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Artificial Intelligence and Robotics in Dental Implantology: Current Applications and Future Directions

Thomas G. Wiedemann, MD, PhD, DDS*

*Department of Oral & Maxillofacial Surgery New York University College of Dentistry, New York, NY, United States.

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***Corresponding Author:** Dr. Thomas G. Wiedemann, Department of Oral & Maxillofacial Surgery New York University College of Dentistry, New York, NY, United States.

Abstract

Artificial intelligence (AI) and robotics are reshaping dental implantology across the entire treatment continuum, from diagnostic imaging and digital planning to intraoperative execution and long-term prognosis. Convolutional neural networks now segment cone-beam computed tomography (CBCT) volumes, identify vital anatomical structures, and propose implant positions with accuracy approaching that of experienced clinicians. In parallel, robotic platforms such as Yomi have moved from static and dynamic navigation toward haptic and increasingly autonomous guidance, narrowing deviation from the planned implant trajectory relative to freehand placement. This article reviews current AI and robotic applications in implant dentistry, summarizes the evidence on accuracy and efficiency, and discusses the technical, regulatory, and ethical challenges that must be addressed before autonomous implant surgery becomes routine clinical practice.

Keywords

Artificial intelligence; robotic surgery; implant surgery; surgical robotics; computer-assisted surgery

Introduction

Dental implants have become the standard of care for replacing missing teeth, but conventional workflows still depend heavily on operator experience for imaging interpretation, prosthetically driven planning, and freehand or template-guided drilling [4, 9]. Over the past decade, the digitization of dentistry — intraoral scanning, CBCT, and computer-aided design/manufacturing — has generated the structured data needed to train machine learning models and to drive robotic manipulators [1,3]. AI is now applied to diagnostic image segmentation, risk stratification, and implant position prediction, while robotic systems translate digital plans into submillimetric surgical execution [2,6]. Bibliometric and scoping analyses report a marked rise in publication output on this topic since 2020, with East Asia and North America as leading contributors [7,8].

This narrative overview summarizes how AI and robotics are currently used in implant dentistry, the clinical evidence supporting their accuracy and efficiency, and the barriers that remain before these technologies achieve widespread, autonomous adoption. For clarity, the discussion is organized along the same continuum a patient experiences: diagnostic imaging and digital planning, intraoperative surgical execution, and postoperative prognosis and long-term monitoring, followed by a synthesis of current limitations and likely near-term developments.

AI in Diagnostic Imaging and Digital Treatment Planning

The earliest and most mature implant-related AI applications lie in image analysis. Deep learning models trained on CBCT and panoramic radiographs can automatically segment the mandibular canal, maxillary sinus floor, and available bone volume, tasks that are time-consuming and prone to inter-observer variability when performed manually [2,3]. A scoping review of pre-surgical digital implant planning found that convolutional neural network-based tools achieved segmentation and landmark-detection accuracies comparable to those of experienced radiologists while substantially reducing planning time [2].

Beyond segmentation, AI algorithms increasingly propose implant number, position, angulation, and size directly from the digital dataset. A case-series study of AI-assisted planning for single-tooth defects reported implant positions that required only minor manual adjustment before finalization, suggesting that such tools can function as a clinical decision-support layer rather than a replacement for operator judgment [7]. Machine learning has also been applied to bone quality classification and to prediction of primary implant stability from radiographic texture analysis, informing decisions about loading protocols [1,4].

Robotic-Assisted Implant Surgery: Platforms and Accuracy

Robotic implant systems are generally categorized as passive (surgeon fully controls the handpiece within a mechanically constrained zone), semi-active (haptic feedback restrains deviation while the surgeon operates the drill), or active/autonomous (the robot performs part of the procedure with clinician supervision) 5,9,10. Yomi (Neocis, USA), the first robotic system to receive FDA clearance for dental implant surgery, exemplifies the semi-active category: an operational arm controlled by the surgeon is paired with a coordinate-measuring-machine arm that continuously tracks the patient's jaw, providing haptic, visual, and auditory feedback that constrains the drill to the virtual surgical plan [15].

Comparative accuracy data favor robotic over freehand placement. In vitro and clinical studies report robotic platform coronal, apical, and angular deviations of approximately 1.0 mm, 1.0 mm, and 2.6° respectively, compared with roughly 1.9 mm, 2.9 mm, and 8.2° for freehand placement 15. An in vitro comparison of dynamic navigation and robotic systems similarly found robotic guidance to yield the lowest angular and depth deviations among the tested modalities 6. Efficiency gains have also been documented: a 2025 multi-site clinical study comparing Yomi to freehand placement reported roughly 45% shorter procedure times for partial-arch cases and an average 80-minute reduction for full-arch cases [16,17].

