Research Article

Global Journal of Medical and Clinical Research

Robotic Precision, AI Intelligence: The Future of Autonomous Dental Surgery

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Citation: Qin Long, et al. Robotic Precision, AI Intelligence: The Future of Autonomous Dental Surgery. *Glob J Med Clin Res*. 2026, 1(1), 01-10.

Received Date: 22 June 2026 **Accepted Date:** 28 June 2026 **Published Date:** 01 July 2026

Abstract

Dental surgery is undergoing a paradigm shift from manual, freehand techniques toward robotic-assisted and ultimately autonomous procedures. This review examines the convergence of artificial intelligence, computer vision, haptic feedback, and robotic actuation in dentistry, focusing on the current state of autonomous implant placement, osteotomy preparation, and soft tissue management. We analyze three tiers of autonomy: (1) robotic-assisted (surgeon-in-the-loop), (2) semi-autonomous (supervisory control), and (3) fully autonomous (no human intraoperative decision). Recent advances demonstrate that fully autonomous implant placement from preoperative planning to osteotomy execution and implant seating can achieve sub millimeter accuracy (entry point error <0.15 mm, angular deviation <1.0°) with zero cortical breaches in cadaver studies, exceeding human performed freehand accuracy by 3 5×. Key enabling technologies include: multi modal imaging (CBCT with intraoperative registration), 6 DOF force torque sensing (0.1 N resolution), and deep learning based anatomical segmentation (Dice >0.95). However, significant barriers remain: regulatory approval for autonomous surgical decision making, high capital costs ($350,000–500,000 per system), and surgeon acceptance in an inherently conservative field. We discuss the trajectory from the first fully autonomous implant procedure (2025) to anticipated regulatory clearance (2028–2030), concluding that while full autonomy in complex multi step procedures remains distant, targeted autonomous tasks will become clinically routine within the next decade.

Keywords: Autonomous Surgery, Robotic Dentistry, Dental Implant, Artificial Intelligence, Computer Assisted Surgery, Haptic Feedback.

1. Introduction

Dental implant placement represents an ideal candidate for robotic automation. The procedure is highly repeatable, relies on precise spatial positioning (tolerances <0.5 mm and <2°), and must be performed on a rigid anatomical structure (bone). Yet despite the availability of static surgical guides and dynamic navigation, the majority of implants worldwide are still placed using freehand technique, with mean angular deviations of 3 5° and entry point errors of 0.8 1.5 mm[1-43].

The fundamental limitation is human. Even experienced surgeons exhibit tremor, fatigue, and subjective decision making variability. The human eye cannot measure bone density in real time, and tactile feedback provides only qualitative information. The human hand cannot execute a perfectly straight osteotomy with micron level precision. These limitations are not weaknesses of the surgeon but inherent constraints of human physiology.

Robotic systems, conversely, can execute pre planned trajectories with repeatable accuracy, integrate real time sensor feedback to adjust for tissue variations, and operate without fatigue. When combined with artificial intelligence for planning and real time decision making, the potential to eliminate human intraoperative error becomes tangible[44-67].

This review examines the current state of robotic and autonomous dental surgery, analyzes the enabling technologies, and assesses the barriers to clinical adoption. We argue that while fully autonomous multi step surgery remains years away, targeted autonomous tasks will become clinically routine within the next decade.

2. State of the Art: Robotic Assisted Dental Surgery

2.1 Current Platforms

Table 1 — Current Robotic Platforms for Dental Implant Placement

Comparison of FDA-approved and research platforms with autonomy level and key features

Platform	Manufacturer	Autonomy Level	Key Feature
Yomi	Neocis	Tactile guidance	Surgeon guides robot, robot prevents deviation
X-Guide	ClaroNav	Navigation-only	Optical tracking, no robotic actuation
NaviDent	Brainlab	Navigation-only	Electromagnetic tracking
Rosa	Medtronic	Surgical assistant	Used in neurosurgery, adapted for dental

The Yomi system is the only FDA approved robotic assisted dental implant system. It provides tactile guidance: the surgeon physically moves the robotic arm, but the robot constrains the drill to the planned trajectory. This is a "surgeon in the loop" model the human remains the primary decision maker.

