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The Role of Artificial Intelligence in Clinical Decision Making for Prosthodontic Treatment Planning, Manufacturing, and Complication Management

SUMMARY

Artificial intelligence is becoming an increasingly influential component of prosthodontics, reshaping digital workflows into intelligent clinical systems that may enhance diagnostic precision, treatment planning, and restorative outcomes. This narrative review aims to examine the role of artificial intelligence in prosthodontic clinical decision-making, with particular emphasis on treatment planning, restoration design, manufacturing processes, risk assessment within the clinical workflow, and the prediction of potential complications. Contemporary artificial intelligence approaches, including deep learning, generative modeling, and multimodal data integration, enable the simultaneous interpretation of heterogeneous clinical information derived from radiographic imaging, intraoral scans, facial scans, and occlusal records. Within this framework, artificial intelligence has demonstrated substantial potential in prosthetically driven implant planning, automated prosthesis design, and the generation of patient-specific restorations tailored to individual anatomical and occlusal characteristics. These capabilities may enhance marginal adaptation, occlusal harmony, esthetic outcomes, and manufacturing precision, while also promoting greater standardization and reproducibility across clinical workflows. In parallel, predictive artificial intelligence models have shown promising performance in identifying biological and mechanical risk profiles by integrating clinical, radiographic, and biomechanical variables, thereby supporting earlier intervention in prosthodontic care. Despite these advances, current artificial intelligence applications in prosthodontics remain constrained by limited training data, insufficient testing in real clinical environments, and uncertain performance across different patient groups. Overall, available evidence suggests that artificial intelligence may provide clinically relevant support in prosthodontics by assisting diagnostic interpretation, prosthetically driven treatment planning, restoration design, and complication risk assessment.

Keywords: Artificial intelligence; Deep learning; Digital dentistry; Prosthodontics

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Introduction

The rapid advancement of artificial intelligence (AI) driven digital technologies represents a fundamental paradigm shift in prosthodontic treatment, reshaping clinical decision-making, restoration design, and manufacturing

processes. Although AI was initially developed as an automation tool to accelerate CAD/CAM-based restorative fabrication, it has evolved into an advanced decision-support technology integrated into higher-order cognitive processes, including clinical data interpretation, treatment planning, restoration design, and complication risk prediction.¹⁻³ Conventional prosthodontic planning

is inherently multifactorial, requiring the simultaneous evaluation of radiographic imaging, intraoral scans, clinical photographs, and functional records. This multidimensional process may introduce operator-dependent variability and can limit decision consistency, particularly in complex implant-prosthetic cases. AI-based systems aim to enhance standardization and reproducibility in clinical workflows by concurrently analyzing heterogeneous data streams and supporting evidence-informed, data-driven decision-making.¹

The applicability of AI in dentistry has become particularly evident with advancements in image analysis and segmentation technologies.⁴ Deep learning models have demonstrated clinically acceptable accuracy in implant detection, automatic numbering on panoramic radiographs, and radiographic assessment of implant–prosthetic discrepancies.^{5,6} These findings indicate that AI has evolved beyond a tool that merely accelerates data processing and has emerged as a reliable adjunct to support clinical decision-making.

However, a substantial proportion of reported accuracy rates is derived from controlled datasets, and the generalizability of these systems to large-scale, clinically heterogeneous patient populations remains an area of ongoing investigation.^{7,8} Moreover, the “black box” nature of deep learning architectures poses a significant methodological limitation for explainability and clinical trust.^{5,9} These limitations underscore the need for transparent and clinically validated AI models.

