, and cardiac simulation, before rapid expansion into surgical planning, oncology, and chronic disease management [2,9]. Dentistry and orthodontics represent among the most recent and rapidly evolving frontiers, with dedicated digital twin applications emerging from 2020 and accelerating in step with improvements in intraoral scanning resolution, cone beam computed tomography, and artificial intelligence-driven biomechanical solvers [10,11]. Understanding this historical trajectory is essential for contextualising current capabilities and setting realistic expectations for the pace of further adoption in clinical orthodontic practice.

Digital twins in orthodontics encompass comprehensive virtual models that integrate patient-specific anatomical data, including dentition, craniofacial structures, and soft tissue profiles, with functional parameters such as occlusal forces, temporomandibular joint dynamics, and growth patterns. These sophisticated models leverage advanced imaging modalities, including cone beam computed tomography, intraoral scanning, and facial photography, to create highly accurate digital representations [12]. The clinical implications of digital twin technology in orthodontics are substantial and multifaceted. Traditional orthodontic treatment planning relies heavily on clinician experience and two-dimensional cephalometric analysis, which may not fully capture the complex three-dimensional nature of dentofacial structures and their biomechanical responses. Digital twins address these limitations by enabling comprehensive visualisation, quantitative analysis, and scenario testing before initiating treatment. Clinicians can evaluate multiple treatment approaches virtually, assess potential risks and complications, and select optimal strategies based on patient specific biomechanical characteristics [13]. Furthermore, digital twins facilitate continuous monitoring and treatment refinement throughout the orthodontic journey, allowing for real time adjustments based on actual patient response rather than predetermined protocols [13]. The construction of a digital twin follows a structured workflow that integrates multimodal imaging, virtual modelling, and biomechanical simulation.

The foundational enabling layer for orthodontic digital twins is the automated segmentation and three-dimensional reconstruction of teeth, roots, and jawbone from dental imaging data, including cone beam computed tomography, intraoral scans, and digital dental models. The digital twin construction workflow integrates multimodal imaging into software interfaces for model segmentation and simulation, enabling precise treatment planning. Recent advances in deep learning have substantially improved the accuracy and clinical feasibility of these processes. Transformer-based architectures incorporating spatial prior-guided bi-directional cross-attention mechanisms have demonstrated state-of-the-art performance in tooth instance segmentation from volumetric dental data, enabling precise delineation of individual tooth boundaries within complex craniofacial anatomy [14]. Hierarchical self-supervised learning strategies applied to three-dimensional intraoral mesh scans have shown that high-quality tooth segmentation can be achieved with significantly reduced annotated training data, addressing a critical bottleneck in clinical dataset curation [15]. For the paediatric population, where mixed dentition stages complicate automated analysis, graph representation learning frameworks operating on individual tooth morphology have demonstrated reliable segmentation performance on dental cone beam computed tomography with variable tooth counts and eruption stages [16]. Furthermore, morphology prior-enhanced segmentation methods specifically designed for high-resolution oral scans have achieved sub-millimetre accuracy in tooth boundary delineation, providing the geometric precision necessary for reliable downstream biomechanical simulation within digital twin frameworks [17]. Integration of these deep learning-based segmentation pipelines into clinical digital twin workflows represents a critical step towards reducing manual annotation burden, improving model fidelity, and enabling scalable deployment across diverse patient populations.

The integration of digital twin technology with emerging innovations such as clear aligner therapy, temporary anchorage devices, and accelerated orthodontics creates synergistic opportunities for enhanced treatment efficiency and predictability. Digital twins can simulate aligner force systems, predict periodontal stress distribution, and optimise staging sequences to achieve desired outcomes whilst minimising treatment duration and biological risks [18]. Additionally, the capacity for virtual try-ons and patient education through digital twin visualisations improves informed consent processes and patient engagement, potentially enhancing treatment acceptance and compliance. The technology also holds promise for training and education, enabling orthodontic residents and practitioners to develop clinical skills through realistic simulations without patient risk [19].

Digital twin technology extends beyond orthodontics with transformative applications across multiple healthcare domains. In chronic wound management, digital twins integrate multi-parametric data including tissue characteristics, bacterial load, and healing trajectories through AI-driven pipelines that track healing progression, enabling the virtual representation to simulate and replicate the actual wound healing process whilst facilitating early identification of non-healing wounds for timely treatment plan adjustments [20]. Healthcare facility management employs digital twins for operational optimization, resource allocation, and pandemic response planning, as demonstrated through social distancing monitoring applications during COVID-19 that virtualize physical spaces and organizational processes through bidirectional communication between digital and physical environments for workplace virus containment [21]. Clinical decision support systems leverage AI-enabled digital twin frameworks such as DECIDE-Twin to provide advanced virtual models of complex real-world clinical systems, transforming decision-making processes through comprehensive development and implementation guidelines that enhance diagnostic accuracy and treatment pathway optimization across diverse medical specialties [22].

While geometric and biomechanical modeling form the foundation of orthodontic digital twins, recent advances in large language models (LLMs) introduce complementary semantic reasoning capabilities that enhance diagnostic accuracy through natural language processing of clinical documentation, patient histories, and compliance narratives, enabling conversational interaction with treatment simulations and interpretation of broader clinical contexts beyond purely biomechanical predictions [23]. However, it is essential to distinguish true digital twin technology, characterized by continuous bidirectional data exchange, real-time computational updates, and adaptive feedback loops, from conventional digital orthodontic workflows that function as static digital models or digital shadows, such as treatment planning based on single CBCT scans updated only at clinical appointments weeks or months apart [24]. Current orthodontic practice faces significant technological barriers to achieving authentic real-time monitoring, including radiation exposure concerns limiting frequent CBCT imaging, computational demands of continuous biomechanical simulation, and practical challenges in acquiring high-frequency patient data outside clinical settings, and whilst foundational digital twin principles are being implemented, full realization of continuous bidirectional synchronization and real-time adaptive treatment remains an aspirational goal requiring further technological development [24].