2.2 Accuracy of Current Systems

A 2024 systematic review reported that Yomi assisted implant placement achieved mean angular deviation of 1.5 2.0° and entry point error of 0.4 0.6 mm, compared to 3.5 4.5° and 0.8 1.2 mm for freehand placement. While statistically significant, these improvements remain modest—the robot guides but does not replace the surgeon[68-85].

2.3 Limitations of Robotic Assistance

Current robotic systems have several limitations:

High cost: Yomi systems cost approximately $200,000 per unit, with additional per case fees. This limits adoption to high volume centers.

Learning curve: Surgeons require 10 20 cases to achieve proficiency, similar to dynamic navigation.

Limited autonomy: All decisions planning, trajectory adjustment, and final seating remain with the surgeon. The robot is a precision tool, not an autonomous agent.

No real time adaptation: Current systems cannot adjust for intraoperative findings (e.g., bone density variations) without surgeon intervention.

These limitations have prompted research into higher levels of autonomy.

3. Enabling Technologies for Autonomous Surgery

3.1 AI Based Preoperative Planning

Autonomous surgery begins with autonomous planning. Deep learning models can now segment mandibular canal, maxillary sinus, and adjacent teeth from CBCT with Dice coefficients >0.95, eliminating manual tracing. Reinforcement learning algorithms can optimize implant position (entry point, angle, depth) to maximize bone volume, nerve distance, and biomechanical alignment generating multiple Pareto optimal plans that the surgeon approves before surgery[86-96].

In a 2025 study, an AI planner generated clinically acceptable implant positions in 97% of cases, with processing time under 60 seconds. This compares favorably to 88% for conventional software assisted planning.

3.2 Real Time Intraoperative Sensing

Autonomous execution requires real time feedback. Key sensors include:

Force torque sensing: 6 axis sensors (0.1 N resolution) can measure drilling resistance in real time, differentiating cortical from cancellous bone and detecting cortical breach before it occurs.

Optical tracking: Sub millimeter tracking (0.05 mm accuracy) monitors drill position relative to the surgical plan. When integrated with a robotic arm, the system can correct deviations in real time[97-119].

Thermal monitoring: Infrared sensors can detect drill overheating (>47°C), triggering irrigation or pausing to prevent thermal necrosis.

3.3 Robotic Actuation

High precision robotic arms (repeatability <0.02 mm) can execute pre planned trajectories with accuracy far exceeding human capability. The KUKA LBR Med, a collaborative medical robot, has been used in autonomous implant studies, achieving 0.12 mm entry point error and 0.9° angular deviation in cadaver models.

3.4 Machine Learning for Real Time Decision Making

The transition from robotic assisted to autonomous requires AI that can make intraoperative decisions: adjusting feed rate based on bone density, detecting and responding to

unexpected anatomical variations, and determining the optimal seating depth to achieve primary stability. Recent work has demonstrated that convolutional neural networks can process force torque data in real time (latency <50 ms) to classify bone type and predict cortical breach with 94% accuracy [120-143].

4. Autonomy Levels in Dental Surgery

4.1 A Proposed Taxonomy

Adapting from the automotive and surgical robotics literature, we propose five levels of autonomy for dental surgery:

Table 2 — Autonomy Levels in Dental Surgery

Five-level taxonomy adapted from automotive and surgical robotics literature

Level	Description	Human Role	Current Status
0	Manual	Surgeon performs all tasks	Current standard
1	Robotic-assisted	Surgeon operates, robot constrains	Yomi (available)
2	Supervisory	Surgeon plans, robot executes with approval	Research
3	Conditional autonomy	Robot executes, surgeon intervenes if needed	Research
4	High autonomy	Robot executes entire procedure	Proof-of-concept (2025)
5	Full autonomy	Robot plans and executes, human not required	Future

4.2 Current Status: Level 1 to Level 2 Transition

Yomi and similar systems operate at Level 1. Level 2 (supervisory) requires the robot to execute the osteotomy autonomously after surgeon approval of the plan. This has been demonstrated in cadaver studies but not yet in clinical practice.

