

From Digital Planning to Physical Execution: A Scoping Review of Physical AI in Dentistry

Mapping Technologies, Clinical Domains, and Evidence Gaps

Wanki Leea, Young-Shin Honga, and Young-Seok Parka,b

a Department of Oral Anatomy, Seoul National University School of Dentistry
b Department of Integrated Dentistry, Seoul National University School of Dentistry

Correspondence: Young-Seok Park, Professor, Department of Integrated Dentistry, Seoul National University School of Dentistry, 101 Daehakro Jongno-gu, Seoul, Republic of Korea; e-mail: ayoayo7@snu.ac.kr

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Abstract

Objectives

Physical AI in Dentistry is defined as artificial intelligence embodied within a physical platform—robotic, haptic, tactile, or actuator-based—capable of sensing, guiding, constraining, or executing dental and oral health procedures. This scoping review aimed to map the current literature on Physical AI in dentistry, characterize major clinical and educational domains, and identify evidence gaps relevant to future research and clinical translation.

Data Sources

A PubMed search (January 2015 – May 2026) using terms related to dental robotics, autonomous and semi-autonomous robotic systems, haptic simulation, tactile robots, force feedback, and robot-assisted surgery was conducted, supplemented by hand-searching of reference lists and key dental journals.

Study Selection

A total of 191 records were identified. After independent dual-reviewer screening, 68 records were excluded (software-only AI, pure dynamic navigation, TORS in non-dental ENT contexts, AI-free mechanical systems, and borderline records conservatively excluded for conceptual coherence). A final set of 123 studies was included.

Results

The literature is dominated by autonomous and semi-autonomous robotic implant placement systems ($n \approx 90$; ~73%), with smaller clusters in robotic endodontics (~13), robotic prosthodontics (~9), robot-assisted oral and maxillofacial surgery (~6), haptic simulation and dental education (~8), and tactile robotic oral hygiene (~3). Evidence derives primarily from in vitro studies, phantom experiments, single-center clinical series, and case reports. Only two randomized controlled trials were identified. Geographic concentration in Chinese institutions is notable (~63% of studies).

Conclusions

Physical AI in dentistry is transitioning from proof-of-concept toward early clinical translation. Robotic implantology is the most mature domain. The field remains methodologically heterogeneous, with insufficient long-term clinical, patient-centered, and cost-effectiveness data. Standardized autonomy classification, reporting checklists, multicenter trials, and regulatory frameworks are urgently needed.

Keywords: Physical AI; dental robotics; autonomous robotic surgery; robotic implantology; haptic simulation; dental education; embodied intelligence; autonomy level; scoping review

INTRODUCTION

Artificial intelligence has become one of the most visible themes in contemporary dental research. Most dental AI applications, however, remain fundamentally screen-based. They detect caries on radiographs, segment anatomical structures on cone-beam computed tomography, classify oral lesions, predict treatment outcomes, assist diagnosis, or support digital treatment planning. In these applications, AI functions primarily as an analytical or cognitive tool. It sees, calculates, predicts, and recommends. A radiographic AI system may identify the mandibular canal, but it does not place an implant. A treatment-planning algorithm may suggest an ideal implant position, but it does not execute the osteotomy. These software-only systems represent virtual or software-centered AI—intelligence operating through data processing and decision support rather than direct physical engagement.

A different paradigm is now emerging. In this newer paradigm, AI is no longer confined to the screen. It is connected to sensors, robotic arms, force-feedback systems, haptic interfaces, navigation platforms, automated cutting devices, or tactile actuators. It does not merely interpret the clinical world; it physically interacts with it. This emerging convergence is referred to in this review as Physical AI in Dentistry.

This concept is closely aligned with the framework of embodied intelligence, which holds that intelligent behavior does not arise from computation alone but from the dynamic coupling of algorithm, body, and environment. Recent commentary in Nature Machine Intelligence has described a conceptual shift 'from embodied intelligence to physical AI,' highlighting the convergence of robotics, sensing, control, and adaptive computation in systems that move intelligence beyond abstract code and into physical action (Nature Machine Intelligence, 2026). Reviews of embodied intelligence in soft robotics similarly emphasize that perception, materiality, and environmental feedback are not peripheral to intelligence but constitutive of it (Biomimetics, 2024).