Despite the promising potential of digital twin technology in orthodontics, several challenges and knowledge gaps remain. The complexity of biological systems, individual variability in tissue response, and limitations in current computational models may affect prediction accuracy and clinical applicability. Questions persist regarding the optimal integration of digital twin technology into existing workflows, the cost-effectiveness of implementation, and the evidence base supporting its clinical superiority over conventional methods. Furthermore, ethical considerations related to data privacy, algorithmic transparency, and the potential for overreliance on technological solutions warrant careful examination.

The primary aim of this review is to provide a comprehensive, evidence-based assessment of digital twin technology's current role and future potential in orthodontic practice. Specific objectives include: (1) analyzing current digital twin applications across the orthodontic treatment continuum, (2) evaluating clinical outcomes and implementation evidence, (3) distinguishing true digital twin capabilities from static digital workflows, (4) identifying technological and practical barriers to implementation, and (5) proposing research priorities for advancing this transformative technology.

2 Method

This narrative review employed a comprehensive literature synthesis approach to examine digital twin applications in orthodontics. Multiple electronic databases were systematically searched, including PubMed, Scopus, Web of Science, IEEE Xplore, and Google Scholar, covering publications from January 2018 to October 2025. The search strategy incorporated key terms and Boolean operators, including 'digital twin' AND 'orthodontics', 'virtual patient model', 'biomechanical simulation', 'predictive modelling', 'artificial intelligence in orthodontics', and related terminology. The temporal scope was deliberately focused on recent publications to capture emerging technologies and current implementation practices whilst acknowledging foundational works where relevant.

Inclusion criteria encompassed peer reviewed journal articles, conference proceedings, technical reports, and clinical case series that described digital twin technology applications in orthodontic diagnosis, treatment planning, biomechanical analysis, or patient monitoring. Both experimental studies and theoretical frameworks were considered to provide comprehensive coverage of the field. Exclusion criteria eliminated studies focusing solely on general dental applications without specific orthodontic relevance, publications not available in English, and articles lacking sufficient methodological detail for quality assessment. The narrative review format was specifically chosen over systematic review or scoping review methodologies to allow for interpretive synthesis, critical analysis, and expert commentary on the emerging and rapidly evolving field of digital twin technology in orthodontics.

Data extraction focused on key domains including technological specifications of digital twin systems, clinical applications, outcome measures, implementation challenges, and future research directions. Information was synthesised thematically rather than through meta-analysis, given the heterogeneity of study designs, outcome measures, and technological platforms across the literature. Quality appraisal considered factors such as methodological rigour, sample size, validation methods, and clinical relevance, whilst acknowledging the preliminary nature of much research in this emerging field. This narrative review did not follow PRISMA guidelines, as these are specifically designed for systematic reviews with quantitative synthesis and meta-analysis, which were not appropriate for this interpretive, thematic synthesis of an emerging technological field. The absence of PRISMA adherence is acknowledged as a methodological limitation in Section 9.0.

2.1 Core Technical Components for Constructing an Orthodontic Digital Twin

Understanding how an orthodontic digital twin is constructed is essential for evaluating its clinical utility and distinguishing it from simpler digital workflows. Three interdependent technical components underpin a functional orthodontic digital twin, each of which must be implemented cohesively to achieve genuine bidirectional synchronisation and adaptive behaviour.

2.1.1 Physical-Virtual Synchronisation and Multi-Source Data Fusion

The foundation of any digital twin is the ability to continuously synchronise a virtual model with its physical counterpart through the integration of heterogeneous data streams [25]. In orthodontics, this entails fusing data from multiple modalities, including cone beam computed tomography for volumetric hard tissue detail, intraoral scanning for surface geometry of dentition, facial photogrammetry for soft tissue profiling, and clinical records containing occlusal and functional parameters [26,27]. Deep learning-based segmentation algorithms (as described in the Introduction) automate the delineation of individual dental structures from these raw inputs, producing the precise geometric meshes required for downstream simulation [28]. Interoperability standards such as Digital Imaging and Communications in Medicine (DICOM) and Standard Tessellation Language (STL) govern data exchange across platforms, although gaps in standardisation remain a practical bottleneck [29] Critically, data fusion in a true digital twin is not a one-time event: as treatment progresses, newly acquired intraoral scans, photographic records, or sensor outputs are continuously integrated, updating the virtual model to reflect the patient's evolving biological state [30]. This is the property that fundamentally distinguishes a digital twin from a static treatment planning model or digital shadow, which is constructed once and not subsequently updated with real-world feedback [31].

2.1.2 Biomechanical Simulation and Predictive Analytics

Once the geometric model is established and continuously updated, the second core component, biomechanical simulation, operates on this representation to predict tooth movement, periodontal tissue response, and appliance performance [32] . Finite element analysis (FEA) is the predominant computational technique, discretising the tooth-periodontal ligament-bone complex into meshes of thousands of elements to solve partial differential equations governing stress and strain under applied forces [33]. Material property assignments, incorporating periodontal ligament viscoelasticity, cortical and cancellous bone anisotropy, and enamel stiffness, are drawn from imaging-derived measurements where possible, enabling patient-specific rather than populationaveraged simulations [34]. Predictive analytics layers, often implemented as machine learning regression models trained on historical treatment datasets, translate FEA outputs and observed tooth displacement patterns into probabilistic outcome forecasts, including estimated treatment duration, risk of root resorption, and likelihood of achieving target tooth positions within specified tolerances. These predictions are iteratively refined as new real-world observations are fed back into the model, enabling the digital twin to improve its accuracy over the course of treatment [35].