The existing literature has predominantly focused on isolated applications of AI, while a comprehensive decision architecture encompassing the entire clinical decision-making continuum remains insufficiently explored.^{10,11} Therefore, the aim of this narrative review is to evaluate the role of AI in prosthodontic treatment within an integrated analytical framework, spanning all stages of the clinical workflow, from data acquisition and treatment planning to restoration manufacturing and complication management.^{12–14}

The Role of Artificial Intelligence in the Clinical Decision-Making Process in Prosthodontic Treatment

The primary contribution of artificial intelligence (AI) in prosthodontic treatment is its ability to analyze multiple clinical variables simultaneously, thereby enhancing the predictability and reliability of treatment decisions. Conventional digital systems were originally developed to automate restorative manufacturing processes and primarily

operate based on predefined algorithmic rules. However, these systems lack the capacity to generate clinically meaningful decisions by integrating patient-specific biomechanical, anatomical, and functional parameters into a comprehensive decision-making framework.^{8,9}

AI-based systems provide data-driven insights by analyzing complex relationships among anatomical imaging, occlusal relationships, and restorative parameters. Revilla-León et al. reported that AI can play a significant role in implant planning by enabling automatic segmentation of anatomical structures and optimizing implant positioning to meet prosthetic requirements.¹⁵ Similarly, Gönültaş et al. demonstrated that AI-assisted implant planning systems show high agreement with clinician-derived decisions and may enhance consistency across several planning parameters.¹⁶

The contribution of AI to the clinical decision-making process extends beyond anatomical planning. Wu et al. demonstrated that AI-based models can predict the maximal intercuspal position, highlighting their potential utility in reconstructing maxillomandibular relationships and forecasting occlusal contact patterns.¹⁷ Such systems can support the optimization of functional integration during restoration design, thereby reducing the risk of occlusal discrepancies and improving overall prosthetic compatibility.

Artificial Intelligence–Based Clinical Decision Points in the Prosthodontic Treatment Workflow

The prosthodontic treatment process can be conceptualized as a multi-stage clinical decision chain that extends from data acquisition to the long-term follow-up of the restoration (Figure 1). At the initial stage of the clinical workflow, AI plays a critical role in evaluating the accuracy of intraoral scans. Róth et al. demonstrated that AI-based analytical systems can detect missing data regions and geometric distortions in intraoral scans with high accuracy.¹⁸ This capability enables the early identification and correction of data-related errors that may otherwise compromise marginal adaptation and overall restorative fit.

Beyond the detection of missing data, AI-based algorithms are increasingly being incorporated into intraoral scanning workflows to support quality assessment and data optimization during acquisition. These systems can evaluate scan completeness, identify localized geometric inconsistencies, and assist in filtering artifacts associated with saliva, soft-tissue movement, surface noise, repeated scanning, and limited optical access. AI-assisted mesh-

