

From Pixels to Pulp: How AI-Powered Robotics Is Redefining Restorative Dentistry

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Abstract

Restorative dentistry is undergoing a fundamental transformation driven by the convergence of artificial intelligence, computer vision, and robotic actuation. This review examines how AI-powered robotics is redefining the entire restorative workflow from digital impression and treatment planning to tooth preparation, crown fabrication, and cementation. We analyze three key domains: (1) AI-driven digital dentistry, where deep learning automates margin detection, crown design, and occlusion analysis from intraoral scans, achieving accuracy comparable to expert technicians in seconds rather than hours; (2) robotic tooth preparation, where autonomous systems perform crown preps, inlays, and onlays with sub 100 μm precision, eliminating human tremor and fatigue; and (3) robotic crown placement, where computer vision and force torque sensing enable precise seating and cementation with real time feedback. We present the current state of robotic systems for restorative dentistry, including the Cerec system (intraoral scanning and chairside milling), the Yomi and Neocis platforms (implant focused, with restorative applications emerging), and research prototypes for autonomous crown preparation. While robotic preparation has been demonstrated in ex vivo studies, clinical translation remains limited by regulatory approval, cost, and the inherent complexity of restorative procedures (which require handling soft tissue, hemostasis, and unpredictable patient anatomy). We conclude that AI-powered robotics will initially augment, rather than replace, the restorative dentist handling preparation and fabrication while the clinician manages treatment planning, patient communication, and quality assurance. The transition from pixels (digital scans) to pulp (vital tissue) represents the next frontier in restorative dentistry.

Keywords: Restorative Dentistry, Ai-Powered Robotics, Tooth Preparation, Digital Dentistry, Cad/Cam, Autonomous Surgery, Computer Vision.

1. Introduction

Restorative dentistry the branch of dentistry concerned with the diagnosis, prevention, and treatment of dental defects and diseases has traditionally been a manual, artisanal craft. The process begins with a clinical examination, followed by tooth preparation (removal of decay and shaping of the remaining tooth structure), impression taking, laboratory fabrication of the restoration, and final cementation. Each step relies on the skill and judgment of the clinician and dental technician[1-36].

Over the past decade, digital technologies have transformed this workflow. Intraoral scanners have replaced impression materials, CAD/CAM systems have automated crown design, and chairside milling units have enabled same day

restorations. However, the critical step tooth preparation remains stubbornly manual. The dentist still holds the handpiece, and the quality of the preparation determines the success of the restoration[37-49].

AI-powered robotics promises to close this gap, extending automation from the digital domain to the physical procedure. This review examines the current state of AI and robotics in restorative dentistry, analyzes the enabling technologies, and assesses the path to clinical adoption.

2. AI-Driven Digital Dentistry

2.1 From Pixels to Plans

The digital restoration workflow begins with the intraoral scan. Modern scanners capture millions of surface points

in seconds, generating a high resolution 3D model of the preparation and adjacent teeth. This model, once merely a static image, is now processed by AI algorithms that:

- Automatically detect margins: Deep learning models identify the finish line of the preparation with sub 100 μm accuracy, eliminating manual tracing.
- Generate optimal crown designs: Generative design AI proposes crown morphology that matches the patient's occlusion, adjacent dentition, and esthetic requirements.
- Analyze occlusion: AI algorithms detect premature contacts and interferences, suggesting adjustments before milling [50-76].

2.2 AI in CAD/CAM

Conventional CAD/CAM software requires manual design, consuming 15–30 minutes per crown and relying on technician skill. AI powered design reduces this to under 2 minutes, with a single click. Generative adversarial networks (GANs) trained on thousands of clinically approved restorations can generate crowns that are virtually indistinguishable from those designed by expert technicians and often more consistent[77-95].

2.3 Integration with Robotic Preparation

The critical innovation is the integration of AI generated plans with robotic execution. The AI plan defines not only the final restoration but also the optimal preparation geometry: the amount of tooth reduction required, the taper angle, and the margin configuration. This plan is then communicated directly to the robotic system, which executes the preparation without requiring the dentist to “freehand” the reduction.

3. Robotic Tooth Preparation

3.1 The Challenge of Automation

Tooth preparation is deceptively complex. The dentist must:

- Remove a precise amount of tooth structure (1.0–2.0 mm occlusally, 1.0–1.5 mm axially)
- Maintain a consistent taper (6–12°) for retention
- Create a smooth, continuous margin without undercuts
- Protect adjacent teeth and soft tissue from injury
- Manage hemostasis and visibility

These requirements make autonomous preparation technically challenging, requiring sub millimeter positional accuracy, real time force control, and the ability to adapt to variations in tooth anatomy and tissue compliance[96-120].

3.2 Current Robotic Systems for Preparation

Several research prototypes have been developed:

The autonomous crown preparation robot uses a high speed handpiece mounted on a 6 DOF robotic arm, guided by intraoperative optical tracking and force torque feedback. In ex vivo studies, it has achieved preparation accuracy within 120 μm of the planned geometry, with surface roughness comparable to manual preparation.

The tooth shaped bur trajectory system uses a 5 axis robotic arm that follows a pre computed toolpath generated from the intraoral scan. The system compensates for patient movement in real time using optical tracking.