2.1.3 Intelligent Decision-Making and Adaptive/Continual Learning

The third component distinguishes a digital twin from a sophisticated simulation environment by endowing it with the capacity to learn from its own predictions and adapt clinical recommendations accordingly [36]. Reinforcement learning and continual learning algorithms monitor divergences between predicted and observed outcomes, adjusting model parameters and treatment suggestions without requiring manual reconfiguration. In practice, this may manifest as automatic mid-course correction proposals within aligner staging software, updated force system recommendations for fixed appliance therapy, or revised appointment scheduling based on observed rates of tooth movement [37]. Explainability frameworks, such as Shapley Additive Explanations (SHAP) and attention visualisation in transformer-based models, are increasingly integrated to surface the factors driving specific recommendations, supporting clinician oversight and regulatory compliance [38]. Together, these three technical layers, data fusion, biomechanical simulation, and adaptive learning, constitute the minimum infrastructure required for a system to qualify as a genuine orthodontic digital twin, as opposed to a static digital workflow or a single-point computational model. Table 1 presents a systematic comparison of conventional digital workflows and true digital twin workflows across key clinical dimensions, illustrating the practical implications of these distinctions.

Table 1: Comparison of Conventional Digital Workflow versus True Digital Twin Workflow in Orthodontics

Dimension	**Conventional Digital Workflow**	**True Digital Twin Workflow**
Data Acquisition [24,39–41]	Single-point or infrequent data capture (e.g., one CBCT scan at treatment planning;	Continuous or near-continuous multi-source data ingestion from intraoral scans,

	intraoral scan at case start). No automatic update mechanism; clinician-initiated only.	photographic records, aligner sensors, and clinical assessments. Automatic model synchronisation upon new data receipt.
Update Frequency [10,24,41]	Static between appointments (weeks to months). Model reflects the patient's status at a single historical time point.	Dynamic; the virtual model is updated iteratively throughout treatment, reflecting the patient's current biological state with minimal lag.
Predictive Capability [10,11,34]	Predictions based on population-level normative data and clinician experience. No self-updating predictive model; outcomes estimated at treatment onset and not revised.	Machine learning models trained on accumulating treatment data generate probabilistic, patient-specific outcome forecasts that are continuously refined as observed data diverges from predictions.
Adaptive Feedback [24,39,42]	No automated adaptive feedback. Treatment plan modifications depend entirely on scheduled clinical review and clinician judgment.	Automated divergence detection triggers adaptive feedback, e.g., mid-course correction suggestions, revised aligner staging, or updated force recommendations, without waiting for a scheduled appointment.
Clinical Monitoring [24,39,41]	Periodic monitoring via scheduled visits; progress assessed visually and radiographically at fixed intervals. Inter-appointment deviations are undetected until the next visit.	Continuous remote monitoring capability; inter-appointment deviations detected via automated analysis of patient-submitted scans or photographs, enabling proactive clinical intervention.
Patient Personalisation [5,43,44]	Personalisation limited to initial anatomical model; biomechanical parameters typically drawn from population averages. No learning from individual patient response patterns.	Deep personalisation through integration of individual imaging-derived tissue properties, observed treatment response trajectories, and

		compliance data; model accuracy improves with each data update cycle.
Practical Example [24,39–41]	Aligner staging designed from a single CBCT and intraoral scan at case commencement; no revision until clinical review at 6-week appointment regardless of actual tooth movement.	Aligner staging updated at each fortnightly scan submission; if observed tooth displacement lags prediction by >0.3 mm, system automatically proposes revised staging or auxiliary attachment placement before the next aligner is printed.

3 Clinical Applications in Diagnosis and Treatment Planning

Digital twin technology has demonstrated significant utility in enhancing diagnostic accuracy and treatment planning precision in orthodontics. The comprehensive three-dimensional visualisation capabilities of digital twins enable clinicians to assess spatial relationships between dental and skeletal structures with unprecedented detail, facilitating identification of subtle malocclusions and asymmetries that may be overlooked in conventional two-dimensional analyses [5]. Digital twins integrate cephalometric measurements, occlusal analysis, and soft tissue evaluation into unified models, eliminating the fragmentation inherent in traditional diagnostic approaches. This holistic representation supports more accurate diagnosis of complex dentofacial deformities and enables better communication amongst multidisciplinary teams managing orthognathic surgery cases [12].

The treatment planning applications of digital twin technology extend across all orthodontic modalities, from conventional fixed appliances to contemporary clear aligner systems. For bracket-based treatments, digital twins can simulate optimal bracket positioning, predict wire engagement patterns, and calculate force systems delivered by various arch wire configurations [18]. The technology enables virtual bracket placement optimisation, potentially reducing chair time and improving treatment efficiency [18]. In clear aligner therapy, digital twins facilitate sophisticated staging algorithms that balance clinical objectives with biomechanical principles, predicting the number of aligners required and identifying movements requiring auxiliary features such as attachments or elastics [45]. The capacity to test multiple treatment scenarios virtually enables evidence-based selection of optimal approaches for individual patients.

Temporary anchorage device planning represents another domain where digital twin technology offers substantial advantages [46]. The precise anatomical mapping provided by digital twins enables identification of optimal insertion sites that maximise bone engagement whilst avoiding critical structures such as tooth roots, nerves, and sinuses [43]. Biomechanical simulations can predict force vectors and moments generated by different anchorage configurations, supporting strategic placement decisions [47]. Some advanced digital twin platforms incorporate augmented reality capabilities, enabling real-time guidance during temporary anchorage device placement by superimposing planned positions onto the clinical field [48].

Extraction versus non-extraction decision-making, one of the most challenging aspects of orthodontic treatment planning, benefits from digital twin simulation capabilities [49]. Clinicians can virtually test both extraction and non-extraction scenarios, assessing their respective impacts on profile aesthetics, occlusal relationships, and functional outcomes [50]. Digital twins enable quantitative comparison of facial changes, overjet and overbite corrections, and arch form modifications associated with different treatment approaches [12]. Patient-specific biomechanical factors such as periodontal biotype, cortical bone thickness, and root morphology can be incorporated into simulations, improving the biological plausibility of predictions [39]. As summarised in Table 2, digital twin applications span multiple treatment phases from initial diagnosis through retention planning, each offering distinct clinical benefits that enhance precision and personalisation of orthodontic care. Representative quantitative evidence for DT-related technologies across these phases is presented in Table 3. As illustrated in Figure 1, the digital twin operates as a closed-loop computational framework enabling continuous bidirectional synchronisation across all orthodontic treatment phases.

