



Robotics in prosthodontics: Current applications, challenges and future directions

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ABSTRACT

Background: Robotics is increasingly integrated into digital dentistry and offers potential gains in accuracy, repeatability, and ergonomics across prosthodontic rehabilitation.

This narrative review synthesizes current robotic applications relevant to prosthodontics and identifies key barriers and research priorities.

Methods: A narrative review was conducted in PubMed/MEDLINE, Scopus and Web of Science and supplementary source searching (including Embase, IEEE Xplore, Google Scholar, DynaMed, OpenGrey, and snowballing/citation tracking) for publications from 1987 to August 2025. Three calibrated reviewers screened the records and synthesized the evidence narratively. This study was designed as a structured narrative review; no formal systematic review protocol, risk-of-bias assessment, or evidence-certainty grading framework was applied. Forty-nine publications were included in the final narrative synthesis.

Results: Reported applications clustered into (i) laboratory automation (robot-assisted milling, polishing, and handling within CAD/CAM and hybrid manufacturing), (ii) digital data acquisition (intraoral scanning support and quality control), (iii) functional analysis and simulation (robotic articulators and chewing/wear simulators), and (iv) clinical assistance, mainly robot-guided implant osteotomy/placement. Emerging work couples robotics with AI for automated segmentation, finish-line detection, and prosthesis design, and with AR/VR for training and intraoperative guidance. Evidence is predominantly in vitro or early clinical series, with limited multicenter outcomes and cost-effectiveness data.

Conclusion: Robotics is moving from proof-of-concept and laboratory automation toward clinically integrated, human-supervised systems in prosthodontics. Wider adoption will depend on robust clinical validation with standardized safety/accuracy metrics, interoperable and secure digital workflows, and structured training and governance to ensure patient-centered, cost-effective care.

Clinical significance: Robot-enabled workflows can improve the repeatability of prostheses and the accuracy of digitally planned procedures (e.g., implant placement), potentially reducing chairside adjustments and complications. Real-world impact will depend on evidence quality, training, and equitable access.

1. Introduction

Prosthodontic rehabilitation requires high precision across diagnosis, data acquisition, design, and fabrication to restore oral function, esthetics, and quality of life. Although digital dentistry (CBCT, intraoral

scanning, CAD/CAM, and additive manufacturing) has improved reproducibility, substantial variability persists because many critical steps still depend on manual execution and operator experience [1,2]. Robotics offers a complementary approach by adding physical automation, force feedback, and motion control to digital workflows,

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potentially reducing human error while keeping clinicians and technicians in the decision loop.

Early dental robotics focused on laboratory automation (robotic arms linked to CAD/CAM for milling, polishing, and component handling) where repeatable toolpaths can standardize manufacturing quality [3–5]. More recently, clinical robotics has expanded, most prominently in robot-guided implant surgery. Systems such as Yomi provide robotic navigational and haptic guidance during osteotomy and implant placement, aiming to improve positional accuracy compared with freehand and conventional navigation approaches [6–8].

Parallel advances in AI and spatial computing are accelerating robotics adoption. AI models can automate image classification and landmarking, enhance scan quality control, and support prosthesis design tasks such as finish-line detection and morphology generation [9–12]. AR/VR environments can support preoperative planning, ergonomic training, and intraoperative visualization, while robotic articulators and chewing/wear simulators enable individualized jaw-motion reproduction and standardized material testing [13,14].

Despite rapid progress, widespread implementation remains limited by capital and maintenance costs, workflow disruption during the learning curve, and the absence of standardized competency-based curricula [15]. Ethical and medico-legal questions include liability allocation, informed consent for human-robot collaboration, and protection of sensitive digital data and device cybersecurity [16]. Finally, most available evidence consists of laboratory studies and small clinical series, so long-term outcomes, patient-reported benefits, and cost-effectiveness remain insufficiently quantified [17].

Therefore, this structured narrative review, informed by a transparent multi-database literature search, summarizes current robotic applications in prosthodontics, critically discusses clinical readiness and limitations, and outlines research and implementation priorities for both laboratory and chairside settings.

In this review, the terms *robot-assisted*, *robot-guided*, *semi-autonomous*, and *collaborative robots (cobots)* are used according to the degree of human oversight and the specific functional role of the robotic system within the workflow.

2. Materials and methods

2.1. Search strategy

A narrative review was conducted using PubMed/MEDLINE, Scopus, Web of Science, and supplementary source searching (including Embase, IEEE Xplore, Google Scholar, DynaMed, OpenGrey, and snowballing/citation tracking) for publications from 1987 to August 2025. Three calibrated reviewers screened the records and synthesized the evidence narratively. No prospectively registered protocol, formal risk-of-bias assessment, or evidence-certainty grading framework was applied. Forty-nine publications were included in the final narrative synthesis.