Physical AI may therefore be understood as artificial intelligence embodied within a physical system capable of sensing, interpreting, guiding, constraining, or executing real-world actions. In dentistry, this includes autonomous or semi-autonomous implant robots, haptic-guided surgical platforms, robotic tooth preparation systems, robot-assisted endodontic access, autonomous osteotomy, haptic simulation for dental education, and tactile robots for oral hygiene. The defining feature is not simply the presence of a robot or a digital interface, but the translation of digital planning, sensing, or adaptive control into physical dental action.

This distinction is clinically important. Dentistry depends heavily on psychomotor precision, spatial judgment, tactile feedback, fine motor control, and physical interaction with hard and soft tissues. The clinical relevance of AI in dentistry will therefore depend not only on what AI can detect or predict, but also on how AI can safely support, guide, or perform physical procedures.

Despite rapid growth, the Physical AI dental literature remains fragmented. Terms such as 'robotic,' 'autonomous,' 'semi-autonomous,' 'dynamic navigation,' 'AI-assisted,' and 'haptic' are used without clear distinction. A scoping review methodology was selected to map the breadth of evidence, characterize the diversity of Physical AI technologies and clinical domains, and identify gaps warranting future systematic evaluation and primary research.

For this review, Physical AI in Dentistry is defined as any dental or oral-health technology in which AI, robotic control, sensor-guided computation, haptic feedback, tactile perception, or autonomous/semi-autonomous decision-making is integrated with a physical platform capable of guiding, constraining, assisting, or executing a dental, oral, craniofacial, educational, or oral-care task.

METHODS

Study Design and Reporting Framework

This scoping review was conducted in accordance with the PRISMA extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018), guided by the Arksey and O'Malley (2005) framework and the refinements of Levac et al. (2010). A scoping review design was selected because the field is heterogeneous in terminology, system architecture, autonomy level, clinical application, and outcome reporting. The aim was to map the breadth, distribution, and maturity of available evidence rather than to estimate a pooled treatment effect. The protocol was not pre-registered in a public registry prior to this submission.

Working Definition and Eligibility Criteria

Eligible systems included, but were not limited to:

- Autonomous or semi-autonomous robotic implant systems
- Robotic systems for endodontic access, post removal, or microsurgery
- Robotic systems for prosthodontic or restorative tooth preparation
- Robot-assisted oral and maxillofacial surgical platforms
- Haptic simulators or force-feedback systems for dental education
- Tactile collaborative robots for oral hygiene or assistive care
- AI-enabled or sensor-guided systems converting digital planning into controlled physical action

Studies were excluded if they: (1) involved software-only AI, diagnostic AI, or treatment planning without physical execution; (2) described pure dynamic navigation without robotic actuation; (3) involved teleoperated TORS without AI autonomy in non-dental ENT/head-and-neck oncology contexts; (4) used 'autonomous' in a professional or administrative sense; (5) described AI-free mechanical testing devices, chewing simulators, or non-adaptive robots; (6) focused on non-dental robotic surgery; or (7) represented borderline cases with insufficiently clear Physical AI integration. A conservative approach was applied to preserve conceptual coherence.

Information Sources and Search Strategy

A PubMed search was conducted in May 2026, restricted to publications from January 2015 onward. The search string was:

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("dental robot"[tiab] OR "robotic dental"[tiab] OR "autonomous robot"[tiab] OR "semi-autonomous robot"[tiab] OR "task-autonomous"[tiab] OR "robotic implant"[tiab] OR "robot-assisted implant"[tiab] OR "robot-assisted surgery"[tiab] OR "haptic simulat"[tiab] OR "force feedback"[tiab] OR "tactile robot"[tiab] OR "autonomous robotic system"[tiab] OR "computer-guided robot"[tiab]) AND ("dentistry"[MeSH] OR "dental"[tiab] OR "oral surgery"[MeSH] OR "dental implant"[MeSH] OR "endodont"[tiab] OR "prosthodont"[tiab] OR "tooth preparation"[tiab]) AND ("2015/01/01"[PDat]:"3000/12/31"[PDat]) NOT ("dynamic navigation"[tiab] NOT "robot"[tiab])
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Supplementary hand-searching was performed on reference lists of included review articles and key dental journals. No language restrictions were applied.

Study Selection

A total of 191 records were identified. Two reviewers independently screened titles and abstracts. Full texts were retrieved for all potentially eligible records and independently assessed. Disagreements were resolved by discussion; persisting disagreements were adjudicated by a third reviewer. Borderline records—including mixed-reality navigation-only systems and studies with unclear Physical AI integration—were excluded conservatively. The complete selection process is presented in the PRISMA-ScR flow diagram (Supplementary Figure S1).

