

Emerging Role of Robotics in Prosthodontics: Clinical Integration and Future Trends

Abstract:

The integration of robotics in prosthodontics is revolutionizing clinical and laboratory workflows. Traditional prosthodontic procedures rely on manual skills and subjective judgment, which can result in variability in outcomes. Robotic systems, combined with digital technologies and artificial intelligence (AI), offer precision, consistency, and efficiency across various prosthodontic applications.

Objective: This narrative review aims to summarize current and emerging applications of robotics in prosthodontics, highlighting clinical benefits, workflow integration, and potential for patient-centered care.

Methods: A comprehensive search was conducted in PubMed, Scopus, and Web of Science for publications from 2010–2025 using keywords such as “robotics,” “prosthodontics,” “implant-supported prosthesis,” “occlusal adjustment,” “rehabilitation robots,” and “haptic feedback.” Studies reporting technological innovations, clinical outcomes, educational applications, and workflow optimization were included.

Results and Discussion: Robotic applications in prosthodontics include implant-supported prostheses, maxillofacial prosthetic fabrication, occlusal adjustment, and rehabilitation training. Haptic robotic systems and patient simulators enhance dental education by improving psychomotor skills and competency assessment. AI-integrated robotic workflows allow adaptive, patient-specific prosthetic planning and execution, reducing human error. In implantology, robotic surgical navigation has been reported to ensure high accuracy, optimal implant placement, and improved prosthetic fit. Rehabilitation robots support jaw, facial, and neuromuscular training post-trauma or surgery. Limitations include high costs, learning curves, and limited long-term clinical evidence.

Conclusion: Robotics in prosthodontics represents a significant advancement toward precision, efficiency, and personalized care. When integrated with AI and digital workflows, these systems enhance prosthetic accuracy, functional outcomes, and patient satisfaction. Further clinical studies are needed to validate their long-term efficacy and facilitate broader adoption.

Key-words: Robotics, Prosthodontics, Implant-Supported Prosthesis, Haptic Feedback, AI, Maxillofacial Prosthetics

Introduction:

Prosthodontics has traditionally relied on the manual skills of clinicians and dental technicians, making precision, reproducibility, and efficiency significant challenges in complex rehabilitations. Recent advancements in digital dentistry, including computer-aided design/computer-aided manufacturing (CAD/CAM), 3D printing, and intraoral scanning, have improved restorative workflows; however, variability in human execution still limits clinical predictability [1-5].

Robotic systems, integrating haptic feedback, artificial intelligence (AI), and machine learning, are emerging as transformative tools in prosthodontics. These technologies facilitate precise tooth preparation, occlusal adjustment,

implant placement, maxillofacial prosthetic fabrication, and patient rehabilitation. Haptic robotic arms and patient simulators enhance educational training, while AI-integrated systems enable adaptive, patient-specific workflows that

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optimize prosthetic design and functional outcomes [6-8]. In implant-supported prosthodontics, robotic surgical navigation ensures sub-millimeter accuracy, may improve prosthetic fit, and enhances load distribution. Additionally, rehabilitation robots support neuromuscular and orofacial training post-trauma or surgery, promoting holistic patient-centered care.

The convergence of robotics and AI represents a paradigm shift toward fully digital, precision-driven prosthodontics, promising increased efficiency, reproducibility, and long-term success. Despite growing interest, evidence regarding clinical efficacy, workflow integration, and long-term outcomes remains limited, necessitating a comprehensive review of current applications and future trends.

Methodology:

A comprehensive narrative review was conducted to synthesize current knowledge on robotic applications in prosthodontics. Literature searches were performed in PubMed, Scopus, and Web of Science databases for studies published between 2010 and 2025. Keywords included: robotics, prosthodontics, implant-supported prosthesis, maxillofacial prosthesis, haptic feedback, AI, occlusal adjustment, rehabilitation robots, and CAD/CAM.

Inclusion criteria were:

- **Studies** describing robotic systems applied to prosthodontic procedures.
- **Reports** on clinical outcomes, technological integration, or educational applications.
- **Reviews** and original research articles evaluating workflow, precision, or patient-centered outcomes.