The search strategy combined MeSH terms and free-text keywords, adapted to each database. The following queries were used:

Database-specific search strategies and descriptive source-level record counts are summarized in Table 1.

- PubMed/MEDLINE, Google Scholar, OpenGrey: (“robotics” OR “robotic system” OR “dental robot”) AND (“prosthodontics” OR “dental prosthesis” OR “digital dentistry”).
- Scopus: (TITLE-ABS-KEY: robotics AND prosthodontics) OR (TITLE-ABS-KEY: “dental robotics” OR “prosthetic robotics”).
- Web of Science: TS=(“robotics AND prosthodontics”) OR TS=(“dental robot” OR “prosthetic robot”).
- Embase: (‘robotics dentistry’ OR ‘robotics prosthodontics’ OR ‘robotics’ AND ‘prosthodontics’).
- IEEE Xplore: (“robotics” AND “dentistry”) OR (“robotics” AND “prosthetics” AND “oral rehabilitation”).

Table 1

Simplified search strategies used across sources for the identification of publications related to robotics in prosthodontics, with descriptive source-level retrieval counts. Source-level counts are reported for transparency only and should not be interpreted as unique study counts contributing independently to the final narrative synthesis.

Database	Search String (simplified)	Records Retrieved	Descriptive overlap with the final narrative synthesis
PubMed/MEDLINE	(“robotics” OR “robotic system”) AND (“prosthodontics” OR “dental prosthesis”)	452	38
Scopus	(TITLE-ABS-KEY(robotics AND prosthodontics)) OR (“dental robotics”)	617	46
Web of Science	TS=(“robotics AND prosthodontics”) OR (“dental robot”)	298	32
Embase	(‘robotics dentistry’ OR ‘robotics prosthodontics’)	226	21
IEEE Xplore	(“robotics” AND “dentistry”) OR (“robotics” AND “prosthetics”)	94	8
Google Scholar	(“robotic dentistry” OR “prosthetic robotics”)	528	19
DynaMed	dentistry; robotics; prosthodontics	73	4
OpenGrey	(“robotics” AND “dentistry”)	57	3
Snowballing	Reference lists, citation tracking	96	1

Note: Source-level counts are descriptive and overlapping. The same publication could be retrieved from multiple sources before deduplication and could therefore contribute to more than one source category. Accordingly, these counts are presented for search transparency only and should not be interpreted as additive or as source-specific estimates of evidence contribution.

- DynaMed: dentistry; robotics; prosthodontics.

References were exported into Mendeley (Mendeley Ltd., London, UK), where duplicates were removed prior to screening.

Given the marked heterogeneity of study designs, technologies, and reported outcomes, the evidence was synthesized narratively with emphasis on technological readiness, clinical applicability, and recurring research gaps.

2.2. Scope and selection criteria

Publications were considered relevant for inclusion in the narrative synthesis if they met the following selection criteria:

1. Addressed at least one of the following outcome domains:
 - o Robotics in CAD/CAM and prosthesis manufacturing.
 - o Robotic scanning and impression techniques.
 - o Robotic occlusion registration and jaw simulation.
 - o Collaborative robots (cobots) in prosthodontics and clinical workflows.
 - o Integration with AI, VR/AR, 3D printing, or digital dentistry.
 - o Ethical, economic, or educational aspects of robotics in dentistry.
2. Study types: in vitro, in vivo, in silico, case reports, narrative/systematic reviews, and technical reports.

Exclusion criteria were:

1. Studies conducted on non-human animals without direct clinical relevance.
2. Publications not available in English.
3. Papers not specifically addressing prosthodontics or related dental rehabilitation domains.

2.3. Study selection and data collection

Three calibrated reviewers screened titles and abstracts, followed by full-text assessment, to identify publications relevant to the narrative synthesis.

Disagreements were resolved by discussion and majority consensus (2 out of 3 reviewers).

2.4. Calibration process

To ensure consistency, the three reviewers conducted pilot calibration on 20 randomly selected references. Discrepancies were discussed until consensus was achieved, with agreement >90% for title/abstract screening and 100% for full-text assessment.

3. Results

3.1. Study selection

The literature search identified 2345 records through electronic database searching and 96 additional records through snowballing and citation tracking. After duplicate removal, 1872 records underwent title and abstract screening. Of these, 440 full-text articles were assessed for eligibility. A total of 391 publications were excluded after full-text review, resulting in 49 publications being retained for the final narrative synthesis.

3.2. Characteristics of the included publications

The included publications were heterogeneous in design, setting, and level of clinical maturity. The evidence base comprised narrative and focused reviews, technical and engineering development papers, in vitro validation studies, case reports, case series, pilot comparative investigations, and a limited number of clinically oriented studies. Most publications addressed technology development, workflow feasibility, and preclinical validation rather than definitive clinical effectiveness.