Table 2: Clinical Applications of Digital Twin Technology Across Orthodontic Treatment Phases

Treatment Phase	Digital Twin Application	Clinical Benefits

Initial Diagnosis [18]	Comprehensive three-dimensional analysis of dental and skeletal relationships with integrated soft tissue assessment	Enhanced diagnostic accuracy and improved detection of subtle asymmetries and malocclusions
Treatment Planning [18]	Virtual simulation of multiple treatment scenarios and biomechanical analysis	Evidence based treatment selection and improved outcome predictability with patient specific optimisation
Active Treatment [13]	Real time progress monitoring with continuous comparison between predicted and actual tooth movements	Early identification of deviations enabling timely treatment modifications and reduced overall duration
Finishing and Detailing [45]	Precision assessment of final tooth positions and occlusal contacts with virtual articulation	Achievement of ideal finishing objectives and improved functional occlusion with reduced adjustment time
Retention and Stability [24]	Prediction of post treatment tooth movement tendencies and simulation of retention protocols	Personalised retention strategies and improved long term stability with early relapse detection

Table 3: Representative Evidence for Digital Twin-Related Technologies in Orthodontics

Study	DT-Related Technique	Outcome Metric	Quantitative Result	Clinical Relevance
Lee et al. (2023) [40]	Digital twin construction by superimposing IOS and alginate impression scans onto CBCT-based reference models; 20 patients; desktop model scanner and CS 3600/i700 wireless IOS	Surface discrepancy between digital dentition models (IOS/alginate) and CBCT-based reference (mm); comparison against CBCT voxel size threshold	All superimposition discrepancies < CBCT voxel size (0.39 mm); alginate impression scanned within 5 min and IOS both confirmed as suitable CBCT supplements; alginate scans delayed 2 h showed greatest, yet still sub-voxel, discrepancies	Validates radiation-free IOS as a primary data source for DT construction and updating, supporting continuous model synchronisation without repeated CBCT exposure
Castroflorio et al. (2023) [24]	3D STL export comparison of final digital models vs. virtual treatment plan (ClinCheck®/Geomagic	Ratio of achieved vs. prescribed tooth movement (° and mm); statistical significance of lack	~0.4° achieved per 1° prescribed for angular/rotational movements; lack of correction significant for	Quantifies systematic undercorrection of angular movements; informs DT overcorrection staging

	Qualify®); 79 prospective aligner patients (mean age 30.8 years); movements assessed across all spatial axes and directions	of correction per movement type and tooth group; effect of aligner change frequency	all movements (P<0.01) except maxillary first molar rotation; 14-day aligner change reduces lack of correction by 12% vs. 7-day protocol	and optimal aligner change frequency protocols for improved treatment predictability
Awad et al. (2022) [18]	3D soft tissue prediction via VSP software (IPS CaseDesigner®); 20 bimaxillary surgery patients; 3D face scan at 4 months post-surgery compared to preoperative simulation using inter-surface distance algorithm	Percentage of face surface correctly predicted (%); regional accuracy variation across facial aesthetic units (cranial vs. lower facial areas)	Correctly predicted soft tissue: 69.4%–96.0% of face surface; cranial regions (upper cheek, nose, upper lip) more accurate than lower facial areas (lower cheek, lower lip, chin)	Supports DT use for patient-facing outcome visualisation in orthognathic planning; identifies lower facial soft tissue prediction as requiring ongoing algorithm refinement
Choi et al. (2019) [45]	Two-layer artificial neural network using 12 cephalometric measurements and 6 additional indexes; 316 patients (160 surgical, 156 non-surgical); 3-stage learning with 4 best-performing models adopted	Diagnostic success rate for surgery/non-surgery decision, surgical type classification, and extraction/non-extraction decision (%)	96% success rate for surgery/non-surgery decision; 91% for combined surgical type and extraction/non-extraction classification	Demonstrates AI diagnostic accuracy sufficient to support DT-integrated clinical decision support for orthognathic treatment planning
Chen et al. (2024) [41]	Deep learning-based cross-temporal multimodal fusion system integrating CBCT and IOS data; incorporates dynamic kernel prior model, resolution restoration, IOS segmentation network optimised for dense point clouds, and a coarse-to-fine registration module to reconstruct root and jawbone information throughout orthodontic treatment	Segmentation accuracy for teeth and jawbone on CBCT (Dice coefficient); IOS segmentation accuracy (Dice coefficient); registration accuracy, average distance error (ADE) for teeth and jawbone (mm)	CBCT Dice coefficients: 94.1% for teeth; 94.4% for jawbone; IOS Dice coefficient: 91.7%; registration ADE: 0.43 mm for teeth; 0.52 mm for jawbone	Enables continuous monitoring of root-to-alveolar bone relationships throughout orthodontic treatment without additional radiation exposure, directly addressing the CBCT frequency limitation that constrains true DT real-time data acquisition

Note: The evidence presented here reflects the current state of the field and underscores the need for larger, prospective, multi-centre validation studies to establish definitive performance benchmarks for orthodontic digital twin systems.