Data Extraction and Synthesis

A structured extraction form captured: first author; year; country; journal; study design; dental domain; Physical AI category; system type; autonomy level; procedure; sample size; primary outcomes; key findings; reported limitations; and safety events. For implant studies, coronal deviation (mm), apical deviation (mm), and angular deviation (°) were the primary quantitative outcomes. Given heterogeneity in designs and outcome measures, synthesis was narrative. Descriptive statistics were calculated within subgroups where sufficient comparability existed.

RESULTS

Study Selection

The PubMed search retrieved 191 records. After independent dual-reviewer screening, 68 records were excluded and 123 studies were included. The most common reasons for exclusion were: TORS/teleoperated ENT robotic surgery in non-dental contexts ($n \approx 19$); borderline cases with insufficient Physical AI integration, conservatively excluded ($n \approx 20$); pure dynamic navigation without robotic actuation ($n = 8$); AI-free mechanical or materials-testing robots ($n = 6$); 'autonomous' used in a non-technological sense ($n = 5$); software-only diagnostic AI ($n = 4$); and non-dental robotic surgery ($n = 2$). The full PRISMA-ScR flow diagram is provided in Supplementary Figure S1.

Publication Trend and Geographic Distribution

The included studies span 2015 to 2026, with a marked acceleration in annual output from 2022 onward and a cumulative evidence base more than doubling between 2021 and 2024 (Supplementary Figure S2). This confirms that Physical AI in dentistry has transitioned from isolated technical reports toward a rapidly expanding translational research field. Chinese research institutions contributed approximately 63% of included studies, particularly in autonomous robotic implantology (Supplementary Figure S4). Additional contributions came from the United States, Korea, Germany, Japan, Belgium, Saudi Arabia, and Italy.

Distribution by Physical AI Category

Figure 1 shows the distribution of included studies across seven Physical AI categories. Robotic implant systems (Category A) dominate with approximately 73% of included studies. The evidence maturity across domains—showing the stark contrast between the RCT-level evidence in robotic implantology and the in vitro-only evidence in Categories D, E, and F—is detailed in Supplementary Figure S3.

Robotic Implantology

System Architecture and Autonomy

Autonomous dental implant robotic systems (ADIRS) perform the complete osteotomy and implant placement sequence under AI control with the surgeon in a supervisory role. Semi-autonomous systems collaborate through haptic feedback or motion constraints. The two most widely studied platforms are: (1) the Yomi system (Neocis, USA), a haptic-guided arm cleared by the US FDA in 2019; and (2) Chinese-developed fully autonomous systems, most prominently from the Fourth Military Medical University (Xi'an), where the robotic arm autonomously drills and inserts implants according to a preoperative CBCT-IOUS fusion plan.

Accuracy Outcomes

Implant placement accuracy was the primary outcome in most Category A studies. Across meta-analyses and comparative studies, pooled mean deviations for autonomous systems were approximately: coronal deviation 0.45–0.77 mm, apical deviation 0.50–0.78 mm, and angular deviation 0.80–1.46°. These compare favorably with dynamic navigation (mean angular ~ 1.78 – 3.71°) and static surgical guides ($\sim 3.5^\circ$).

Clinical Applications

Applications extend beyond standard single-tooth implant placement to include: zygomatic implants; All-on-4 and full-arch edentulous rehabilitation; immediate post-extraction implant placement; maxillary sinus floor elevation with force-feedback membrane breakthrough detection; tilted implants in atrophic ridges; and osseodensification protocols. No cases of major vascular or nerve injury attributable to robotic malfunction were reported across included studies.

Robotic Endodontics and Apical Surgery

Thirteen studies described robot-assisted endodontic procedures. The most investigated application was autonomous robotic system (ATR) guidance for fiber post removal, with multiple in vitro comparisons demonstrating significantly shorter operative time and reduced dentinal loss versus dynamic navigation and conventional microscope-ultrasonic techniques. Robot-assisted endodontic microsurgery in anatomically challenging locations was demonstrated in case reports. A computer-controlled CO₂ laser ablation system integrated with CBCT and augmented reality completed all 20 in vitro access preparations across six preparation designs without iatrogenic error. Evidence remains primarily in vitro and case-level.

Robotic Prosthodontics and Restorative Dentistry

Nine studies reported robot-assisted preparation for prosthetic restorations. The Lupin semi-active robotic system (Peking University) demonstrated RMS preparation errors of 0.15–0.30 mm in veneer preparation, within clinically acceptable thresholds. For removable partial denture guiding plane preparation, a robotic system reduced inter-guiding-plane angular deviation from $13.41^\circ \pm 8.86^\circ$ (freehand) to $1.93^\circ \pm 1.04^\circ$, a clinically significant improvement for path-of-insertion parallelism.