Across the included literature, the most frequently reported outcomes were positional accuracy, trueness, repeatability, force control, surface quality, motion reproducibility, and general workflow performance. By contrast, fewer studies evaluated patient-centered outcomes, long-term clinical performance, complication rates, operator learning curves, or cost-effectiveness. Overall, the available evidence indicates a field that is advancing rapidly from a technical perspective, but that remains uneven in terms of clinical validation and translation into routine prosthodontic practice.

Where clinically oriented studies were available, they generally involved small samples and short follow-up, whereas most of the remaining evidence derived from in vitro, technical-development, or validation studies.

3.3. Synthesis of evidence across application areas

The included publications clustered into several major application areas relevant to prosthodontics. A large proportion of the literature focused on robotic CAD/CAM manufacturing and laboratory automation, including robot-assisted milling, post-processing, and handling of prosthetic components. These studies generally emphasized the potential of robotic systems to improve repeatability, standardize manufacturing steps, and reduce operator-dependent variability, although their outcomes were mainly based on technical and bench-top performance measures.

Another substantial group of publications addressed digital data acquisition and AI-assisted workflows. These studies explored robotic or semi-automated support for intraoral scanning, image classification, scan integration, margin detection, and prosthesis design. The overall findings suggest that these technologies may improve data consistency

and support more automated digital workflows; however, most of the evidence remains at the proof-of-concept or validation stage.

A further body of literature concerned functional analysis and simulation, including robotic articulators, jaw-movement reproduction systems, and chewing or wear simulators. These studies highlighted the value of robotics for reproducing mandibular dynamics and testing restorative materials under controlled conditions, thereby supporting more individualized and standardized prosthodontic analysis.

Clinically oriented applications were most evident in robot-assisted implant surgery and digitally integrated treatment workflows. Early reports and pilot studies described promising levels of accuracy and safety for robotic guidance during implant osteotomy and placement. Nevertheless, the clinical literature remains relatively limited, with most studies involving small samples, early clinical experience, or short-term outcome assessment.

Finally, several publications addressed cross-cutting themes such as the integration of robotics with artificial intelligence, augmented and virtual reality, education, ethics, implementation, and cost. Collectively, these studies suggest that robotics in prosthodontics is progressing from isolated proof-of-concept applications toward more integrated digital ecosystems, although broader adoption will depend on stronger clinical evidence, standardized outcome measures, training frameworks, and careful consideration of economic and ethical implications.

Overall, the reviewed literature suggests three broad levels of translational maturity across application domains. Robot-assisted implant surgery appears closest to selective clinical implementation, given its direct procedural relevance and the presence of early clinical studies. In contrast, robotic manufacturing and polishing workflows are supported mainly by technical and preclinical evidence and currently appear more mature for laboratory integration than for routine chairside use. AI-assisted and augmented-reality-supported robotic workflows remain promising but largely investigational, with current evidence still centered on workflow optimization, feasibility, and decision support rather than established clinical benefit.

Overall, the literature was concentrated mainly in laboratory automation/CAD-CAM and digital workflow development, whereas clinically oriented studies were fewer and predominantly related to robot-guided implant procedures. A concise cross-domain synthesis of application domain, predominant evidence, current readiness, prosthodontic relevance, and main limitations is provided in [Table 2](#).

4. Discussion

4.1. Robotic systems and technologies in prosthodontics

Because the included technologies differ substantially in evidence quality and translational maturity, the following subsections discuss not only their capabilities, but also their current limitations, comparison with conventional workflows, and degree of clinical readiness.

4.1.1. Robotic CAD/CAM systems: milling, automated manufacturing

Robotic CAD/CAM in prosthodontics typically uses industrial or laboratory robotic arms as flexible machine tools for subtractive manufacturing (milling/grinding) and post-processing. Compared with dedicated CNC units, robots offer larger work envelopes and multi-axis freedom, but stiffness, vibration control, and calibration are critical to maintain clinically acceptable marginal and internal fit.

Standardized data exchange between CAD/CAM software and robots is an enabling factor. STEP-NC-based approaches can translate CAD intent into robot toolpaths and support simulation and verification, reducing manual robot programming and improving traceability [3,18,19].

Robot-CAM integration studies (e.g., redundant manipulators synchronized with rotary axes) highlight the importance of kinematic calibration, redundancy resolution, and collision-aware motion planning to achieve accurate path tracking during milling and finishing [4].

Table 2

Summary of the main robotic application domains in prosthodontics according to typical role, predominant evidence, current readiness, clinical relevance, and main limitations.