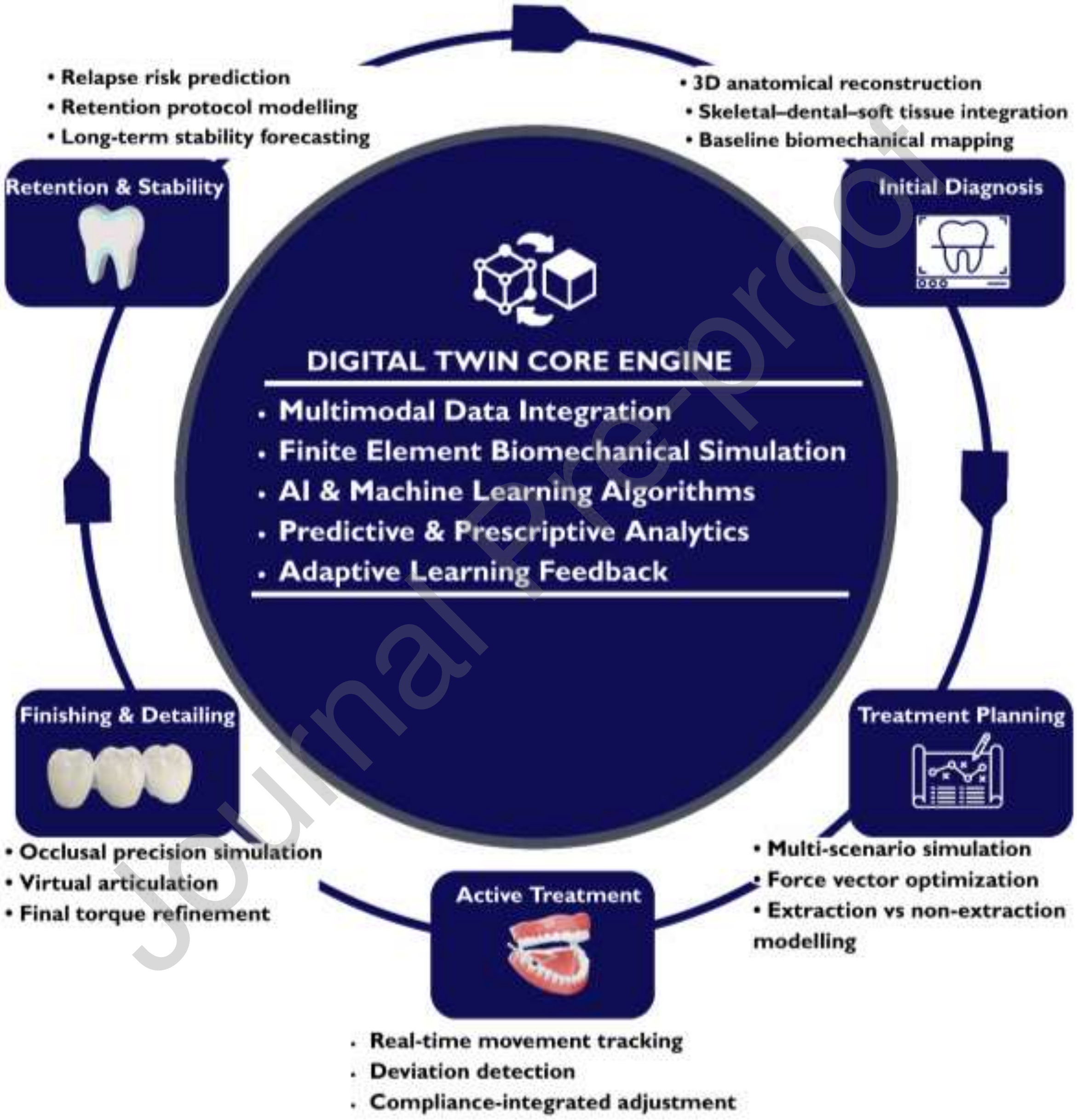

Figure 1. Closed-loop digital twin framework across the orthodontic treatment continuum. The digital twin core integrates multimodal imaging data, biomechanical simulation, and artificial intelligence–driven predictive analytics. Bidirectional synchronization enables continuous updating between the patient's physical progression and the virtual model. Adaptive feedback mechanisms support dynamic recalibration of treatment strategies across

diagnosis, planning, active treatment, finishing, and retention phases, distinguishing true digital twin systems from static digital workflows.

4 Biomechanical Analysis and Force Optimisation

The biomechanical sophistication of digital twin technology represents one of its most compelling advantages in orthodontic applications [18]. Finite element analysis integrated within digital twins enables detailed simulation of stress and strain distributions within periodontal tissues, bone, and teeth when subjected to orthodontic forces [51,52]. These simulations provide insights into the mechanical environment created by different appliance configurations, supporting the design of force systems that optimise biological responses whilst minimising adverse effects such as root resorption or dehiscence. The capacity to visualise stress concentrations and identify areas at risk for tissue damage before initiating treatment represents a significant advancement in biological orthodontics [53].

Force magnitude and direction optimisation through digital twin simulation addresses the longstanding challenge of balancing treatment efficiency with biological safety [54]. Traditional orthodontic force systems rely on generalised principles and clinical experience, which may not account for individual variations in tissue response thresholds. Digital twins enable patient-specific force calibration based on periodontal ligament properties, bone density, and root morphology derived from imaging data [5,43]. Simulation studies have demonstrated that personalised force systems optimised through digital twin analysis can potentially reduce treatment duration whilst maintaining periodontal health parameters [31]. The technology also facilitates the identification of optimal force application points and vectors for complex movements such as intrusion or torque correction [55].

The prediction of centre of rotation and moment to force ratios represents another area where digital twin technology enhances biomechanical precision [43]. Controlled tipping versus bodily translation of teeth requires careful consideration of force systems and their resulting moments, which vary based on appliance geometry and material properties [56]. Digital twins can simulate these biomechanical relationships for individual patients, enabling clinicians to design appliance configurations that achieve intended movement patterns [12]. This level of biomechanical control is particularly relevant in contemporary treatments emphasising minimal anchorage preparation and efficient mechanics [56].

Temporomandibular joint loading analysis through digital twin simulation offers insights into the functional implications of orthodontic treatment. Changes in occlusal relationships and mandibular positioning during treatment can alter joint loading patterns, potentially affecting temporomandibular joint health and comfort [57]. Digital twins incorporating dynamic occlusal analysis and joint biomechanics can predict loading changes throughout treatment, enabling clinicians to identify and mitigate approaches that may increase joint stress. This functional consideration is particularly important in adult orthodontics, where preexisting temporomandibular disorders are more prevalent [40,57]. As shown in Figure 3, digital twin–based finite element simulations provide detailed visualisation of stress patterns and predicted tooth movement, supporting personalised force optimisation and biologically safe treatment planning.