Exclusion criteria included:

- **Studies** not directly related to prosthodontics.
- **Non-English** publications and conference abstracts without full text.

Selected articles were analyzed to summarize technological principles, clinical applications, workflow integration, educational impact, limitations, and future directions. The synthesis highlights both current evidence and emerging trends, providing a consolidated overview of robotics in prosthodontic practice.

3. Applications of Robotics in Prosthodontics

3.1 Industrial Robotic Arms in Prosthodontics:

Industrial robotic arms represent the most mature form of robotic integration in prosthodontics and are primarily

focused on the physical fabrication of prosthetic components. This section focuses exclusively on robotic fabrication hardware and excludes workflow automation or human-robot interaction. Operating with six or more degrees of freedom, these systems overcome the geometric limitations of conventional 3- and 5-axis dental milling machines by enabling continuous tool reorientation and unrestricted multi-axis movement. Their use has been particularly impactful in the laboratory fabrication of implant frameworks, full-arch prostheses, and maxillofacial components, where complex geometries and long-span accuracy are critical.

Robotic arms facilitate optimized cutting trajectories, reduced tool chatter, and improved surface consistency, especially when machining high-strength ceramics such as zirconia and hybrid materials. The clinical benefit of these systems is largely indirect, reflected in improved marginal adaptation and internal fit at the laboratory level rather than enhanced chairside efficiency. Compared with advanced CAD/CAM milling systems, the principal advantage of industrial robotic arms lies in geometric and material-handling flexibility, rather than consistent improvements in marginal accuracy for routine single-unit restorations.

3.2 Robotic Automation in Dental Laboratories:

Robotic automation has redefined dental laboratory workflows by enabling continuous, standardized, and scalable prosthesis production. Collaborative robots (cobots) are increasingly employed due to their ability to operate safely alongside human technicians without extensive physical barriers. These systems perform repetitive and precision-sensitive tasks, including model transfer, disc loading, sintering tray handling, polishing, and surface finishing.

Automated laboratory robotics reduce technician fatigue and inter-operator variability, which are common contributors to prosthetic inaccuracies. Robotic quality-control systems equipped with optical scanners and AI-driven comparison software assess deviations between designed and fabricated restorations, allowing real-time correction before clinical delivery. This closed-loop feedback enhances reproducibility and significantly reduces remakes.

From an economic perspective, robotic automation supports high-throughput prosthodontic production while maintaining consistent quality, making it particularly advantageous for centralized laboratories and academic institutions.

3.3 Autonomous Prosthesis Fabrication Robots:

Autonomous prosthesis fabrication robots represent an advanced evolution of industrial robotic arms through the integration of sensors, feedback systems, and adaptive control

algorithms. Unlike conventional robotic arms that execute predefined toolpaths, autonomous systems can adjust fabrication parameters in real time, enabling self-correction during milling, finishing, or post-processing. This section addresses robotic workflow supervision rather than prosthesis manufacturing or clinical manipulation.

In prosthodontics, these systems are being explored for applications such as multi-material fabrication, automated polishing, and adaptive milling of implant-supported and full-arch prostheses. Their defining characteristic is process autonomy rather than mechanical reach, which differentiates them from the robotic arms described in Section 3.1. Despite promising in vitro outcomes, high acquisition costs, complex programming requirements, and maintenance demands currently limit their widespread adoption. Importantly, autonomous robotic fabrication has not yet demonstrated consistent clinical superiority over optimized CAD/CAM workflows in routine prosthodontic practice.

3.4 Robotic Automation and Collaborative Robots (Cobots) in Dental Laboratories:

Robotic automation in dental laboratories is primarily directed toward workflow support rather than prosthesis fabrication or design. This section discusses collaborative and haptic robotics, distinct from autonomous fabrication or digital workflow control. Collaborative robots, or cobots, are specifically designed to operate safely alongside human technicians and assist with repetitive or ergonomically demanding tasks such as resin dispensing, polishing, framework finishing, and prosthesis transport between digital workstations.