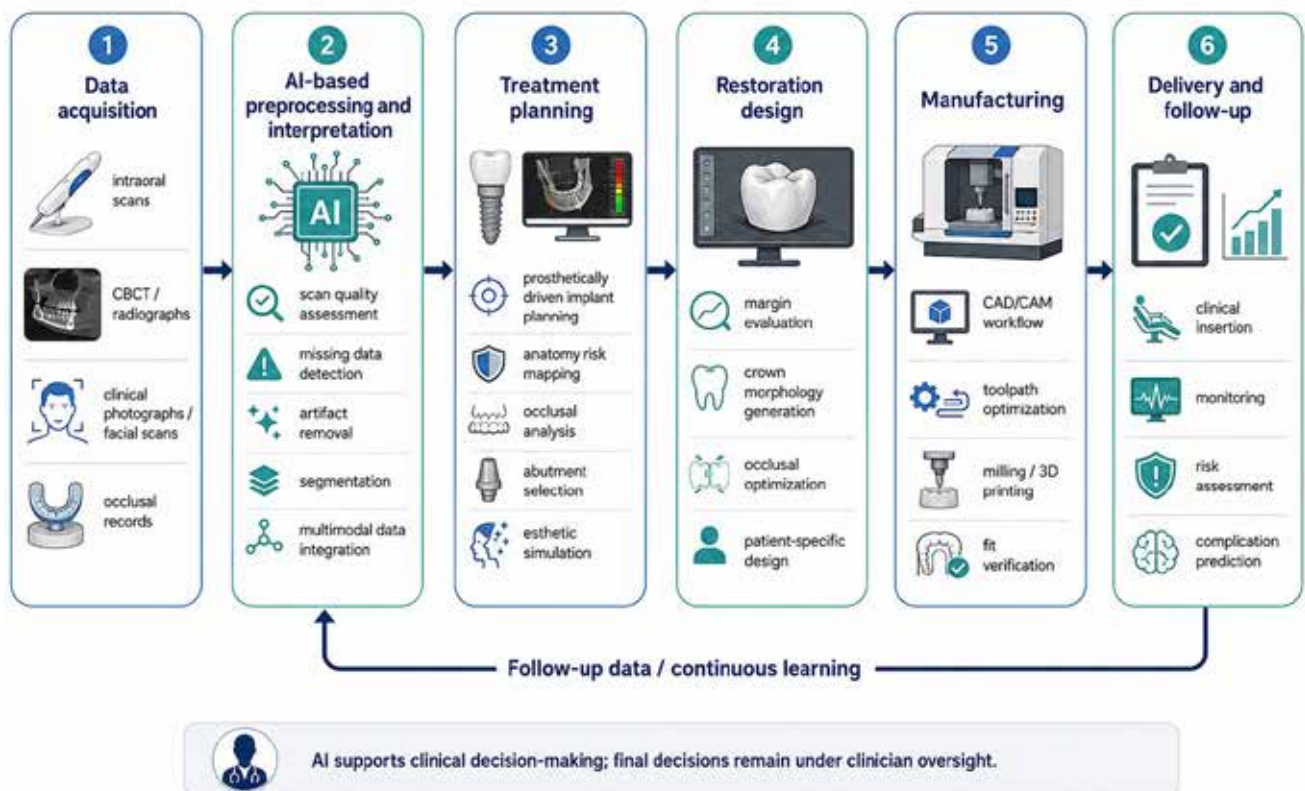


Figure 1. Schematic representation of the artificial intelligence-supported prosthodontic workflow.

completion algorithms may also reconstruct incomplete regions of digital impressions, particularly at interproximal surfaces and in anatomically complex areas, thereby improving scan continuity and reducing reliance on manual correction.¹⁸

Recent deep learning-based point-cloud completion models have demonstrated high geometric fidelity in reconstructing missing intraoral scan regions and preserving fine anatomical details more effectively than conventional surface-reconstruction methods.¹⁹ Generative network architectures have similarly shown the potential to restore incomplete crown datasets rapidly, supporting their possible integration into real-time or near-real-time scanning workflows.²⁰ In implant-supported digital impressions, AI-assisted library-matching protocols can automatically recognize scanned components, such as implant scan bodies, and align them with standardized virtual library geometries. This approach may improve reproducibility and reduce operator-dependent variability, particularly when optimized scan-body designs are used.^{21,22}

Nevertheless, the effect of AI-assisted correction and alignment on scan trueness remains inconsistent. Some studies have reported increased linear and angular deviations when automated scan-body recognition was performed before complete acquisition of the scan-body geometry.²³ Therefore, although AI-based tools may improve scan

completeness, consistency, artifact management, and workflow efficiency, their influence on absolute accuracy remains dependent on the scanner, scanning strategy, component geometry, and software protocol.

Preparation and margin evaluation are among the final reversible stages of the restoration design process. AI-based analytical systems assess margin continuity, the presence of undercuts, and preparation adequacy according to standardized criteria, providing early feedback that enables clinicians to either proceed with the design or modify the preparation as needed. This capability enhances the consistency and overall quality of restoration design, particularly in cases involving multiple restorations.²⁴