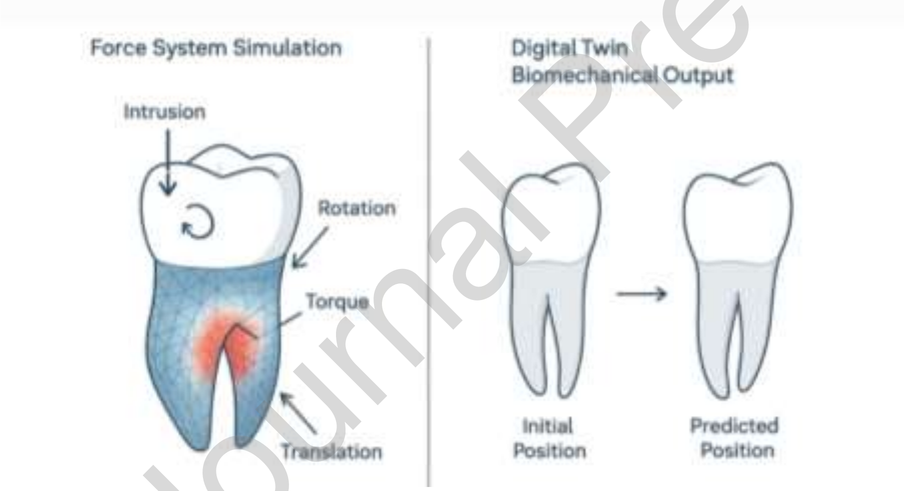

Figure 3. Biomechanical simulation of orthodontic forces using digital twin technology.

5 Real-Time Monitoring and Adaptive Treatment

The dynamic nature of digital twin technology enables continuous monitoring of treatment progress through periodic updates with new clinical data [58]. Unlike conventional treatment approaches that rely on scheduled appointments and clinician assessment, digital twins can integrate data from intraoral scans, photographs, or even patient-uploaded images to track tooth movement patterns between visits. This continuous monitoring capability enables early identification of deviations from predicted outcomes, supporting proactive intervention before significant discrepancies develop [13]. The technology is particularly valuable in remote monitoring scenarios and teledentistry applications, where digital twins serve as virtual proxies enabling clinician oversight without requiring frequent office visits [59].

The clinical pathway implications of digital twin integration differ substantially from those of conventional orthodontic monitoring. Under a conventional model, scheduled reviews occur every six to eight weeks, with treatment deviations detectable only at the point of the visit, potentially four to six weeks after onset, limiting timely intervention [24,39]. Under a digital twin-enabled model, patients submit fortnightly intraoral scans via consumer-grade scanners; the system registers each scan against the continuously updated virtual model using coarse-to-fine registration, achieving average distance errors of 0.43 mm for teeth and 0.52 mm for jawbone [41], and generates a divergence report without additional radiation exposure. Where displacement lags the simulation beyond a clinically defined threshold, informed by evidence that angular movements are undercorrected at approximately 0.4° per 1° prescribed [24], the system proposes a protocol response such as extended aligner wear or attachment modification. The clinician reviews and communicates the revised plan asynchronously, an approach associated with a 28% reduction in unscheduled follow-up visits [39], reorienting the clinical model from reactive, appointment-driven review to continuous, data-informed monitoring.

Adaptive treatment protocols represent a significant advancement enabled by digital twin technology [10]. Traditional orthodontic treatment follows predetermined plans established at the outset, with modifications made reactively when outcomes diverge from expectations. Digital twins enable proactive treatment adaptation based on observed responses to initial movements [10,60]. Machine learning algorithms analyse actual tooth movement patterns and tissue responses, updating predictions and automatically suggesting treatment modifications to optimise outcomes. This adaptive approach acknowledges the inherent biological variability amongst patients and the limitations of initial predictions, embracing iterative refinement as a core treatment philosophy. Some platforms incorporate automated midcourse correction suggestions, streamlining the revision process for clinicians [61].

A critical practical question concerns how a true digital twin can acquire data in real time or near-real time given radiation concerns that preclude frequent cone beam computed tomography imaging. Several complementary strategies offer feasible alternatives [10,62]. Intraoral scanning with consumer-grade or handheld devices generates three-dimensional surface geometry without ionising radiation and, whilst insufficient to capture root or alveolar bone morphology, is adequate for tracking crown-level tooth movement and inter-arch occlusal changes [40] Validated photogrammetric methods using structured-light face scanners can track soft tissue and dental arch changes from digital photographs, with studies demonstrating mean surface deviations below 0.5 mm against direct intraoral scan references [18]. Sensor-embedded orthodontic appliances, including aligners with thin-film piezoelectric sensors and smart brackets with micro-accelerometers, represent an emerging paradigm for continuous biomechanical data capture, recording force magnitudes, wear duration, and occlusal contact patterns in real time [39]. AI-driven change detection algorithms can additionally identify clinically significant crown position deviations from sequential smartphone photographs, achieving sub-millimetre sensitivity under standardised protocols in early feasibility studies [39]. Where updated volumetric data is genuinely required, low-dose CBCT protocols with iterative reconstruction can reduce effective radiation doses to levels approaching panoramic radiography, enabling more selective use in cases where root assessment is clinically critical [24]. Deployed in combination according to case-stage requirements, these modalities provide a practical, radiation-responsible framework for achieving the near-continuous data flow a genuine orthodontic digital twin requires.

Compliance monitoring through digital twin technology addresses one of the most challenging aspects of orthodontic treatment [63]. Patient cooperation with elastics, aligner wear, and oral hygiene protocols significantly influences treatment outcomes and duration. Digital twins can incorporate compliance data from various sources, including embedded sensors in aligners, patient-reported outcomes through mobile applications, and photographic documentation [18]. Correlation of compliance patterns with treatment progress enables clinicians to identify relationships and counsel patients more effectively. Predictive models can forecast final outcomes based on observed compliance levels, supporting realistic expectation setting and potentially motivating improved adherence through visualisation of compliance impact [64].

