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Review Article

From Static Restorations to Adaptive Prosthodontics: Digital Twins, Occlusal Intelligence and Predictive Functional Rehabilitation: A Narrative Review

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Abstract

Digital technologies have transformed prosthodontic rehabilitation, yet treatment planning remains largely static, based on anatomical records captured before treatment begins. Digital twins offer a different model, integrating anatomical, functional, biomechanical and behavioral patient data into a computational representation that is updated throughout the care process. The aim of this narrative review was to evaluate the extent to which patient-specific digital twins can advance prosthodontics from a restorative discipline toward a predictive and adaptive rehabilitation science. Literature identified through PubMed was reviewed across five domains: the limitations of conventional planning; the technologies used to construct digital twins; functional biomechanics beyond static occlusion; predictive modeling of prosthetic complications; and continuous monitoring through sensors and artificial intelligence. Evidence indicates that dynamic functional data meaningfully refine planning and that predictive models may identify restorations at risk of failure before failure occurs. Clinical validation nevertheless remains limited, with few prospective studies, heterogeneous methods and unresolved questions of interoperability, data governance and regulation before these systems enter routine clinical use.

Keywords: Digital Twins; Adaptive Prosthodontics; Occlusal Intelligence; Predictive Modeling; Continuous Monitoring; Virtual Patient

Introduction

Prosthodontic rehabilitation has undergone a broad digital transformation over the past two decades, driven by advances in Cone-Beam Computed Tomography (CBCT), intraoral and extraoral scanning, virtual planning of removable and fixed prostheses, virtual implant planning, occlusal splint design, computer-assisted implant surgery and Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technologies [1]. These innovations have improved diagnostic accuracy, prosthetically guided implant positioning, the fit of restorations and occlusal contacts and the reproducibility of restorative procedures, allowing increasingly complex rehabilitations to be performed with greater precision [2]. Recent high-level evidence shows that computer-assisted workflows, particularly robotic surgery, significantly reduce coronal, apical and angular deviations compared with conventional freehand techniques, consolidating the role of digital technology in optimizing implant placement [3].

Despite these advances, contemporary prosthodontic planning remains fundamentally static. Current digital workflows rely primarily on anatomical information captured prior to treatment, including CBCT images, extraoral and intraoral scans and digital diagnostic wax-ups [4]. Although modern planning software permits detailed three-dimensional visualization and facilitates prosthetically guided positioning, its capacity to integrate functional behavior, biomechanical adaptation, tissue remodeling and long-term biological response remains limited. Planning therefore continues to focus on the geometric accuracy of the procedure rather than on predicting functional behavior and long-term prosthetic performance [1].

This limitation carries considerable clinical weight, because the success of removable, fixed and implant-supported rehabilitation depends on a complex interaction among anatomical, biological, biomechanical, functional and patient-related factors. Precise placement of prosthetic components or implants is only one determinant of therapeutic success [5]. The characteristics of hard, soft and peri-implant tissues; the quality of the prosthetic foundation and available bone; occlusal loads; systemic disease; patient habits; and maintenance all influence biological stability and longevity. A comprehensive preoperative evaluation of these factors is therefore essential to clinical predictability, yet such variables remain difficult to incorporate into conventional digital planning systems [5].

Biological and mechanical complications also continue to occur even when rehabilitation is executed with high technical accuracy. Peri-implantitis, progressive bone loss, mucosal recession, screw loosening, ceramic fracture, restoration wear and ultimately implant loss usually reflect the cumulative interaction of multiple biological and biomechanical factors rather than surgical positioning alone [6]. Roccuzzo and colleagues observed that peri-implantitis frequently reflects the accumulation of errors throughout the therapeutic sequence, including patient selection, diagnosis, planning, prosthetic design and maintenance, demonstrating that success is multifactorial rather than exclusively technical [6]. Similarly, Monje and Nart showed that implant removal usually results from the progressive interaction between biological complications and biomechanical or prosthetic overload, which highlights the limits of current planning paradigms [7].