4.3 Level 3 and Beyond: The Autonomous Implant Procedure

In 2025, the first fully autonomous implant placement (Level 4) was reported in a beagle model. The system performed preoperative AI planning, registration, osteotomy, and implant seating with zero human intraoperative decisions. Angular deviation was 0.8°, entry point error 0.12 mm, and cortical breach rate 0% significantly superior to human performed controls[144-167].

This proof of concept demonstrates technical feasibility. The remaining barriers are regulatory, not technical.

5. Clinical Validation and Outcomes

5.1 Cadaver Studies

Multiple cadaver studies have compared autonomous vs. freehand and robot assisted implant placement:

Table 3 — Accuracy Comparison (Cadaver Studies)

Autonomous vs. robot-assisted vs. freehand implant placement accuracy

Method	Angular Deviation	Entry Point Error	Cortical Breach Rate
Freehand (human)	3.2–4.8°	0.7–1.2 mm	5–12%
Robot-assisted (Yomi)	1.5–2.0°	0.4–0.6 mm	1–2%
Autonomous (research)	**0.8–1.0°**	**0.10–0.15 mm**	**0%**

Autonomous systems achieve 3 5× accuracy improvement over freehand and 1.5 2× over robot assisted.

5.2 Animal Studies

In beagle models, autonomous implant placement achieved 74% bone implant contact at 3 months, significantly higher than conventional implants (62%), likely due to reduced surgical trauma and precise seating.

5.3 First in Human Trials

As of 2026, first in human trials of autonomous dental implant placement have not yet been reported. Regulatory approval is expected 2028 2030[168-189].

6. Barriers to Clinical Adoption

6.1 Regulatory Approval

Autonomous surgical systems require FDA premarket

approval (PMA), a rigorous process requiring clinical trials demonstrating safety and efficacy. The FDA has not yet established a clear pathway for autonomous surgical decision making, though draft guidance is expected in 2027.

6.2 Cost

Autonomous systems are estimated to cost $350,000 500,000 per unit double the cost of current robotic assisted systems. This limits adoption to high volume implant centers. However, costs are expected to decrease as the technology matures.

6.3 Surgeon Acceptance

Dentists are a conservative profession. Many surgeons express reluctance to delegate intraoperative decisions to an algorithm, citing concerns about accountability, unforeseen complications, and loss of skill. Education and demonstrated safety will be essential for adoption[190-210].

6.4 Liability

Who is responsible when an autonomous system makes an error? The manufacturer? The surgeon who approved the plan? The hospital? This legal ambiguity must be resolved before widespread adoption.

7. Future Directions

7.1 Multi Step Autonomous Procedures

Current autonomous systems focus on implant placement. Future systems will extend to:

- Tooth preparation: Autonomous crown preparation using high speed burs.
- Endodontics: Autonomous access cavity preparation and canal cleaning.
- Oral surgery: Autonomous tooth extraction and osteotomy for orthognathic surgery.

7.2 Integration with Digital Workflows

Full integration with intraoral scanning, CAD/CAM, and 3D printing will enable same day autonomous implant placement with immediate provisional restoration.

7.3 Remote and Telesurgery

Autonomous systems could enable remote surgery: the robot executes the plan without a surgeon physically present. This has implications for military dentistry, disaster response, and underserved regions.

7.4 Continuous Learning

Federated learning across autonomous systems could enable continuous improvement without centralized data sharing, improving accuracy and safety over time[211-218].

8. Conclusion

The convergence of robotic precision and artificial intelligence is transforming dental surgery. Robotic assisted systems (Level 1) are clinically available, providing modest accuracy improvements over freehand. Autonomous implant placement (Level 4) has been demonstrated in proof of concept cadaver and animal studies, achieving sub millimeter accuracy (0.12 mm, 0.9°) with zero cortical breaches outperforming human performed procedures by 3 5×. The remaining barriers are regulatory, financial, and cultural, not technical. Autonomous dental surgery will not replace surgeons; it will augment them, eliminating human error while preserving clinical judgment for complex cases. The transition will be gradual: targeted autonomous tasks (osteotomy preparation, implant seating) will become routine within the next decade, while fully autonomous multi step procedures remain a longer term goal. The future of dental surgery is not human or machine it is human machine collaboration, with machines handling precision and repetition, and humans providing judgment, compassion, and accountability.

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