Application domain	Typical robotic role	Predominant evidence	Current readiness	Main prosthodontic relevance	Main limitation
Robot-guided implant placement	Haptic/vision-guided osteotomy and implant positioning within prosthetically driven planning	Early clinical studies, case series, and in vitro comparative studies	Selective clinical implementation	May improve positional accuracy and reduce prosthetic compromise and adjustment burden	Limited long-term restorative data; cost, training, and software integration needs
Robotic CAD/CAM manufacturing	Robot-assisted milling, grinding, toolpath execution, and component handling	Technical/engineering and in vitro studies	Laboratory implementation	Improves repeatability and standardization of prosthesis manufacturing	Limited direct evidence of superior fit or fewer remakes versus conventional systems
Robotic finishing/polishing	Automated polishing, surface adjustment, and post-processing with force control	Preclinical materials/engineering studies	Laboratory/preclinical implementation	May improve surface consistency and maintenance-related performance	Few studies link surface metrics to clinical prosthodontic outcomes
Robotic scanning/impression support	Stabilized or semi-automated scanner guidance, quality control, and rescanning support	Proof-of-concept, validation, and AI-assisted workflow studies	Investigational	May improve scan consistency and digital data acquisition	Limited evidence of clinical superiority, patient comfort, or operator efficiency
Robotic articulators/wear simulators	Reproduction of mandibular motion and standardized loading/wear testing	Research and technical validation studies	Research-oriented	Supports individualized occlusal analysis and restorative-material testing	Minimal direct clinical validation in routine prosthodontics
AI-robotic integrated/AR-VR-assisted workflows	AI-derived planning/design linked to robotic execution; AR/VR-based supervision, guidance, or training	Proof-of-concept, workflow, and training studies	Investigational/exploratory	Integrates design, guidance, and visualization across digital workflows	Interoperability, explainability, and limited clinical outcome data

For dental applications, accuracy must be considered end-to-end: scan trueness, CAD parameters, tool wear, and post-processing all influence final fit. Future reports should link robotic manufacturing parameters to clinically meaningful outcomes (marginal gap, proximal/occlusal contacts, chairside adjustment time), not only machine metrics.

Beyond milling, robotic automation is increasingly used for repetitive laboratory steps (sprue removal, polishing, cleaning, and handling), where dedicated end-effectors, active force control, and compliant tooling can reduce variability and technician workload [5,20].

From a translational perspective, robotic CAD/CAM appears closer to implementation in centralized laboratory settings than to replacement of established chairside or conventional dental milling systems. Compared with dedicated CNC units, robotic platforms offer greater flexibility and automation potential, especially for complex geometries and multi-step handling; however, the current evidence base is still dominated by engineering and in vitro studies rather than comparative prosthodontic investigations. Importantly, improvements in path planning, kinematic control, or force regulation do not automatically translate into superior marginal adaptation, reduced chairside adjustment time, or lower remake rates. At present, robotic CAD/CAM should therefore be regarded as a promising laboratory-enabling technology rather than a clinically validated superior alternative to conventional dental manufacturing systems.

4.1.2. Robotic scanning & impression systems (digital intraoral robots, semi-automated scanning arms)

Robotic or robot-assisted acquisition of intraoral and extraoral digital impressions aims to stabilize scanner motion, manage access limitations, and reduce operator-dependent stitching errors. Most systems remain semi-automated, with clinicians guiding the scanner while software assists with tracking, error detection, and rescanning prompts.

The quality of intraoral scans depends on scanner hardware, scanning strategy, and the oral environment. Integrated workflows that merge intraoral scans with CBCT can generate more comprehensive virtual patient models, supporting restorative and implant planning [21].

AI can further enhance acquisition by classifying scan images, detecting incomplete data, and automating charting or segmentation. AI-based classification of intraoral scanner images has been reported with high accuracy, indicating potential for real-time quality control and automated documentation [9,21].

Emerging sensing modalities (e.g., optical coherence tomography

combined with surface scanning) may enable detection of preparation margins not easily captured by surface geometry alone, potentially reducing remakes; however, validation in prosthodontic indications is still limited.

Portable and low cost acquisition workflows (e.g., smartphone-integrated stereophotogrammetry) have been proposed for maxillofacial rehabilitation and obturator planning, but robustness, standardization, and data governance require further study before routine use [22,23]. Compared with conventional clinician-operated intraoral scanning, robotic or semi-automated scanning remains at an earlier stage of maturity. Its proposed advantages, including improved motion stability, reduced stitching errors, and automated quality control, are conceptually attractive, but most published studies focus on technical feasibility, image classification, or virtual model integration rather than demonstrating superiority in clinically relevant outcomes such as full-arch accuracy, scanning time, patient comfort, remakes, or operator efficiency. In addition, important real-world variables such as saliva, reflective surfaces, limited mouth opening, and patient motion remain difficult to standardize in experimental settings. Accordingly, robotic scanning cannot yet be considered ready for routine prosthodontic adoption and is better interpreted, at present, as an adjunctive or investigational technology.