Robot-Assisted Oral and Maxillofacial Surgery

Six studies described robot-assisted orthognathic and maxillofacial procedures. A foundational phantom study from Seoul National University developed a six-degree-of-freedom autonomous bone repositioning robot that executed CT-based plans with submillimeter accuracy (Woo et al., 2017). Robot-assisted mandibular reconstruction with fibula flap transfer achieved mean deviation of 1.22 mm versus 1.58 mm (navigation) and 2.31 mm (freehand). Evidence remains at proof-of-concept level.

Haptic Simulation and Dental Education

Eight studies examined haptic simulation platforms providing adaptive, real-time AI feedback for dental skill training. A distinctive study of postgraduate trainees using robotic computer-assisted implant surgery (r-CAIS) found that accuracy metrics showed no statistically significant deterioration across training days while preparation times improved significantly—reframing Physical AI as a precision scaffold that preserves safety while accelerating efficiency learning.

Tactile Robots and Oral Hygiene

Three in vitro studies from the Hannover group demonstrated that a seven-axis tactile collaborative robot achieved interproximal and buccal plaque removal statistically comparable to a trained human operator, using integrated force-torque sensing to maintain safe contact dynamics. Authors highlighted translational potential for patients with limited manual dexterity or neurodegenerative disease.

DISCUSSION

Principal Findings

This scoping review mapped 123 studies on Physical AI in dentistry, providing the first systematic evidence map applying the Physical AI framework across robotic, haptic, tactile, and sensor-actuated dental technologies. Robotic implantology is clearly the most mature domain, while other domains—endodontics, prosthodontics, oral and maxillofacial surgery, dental education, and oral hygiene robotics—remain at earlier stages. This imbalance is captured visually in Figure 1 (category distribution) and in the evidence maturity matrix (Supplementary Figure S3).

From Software Intelligence to Embodied Clinical Action

Physical AI represents a fundamentally different form of intelligence from software-only dental AI. A radiographic AI system may identify the mandibular canal, but it does not place an implant. A treatment-planning algorithm may suggest an ideal position, but it does not execute the osteotomy. A robotic implant system translates digital planning into physical action. The risk profile, validation requirements, ethical implications, and professional responsibilities are therefore categorically different. When AI physically acts on human tissue—drilling bone, resecting tissue, guiding a scaler—questions of safety, accountability, informed consent, and liability enter entirely new territory.

The Autonomy Problem: A Proposed Classification Framework

A major challenge across the included literature is inconsistent use of terminology. 'Robotic,' 'autonomous,' 'semi-autonomous,' 'computer-assisted,' and 'navigation-guided' are used without clear distinction—with significant clinical and regulatory consequences. A static surgical guide, a dynamic navigation system, a haptic-constrained robotic arm, and a task-autonomous drilling robot represent profoundly different levels of physical agency.

This review proposes a seven-level autonomy classification framework for Physical AI in dentistry (Figure 2), adapted from analogous frameworks in surgical robotics and autonomous vehicles. Most current dental Physical AI systems operate at Levels 3–4. Future studies should report autonomy level explicitly using a defined framework.

Accuracy Is Necessary but Not Sufficient

Figure 1. Distribution of Included Studies by Physical AI Category

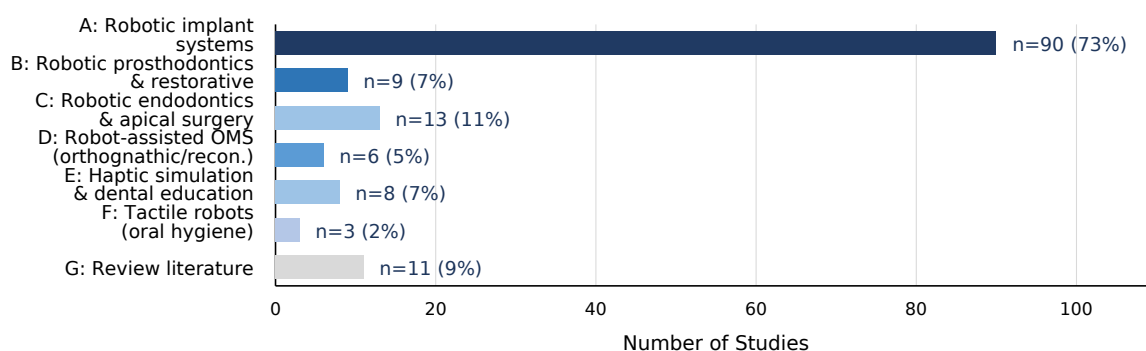


Figure 1. Distribution of included studies by Physical AI category (n = 123). Percentage values represent proportion of total included studies.