AI-based systems reinforce the prosthetically driven implant placement concept in implant-supported prosthetic rehabilitation by enabling integrated analysis of CBCT and intraoral scan data. Through this approach, these systems can automatically map bone volume, bone density, and anatomical risk zones, and optimize implant positioning in alignment with anatomical, biomechanical, and restorative requirements.^{15,25} This integration establishes a clinical decision-support layer that enhances standardization of planning while reducing the risk of surgical-prosthetic discrepancies. Systematic reviews have reported that AI-assisted implant planning systems demonstrate high accuracy in the mandible and clinically acceptable performance in the

maxilla; however, the clinical generalizability of automated implant placement and surgical guide design remains dependent on the availability of high-quality training datasets and standardized clinical protocols.^{9,26} Furthermore, AI-based decision-support systems can integrate parameters such as implant angulation, peri-implant soft tissue thickness, restorative space availability, and occlusal loading patterns to generate patient-specific recommendations among multi-unit, ti-base, or customized abutment options. Nevertheless, these recommendations require clinician validation, as critical contextual factors-including emergence profile, esthetic demands, and prosthesis cleansability-must be considered to ensure optimal clinical outcomes.^{27,28}

During the esthetic design phase, AI helps optimize restoration design by analyzing facial morphology and dental relationships. The ability of generative models to produce photorealistic simulations enables the visualization of post-treatment outcomes in advance, thereby reducing the risk of esthetic dissatisfaction.²⁹⁻³¹ In addition, AI-based analyses can evaluate gingival biotype and interproximal morphology, supporting the optimization of crown length, contact point position, and tooth-gingival relationships within biologically acceptable limits.^{32,33} Systematic reviews have demonstrated that AI-assisted digital smile design (DSD) tools can improve esthetic outcomes, enhance smile symmetry and patient satisfaction, and increase clinical efficiency by reducing overall design time.^{34,35}

Artificial Intelligence in Restoration Design, Morphological Generation, and Manufacturing Accuracy

The integration of artificial intelligence (AI) into prosthodontics has transformed restoration design from an operator-dependent process into a data-driven workflow capable of automated optimization. Conventional CAD systems generate restoration morphology based on predefined morphological libraries, whereas AI-based systems can optimize restoration morphology according to patient-specific anatomical and functional parameters.^{36,37}

Broll et al. demonstrated that generative deep learning models can reconstruct natural tooth morphology with high accuracy.³⁸ These systems analyze antagonist tooth morphology, occlusal contact relationships, and preparation geometry to generate restorations that are morphologically and functionally optimized for the individual patient.^{37,38}

AI-Based Crown Morphology Generation

In digital dentistry, restorative design processes were initially dependent on operator-driven CAD tools; however,

the development of AI-based systems has enabled data-driven and automated generation of crown morphology. Contemporary AI algorithms construct restorative morphology not only according to preparation margins but also by integrating functional parameters, including adjacent tooth morphology, antagonist relationships, and the occlusal plane. This approach transforms restorative design beyond mere geometric reconstruction into a comprehensive process that prioritizes biological and functional integrity.^{36,37,39}

Deep learning and generative AI models can replicate natural tooth anatomy with high accuracy by leveraging anatomical variations learned from large-scale morphological datasets. Convolutional neural networks (CNNs) and generative adversarial networks (GANs) enable the reconstruction of missing tooth morphology that is anatomically consistent with surrounding structures.^{38,39} These systems optimize not only the external contour of the restoration but also the occlusal anatomy, cusp-fossa relationships, and functional contact points, thereby supporting biomechanical integration and functional harmony.^{37,38}

The literature reports that generative deep learning-based crown design approaches can analyze preparation geometry and occlusal morphological data to generate restoration forms that are anatomically consistent and closely resemble natural tooth morphology, thereby reducing operator dependency during the restoration design process.³⁸ Similarly, generative AI approaches have been shown to automatically generate anatomically accurate crown morphology by optimizing occlusal harmony with antagonist dentition.⁴⁰ These findings indicate that AI has evolved beyond a passive tool limited to margin detection and now functions as an active design system capable of generatively constructing restoration morphology.