Cobots enhance workflow efficiency and consistency while reducing technician fatigue and occupational risk. Unlike industrial or autonomous fabrication robots, they do not directly influence prosthetic accuracy, material adaptation, or design complexity. Their role is complementary, enabling technicians to focus on esthetic customization and clinical judgment. Consequently, cobots augment—but do not replace—CAD/CAM systems or robotic fabrication technologies, occupying a clearly distinct supportive position within digital prosthodontic workflows.

Collaborative robots complement rather than replace CAD/CAM and robotic fabrication systems, as they do not directly contribute to prosthetic design or accuracy. [Table 1]

3.5 Robotic Impression Systems and Intraoral Robotic Scanning:

Robotic impression systems and intraoral robotic scanning represent a convergent and rapidly evolving advancement in digital prosthodontics. These systems integrate robotic manipulation, high-resolution optical scanning technologies, force-feedback control, and intelligent motion planning to enhance the accuracy, repeatability, and standardization of intraoral data acquisition. Unlike conventional handheld intraoral scanners, which are highly operator-dependent, robotic-assisted systems aim to reduce human variability by executing pre-programmed, optimized scanning trajectories under controlled kinematic and force parameters.

In most experimental and emerging clinical configurations, industrial robotic arms or collaborative robots (cobots) are coupled with optical intraoral scanners or hybrid tactile-optical probes. The robotic platform precisely regulates scanner orientation, angulation, speed, focal distance, and scanning pressure, thereby minimizing cumulative stitching errors and spatial distortion. These advantages are particularly relevant in full-arch edentulous scans, multi-implant restorations, and All-on-X prostheses, where freehand scanning is susceptible to progressive inaccuracies over long spans and limited anatomical landmarks.

Robotic intraoral scanning has been proposed to improve superior trueness and precision compared with manual scanning, especially in cases involving angulated implants, multi-unit abutments, and divergent implant trajectories. However, current evidence is largely derived from conventional scanning systems, with limited direct clinical validation of fully robotic intraoral scanning [9-12]. By maintaining consistent scanning paths, overlap patterns, and scanning geometry, robotic systems enable reliable reproduction of inter-implant distances—an essential prerequisite for achieving passive prosthetic fit and reducing mechanical complications such as framework misfit and screw loosening. Moreover, the ability of robotic systems to reproduce identical scan trajectories across multiple sessions allows longitudinal monitoring of peri-implant tissues, prosthetic wear, and dimensional changes, which is difficult to achieve with operator-dependent scanning techniques [13-15].

A significant advancement within robotic impression systems is the incorporation of force and haptic feedback mechanisms. These technologies enable real-time modulation of scanning pressure based on tissue compliance, preventing excessive mucosal compression and distortion during soft tissue

capture. Accurate recording of peri-implant soft tissue contours is critical for emergence profile design, prosthetic contouring, and esthetic outcomes in implant-supported rehabilitations. Robotic systems equipped with force sensors can maintain optimal contact forces, thereby improving soft tissue fidelity while enhancing patient comfort and scan consistency.

Experimental miniature intraoral scanning robots and robotic positioning systems have further demonstrated improved accuracy in digitizing full-arch implant situations, where conventional scanning is challenged by saliva control, limited access, and cumulative stitching errors.[18,19] Integration of robotic motion control with digital workflow platforms facilitates seamless data transfer to CAD/CAM environments, supporting prosthesis design, virtual articulation, occlusal analysis, and automated manufacturing workflows, thereby strengthening the end-to-end digital prosthodontic pipeline [11-13]

Despite these advantages, several challenges currently limit widespread clinical adoption. Intraoral anatomical variability, restricted oral access, involuntary patient movement, tongue interference, and comfort considerations pose significant technical obstacles to fully autonomous robotic navigation. Additionally, existing systems require complex calibration protocols, high capital investment, and close clinician oversight, necessitating multidisciplinary expertise spanning prosthodontics, robotics, and software engineering. Consequently, robotic impression and scanning technologies remain largely confined to research laboratories and experimental clinical environments, rather than routine chairside prosthodontic practice.