These efficiency gains are not purely a matter of convenience. Shorter chair time reduces intraoperative bleeding risk and patient fatigue, and the flapless, minimally invasive approach enabled by robotic haptic constraint has been associated with faster soft-tissue healing in early clinical reports 15,16. Robotic guidance is also being extended to technically demanding scenarios such as zygomatic implant placement, where the margin for angular error is small and the anatomical corridor is narrow, and where several authors argue the accuracy advantage of robotics over freehand or even static-guide techniques is most clinically meaningful [9,10].

Toward Autonomous Systems

Newer platforms are moving beyond haptic guidance toward greater autonomy. Systems such as YekeBot integrate AI-driven planning with a robotic arm capable of executing portions of the osteotomy with reduced real-time operator input, and a fully autonomous robotic dental procedure on a human patient was reported for the first time in 2024, drawing considerable attention within the profession 12,13. Technology-readiness assessments classify most currently marketed dental robots as semi-autonomous, noting that regulatory clearance, liability frameworks, and clinician acceptance remain the principal barriers to fully autonomous systems reaching mainstream practice [12].

Predictive Analytics, Prognosis, and Peri-Implant Monitoring

AI is also applied after implant placement. Machine learning models trained on clinical, radiographic, and patient-level variables have been used to predict implant survival, marginal bone loss, and risk of peri-implantitis, with several models reporting area-under-the-curve values exceeding 0.80 11,14. Such tools could eventually support individualized maintenance schedules and earlier intervention in patients at elevated biological risk, although most predictive models still require external validation across diverse populations before clinical deployment [14,19].

Large language models (LLMs) such as ChatGPT are being explored as adjuncts for patient education and even clinician queries about implant protocols. A cross-sectional evaluation of ChatGPT-generated responses on dental implants and peri-implant phenotype found generally acceptable but variable reliability, underscoring that LLM output should supplement, not substitute for, professional clinical judgment [20].

Challenges and Limitations

Several barriers temper enthusiasm for AI and robotics in implantology. Model performance depends on training-data quality and diversity; algorithms developed on a single population or scanner type may not generalize well [2,14]. Robotic systems carry substantial acquisition and maintenance costs, require additional operator training, and add setup time that may offset some efficiency gains in low-volume practices [9,10]. Regulatory pathways for autonomous or semi-autonomous surgical decision-making remain incompletely defined, and questions of liability when an AI-generated plan or robotic deviation contributes to an adverse outcome are still largely unresolved [12,13]. Finally, over-reliance on automated planning risks de-skilling clinicians in fundamental anatomical and prosthetic judgment, an outcome that several authors caution against even as they endorse AI as a decision-support tool [1,4].

Patient-facing considerations also warrant attention. Informed consent should clearly explain the role of AI-generated plans and robotic assistance, including their known deviation ranges, so patients can weigh these against conventional guided or freehand approaches [9,13]. Workforce implications are similarly debated: rather than displacing surgeons, most current evidence positions AI and robotics as tools that shift clinician effort toward supervision, judgment, and management of complex or atypical cases, while repetitive planning and drilling steps become increasingly automated [1,12].

Future Directions

Near-term development is likely to focus on tighter integration between AI planning software and robotic execution, real-time intraoperative feedback using computer vision to detect deviations from the surgical plan, and expanded use of predictive analytics for long-term peri-implant surveillance [1,6,14].

Multimodal AI systems that combine imaging, genomic, and patient-reported data may eventually enable truly personalized implant protocols, while advances in haptics and force sensing could allow robots to safely assume greater autonomy in bone preparation, particularly for complex cases such as zygomatic implants or immediate-loading full-arch rehabilitation [5,6]. Realizing this potential will require prospective multicenter trials, standardized reporting of accuracy outcomes, and collaborative development of regulatory and training frameworks specific to dental robotics [8,12].

Conclusion

AI and robotics are no longer experimental curiosities in implant dentistry; they are measurably improving diagnostic accuracy, surgical precision, and procedural efficiency relative to conventional freehand and even static-guide workflows 2,6,16. Current evidence supports their use as adjuncts that augment, rather than replace, clinical expertise. As autonomous capabilities mature and as validation, regulatory, and training frameworks catch up with the technology, AI-guided robotic implant surgery is positioned to become an increasingly routine component of implant dentistry over the coming decade [12,13].

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