These findings indicate that prosthodontic planning must evolve beyond static anatomical reconstruction toward dynamic, patient-specific computational models that integrate anatomical, biomechanical, functional, biological and behavioral information throughout treatment [8]. Digital twin technology has emerged as one of the most promising paradigms in this context. Beyond a three-dimensional representation of oral structures, an integrated digital twin continuously incorporates anatomical, biomechanical, functional and biological data to simulate therapeutic scenarios, predict outcomes, monitor changes over time and support personalized decision-making [9]. The general architecture of such a model is outlined in Fig. 1.

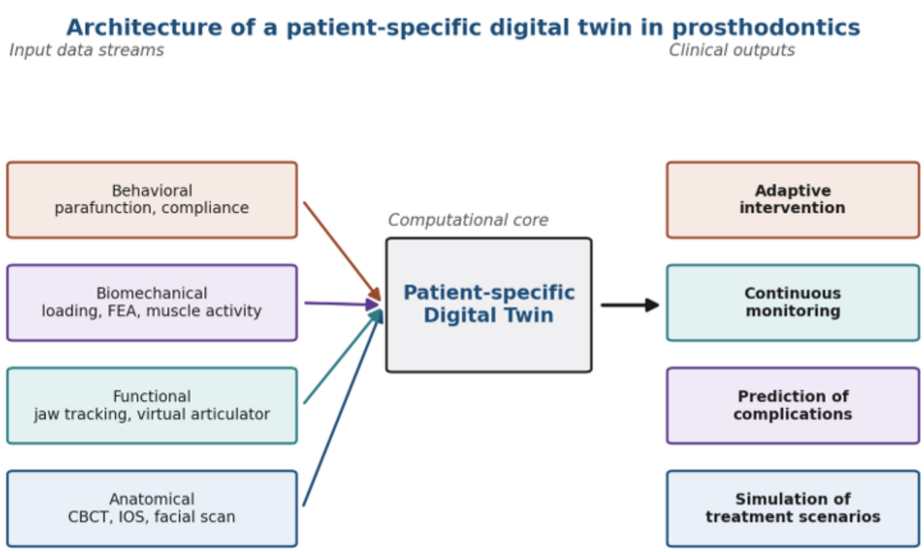

Figure 1: Architecture of a patient-specific digital twin in prosthodontics. Anatomical, functional, biomechanical and behavioral data streams are integrated into a continuously updated computational model that supports simulation, prediction, monitoring and adaptive intervention [8,9].

Applications of digital twins are expanding rapidly across dentistry, including prosthodontics, orthodontics, endodontics and dental education. The technology nevertheless remains at an early stage, characterized by few clinical studies, heterogeneous methodology and limited clinical validation [4,10]. A scoping review by Duggal and colleagues concluded that although digital twins hold considerable potential to strengthen diagnostic accuracy, treatment simulation, clinical monitoring and personalization of care, standardized protocols, robust regulatory frameworks and prospective clinical studies are still required before routine implementation [10]. Digital twins therefore represent an opportunity to transform prosthodontics from a discipline focused on restoring lost structures into a predictive and adaptive rehabilitation science capable of anticipating the biological, biomechanical and functional behavior of a rehabilitation before treatment begins [8-10].

Aim and Objectives

The aim of this narrative review was to evaluate the extent to which patient-specific digital twins can advance prosthodontics from a restorative discipline toward a predictive and adaptive rehabilitation science. The specific objectives were to examine the limitations of conventional static planning, to describe the technologies required to construct patient-specific digital twins, to analyze functional biomechanics beyond static occlusion, to assess the predictive modeling of prosthetic complications and to appraise continuous monitoring through sensors and artificial intelligence. This review does not address CAD/CAM workflows, digital impression techniques or prosthesis fabrication methods; instead, it evaluates how digital twins integrate biomechanical, anatomical, functional and behavioral patient data to predict long-term prosthetic performance prior to treatment delivery.