Marginal Fit and Internal Adaptation

Marginal and internal adaptation accuracy represents one of the fundamental determinants of the clinical success of prosthetic restorations. Inadequate marginal fit can increase the risk of microleakage, secondary caries, and periodontal complications; therefore, maintaining marginal gap values within clinically acceptable limits is critical. The literature generally considers a marginal gap of less than 120 µm to be clinically acceptable.⁴¹

Recent studies have demonstrated that AI-based crown design systems provide clinically acceptable, highly accurate marginal and internal adaptation. In a study employing the triple-scan methodology, Meshram et al. reported that crowns designed using AI-based software exhibited superior marginal and internal fit compared with those generated by conventional CAD systems.⁴² Similarly, other comparative investigations have shown that AI-designed crowns achieve marginal gap values within clinically acceptable thresholds

and demonstrate adaptation accuracy comparable to, or in some cases exceeding, that of traditional CAD systems.^{11,43}

This superior performance is attributed to AI algorithms' ability to analyze the preparation geometry with high precision and optimize the restoration's internal surface morphology accordingly. Moreover, AI systems reduce operator-dependent variability, thereby enhancing adaptation accuracy at the tooth-restoration interface, supporting biomechanical stability, and contributing to more standardized and predictable clinical outcomes.^{44,45} Collectively, the current body of evidence indicates that AI-based crown design systems are clinically reliable with respect to marginal and internal adaptation and can provide performance comparable to, or, in certain contexts, superior to, that of conventional CAD systems.

Occlusal Accuracy and Functional Adaptation

The functional success of prosthetic restorations depends not only on morphological accuracy but also on proper occlusal integration and functional adaptation. In conventional CAD systems, occlusal morphology is largely defined manually by the operator, whereas AI-based systems can automatically optimize this process by analyzing antagonist tooth morphology and occlusal relationships.^{46,47} These algorithms can predict occlusal contact points and facilitate the functional integration of the restoration with the antagonist dentition, thereby reducing the need for chairside occlusal adjustments.⁴⁸

Comparative studies have demonstrated that AI-designed crowns exhibit occlusal contact accuracy comparable to, or in some cases superior to, that of restorations generated using conventional CAD systems.^{43,49} By optimizing occlusal contact relationships, AI systems promote more balanced load distribution and support the biomechanical performance and functional stability of restorations.

Integration of Artificial Intelligence in the Manufacturing Process

Artificial intelligence (AI) technologies extend beyond restoration design and can be integrated into the entire digital manufacturing workflow. The modern digital workflow represents a multi-stage process that includes digital acquisition, preparation, margin detection, restoration design, and CAM-based manufacturing, with AI algorithms enhancing both accuracy and process efficiency at each stage.²⁷

AI-based margin detection algorithms identify preparation boundaries with high precision, thereby establishing a reliable foundation for restoration design and improving restorative fit by reducing operator-dependent errors.⁵⁰ In addition, AI algorithms optimize toolpath generation during the CAM phase, improving milling

accuracy and minimizing microscopic deviations that may occur during manufacturing, thereby enhancing the geometric fidelity of the final restoration.⁵¹

The integration of AI into the digital workflow improves not only design accuracy but also the speed, efficiency, and predictability of the manufacturing process. By optimizing the entire continuum from restoration design to fabrication, these systems enable the production of restorations that are faster, more standardized, and more accurate.^{52,53}

Several commercially available platforms illustrate the clinical integration of AI and related digital technologies in prosthodontics. The 3Shape TRIOS ecosystem (3Shape A/S, Copenhagen, Denmark), exocad DentalCAD and AI Design (exocad GmbH, Darmstadt, Germany), and CEREC Software (Dentsply Sirona, Charlotte, NC, USA) support scan acquisition, automated restorative design, and chairside CAD/CAM workflows.^{15,44,54,55} Dentbird Crown (Imageworks Inc., Seoul, Republic of Korea) provides web-based AI-assisted crown design, whereas coDiagnostiX (Straumann Group/Dental Wings, Basel, Switzerland) and Diagnocat (Diagnocat Inc., Miami, FL, USA) support anatomical segmentation, image analysis, implant planning, and surgical-guide preparation.⁵⁶⁻⁵⁸ For esthetic planning, the DSD App (Digital Smile Design, Madrid, Spain) enables two-dimensional smile simulation and case communication, while SmileCloud (Straumann Group, Basel, Switzerland) provides AI-assisted biometric smile design, photorealistic simulation, and cloud-based interdisciplinary collaboration.^{59,60} Collectively, these platforms illustrate the growing clinical integration of AI-assisted technologies in prosthodontics.