The integration of growth prediction models with digital twin technology enhances treatment planning for adolescent patients [65]. Longitudinal growth data and artificial intelligence algorithms can estimate future craniofacial development patterns, enabling treatment timing optimisation and growth modification strategies [66]. Digital twins incorporating growth predictions allow clinicians to visualise treatment outcomes at skeletal maturity, considering both orthodontic tooth movement and expected skeletal changes [18]. The capacity to simulate different timing scenarios helps identify optimal intervention windows for various treatment modalities [66].

6 Patient Engagement and Education

Digital twin visualisation capabilities offer powerful tools for patient education and treatment acceptance [11]. The ability to show patients realistic three-dimensional representations of their current dentition and predicted treatment outcomes facilitates understanding of proposed interventions in ways that traditional plaster models and two-dimensional images cannot match [67]. Interactive manipulation of digital twins enables patients to view their malocclusion from various perspectives, appreciate the complexity of movements required, and visualise step by step progression towards treatment goals [18]. This enhanced understanding may improve informed consent quality and set realistic expectations regarding treatment duration and complexity.

Virtual try-on features within digital twin platforms enable patients to preview aesthetic outcomes before committing to treatment [44]. Soft tissue prediction algorithms can simulate changes in lip position, facial profile, and smile aesthetics resulting from different treatment approaches. This visualisation capability is particularly valuable when presenting extraction versus non-extraction options or discussing orthognathic surgery possibilities, where facial changes represent primary patient concerns [68]. Studies suggest that visual presentation of predicted outcomes through digital twin technology positively influences treatment acceptance rates, particularly amongst adult patients for whom aesthetic considerations are paramount [69].

Patient engagement throughout active treatment benefits from digital twin technology through progress visualisation and gamification elements. Mobile applications connected to digital twin platforms can show patients their treatment journey, highlighting accomplished movements and remaining objectives [69]. Some platforms incorporate achievement systems that reward compliance milestones and treatment progress, leveraging behavioural psychology principles to enhance motivation [70]. The transparency provided by continuous digital twin updates may improve patient satisfaction by demonstrating tangible progress even when changes are not immediately perceptible in daily life [44].

The educational benefits of digital twin technology extend to multidisciplinary case management, where clear communication amongst specialists is essential for optimal outcomes [71]. Digital twins serve as common reference points for orthodontists, oral surgeons, periodontists, and restorative dentists involved in comprehensive rehabilitation cases [72]. The three-dimensional visualisation and simulation capabilities facilitate discussion of treatment sequencing, anticipated outcomes, and potential complications. Some platforms enable asynchronous collaboration, where team members can review digital twins and provide input remotely, potentially improving access to specialist consultation in underserved areas [46,73].

7 Implementation Challenges and Barriers

Despite the compelling potential of digital twin technology, several practical challenges impede widespread implementation in orthodontic practice [74]. Computational requirements for sophisticated biomechanical simulations and artificial intelligence algorithms can be substantial, necessitating high-performance computing infrastructure that may exceed the capabilities of typical practice environments. Cloud-based solutions address some computational limitations but introduce concerns regarding data transmission speeds, latency in interactive applications, and ongoing subscription costs [62]. The initial investment required for hardware, software, and training may be prohibitive for some practitioners, particularly in solo or small group practices where return on investment timelines are uncertain. As outlined in Table 4, implementation challenges span multiple categories from technical infrastructure to regulatory frameworks, each requiring targeted solutions for successful adoption.

Data integration complexity represents another significant barrier to digital twin implementation [75]. Orthodontic digital twins require inputs from multiple sources, including cone beam computed tomography, intraoral scanners, facial scanners, and clinical records. Ensuring seamless integration of data from different manufacturers and formats requires sophisticated interoperability standards that are not uniformly established across the industry [18,76]. The Digital Imaging and Communications in Medicine standard provides some framework for medical imaging interoperability, but its implementation in dentistry remains incomplete [77]. Proprietary data formats and closed ecosystems limit the transferability of information between platforms, creating vendor lock-in concerns and complicating multi-platform workflows [78].

The accuracy and reliability of digital twin predictions remain subject to ongoing validation requirements. Whilst studies demonstrate promising results in controlled conditions, real world clinical performance may vary based on factors not fully captured in current models [79]. Individual biological variability, tissue healing characteristics, patient compliance patterns, and unforeseen complications can cause discrepancies between predicted and actual outcomes [80]. The lack of standardised validation protocols makes it difficult to compare different digital twin platforms objectively or establish evidence-based guidelines for clinical application [81]. Long term prospective studies tracking digital twin predictions against final outcomes are needed to build confidence in the technology's clinical utility [74].

Regulatory and ethical considerations surrounding digital twin technology in orthodontics warrant careful attention [82]. The classification of digital twin software as medical devices or clinical decision support tools affects regulatory oversight requirements in different jurisdictions [83]. Questions regarding liability when automated algorithms suggest treatment modifications, the transparency of artificial intelligence decision making processes, and the appropriate balance between algorithmic recommendations and clinician judgment require thoughtful consideration [84]. Data privacy and security concerns are particularly significant given the sensitive nature of health information and the potential for unauthorised access to detailed anatomical representations [85].