Methodology

A narrative review was conducted using PubMed to identify relevant literature. Systematic reviews, observational studies, randomized clinical trials and mechanistic investigations published within the last five years were prioritized, supplemented by earlier foundational work. Studies were selected for relevance to digital twin applications in prosthodontics, including the acquisition of anatomical and functional records, biomechanical modeling, prediction of prosthetic complications and continuous monitoring technologies. Given the narrative design, no formal quality-scoring protocol or quantitative synthesis was applied.

Construction of Patient-Specific Digital Twins

A digital twin is an active digital representation of a physical system, constructed from patient data and computational modeling, that supports accuracy, replication, tracking and adaptation [9]. Although digital twins have demonstrated value across several healthcare disciplines, their translation into dentistry is comparatively recent and broad integration will require sustained interdisciplinary collaboration [11]. Constructing a patient-specific twin depends on the acquisition of several complementary data streams, summarized in Table 1.

Data stream	Acquisition technology	Contribution to the twin	Principal limitation	Reference
Skeletal and dental anatomy	CBCT	Three-dimensional hard-tissue reference	Inaccurate representation of the dentition	[12]
Dental surface detail	Intraoral scanning	High-precision virtual models	Edentulous and complete-arch cases; operator dependence	[2,13]
Facial morphology	Facial scanning	Extraoral reference and esthetic integration	Variation between scanning methods	[14]
Maxillomandibular relationship	Virtual articulator	Simulation of mandibular movement	Cross-mounting accuracy still uncertain	[15,16]
Mandibular kinematics	Jaw tracking systems	Time-sequential occlusal contact and loading	Validity for dynamic occlusion needs evaluation	[17]

Data stream	Acquisition technology	Contribution to the twin	Principal limitation	Reference
Muscle activity	Surface electromyography	Functional and neuromuscular data	Standardization of recording protocols	[18]

Table 1: Data streams and acquisition technologies used to construct patient-specific digital twins, with their principal current limitations. References are cited individually for each data stream.

Anatomical acquisition forms the foundation. CBCT, three-dimensional dental scanning and facial scanning together support comprehensive interdisciplinary planning [19]. CBCT provides detailed three-dimensional imaging for diagnosis and improves the quality of multidisciplinary outcomes, although it may inaccurately represent the dentition, a fact that must be recognized [12]. These records allow the position of the maxilla, mandible and occlusion to be established for planning purposes [19].

Intraoral scanners produce high-precision virtual models and recent developments have improved their speed, resolution and functionality, eliminating the need for scanning powder and allowing integration with other digital tools. They are widely used in restorative dentistry and offer accuracy advantages over earlier methods, although difficulties persist in edentulous patients and complete-arch implant impressions [2]. Facial scanning is increasingly used to reconstruct three-dimensional facial images, effectively creating a digital twin of the face, so the reliability and limitations of these scanners warrant careful evaluation [14]. Operator factors also matter, since inexperience and limited skill reduce scan quality and increase patient dissatisfaction, whereas structured practice is associated with improved precision and efficiency [13].

Beyond static anatomy, the virtual articulator is a computer-based system that reproduces maxillomandibular relationships and simulates mandibular movement. In prosthodontics, it should be regarded as an adjunct to the mechanical articulator for diagnosis and planning, particularly in cases requiring modification of the vertical dimension of occlusion; accurate reproduction of jaw movement requires that digitized models be correctly mounted [15]. The accuracy of cross-mounting procedures within a fully digital workflow nevertheless remains uncertain despite extensive study of digital interocclusal registration [16].

Jaw tracking systems provide digitized occlusal analysis, with several approaches available, including ultrasonic systems, photometric devices and algorithm-based methods. These systems examine occlusal contacts in a time-sequential manner together with the distribution of pressure across occlusal surfaces [17]. Surface electromyography complements anatomical imaging by recording and analyzing muscle activity through cutaneous electrodes, making it an important component of a comprehensive patient-specific model [18].