The included literature is dominated by accuracy metrics. Positional and angular deviation data are measurable and relevant—but accuracy alone does not establish clinical superiority. Future research must determine whether Physical AI improves outcomes that matter to patients and health systems: complication rates, pain, swelling, healing, implant survival, prosthetic success, tooth survival, tissue preservation, peri-implant bone loss, anxiety levels, patient satisfaction, clinician fatigue, training efficiency, cost-effectiveness, and access to care. None of these patient-centered endpoints are well-addressed in the current Physical AI dental literature.

Evidence Maturity and Geographic Concentration

The field is highly concentrated geographically, primarily in Chinese institutions (see Supplementary Figure S4). This concentration has accelerated innovation but raises concerns about external validity. Independent replication, multicenter studies across diverse clinical and anatomical contexts, and international regulatory evaluation are needed before reported accuracy data can be considered broadly generalizable.

Underdeveloped Domains and the Role of Academic Institutions

The concentration of evidence in implant dentistry reflects commercial priorities. Physical AI in endodontics could improve access accuracy and tooth preservation. Robotic prosthodontics could standardize minimally invasive preparations. Haptic simulation could address faculty shortages and provide objective psychomotor assessment. Tactile oral hygiene robots could assist patients with disability, neurodegenerative disease, or age-related functional decline.

These underdeveloped areas are unlikely to attract commercial investment commensurate with their public health significance. They require investigator-initiated, publicly funded, long-horizon research that national and public universities are best positioned to conduct. The foundational orthognathic robotic surgery work from Seoul National University (Woo et al., 2017) and the Dentronics tactile robot studies from Hannover exemplify this academic imperative. As Physical AI transitions from laboratory curiosity to clinical infrastructure, academic dental institutions have both the opportunity and the responsibility to shape its development toward broad patient benefit.

Implementation, Safety, and Accountability

Clinical adoption will require more than technical feasibility. Implementation barriers include cost, training, calibration, registration errors, patient movement, workflow complexity, and regulatory approval. Safety reporting is currently insufficient: future studies should systematically report device malfunctions, registration failures, aborted procedures, override events, soft-tissue injuries, thermal injury, neurological complications, and operator interventions. Accountability—the distribution of responsibility among clinician, manufacturer, software developer, institution, and regulator when a robotic system acts on human tissue—is almost entirely absent from current literature but will become urgently relevant as autonomy levels increase.

A Proposed Standardized Reporting Checklist for Physical AI in Dentistry

A standardized reporting checklist would substantially improve comparability and accelerate evidence synthesis. At minimum, future reports should include:

- System name, manufacturer, and software version
- Autonomy level (using a defined framework, e.g., Levels 0–6 as proposed above)
- Sensing modalities (optical tracking, force/torque sensing, imaging, etc.)
- Registration workflow and imaging inputs (CBCT, IOS, CBCT-IOS fusion)
- Planning software and version

- Actuator type and degrees of freedom
- Haptic or force-feedback mechanism (if applicable)
- Calibration method and reported calibration error
- Human override mechanism description
- Intraoperative monitoring and safety boundaries
- Failure handling protocol
- Operator training criteria (hours, cases, proficiency thresholds)
- Primary outcome definitions and measurement method
- Adverse event definitions and systematic reporting
- Follow-up duration and long-term outcome data where applicable

Such reporting would distinguish true technological improvement from differences caused by study design, operator experience, or measurement approach. A consensus reporting extension tailored to Physical AI dental studies—analogue to CONSORT or STROBE—should be developed through coordinated effort among dental research organizations, engineering societies, and regulatory bodies.