Future developments are expected to focus on deep integration with artificial intelligence (AI). AI-driven algorithms may enable real-time error detection, adaptive path planning, dynamic response to patient movement, and automated correction of incomplete data capture. Through continuous learning from anatomical datasets and prior scans, intelligent robotic systems may ultimately achieve fully autonomous, patient-specific intraoral scanning, significantly reducing operator dependency and redefining accuracy benchmarks in digital prosthodontics.

3.6 Robot-Assisted Tooth Preparation:

Robot-assisted tooth preparation systems represent an emerging application of robotics aimed at improving the precision, reproducibility, and standardization of tooth reduction procedures in prosthodontics. These systems are designed to translate digitally planned preparation

parameters—such as reduction depth, convergence angle, taper, margin configuration, and finish-line continuity—into highly controlled mechanical execution. By integrating CAD-based planning with robotic motion control, these platforms seek to overcome the inherent variability associated with manual tooth preparation [17-20].

The workflow of robot-assisted tooth preparation typically begins with high-resolution intraoral scanning or CBCT imaging, followed by virtual treatment planning within CAD software. The desired preparation geometry is digitally defined, including occlusal clearance, axial reduction, margin depth, and insertion path. These parameters are then converted into executable tool paths using computer-aided manufacturing (CAM) algorithms, which guide robotic arms equipped with rotary cutting instruments or micromotors. Advanced systems incorporate real-time position tracking, force control, and collision avoidance to ensure adherence to planned reduction boundaries while minimizing the risk of over-preparation.

In vitro investigations have demonstrated improved robot-assisted tooth preparations exhibit superior consistency and geometric accuracy compared with conventional freehand techniques. Studies evaluating parameters such as total occlusal convergence, axial wall uniformity, margin continuity, and depth control have reported significantly reduced inter-operator variability when robotic systems are employed [17-20]. This level of consistency is particularly critical for full-coverage restorations, where excessive taper or uneven reduction can compromise retention, resistance form, and marginal integrity [16].

Robot-assisted preparation is also highly relevant in implant prosthodontics, particularly during abutment preparation and modification. Accurate abutment geometry is essential for ensuring optimal prosthetic seating, load distribution, and long-term mechanical stability. Robotic systems allow controlled modification of prefabricated or custom abutments according to digitally planned prosthetic requirements, reducing the risk of overheating, surface irregularities, or dimensional inaccuracies that may occur during manual adjustment [17-20].

Despite these advantages, clinical implementation of fully autonomous robotic tooth preparation remains limited. Ethical, legal, and safety considerations—particularly concerning irreversible hard tissue removal—necessitate strict clinician oversight. Current systems are therefore predominantly designed as semi-autonomous or cooperative platforms, in which the clinician retains control while the

robotic system provides guidance, constraint-based motion, or depth-limiting assistance. Such shared-control models align with contemporary regulatory frameworks and enhance patient safety.

In dental education, robot-assisted and haptic-based preparation systems have gained greater acceptance. These platforms allow students to practice standardized tooth preparations with objective feedback on reduction accuracy, taper, and margin design. By providing quantifiable performance metrics, robotic simulators help bridge the gap between preclinical simulation and clinical competence. At present, robot-assisted tooth preparation does not outperform expert clinicians in routine cases.

Future developments in robot-assisted tooth preparation are expected to focus on deeper integration with artificial intelligence (AI), real-time optical tracking, and adaptive force-feedback systems. AI-driven algorithms may enable dynamic adjustment of preparation paths based on tooth morphology, enamel thickness, and patient-specific occlusal schemes. As safety validation, regulatory approval, and clinical confidence evolve, robot-assisted tooth preparation may transition from experimental and educational use toward selective clinical adoption in complex prosthodontic workflows [17-20].