Taken together, the integration of facial scanning, intraoral scanning, CBCT, mandibular movement tracking and muscle recording has enabled the development of the dynamic virtual patient, with defined advantages for recording information and applying it clinically [4]. These technologies provide valuable planning tools for prosthodontic care, although their validity for assessing static and dynamic occlusion requires further evaluation [17,20].

Functional Biomechanics Beyond Static Occlusion

The transition from static to function-oriented prosthodontics requires more than an accurate anatomical representation of the patient. Oral function is governed by the dynamic interaction among mandibular motion, occlusal contacts, masticatory muscles and functional loading, all of which influence the biomechanical behavior of the stomatognathic system [21]. Integrating these patient-specific factors into digital workflows provides a more complete understanding of oral function and supports functionally driven rehabilitation [22].

Patient-specific jaw-motion analysis may reveal functionally relevant contact asymmetries that are not evident during conventional static occlusal assessment, underlining the need for functional evaluation in complex prosthetic rehabilitation [23]. Digital mandibular tracking addresses this limitation by integrating patient-specific kinematic recordings with digital dental models and joint imaging, enabling evaluation of functional stability and optimization of appliance design beyond conventional static maxillomandibular records [24]. Building on these functional records, digitally guided full-mouth rehabilitation aims to establish a stable mandibular relationship throughout function rather than relying solely on static occlusal records [25].

Incorporating patient-specific dynamic articulation into the workflow may therefore improve anterior guidance, reduce chairside adjustments and yield highly accurate restorations, although comparative clinical evidence remains limited [23,25].

Clinical jaw-tracking studies demonstrate that mandibular kinematics are patient-specific, influenced by skeletal morphology and cannot be reliably inferred from anterior occlusal morphology alone [20]. Patient-specific anatomical models therefore become functionally meaningful only when anatomical registration is complemented by reproducible mandibular motion data [22].

Mandibular function arises from the coordinated interaction among the dentition, temporomandibular joints, masticatory muscles and associated craniofacial structures, indicating that oral biomechanics cannot be adequately interpreted by evaluating individual components in isolation [21]. Experimental evidence shows that controlled jaw clenching modifies dynamic motor performance, confirming that masticatory muscle activity contributes to functional biomechanics beyond static occlusal relationships [26]. Alterations in masticatory muscle stiffness and mechanical behavior further influence mandibular biomechanics, supporting the need to consider patient-specific muscle characteristics when evaluating functional loading [27].

Functional loads vary continuously in magnitude and direction during oral activity [28]. Changes in occlusal contact distribution modify joint loading through the coupled behavior of the teeth, periodontal tissues, masticatory muscles and temporomandibular joints [29]. Identical muscular forces may nevertheless generate different stress patterns depending on the condition of the temporomandibular joint and the individual capacity for neuromuscular adaptation [30,31]. Supporting this concept, muscle-driven finite element simulations reproduce physiological temporomandibular joint mechanics more accurately than displacement-based models, identifying muscle recruitment as a key determinant of patient-specific joint loading [32].

Considering oral function as a dynamic biomechanical process enhances the clinical relevance of patient-specific digital rehabilitation. This functional perspective provides the foundation for the predictive modeling of prosthetic performance and complications discussed in the following section.

Predictive Modeling of Prosthetic Complications

Prosthetic complications remain one of the principal challenges affecting the long-term success of fixed prosthodontic rehabilitation [33]. Despite substantial advances in restorative materials and digital workflows, mechanical and biological failures continue to occur due to the complex interactions among material properties, prosthetic design, occlusal loading, patient-specific functional behavior and clinical execution [34]. Rather than treating these complications as isolated events, contemporary prosthodontics increasingly recognizes them as multifactorial processes that may be anticipated through predictive modeling [35]. By integrating clinical records, digital imaging, biomechanical parameters and longitudinal patient data, predictive models may support individualized planning and facilitate early identification of restorations at greater risk of failure [35]. The principal complications and their determinants are summarized in Table 2.