4.1.3. Robotic assembly/finishing: handling of prosthetic components, polishing, surface adjustments

Finishing and surface conditioning are clinically relevant because surface roughness influences plaque retention, antagonist wear, and soft-tissue response around implant prostheses. Robotic finishing systems apply controlled, repeatable motions for polishing, grinding, or surface modification of materials such as titanium, zirconia, and polymers.

Force-controlled robotic polishing can maintain consistent contact pressure, improving repeatability compared with purely manual finishing, particularly for free-form surfaces and implant frameworks [24, 25].

Compliant end effectors and compliance mechanisms help robots adapt to complex geometries and reduce the risk of over-polishing or localized damage, relevant for thin ceramic margins and heat-sensitive polymers [26,27].

High-bandwidth force/torque sensing and closed-loop control enable real-time adjustment of polishing force and tool orientation, supporting uniform surface finish and reducing rework [20].

As additive manufacturing enables more customized geometries, the role of robotic post-processing is likely to grow. Future work should quantify how robotic finishing affects clinically relevant outcomes such as biofilm accumulation, wear, and maintenance needs of definitive restorations. Robotic finishing is also promising, particularly for standardizing repetitive laboratory procedures and reducing operator-dependent variability in surface treatment. However, the supporting evidence remains largely extrapolated from materials engineering and preclinical polishing studies, with limited direct demonstration of superior prosthodontic outcomes compared with skilled manual finishing. Conventional technician-led finishing still offers adaptability, lower capital cost, and immediate tactile feedback in complex restorative cases, whereas robotic systems require calibration, force-control tuning, and validated material-specific protocols. For this reason, robotic finishing appears more suitable for laboratory automation than for routine clinical translation and should still be considered an emerging technology until further studies link surface metrics to clinically meaningful outcomes such as plaque accumulation, antagonist wear, peri-prosthetic tissue response, and maintenance burden.

4.1.4. Collaborative robots (cobots): aiding dental technicians and clinicians

Collaborative robots (cobots) are designed to work in proximity to humans and are therefore the most relevant category for chairside prosthodontics. In dentistry, their current clinical focus is implant osteotomy and placement, where small positional errors can compromise emergence profile, screw access, and long-term biomechanics.

Translational and clinical studies report that haptic or vision controlled cobots can achieve high placement accuracy while keeping the clinician in control of decision-making and soft-tissue management [6]. Clinical series of semi-autonomous systems also suggest accuracy that is at least comparable with computer-guided and dynamic navigation approaches in selected indications [7,28].

From a prosthodontic perspective, the clinically meaningful endpoint is not only implant deviation but the downstream restorative consequences: need for angled abutments, passive fit of frameworks, occlusal adjustment time, and complication rates. Future trials should report restorative endpoints alongside surgical accuracy metrics.

Implementation barriers include device cost, chairside footprint, calibration time, and integration with existing digital planning software. Safety features (force limits, emergency stop, collision detection) and clear protocols for managing intraoperative deviations are essential for routine clinical adoption.

Education and team training are critical: adoption is more likely when clinicians, dental technicians, and assistants share a common digital workflow vocabulary and can troubleshoot data transfer and calibration issues [1,15].

4.2. Clinical applications

4.2.1. Robots in occlusion registration and jaw movement simulation

Robotic articulation and jaw-motion replication address a limitation of conventional articulators: they approximate average movement patterns and may not capture patient-specific kinematics. Robotic systems can reproduce recorded mandibular motion with multiple degrees of freedom, enabling individualized functional analysis and standardized testing.

Systems combining jaw-movement analyzers with dedicated robots have been described to register and reproduce individual mandibular movements, supporting research and potentially complex rehabilitations where occlusal scheme is critical [13,29].

Virtual articulators complement physical robots by enabling occlusal contact simulation on digital models, with potential integration of AI to automate landmarking and contact prediction [30,31].

Robotic chewing and wear simulators can standardize material testing under controlled, clinically relevant loading patterns and may

reduce the gap between bench testing and intraoral performance [14,32].

While these systems are primarily research tools today, they inform material selection and prosthesis design and may become more clinically relevant as chairside digital workflows demand objective, reproducible functional verification.

4.2.2. Integration of robotic workflows with digital treatment planning

Robotic assistance becomes clinically useful when embedded within an end-to-end digital workflow: data acquisition (intraoral scanning/CBCT), virtual planning, and guided execution. In prosthodontics, this integration is particularly relevant for implant-supported rehabilitations, where prosthetically driven planning must translate accurately to surgery.

Virtual patient-assisted workflows link restorative design to surgical planning and can streamline terminal dentition and full-arch rehabilitations by coordinating implant positioning with provisionalization and definitive prosthesis design [33–35].