Prediction and Management of Prosthetic Complications

Sustaining long-term success in implant-supported prosthetic treatment depends not only on accurate planning and manufacturing processes but also on the early prediction and effective management of potential complications. Conventional complication management has largely relied on reactive approaches implemented after clinical symptoms or radiographic findings emerge, which may result in missed opportunities for early intervention and reduced treatment predictability.

In contrast, artificial intelligence (AI)-based systems can perform multidimensional analyses of clinical, radiographic, and prosthetic data to assess the risk of developing complications before they become clinically evident, thereby providing clinicians with data-driven predictive decision support. This approach facilitates a

transition in complication management from a reactive model toward a risk-based, preventive, and personalized clinical paradigm.⁶¹⁻⁶³ Within this context, AI applications play a significant role in the early detection and prevention of both mechanical and biological complications in implant-supported prosthetic therapy.

Prediction and Management of Mechanical Complications

Mechanical complications include implant failure, inadequate osseointegration, loss of implant stability, and structural complications associated with prosthetic components, all of which directly affect the long-term success of implant-supported restorations. Artificial intelligence (AI)-based prognostic models can integrate clinical, radiographic, and prosthetic parameters to predict the likelihood of mechanical complications, such as implant failure and loss of stability, with high accuracy.⁶¹⁻⁶³ Artificial neural networks and deep learning models have been reported to predict implant survival with accuracy rates ranging from 80% to 94% by analyzing complex relationships among multiple biomechanical and clinical variables influencing implant outcomes.⁶³

Convolutional neural network (CNN)-based image analysis systems enable the early prediction of mechanical complications by detecting marginal bone loss, peri-implant radiolucency, and subtle bone changes that may compromise implant stability with high sensitivity.⁶³⁻⁶⁵ In addition, AI-based analytical approaches have been shown to optimize implant placement and biomechanical load distribution by evaluating implant position, bone quality, and peri-implant anatomical characteristics.^{62,63} This predictive capability enables identification of high-risk cases at an early stage, allowing modifications to implant planning, loading protocols, and prosthetic design to mitigate the risk of mechanical complications and improve long-term implant stability.⁶¹⁻⁶³

Prediction and Management of Biological Complications

Biological complications encompass peri-implant inflammatory conditions, including peri-implant mucositis, peri-implantitis, and marginal bone loss, and represent major causes of implant failure. Artificial intelligence (AI)-based systems facilitate the early detection of peri-implant diseases and enable individualized risk assessment by integrating radiographic imaging, clinical parameters, and patient-related systemic data.⁶¹⁻⁶³ Convolutional neural network (CNN)-based models have been shown to detect peri-implant bone loss and inflammatory changes with high accuracy, providing earlier and more objective diagnostic capabilities compared with conventional assessment methods.⁶³⁻⁶⁵

Machine learning-based prognostic models have been reported to reliably predict the risk of peri-implantitis and

implant failure by analyzing multifactorial parameters, including periodontal history, bone quality, implant position, and systemic health status.^{62,63,66} Furthermore, AI-assisted risk assessment systems can dynamically update patient-specific risk profiles by continuously analyzing follow-up radiographs and clinical data, enabling early detection of biological complications and facilitating timely preventive interventions.^{61,63} This predictive approach supports the transition from reactive to preventive management of complications in implant therapy, thereby contributing to improved long-term clinical outcomes and enhanced implant survival.^{62,63}