Complication	Principal determinants	Data required for prediction	Reference
Ceramic fracture	Restoration design, connector dimensions, material thickness, occlusal load	Material type, connector geometry, restoration location, occlusal scheme	[33]
Veneer chipping	Weak interface between veneering ceramic and zirconia framework	Monolithic versus veneered configuration; loading pattern	[36,37]
Implant overload	Restoration design, implant distribution, crown-to-implant ratio, cantilever length, prosthetic fit	Prosthetic configuration, parafunction, patient-specific loading	[34]
Screw loosening	Preload loss under cyclic loading, connection geometry, tightening torque	Connection type, torque protocol, prosthetic position, force direction	[38]
Tooth wear	Highly individual; prior wear does not	Sequential intraoral scans with	[39,40]

Complication	Principal determinants	Data required for prediction	Reference
progression	predict future progression	automated comparison	
Loss of vertical dimension	Not inevitable; dentoalveolar compensation may preserve the relationship	Functional, esthetic, phonetic and restorative assessment	[41]

Table 2: Principal prosthetic complications, their multifactorial determinants and the data required for predictive modeling. References are cited individually for each complication.

Among mechanical complications, ceramic fracture and veneer chipping remain the most common technical failures in zirconia-based restorations [33,36]. Although zirconia offers excellent mechanical performance and favorable long-term survival, fracture may still occur when restoration design, connector dimensions, material thickness or occlusal loading are unfavorable [33]. Porcelain-veneered zirconia restorations consistently show a higher incidence of veneer chipping than monolithic zirconia because of the weaker interface between veneering ceramic and framework [36]. Long-term clinical data also indicate that implant-supported zirconia prostheses with veneering porcelain remain susceptible to chipping despite high survival rates [37]. Predictive models should therefore integrate restorative material, prosthetic configuration, restoration location, connector geometry and occlusal characteristics rather than relying on material selection alone [37].

Mechanical complications in implant-supported restorations are likewise determined by multiple interacting variables. Functional overload, particularly in patients with parafunctional habits or unfavorable occlusal schemes, may contribute to screw loosening, component fracture and prosthetic failure. Implant overload is nevertheless influenced by restoration design, implant distribution, crown-to-implant ratio, cantilever length, prosthetic fit and patient-specific loading patterns rather than by any single mechanical factor [34]. Similarly, screw loosening results from gradual preload loss during cyclic loading and is affected by connection geometry, tightening torque, prosthetic position and the direction of occlusal force [38]. Integrating these biomechanical and clinical variables may enable predictive models to identify restorations that require closer maintenance before catastrophic failure occurs [35].

Patient-related functional change should also be incorporated into predictive systems. Tooth wear progression is dynamic and highly individual, varying among patients, teeth and even different surfaces of the same tooth [39]. Longitudinal evidence shows that prior wear patterns do not necessarily predict future progression, underscoring the need for continuous monitoring [39]. Advances in artificial intelligence have expanded this capability by enabling the automated comparison of sequential intraoral scans, thereby providing objective quantification of tissue loss and reducing operator-dependent variability [40]. Such technologies may improve individualized risk assessment, optimize recall intervals and support restorative decisions before extensive structural damage develops [40].

Preservation of the occlusal vertical dimension is a further consideration [41]. Severe tooth wear does not inevitably produce loss of vertical dimension, because dentoalveolar compensation frequently maintains the vertical relationship despite substantial tissue loss. Increasing the occlusal vertical dimension should therefore follow comprehensive functional, esthetic, phonetic and restorative evaluation rather than wear severity alone and current consensus recommendations advocate individualized, minimally invasive rehabilitation with careful diagnostic assessment before the vertical dimension is altered [41].

Overall, predictive modeling represents a promising strategy for improving prosthodontic decision-making by integrating restorative design, material properties, implant biomechanics, occlusal function, digital monitoring and patient-specific characteristics. Rather than replacing clinical judgment, such models provide an evidence-based tool that supports individualized planning and may reduce prosthetic complications over the long term [33,35,40].