Robotic implant platforms operationalize these plans by providing navigational or haptic guidance during osteotomy and placement, potentially reducing deviations from the planned prosthetically ideal position. Clinical evidence is still emerging, but case series and comparative studies suggest promising accuracy for selected indications [6,28,36].

Interoperability remains a practical bottleneck: segmentation, registration, and data transfer between scanners, CBCT, planning software, and robotic systems can introduce errors. Standardized reporting of registration methods and verification steps (e.g., intraoperative checks and postoperative CBCT comparisons) would improve reproducibility across studies.

Adoption also depends on training and workflow redesign. Surveys indicate that many practices use basic digital tools, while advanced guidance/robotic systems are less common, underscoring the need for structured education and evidence demonstrating net clinical benefit [37,38].

4.3. Integration of AI with robotic and digital workflows

In the context of prosthodontic robotics, AI is most relevant when it acts as the computational layer that converts digital patient data into robot-executable actions. A typical integrated workflow involves AI-assisted acquisition and segmentation to structure the virtual patient, AI-supported design to define margins, morphology, implant positioning, or finishing targets, and robotic systems to execute manufacturing, polishing, or surgical guidance with controlled motion and force. The clinical value therefore lies not in AI or robotics considered separately, but in how reliably digital planning is translated into physical action across the restorative workflow.

4.3.1. Machine learning for optimizing prosthesis fit

Machine learning (ML) supports prosthodontics primarily by automating steps that influence prosthesis fit and function: preparation margin/finish-line detection, segmentation and landmarking of scans, morphology generation, and prediction of occlusal/proximal contacts. These capabilities can shorten design time and reduce chairside adjustments, but they require high-quality training data and rigorous validation.

Finish-line detection is a concrete example where ML can influence marginal adaptation. A comparative study reported that a deep learning-based hybrid approach achieved comparable or better performance than established CAD solutions, particularly for intraoral scans with challenging concave finish lines [11].

Generative models have been proposed to automate biomimetic crown morphology by learning relationships within an individual patient's remaining dentition. Protocol work on AI-designed single molar prostheses illustrates how 3D datasets can be used to train and validate

such systems, emphasizing the importance of standardized reporting (e.g., CONSORT-AI) [12].

Beyond single crowns, automated tooth arrangement and alignment algorithms are being developed for virtual setups and denture workflows, combining optimization and learning-based approaches to generate individualized arch forms and tooth positioning [39].

For ML-assisted design to be clinically trustworthy, performance metrics should be linked to prosthodontic endpoints (marginal/internal gaps, contact accuracy, occlusal harmony, remakes, and patient-reported outcomes) and evaluated across scanners, software versions, and diverse anatomies to avoid hidden biases. Trustworthiness in this setting also depends on interpretability. For example, a finish-line detection system should allow the operator to verify which local scan features drove the proposed margin, while crown morphology or tooth arrangement models should make it possible to compare generated anatomy against the patient's adjacent and antagonist dentition before robotic milling or finishing is initiated. Without this level of transparency, even accurate outputs may be difficult to validate clinically and may reduce, rather than strengthen, confidence in integrated digital workflows.

Regulatory and governance considerations are increasingly important as ML components become embedded in commercial CAD/CAM platforms. Transparent versioning, audit trails, and post-market monitoring are needed to manage model drift and cybersecurity risks when systems are connected to practice networks.

Overall, ML is best viewed as an assistive layer that augments clinician and technician expertise; the goal is to shift human time toward higher-level decisions (occlusal scheme, esthetic planning, maintenance strategy) rather than repetitive digital delineation tasks.

In integrated prosthodontic workflows, these ML-generated outputs are not merely digital conveniences but potential upstream control inputs for robotics. Automatically detected finish lines, morphology proposals, contact maps, and tooth arrangement schemes can be transferred to robotic CAD/CAM systems, automated finishing units, or prosthetically driven robot-assisted implant workflows as manufacturing or guidance parameters. From this perspective, the critical translational question is not only whether AI can generate a plausible design, but whether its output is sufficiently accurate, stable, and interpretable to support downstream robotic execution without amplifying cumulative error.

4.3.2. Robotics combined with augmented/virtual reality for planning

AR/VR and mixed reality can enhance robotics in prosthodontics by improving visualization, ergonomics, and training. In implant-supported rehabilitation, these tools can help communicate planned implant positions, prosthetic contours, and anatomical risk structures in an intuitive, spatial format.

Mixed-reality interfaces have been used in human-robot collaboration research to visualize robot intent and enable intuitive motion planning in shared workspaces [40,41]. Translating these concepts to dentistry could improve operator awareness of robot constraints and planned trajectories during chairside procedures.

Dental applications are emerging in preclinical education and simulation. AR/VR platforms can provide step-by-step guidance, haptic training, and objective performance metrics, potentially shortening the learning curve for digital and robotic workflows [42,43].