3.7 Haptic Robotic Arms and Robotic Patient Simulators:

Haptic robotic systems are designed to provide real-time force feedback that closely replicates the tactile sensations encountered during tooth preparation, finish-line formation, and prosthodontic procedures. By simulating variations in enamel, dentin, and restorative material resistance, these systems enable users to develop refined psychomotor skills and tactile sensitivity in a controlled environment [17]. Consequently, haptic technology has become an integral component of contemporary dental education, particularly in preclinical prosthodontic training.

Robotic patient simulators combine haptic feedback with immersive virtual reality (VR) platforms, allowing trainees to perform complete prosthodontic workflows—from tooth preparation and impression-making to occlusal adjustment and prosthesis evaluation—under standardized and repeatable conditions. These systems generate objective performance metrics such as preparation depth, convergence angle, surface smoothness, and procedural time, facilitating competency-based assessment and personalized feedback. Studies have demonstrated that students trained using haptic simulators exhibit improved hand–eye coordination,

procedural confidence, and consistency compared with conventional phantom-head training [17-20].

Beyond education, haptic robotic systems hold potential for intraoperative applications. Experimental studies suggest that force-feedback–guided robotic assistance could support minimally invasive tooth preparations by limiting excessive reduction and enhancing preparation accuracy, particularly in esthetically demanding cases [21]. As sensor precision and computational capabilities continue to improve, haptic robotics may evolve from training tools into adjunctive clinical aids in prosthodontic practice.

3.8 Robotics in Maxillofacial Prosthesis Fabrication:

Maxillofacial prosthetics represents one of the most impactful and clinically significant applications of robotics within prosthodontics. Facial prostheses demand exceptional accuracy to restore facial symmetry, esthetics, retention, and biomechanical compatibility, particularly in patients with congenital defects, trauma, or post-oncologic resections. Robotic systems facilitate precise digitization of facial defects using high-resolution scanning, enabling mirror imaging of unaffected structures and CAD-driven prosthesis design [23-24].

Robotic-assisted manufacturing and additive manufacturing techniques ensure consistent prosthesis thickness, surface texture, and marginal adaptation, thereby improving durability and esthetic integration [25]. The automation offered by robotic fabrication minimizes operator-dependent variability and enhances reproducibility, which is critical in complex facial reconstructions. Furthermore, robotics has the potential to enable precise positioning of retention features, including magnets and bar-clip systems, improving prosthesis stability and patient comfort.

In implant-retained maxillofacial prostheses, robotic technologies enhance the accuracy of implant planning, attachment placement, and framework fabrication. Robot-guided workflows allow for precise alignment between implants and prosthetic components, reducing mechanical complications and improving long-term outcomes [25,26]. As digital imaging, robotics, and biomaterials continue to converge, robotic systems are expected to play a central role in advancing personalized, functional, and esthetically superior maxillofacial prosthetic rehabilitation.

3.9 Robotic occlusal adjustment systems:

Currently, evidence for robotic occlusal adjustment remains

limited and largely experimental. Robotic occlusal adjustment systems integrate digital occlusal analysis with automated mechanical execution to optimize prosthetic occlusion with high precision. These systems utilize data obtained from virtual articulators, intraoral pressure-mapping devices, and optical scanning to identify occlusal contacts and interferences. The robotic actuators then perform targeted adjustments at the micron level, minimizing manual variability and subjective interpretation.

By standardizing occlusal refinement, robotic systems may improve load distribution across prosthetic and natural dentition, reducing post-insertion discomfort, bruxism-related wear, and temporomandibular joint stress. They are particularly advantageous in complex cases, such as full-mouth rehabilitations or multi-unit implant-supported restorations, where precision is critical for long-term prosthesis function and patient comfort. Additionally, these systems can record and store occlusal adjustment data, allowing longitudinal monitoring of occlusal stability and prosthetic performance [27,28].

Emerging research suggests potential applications beyond post-insertion adjustments, including real-time intraoperative occlusal guidance during prosthetic try-ins, automated equilibration of implant-supported prostheses, and integration with AI-driven predictive modeling for dynamic occlusal optimization. These developments indicate a shift toward fully digital, objective, and minimally invasive occlusal management in prosthodontics.