Adaptive Prosthodontics Through Continuous Monitoring

The integration of continuous monitoring technologies into prosthodontics represents a shift from episodic clinical evaluation toward adaptive, data-driven rehabilitation [42]. Conventional prosthetic maintenance relies mainly on scheduled follow-up visits, during which clinicians identify complications that may have developed weeks or months earlier. Adaptive prosthodontics instead incorporates wearable sensors, instrumented prostheses, digital follow-up and artificial intelligence to monitor functional performance in near real time, allowing earlier detection of biomechanical changes and individualized intervention before irreversible complications occur [42]. This closed-loop relationship between planning, delivery, monitoring and adaptation is illustrated in Fig. 2.

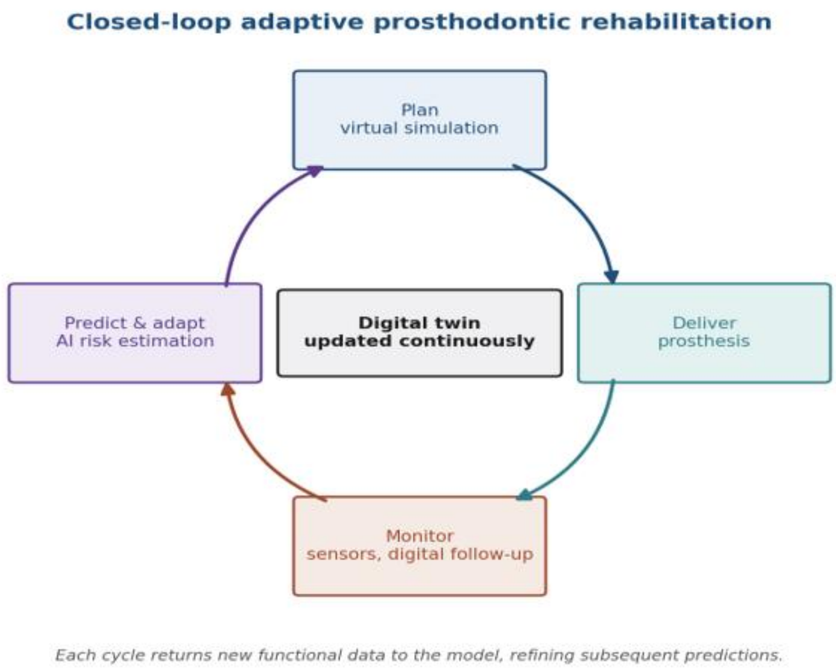

Figure 2: Closed-loop adaptive prosthodontic rehabilitation. Planning, delivery, monitoring and prediction form a continuous cycle in which each stage returns functional data to the digital twin, refining subsequent decisions [9,42,43].

Sensor technologies have become increasingly relevant because they can capture functional information that conventional chairside examination cannot [43]. A systematic review of wireless sensors for assessing occlusal and bite forces found that the devices evaluated were valid, accurate and reproducible, supporting their use for objective measurement of functional loading [44]. Such data provide evidence of functional adaptation, parafunctional activity and loading patterns that would otherwise remain undocumented between appointments and wireless transmission additionally enables remote data capture [43].

The concept of the instrumented or bio-intelligent prosthesis extends this principle by embedding sensing capability within the restoration itself. Such systems are designed to detect mechanical, chemical or thermal cues and to couple these inputs to computational analysis, with the stated objective of transforming prostheses from passive restorations into devices that actively monitor oral and systemic health [42]. Nanomaterial-based biosensors have been described for implant surveillance and the early identification of prosthesis-related complications [43]. It should be emphasized that these systems remain largely developmental, since the available literature consists predominantly of laboratory work, prototypes and early feasibility studies rather than clinical trials demonstrating improved prosthetic outcomes [45].