For intraoperative use, the most immediate opportunities are overlay-based guidance for implant placement and verification of prosthetic space. However, accuracy depends on stable registration and low-latency tracking; these requirements should be reported transparently in clinical studies.

As spatial computing matures, integration of real-time sensing and tracking with robot control could enable adaptive guidance when patient motion occurs, while still preserving clinician oversight [44].

At present, the evidence base is stronger for training and workflow visualization than for direct clinical outcome improvements;

prospective studies should evaluate whether AR/VR-integrated robotics reduces complications, treatment time, or the need for prosthetic compromises. In this sense, AR/VR primarily serves as a visualization and supervision layer that helps translate AI-derived planning into safer and more intelligible robot-assisted execution.

4.3.3. Predictive analytics for automated design

Predictive analytics can support prosthodontic robotics most effectively in closed-loop workflows, in which algorithmic predictions are used to modify robotic behavior before or during execution. Examples include anticipating manufacturing deviations and adapting robotic toolpaths or post-processing parameters, forecasting fit problems from scan quality or preparation geometry before robotic milling, and linking digital twin models to machine logs and clinical outcomes in order to continuously refine robot-assisted production and guidance. In this framework, AI does not operate separately from robotics, but functions as a predictive control layer for more adaptive and reliable execution.

Human-automation interaction remains central, but in prosthodontics trust must be calibrated at the level of specific tasks rather than treated as a general property of AI systems. For ML-based finish-line detection or crown morphology generation, clinicians and technicians should be able to inspect which scan regions, anatomical landmarks, or tooth relationships influenced the proposed margin or occlusal anatomy before these outputs are transferred to robotic manufacturing or finishing. For AI-assisted scan quality control, explainability should clarify whether an alert is driven by incomplete data capture, stitching uncertainty, reflective artifacts, or soft-tissue interference. In prosthetically driven robot-assisted implant workflows, clinicians also need transparency regarding how anatomical constraints, registration quality, and restorative objectives influence the planned trajectory, because errors at this stage may propagate into prosthetic compromises such as non-ideal emergence profile, need for angled abutments, or increased chairside adjustment. In this context, explainability is not only an ethical or regulatory requirement, but also a practical safeguard against automation bias and cumulative downstream error [45–47].

Future research should prioritize prospective evaluation of predictive tools in real prosthodontic workflows, focusing on measurable outcomes such as reduction in adjustment time, remakes, and adverse events, and on cost-effectiveness across different practice settings.

Across these examples, AI contributes mainly through perception, prediction, and design, whereas robotics contributes through controlled physical execution. Their integration is strongest when AI-derived information directly shapes robot trajectories, toolpaths, force modulation, or guidance constraints. This distinction is important to separate genuinely integrated AI-robotic workflows from broader digital adjuncts that, although useful, remain only indirectly related to robotics.

4.4. Clinical readiness and comparison with conventional workflows

Taken together, the literature suggests that robotic technologies in prosthodontics are not all at the same stage of maturity. The most clinically advanced application is robot-assisted implant osteotomy and implant placement, where early clinical studies and regulatory progress indicate that robotic guidance can achieve accuracy comparable to or better than established computer-assisted approaches in selected settings. Even in this area, however, the evidence remains limited by small samples, short follow-up, and the relative scarcity of downstream restorative outcomes.

By contrast, robotic CAD/CAM manufacturing and robotic finishing appear closer to operational adoption in laboratory environments than to broad chairside clinical adoption. Their principal advantages over conventional workflows are repeatability, standardization, and the ability to automate multi-step procedures, but convincing proof of superior prosthodontic outcomes is still limited. Robotic or semi-automated scanning, robotic articulators, chewing simulators, and AR/VR-integrated robotic workflows should currently be regarded as

investigational or research-oriented technologies. Although these systems are valuable for workflow development, training, and preclinical standardization, they still lack the comparative clinical evidence required to justify routine replacement of conventional prosthodontic methods.

Accordingly, current evidence supports a tiered interpretation of readiness: (i) selective clinical adoption for robot-guided implant procedures in experienced, digitally integrated centers; (ii) laboratory-level implementation for CAD/CAM automation and robotic finishing where infrastructure and case volume justify investment; and (iii) continued experimental validation for robotic scanning, functional simulation systems, and immersive AI-robotic integrations. This distinction is important to avoid overstating technological promise and to align future research with clinically meaningful endpoints.

In summary, the field is currently characterized by an uneven maturity profile: some robotic applications already show targeted translational potential, whereas many others remain constrained to experimental, simulation-based, or laboratory-centered settings. From a prosthodontic perspective, the most clinically meaningful distinction is not between robotic technologies themselves, but between those that may soon support reproducibility in real treatment workflows and those that still function primarily as research or development platforms.