3.10 Rehabilitation Robots for Maxillofacial Prosthodontic Patients:

Most applications are extrapolated from broader medical rehabilitation robotics literature, as dental-specific clinical studies remain limited. Rehabilitation robots are increasingly applied to support patients undergoing prosthodontic rehabilitation following trauma, oncologic surgery, congenital defects, or neuromuscular disorders[29]. These systems assist in functional re-education of the orofacial complex, including jaw movement training, speech therapy, swallowing exercises, and facial muscle strengthening, complementing prosthetic rehabilitation.

Integration of prosthetic devices with robotic rehabilitation platforms enhances patient adaptation, accelerates neuromuscular coordination, and may improve compliance with therapeutic protocols. For example, patients using implant-supported mandibular prostheses can benefit from robot-guided jaw opening and closing exercises to optimize

occlusal function, whereas facial prosthesis patients may perform robot-assisted mimicry or muscle re-education to improve esthetic and functional outcomes [29, 30].

Furthermore, rehabilitation robots can collect objective performance metrics—such as range of motion, bite force distribution, and muscle activity—providing clinicians with quantifiable feedback to tailor therapy. The combination of prosthetic rehabilitation with robotic training represents a holistic, patient-centered approach, aiming to restore both function and quality of life.

3.11 Deep Integration of Robotics with Artificial Intelligence:

The integration of artificial intelligence (AI) with robotic systems in prosthodontics has ushered in a new era of adaptive, data-driven treatment execution. Machine learning and deep learning algorithms enable robotic platforms to analyze extensive datasets of prosthodontic outcomes, including patient anatomy, occlusal parameters, material performance, and post-insertion complications. By leveraging these data, AI-enhanced robotics may enable semi-autonomous or future autonomous systems to optimize design parameters, anticipate potential procedural challenges, and adjust robotic actions in real time, thereby improving precision and predictability [7].

Such integration facilitates personalized prosthodontic care, as robotic systems can dynamically adapt workflows to the unique anatomical and functional requirements of each patient. For instance, occlusal forces, jaw kinematics, and tissue resilience can be incorporated into the robotic control system, enabling the fabrication and adjustment of prostheses that are patient-specific and functionally optimized. Additionally, AI-driven predictive analytics can identify potential complications such as implant overload, prosthetic misfit, or material wear, allowing pre-emptive adjustments and reducing the risk of clinical failure [7,8,31].

Emerging research highlights the potential for fully autonomous robotic systems guided by AI, capable of performing tasks ranging from tooth preparation and occlusal adjustment to complex full-arch rehabilitations, with continuous learning from procedural outcomes to improve subsequent treatments. This convergence of robotics and AI marks a transformative step toward precision, efficiency, and evidence-based prosthodontic practice.

3.12 Workflow Analysis of Robotic Prosthodontic Systems:

Robotic prosthodontic workflow is conceptualized as a

closed-loop, digitally integrated process that encompasses data acquisition, AI- assisted planning, robotic manufacturing, automated quality inspection, and clinical delivery. Initially, high-resolution digital data—including intraoral scans, CBCT imaging, and functional occlusal measurements—are captured and processed. AI algorithms then analyze these datasets to generate optimized treatment plans, guiding robotic fabrication and adjustment of prosthetic components [6, 31-33].

The robotic execution phase involves precise material removal, additive manufacturing, or assembly, with real-time feedback from sensors to ensure adherence to design specifications. Automated inspection systems further evaluate prosthetic dimensions, surface quality, and occlusal contacts, generating objective metrics for clinical verification. Finally, digitally guided clinical delivery integrates prostheses with patient anatomy, minimizing manual adjustments and enhancing fit and function [32].

This structured, AI-integrated workflow minimizes human error, reduces variability, and may improve operational efficiency, while providing traceable documentation for quality assurance and regulatory compliance. By combining robotics, AI, and digital dentistry, such workflows embody the principles of precision prosthodontics and support the evolution toward fully digitized, patient-centered restorative ecosystems.