Limitations

- The search was primarily PubMed-based. Relevant engineering conference proceedings, IEEE publications, robotics journals, and non-indexed technical papers may have been missed. Future updates should include Embase, Scopus, and IEEE Xplore.
- The definition of Physical AI is necessarily evolving and not universally standardized. Borderline technologies—particularly mixed-reality navigation systems and dynamic navigation with emerging AI components—were excluded conservatively. This may have excluded some studies qualifying under a broader definition.
- Study designs and outcome measures were highly heterogeneous, precluding quantitative synthesis across the full dataset. Cross-study comparisons should be interpreted cautiously.
- The included evidence is likely affected by publication bias. Early robotic studies are more likely to report successful feasibility outcomes. Neutral or negative results may be under-represented.
- The rapid pace of development means the evidence base may change substantially within a short period. New commercial platforms, regulatory approvals, and clinical trial results may alter the conclusions of this review.
- The review protocol was not pre-registered in OSF or a similar public registry prior to the search and data extraction, limiting transparency and increasing the risk of post-hoc modification of eligibility criteria.

CONCLUSION

This scoping review maps 123 studies on Physical AI in dentistry, providing the first systematic evidence map that defines and applies the Physical AI framework across robotic, haptic, tactile, and sensor-actuated dental technologies. The field is characterized by rapid growth and technical maturation in autonomous robotic implant systems, with compelling accuracy data and an emerging body of clinical evidence including two randomized controlled trials.

Beyond implant robotics, Physical AI applications in prosthodontics, endodontics, orthognathic surgery, haptic simulation, and oral hygiene robotics represent smaller but meaningful clusters that demonstrate the breadth of the emerging paradigm. The evidence base remains dominated by in vitro studies, single-center clinical series, and geographically concentrated research outputs. High-quality multicenter trials, standardized outcome frameworks, long-term clinical data, and patient-centered outcome research are the priorities for the next phase.

Table 1. Representative implant placement accuracy data by technology type. NS = not statistically significant; DNS = dynamic navigation system; * $p < 0.01$.

Technology	Coronal Dev. (mm)	Apical Dev. (mm)	Angular Dev. (°)	Study Design
Autonomous robot (pooled meta-analysis)	0.45-0.60	0.50-0.63	0.80-1.24	Meta-analysis
Semi-autonomous robot (clinical)	0.60-0.91	0.60-1.06	1.46-3.07	Clinical retrospective
Robot vs. DNS (RCT)	NS vs. DNS	NS vs. DNS	1.01 vs. 1.78*	RCT (n=40)
Dynamic navigation (comparator)	0.99-1.26	0.70-1.51	1.78-3.71	Various
Static surgical guide (reference)	~1.1	~1.3	~3.5	Systematic review

The autonomy level framework and standardized reporting checklist proposed in this review offer practical tools for improving comparability, guiding regulatory evaluation, and establishing clearer professional expectations about the role of human oversight in physically autonomous dental systems.

Physical AI should be viewed neither as a distant fantasy nor as a fully established clinical standard. It is an emerging translational field with substantial promise, but its future depends on rigorous validation, transparent reporting, careful autonomy classification, and a commitment to clinical value beyond technological novelty.

The essential question is no longer whether AI can assist dentistry from the screen. The next question is how safely, responsibly, and meaningfully AI can enter the physical space of dental care.

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There is no conflicts of interest.

DATA AVAILABILITY

The full classified dataset is available from the corresponding author upon reasonable request.

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Figure 2. Proposed Autonomy Level Framework for Physical AI in Dentistry

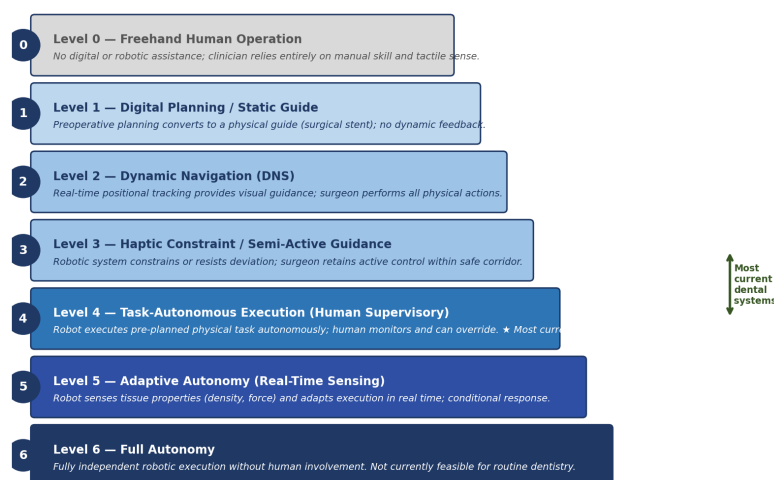


Figure 2. Proposed autonomy level framework for Physical AI in Dentistry (Levels 0-6). Most current dental robotic systems operate between Levels 3 and 4. Level 6 full autonomy is not currently clinically feasible.