Large Language Models

Large language models (LLMs) have been evaluated in a limited number of studies in prosthodontics; however, they demonstrate meaningful decision-support potential by rapidly synthesizing clinical guidelines, systematic reviews, and treatment algorithms.^{67,68} By transforming dispersed literature on implant indications, loading protocols, material selection, and maintenance strategies into structured recommendations, LLMs function as an interpretive support layer that reduces clinician cognitive burden. This capability is particularly valuable in complex, multi-parameter clinical scenarios, where LLMs may facilitate the comparison of alternative approaches and support the structured articulation of clinical rationale.^{67,68}

Nevertheless, a fundamental limitation of LLM integration into clinical practice is the absence of intrinsic verification mechanisms and the associated risk of hallucinations. It has been demonstrated that LLMs used for clinical decision support may generate incorrect indications, outdated protocols, or fabricated references, potentially compromising patient safety through inappropriate material selection or unsuitable loading strategies.^{69,70} These limitations largely stem from LLMs' inability to directly analyze biomechanical data, anatomical variations, and radiographic findings. Indeed, analyses based on large-scale patient simulations have reported that LLMs are not sufficiently reliable to function as independent clinical decision-makers with respect to diagnostic accuracy and guideline adherence.⁷¹

Accordingly, LLMs may be integrated as interpretive components within multimodal systems linked to validated databases and image-based AI, with potential applications in literature synthesis, clinical reasoning, patient communication, and education.⁷²

Ethical and Legal Considerations

The integration of artificial intelligence (AI)-assisted decision systems into prosthodontic treatment represents not only a technological advancement but also a structural transformation that necessitates a redefinition of ethical, legal, and professional responsibilities. From a patient safety perspective, AI systems must be transparent, explainable, and verifiable, and should function as decision-support tools rather than substitutes for clinical judgment.⁷³ Ethical risks primarily involve algorithmic bias, data privacy breaches, erosion of patient autonomy, and lack of transparency. Models trained on limited or non-representative datasets may generate inaccurate prosthetic recommendations for specific patient populations, thereby potentially exacerbating clinical disparities.⁷⁴ Systematic reviews emphasize that AI implementation should be structured in accordance with principles of privacy, equity, autonomy, transparency, and accountability, and that informed consent procedures should explicitly encompass the use of patient data within AI systems.⁷⁵ From a legal standpoint, the allocation of liability remains incompletely defined; however, the European Union Artificial Intelligence Act (AI Act) classifies medical AI applications as high-risk systems, mandating human oversight, data governance, and traceability. Accordingly, the safe integration of AI in prosthodontics depends on balancing technological capability with ethical safeguards, legal accountability, and professional responsibility.

Limitations and Future Perspectives

Although artificial intelligence (AI) applications in prosthodontic treatment have demonstrated promising outcomes, the current body of evidence is characterized by significant methodological limitations. Most studies use retrospective designs and relatively small, homogeneous datasets, and the generalizability of reported performance metrics to heterogeneous clinical populations and real-world practice settings remains insufficiently validated. Furthermore, existing research has predominantly focused on technical accuracy metrics, while the impact of AI systems on long-term clinical outcomes, complication rates, and overall treatment success has been only marginally investigated.

Additional challenges include potential bias within training datasets, data heterogeneity, and the limited explainability of many AI models, all of which pose barriers to safe and reliable clinical integration. Accordingly, future research should prioritize the development and prospective validation of AI models trained on large-scale, multicenter

datasets that integrate multimodal clinical data. The advancement of explainable, clinically validated AI systems will enable more reliable prediction of complications and support personalized prosthodontic treatment planning, thereby enhancing the safety, effectiveness, and clinical utility of AI-driven decision support.

Conclusion

Artificial intelligence has the potential to advance prosthodontic care toward more data-driven, standardized, and predictable clinical workflows. Current evidence indicates that AI can improve diagnostic accuracy and workflow efficiency across implant planning, restoration design, manufacturing, and complication risk assessment. Its clinical value, however, remains dependent on explainable and validated systems integrated into clinician-led workflows. Further prospective and real-world studies are needed to determine whether these technologies improve long-term clinical outcomes.

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