3.13 Robotics in Implant-Supported Prosthodontics:

Implantology has emerged as one of the primary domains where robotic systems are demonstrating transformative potential. Robotic integration spans the entire workflow from diagnostic planning and virtual implant positioning to precise surgical execution and final prosthetic restoration thereby enhancing procedural accuracy, predictability, and overall clinical efficiency [31-34].

Robotic Surgical Navigation:

Dynamic navigation systems, such as Yomi® (Neocis, USA), employ robotic arms and haptic-feedback mechanisms to guide osteotomy and implant placement in real time. Preoperative planning integrates CBCT imaging with intraoral scanning to generate precise surgical trajectories, including drill angulation, depth, and orientation. During surgery, the robotic system continuously monitors and adjusts handpiece motion to adhere to the preloaded plan, providing tactile feedback to the clinician [3-5].

The clinical benefits of robotic surgical navigation include:

High placement accuracy, reducing deviation from planned positions.

- **Improved** parallelism in multi-implant cases, enhancing prosthetic outcomes.
- **Avoidance** of critical anatomical structures, minimizing the risk of nerve or sinus injury.
- **Reduced** surgical time and improved operator confidence in complex or high-risk cases.

Prosthetic Implications:

Robotic-assisted implant placement directly impacts prosthetic rehabilitation. Enhanced precision allows for improved passive fit of multi-unit frameworks, reducing stress at the implant-abutment interface. Accurate implant positioning contributes to optimal distribution of occlusal forces, thereby decreasing the risk of prosthetic complications. Additionally, robotics facilitates immediate-loading protocols by ensuring predictable implant alignment and stability, which can enhance patient satisfaction and functional outcomes [34-36].

The integration of robotics in implant-supported prosthodontics represents a significant step toward fully digital, patient-specific workflows, combining surgical accuracy with prosthetic excellence. [Table 2]

4. Challenges and Limitations:

Despite the transformative potential of robotics in prosthodontics, several challenges limit widespread adoption. High acquisition and maintenance **costs of robotic systems**, including surgical navigation devices, haptic arms, and AI-integrated platforms, restrict accessibility, especially in smaller clinics and developing regions. **Steep learning curves** and the need for specialized clinician and technician training further complicate implementation [7].

Technological limitations remain. Haptic feedback may not fully replicate the nuanced tactile sensations encountered in manual tooth preparation and prosthesis adjustment, potentially affecting the precision of certain procedures [21]. AI-driven robotics relies heavily on large, high-quality datasets; insufficient clinical data can reduce predictive accuracy and adaptive functionality [7]. Interoperability with existing digital workflows, such as CAD/CAM, 3D printing, and intraoral scanning, is inconsistent, creating workflow integration challenges.

From a clinical perspective, long-term evidence on prosthetic survival, complication rates, and patient-centered outcomes is limited [31-35]. Regulatory approval processes, standardization of robotic protocols, and medico-legal considerations pose additional barriers. Moreover, over-reliance on technology introduces risks of system malfunctions during critical procedures.

5. Future Prospects:

The future of prosthodontic robotics is promising, driven by advances in AI, machine learning, soft robotics, and additive manufacturing. AI-enhanced systems are expected to provide fully adaptive, patient-specific workflows capable of predicting complications and optimizing prosthetic design in real time.

Integration with digital diagnostics, virtual articulation, and intraoral scanning may enable fully automated fabrication of implant-supported and maxillofacial prostheses with higher precision and efficiency [7]. Rehabilitation robots are likely to offer personalized neuromuscular and facial training, improving functional outcomes and patient satisfaction [29].

As technologies mature, costs are expected to decrease, and wider adoption will be facilitated through standardized training programs, clinical guidelines, and evidence-based workflows. Longitudinal clinical trials, cost-effectiveness studies, and workflow optimization research are essential to validate these technologies for routine prosthodontic practice. The combination of robotics, AI, and digital dentistry has the potential to establish precision prosthodontics as a mainstream clinical paradigm, improving both procedural accuracy and long-term patient outcomes.