Digital follow-up platforms complement sensor data by integrating patient-generated information with clinical records. An overview of systematic reviews and meta-analyses found that teledentistry can improve access to and quality of oral healthcare, while noting variability in study quality across the underlying reviews [46]. Applied to prosthodontics, such platforms allow evaluation of prosthetic performance between scheduled appointments and support recall intervals based on individual risk rather than fixed schedules, although evidence specific to prosthetic maintenance remains limited [47]. Artificial intelligence provides the analytical layer for these data. Systematic evaluation of artificial intelligence in prosthodontics indicates a growing application to treatment planning, outcome prediction and analysis of clinical records, with performance varying by task and dataset [48]. Machine learning models may combine clinical variables, digital scans and sensor outputs to estimate the probability of technical complications and the automated analysis of sequential intraoral scans described earlier illustrates how such monitoring can function in practice [35,40]. Reported systems nevertheless perform specific, narrowly defined tasks rather than managing rehabilitation as a whole [49].

Combined with a digital twin, continuous feedback could in principle allow the model and eventually the prosthesis, to be adjusted as anatomical remodeling, aging or changes in masticatory behavior occur [8,9]. This remains a conceptual objective rather than a demonstrated clinical capability. Substantial obstacles persist, including the need for long-term validation of monitoring devices and unresolved questions of data security, patient privacy, interoperability and regulatory approval [11,50]. Continuous monitoring nonetheless offers a plausible route toward earlier diagnosis and more personalized prosthetic maintenance, provided its claims remain proportionate to the evidence [42,48].

Conclusion

Digital twins may integrate follow-up data over time, keeping the virtual model current throughout rehabilitation so that clinicians can evaluate prosthetic performance and determine whether modification is required. This may reveal biological and functional changes that develop after treatment, including early bone remodeling or altered muscle function, allowing follow-up to be adjusted to individual need rather than to fixed maintenance intervals. Artificial intelligence supports this closed-loop model, with current prosthodontic applications concentrated in treatment planning, outcome prediction and analysis of clinical records [48]. Reported systems nevertheless perform specific tasks rather than managing rehabilitation as a whole and responsibility for patient care remains with the clinician [49]. Data privacy, transparency, algorithmic bias, informed consent and the diversity of training data are recurring concerns, with regulatory oversight and continuous evaluation identified as prerequisites for routine implementation [45,50]. Translation will further require consistent data exchange between systems, clinician training and collaboration among clinicians, engineers and developers [11]. The principal barriers are summarized in Table 3.

Barrier	Current status	Requirement for translation	Reference
Clinical validation	Predominantly reviews, conceptual papers and feasibility studies	Prospective studies with defined outcome measures	[10,45]
Methodological standardization	Heterogeneous protocols across investigations	Agreed acquisition, modeling and reporting standards	[10]
Interoperability	Digital systems exchange data inconsistently	Common data formats across platforms	[11]
Data governance	Privacy, consent and security repeatedly identified as concerns	Explicit consent frameworks and secure data handling	[11,45]
Algorithmic fairness	Performance may vary with training data diversity	Representative datasets and transparent reporting	[50]
Regulation and training	Frameworks and clinician education still developing	Regulatory oversight and structured training pathways	[45,50]

Table 3: Translational barriers to clinical implementation of digital twins in prosthodontics, with the current maturity of supporting evidence. References are cited individually for each barrier.

In relation to the aim stated at the outset, patient-specific digital twins can already integrate anatomical and functional data in ways that meaningfully refine planning and predictive models can identify restorations at elevated risk. What remains undemonstrated is that this integration improves long-term clinical outcomes, since prospective validation, standardized protocols and interoperable systems are largely absent. Digital twins are therefore best described at present as a credible and rapidly developing framework for predictive and adaptive prosthodontics rather than an established clinical reality.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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Ethical Statement
This manuscript is a narrative literature review and did not involve human participants, animal subjects or patient data. No ethical approval was required.

Informed Consent Statement
Not applicable.

Authors' Contributions
All authors contributed equally to this paper.

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