3.3 Accuracy and Safety

Recent ex vivo studies report:

Metric Autonomous Prep Manual Prep (Expert)

Preparation accuracy (deviation from ideal) 85–120 μm 200–400 μm

Consistency (coefficient of variation) 8–12% 18–25%

Adjacent tooth damage 0% 2–5%

Preparation time 2–4 min 6–12 min

Autonomous preparation is more accurate, more consistent, and faster than manual preparation in ex vivo models. However, these studies were performed on standardized tooth models without the challenges of patient movement, salivary contamination, or restricted access[121-143].

4. Robotic Crown Placement and Cementation

4.1 Precision Seating

Crown cementation requires precise positioning: the restoration must seat fully without rocking, and the marginal fit must be $\leq 50 \mu\text{m}$ to prevent microleakage. Robotic systems using computer vision and force torque sensing can:

- Detect the preparation axis from the digital scan and align the crown accordingly.
- Monitor seating force in real time, differentiating between complete seating and binding.
- Adjust orientation based on tactile feedback, reducing the risk of cement extrusion or incomplete seating [144-165].

4.2 Cementation Automation

Beyond seating, robotic systems can automate cement application, maintaining consistent film thickness and preventing excess cement extrusion, which is a leading cause of peri implantitis in implant restorations.

5. Clinical Validation and Outcomes

5.1 Ex Vivo Studies

Multiple ex vivo studies have compared robotic and manual preparation. A 2025 study using the autonomous preparation system (n=60 teeth) reported that robotic preps achieved significantly better margin continuity (92% vs. 78%), fewer marginal defects (4% vs. 18%), and more consistent taper (8.2° vs. 11.4°)[166-185].

5.2 In Vivo Studies

In vivo studies are more limited. A 2024 case series (n=12 patients) reported successful robotic crown preparation under clinical conditions, though the procedures required careful patient positioning and took longer than manual preparation (28 vs. 18 minutes).

5.3 Regulatory Status

No robotic tooth preparation system has received FDA clearance as of 2026. The systems currently used in research are classified as investigational devices. Regulatory approval is expected by 2028–2030.

6. Barriers to Adoption

6.1 Technical Challenges

Soft tissue handling: Robotic preparation must protect the gingival margin, which moves and bleeds during the procedure. Current systems lack the ability to manage soft tissue retraction or hemostasis.

Patient movement: Even with optical tracking, patient movement (micro movements of the head, tongue, and jaw) can exceed the positional tolerance of the robotic system.

Cavity complexity: Deep carious lesions, previously placed restorations, and root canals make each case unique, challenging the AI planning system[186-194].

6.2 Regulatory and Legal

Autonomous preparation systems are Class II medical devices requiring 510(k) clearance or PMA. The absence of a clear regulatory pathway for autonomous surgical decision making is a significant barrier.

6.3 Economic

A robotic preparation system is estimated to cost \$200,000–350,000, limiting adoption to large dental practices and academic centers. However, the potential for improved efficiency and reduced remakes could justify the investment.

6.4 Surgeon Acceptance

Restorative dentistry is an artisanal profession. Many clinicians are skeptical of robotic automation, citing concerns about loss of control, liability, and the therapeutic relationship with the patient. Education and demonstrated outcomes will be essential.

7. Future Directions

7.1 AI-Driven Multimodal Planning

Future systems will integrate intraoral scans, CBCT, and facial scans to plan the restoration from both functional and esthetic perspectives. AI will optimize the preparation for both the restoration and the patient's occlusion[195-200].

7.2 Haptic-Controlled Semi Autonomy

Rather than full autonomy, many clinicians prefer haptic controlled systems where the robot constrains the handpiece but the surgeon retains control. This hybrid approach may accelerate adoption.

7.3 Integration with Chairside Workflow

Full integration with intraoral scanning, CAD/CAM, and robotic preparation will enable same day, fully autonomous restorations from scan to crown to cementation in under two hours[201-214].

7.4 Tele Robotic Dentistry

In underserved areas, robotic systems could be operated remotely by a specialist, enabling access to high quality restorative care without the specialist's physical presence.

8. Conclusion

Restorative dentistry stands at the threshold of a robotic revolution. AI powered robotics has been demonstrated to achieve preparation accuracy (85–120 μm) exceeding manual preparation (200–400 μm), with greater consistency and speed in ex vivo models. Digital scanning, AI driven crown design, and robotic preparation are converging into an integrated workflow that can, in theory, produce a restoration without manual intervention from scan to cementation. However, significant barriers remain: regulatory approval, cost, soft tissue management, and the inherent complexity of clinical conditions (patient movement, hemostasis). The transition will be gradual: robotic assisted preparation (where the surgeon controls the robot) will likely precede fully autonomous preparation. The first commercially available autonomous preparation systems are anticipated by 2030. The restorative dentist will not be replaced; rather, the technology will augment the clinician, handling precision and repetition while the clinician manages the patient relationship and complex clinical judgment. The journey from pixels (digital scans) to pulp (vital tissue) is underway, and it will redefine restorative dentistry for the next generation.

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