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Table 1: Comparative Summary: Robotic Prosthodontics vs Conventional Digital CAD/CAM Workflows

Dimension	Conventional CAD/CAM	Advanced	Key Interpretation	Clinical
HARDWARE ARCHITECTURE	Multi-axis industrial robots, autonomous systems, or cobots with ≥6 DOF	3- or 5-axis milling machines, standalone scanners and printers	Robotics offers greater kinematic freedom. CAD/CAM is simpler and purpose-built	
WORKFLOW CONTROL	Open, reconfigurable workflows; may include closed-loop feedback	Predefined, linear digital workflows	Robotics excels in adaptable or non-standard cases	
MANUFACTURING ACCURACY	High positional accuracy; adaptive correction possible	High and predictable accuracy for routine prostheses	Marginal differences clinically for single-unit restorations	
INDICATION SPECTRUM	Full-arch frameworks, long-span prostheses, maxillofacial components	Single crowns, short-span FPDs, routine implant prostheses	Robotics adds value mainly in complex cases	
SURFACE QUALITY & TOOL ACCESS	Continuous tool reorientation has the potential to enable uniform surface finishing	Limited by tool angulation and axis constraints	Advantageous for complex geometries	
ERROR MANAGEMENT	Potential for real-time detection and correction	Errors identified post-fabrication	Autonomous robotics remains experimental	
LABORATORY INVESTIGATION	Requires space, safety protocols, advanced programming	Easily integrated into existing labs	CAD/CAM remains more scalable	
COST & COMPLEXITY	High capital investment and maintenance	Lower cost, established ROI	Robotics not yet cost-effective for routine use	
HUMAN EXPERTISE DEPENDENCY	Reduced for repetitive tasks; still needed for planning and esthetics	High reliance on technician skill for finishing and customization	Robotics complements rather than replaces expertise	
CLINICAL EVIDENCE BASE	Limited long-term clinical outcome data	Extensive clinical validation	Evidence gap limits widespread adoption	

Table 2: Current status, evidence level, and future potential of robotics in implant prosthodontics

Domain	Current Application	Technology Used	Evidence Level	Clinical Impact	Future Potential
Implant planning	CBCT-based virtual planning with prosthodontically driven positioning	AI-assisted planning software, digital workflows	Moderate (clinical + observational studies)	Improved implant positioning accuracy and prosthetic predictability	Fully automated treatment planning integrating AI and biomechanics
Surgical placement	Static guides and dynamic navigation; early robotic-assisted placement	Navigation systems, robotic arms (e.g., semi-autonomous systems)	Moderate (in vitro + limited clinical studies)	Enhanced precision, reduced operator variability	Fully autonomous implant placement with real-time feedback
Intraoperative guidance	Real-time tracking of drill position and angulation	Optical tracking, haptic feedback systems	Moderate	Increased safety and reduced surgical errors	AI-driven adaptive correction during surgery
Prosthesis design	Digital design using CAD/CAM with AI-assisted suggestions	CAD software, AI algorithms	Limited to moderate	Improved customization and workflow efficiency	Fully automated prosthesis design with predictive occlusion
Prosthesis fabrication	CAD/CAM milling and 3D printing	Milling machines, additive manufacturing	Strong (well-established)	High precision and reproducibility	Integration with robotic finishing and automated adjustments
Occlusal optimization	Digital occlusal analysis (non-robotic)	T-Scan, digital occlusion systems	Limited	Improved occlusal force distribution assessment	Robotic real-time occlusal adjustment systems
Postoperative rehabilitation	Limited integration with prosthodontics; mainly medical robotics	Rehabilitation robots, neuromuscular training systems	Limited (extrapolated evidence)	Potential improvement in functional recovery	Personalized robotic rehabilitation integrated with prostheses
Workflow integration	Partially digital workflows with limited robotic integration	CAD/CAM, AI platforms	Moderate	Improved efficiency and reduced treatment time	Fully integrated closed-loop robotic workflow from diagnosis to delivery