Table 4: Implementation Challenges and Potential Solutions for Digital Twin Technology in Orthodontics

Challenge Category	**Specific Barriers**	**Potential Solutions**
Technical Infrastructure [86]	High computational requirements and hardware costs limiting accessibility for smaller practices	Cloud based computing solutions and scalable subscription models reducing upfront investment requirements
Data Integration [87]	Incompatible data formats and proprietary systems preventing seamless information exchange	Industry-wide adoption of open standards and application programming interfaces for interoperability

Clinical Validation [11]	Insufficient long-term evidence comparing digital twin predictions with actual treatment outcomes	Prospective multicentre studies and standardised validation protocols with outcome registries
Workflow Integration [74]	The complexity of incorporating digital twin technology into established clinical workflows and routines	Comprehensive training programmes and user-friendly interfaces with clinical decision support
Cost Effectiveness [88]	Uncertain return on investment and lack of reimbursement models for digital twin applications	Economic evaluation studies and demonstration of improved outcomes justifying additional costs
Regulatory and Ethical [89]	Unclear regulatory pathways and data privacy concerns with algorithmic decision-making systems	Establishment of clear regulatory frameworks and robust cybersecurity protocols with transparency standards

8 Future Directions and Emerging Applications

The future evolution of digital twin technology in orthodontics is likely to emphasise increased automation, enhanced artificial intelligence capabilities, and broader integration with digital dentistry workflows [66]. Machine learning algorithms will continue improving in prediction accuracy as they are trained on larger datasets encompassing diverse patient populations and treatment outcomes [90]. The incorporation of genomic and proteomic data may enable personalised predictions based on individual biological markers affecting bone remodelling and tissue response [18,74]. Advanced imaging modalities, exemplified by phase-contrast X-ray micro-CT systems that enable three-dimensional virtual histopathology with unprecedented cellular-level resolution, represent complementary technologies that can enhance digital twin anatomical accuracy and biological fidelity [91].

Virtual reality and augmented reality technologies present exciting opportunities for digital twin interaction and application. Virtual reality environments could enable immersive treatment planning where clinicians manipulate three-dimensional patient representations using intuitive gestural interfaces [48]. Augmented reality applications could overlay digital twin information onto real patient views during clinical procedures, supporting precise bracket placement, temporary anchorage device insertion, or wire bending [48]. These mixed reality applications may enhance procedural accuracy whilst reducing the cognitive load associated with translating digital plans into clinical execution [38]. Educational applications of virtual reality integrated digital twins could revolutionise orthodontic training [18].

The integration of digital twin technology with three-dimensional printing capabilities creates opportunities for customised appliance fabrication optimised for individual patient biomechanics [92]. Digital twins can inform the design of patient-specific brackets with optimised slot angulations, custom arch wires with predetermined force systems, or individualised aligners with targeted force application areas. The combination of biomechanical simulation and additive manufacturing may enable novel appliance designs that were previously impractical [93].

Teledentistry and remote orthodontic care will likely be significantly enhanced by digital twin technology [18]. The comprehensive patient representation provided by digital twins enables remote clinicians to assess treatment progress and make informed decisions without physical examination. Advanced platforms may incorporate automated progress assessments that flag cases requiring clinician review, improving efficiency in remote monitoring programmes [74]. The democratisation of orthodontic care through technology-enabled remote delivery could improve access in underserved regions, though careful consideration of quality standards and appropriate case selection remains essential [19].

9 Limitations of the Review

This narrative review possesses inherent limitations that warrant acknowledgement. The rapidly evolving nature of digital twin technology means that recent developments may not yet be reflected in peer reviewed literature, potentially underrepresenting current capabilities. The narrative review methodology, whilst enabling comprehensive synthesis and expert interpretation, lacks the systematic rigour and bias minimisation protocols of systematic reviews. Selection bias in literature identification and interpretation is possible, though efforts were made to include diverse perspectives and study designs.

The limited availability of long-term clinical outcome data represents a significant knowledge gap. Most published studies report short term results or validation against surrogate outcomes rather than definitive treatment endpoints. The relative novelty of digital twin technology means that studies examining post retention stability, patient satisfaction, or long-term functional outcomes are scarce. Additionally, much of the available literature originates from academic centres or technology developers, potentially introducing publication bias favouring positive results.

Economic evaluations of digital twin technology remain limited, making it difficult to assess cost effectiveness or return on investment comprehensively. The costs associated with technology implementation extend beyond acquisition expenses to include training, workflow adaptation, and ongoing support, which are not consistently reported in the literature. This narrative review did not follow PRISMA guidelines, as these are specifically designed for systematic reviews with quantitative synthesis and meta-analysis, which were not appropriate for this interpretive, thematic synthesis of an emerging technological field.

10 Conclusion

Digital twin technology represents a transformative innovation in orthodontic practice, offering unprecedented capabilities for diagnosis, treatment planning, biomechanical analysis, and patient monitoring. The integration of comprehensive three-dimensional patient representations with artificial intelligence algorithms and real-time data synchronisation creates opportunities for truly personalised, evidence-based orthodontic care. Current applications demonstrate substantial potential for improving treatment predictability, optimising force systems, and enhancing patient engagement through sophisticated visualisation capabilities.

However, significant challenges must be addressed before digital twin technology achieves widespread adoption in routine orthodontic practice. Technical infrastructure requirements, data integration complexities, validation needs, and cost considerations represent practical barriers that may limit accessibility, particularly for smaller practices and underserved regions. The evidence base supporting clinical superiority of digital twin enhanced treatment over conventional methods remains developing, with long term outcome studies needed to establish definitive value propositions.

Future developments in digital twin technology will likely emphasise enhanced artificial intelligence capabilities, improved prediction accuracy through larger training datasets, and seamless integration with broader digital dentistry ecosystems. The convergence of virtual reality, augmented reality, and three-dimensional printing technologies creates exciting possibilities for next-generation orthodontic care delivery. Research priorities should focus on prospective validation studies, cost-effectiveness analyses, implementation science investigations, and the development of standardised protocols for digital twin applications.

CRediT Authorship Contribution Statement

David B. Olawade: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Project Administration, Conceptualization. Emmanuel O. Oisakede: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. Oluwakemi Jumoke Bello: Writing – review & editing, Writing – original draft, Methodology, Investigation. Claret Chinenyenwa Analikwu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Software. Eghosasere Egbon: Writing – review & editing, Writing – original draft, Methodology, Investigation, Visualization. John Oluwatosin Alabi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- Digital twins integrate imaging, AI, and biomechanics for orthodontic care
- Technology enables personalized treatment planning with outcome predictions
- Real time monitoring enables adaptive treatment protocols for patient care
- Biomechanical simulations optimize patient specific biomechanical responses
- Patient engagement improves through realistic visual treatment simulations.