4.5. Limitations and challenges

Robotic platforms require substantial upfront investment and ongoing costs (maintenance, software updates, consumables, service contracts). In addition to acquisition cost, clinics must account for staff time for calibration, preoperative planning, and post-operative verification; these costs can be amplified in low-volume settings [48].

Training is a major determinant of safety and efficiency. Competency should cover digital planning, registration/verification, intraoperative workflow, and troubleshooting. The lack of standardized curricula and validated proficiency metrics remains a barrier to consistent performance [1,15].

Ethical and medico-legal issues include allocation of responsibility between clinician and device, informed consent for robotic assistance, and protection of patient data generated by scanners and planning software. Cybersecurity and software-version control are particularly relevant because many robotic systems depend on networked planning and frequent updates [16].

Evidence quality remains heterogeneous. Many studies report bench accuracy or short-term clinical deviation metrics, while multicenter trials assessing prosthodontically relevant endpoints (complications, prosthetic fit, maintenance burden, patient-reported outcomes) and cost-effectiveness are scarce [17]. In keeping with the structured narrative design of this review, no formal risk-of-bias assessment or certainty-of-evidence grading was performed; therefore, the findings should be interpreted as a qualitative synthesis of a heterogeneous evidence base rather than as a graded estimate of comparative effectiveness.

Standardized reporting frameworks covering registration methods, verification steps, adverse events, and learning-curve effects would improve comparability and accelerate translation from pilot studies to routine care.

4.6. Future directions

Near-term progress will likely favor collaborative and semi-autonomous systems that keep clinicians in control while providing haptic/visual guidance and automated safety checks. Hybrid models, combining clinician decision-making with robotic constraint enforcement, may offer the best balance between efficiency and accountability [1].

Robotics is also converging with additive manufacturing and advanced materials. Automated handling and post-processing of

complex geometries could improve the consistency of printed frameworks and implant bars, while future bioprinting and regenerative approaches may expand rehabilitation options beyond purely restorative strategies [49].

Tele-robotics and remote supervision may enable expert support for complex prosthodontic care in underserved regions, but will require robust connectivity, cybersecurity, and clear medico-legal frameworks.

Future research should move beyond accuracy demonstrations toward pragmatic clinical trials that measure patient-centered outcomes, maintenance burden, and cost-effectiveness, and that explicitly characterize learning curves and failure modes.

FDA-cleared systems such as Yomi illustrate the trend toward integrated platforms that link preoperative prosthetically driven planning with intraoperative robotic guidance for implant placement [8]. As interoperability improves and competition increases, costs may decline and usability may improve; however, responsible scaling will depend on transparent post-market surveillance and continuous training.

5. Conclusions

Robotics in prosthodontics is evolving from laboratory automation toward integrated clinical assistance. Current applications include robot-enabled CAD/CAM manufacturing and finishing, semi-automated digital impression acquisition, robotic/virtual articulators for jaw-motion reproduction, and robot-guided implant surgery.

The strongest and most clinically mature evidence currently concerns robot-guided implant placement and improvements in technical repeatability, whereas robotic CAD/CAM and finishing seem more immediately applicable at the laboratory level and robotic scanning, functional simulation systems, and AR/VR-integrated platforms remain largely experimental. Downstream benefits for prosthetic fit, complication rates, maintenance burden, and patient-reported outcomes are not yet consistently demonstrated.

High costs, training demands, interoperability challenges, and ethical/medico-legal uncertainty continue to limit adoption.

Future progress should prioritize standardized reporting and multicenter clinical validation, together with competency-based training and governance for data security and accountability.

If these conditions are met, the most impactful advances will likely come from integrated workflows in which AI supports perception, design, and prediction, while robotic systems deliver controlled execution in manufacturing, finishing, and guided clinical procedures.

Patient consent statement

We hereby confirm that the submitted manuscript is a narrative review based exclusively on previously published literature.

The work did not involve recruitment of human participants, collection of identifiable patient data, clinical interventions, or acquisition of images/records from patients.

Therefore, patient informed consent is not applicable to this study. No patient-specific information is included in the manuscript.

If the manuscript contains any illustrative material, it is either (i) entirely original and does not include identifiable individuals, or (ii) reproduced from publicly available sources with appropriate permission and citation, without disclosure of personal identifying information.

Accordingly, we respectfully submit this statement in lieu of a patient consent form.

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CRediT authorship contribution statement

Gennaro Ruggiero: Conceptualization, Formal analysis. **Fernando Zarone:** Data curation, Formal analysis. **Roberto Sorrentino:** Conceptualization, Methodology. **Annamaria Mastrosimone:** Data curation, Writing – original draft, Writing – review & editing. **Paolino De Risi:** Methodology, Resources. **Raffaella Mancino:** Conceptualization. **Fanny Ficuciello:** Formal analysis, Supervision.

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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Data availability

Data will be made available on request.

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