Robotics in endodontics: an integrative review of autonomy and translational readiness.

Figures

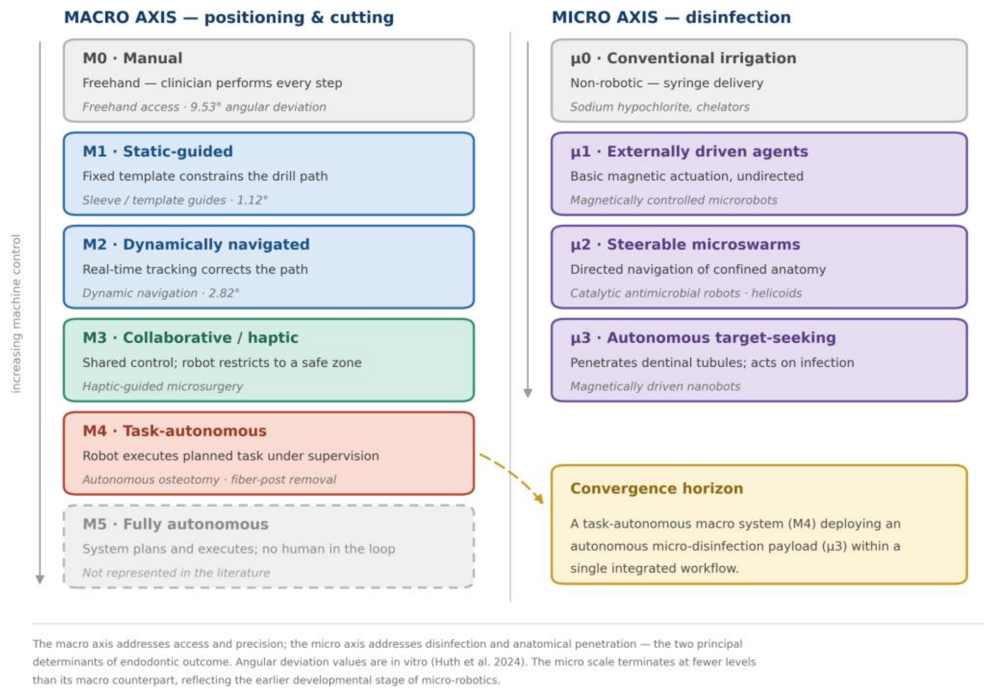

Figure 1: A dual-axis framework for robotic autonomy in endodontics. The macro axis (M0-M5) grades positioning and cutting autonomy, ascending from freehand operation (M0) through static-guided (M1) and dynamically navigated (M2) modes in which the clinician still executes, to collaborative haptic control confining the operator to a planned safe zone (M3) and task-autonomous execution under supervision (M4); a fully autonomous mode (M5) is not represented in the literature. The parallel micro axis (μ0-μ3) grades disinfection autonomy, from conventional irrigation (μ0) through externally driven magnetic agents (μ1) and steerable microswarms (μ2) to autonomous target-seeking nanorobots able to penetrate dentinal tubules (μ3). The micro scale terminates at fewer levels than its macro counterpart, reflecting the earlier developmental stage of micro-robotics. The dashed arrow marks the convergence horizon: a task-autonomous macro system delivering an autonomous micro-disinfection payload within a single integrated workflow. Angular deviation values shown are in vitro.

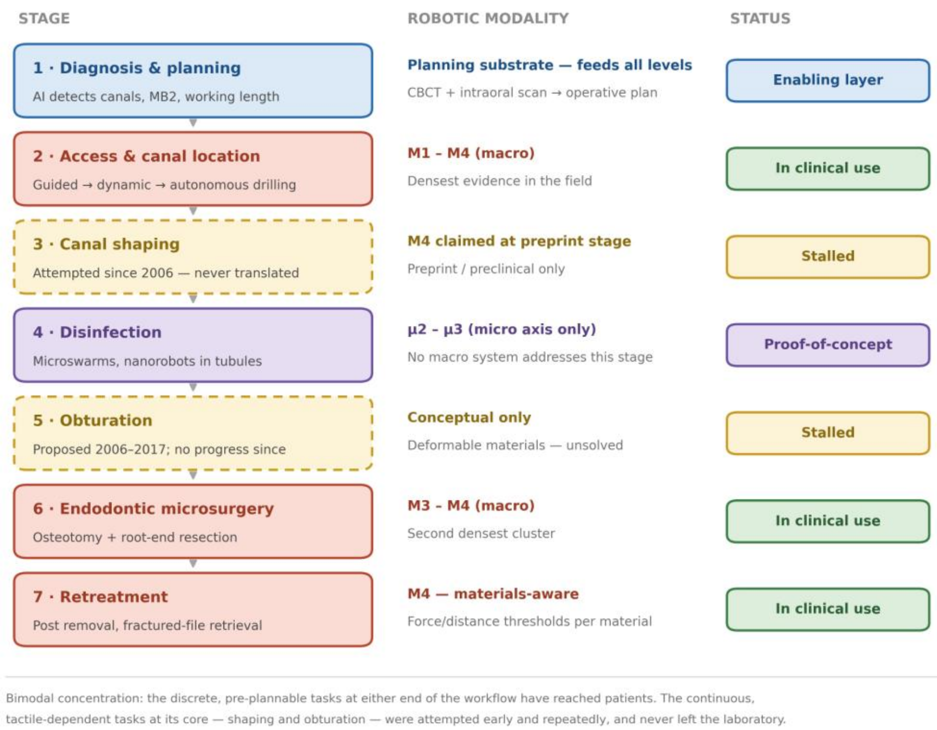

Figure 2: Robotics mapped across the endodontic workflow. Each of seven endodontic stages is mapped to the robotic modalities reported for it and to the translational status of that work. Diagnosis and planning functions as an enabling layer rather than a robotic act: artificial-intelligence detection of canal anatomy converts volumetric and intraoral scan data into the operative plan that every downstream level executes. Access and canal location carries the densest evidence, spanning M1 to M4, and endodontic microsurgery and retreatment form a second cluster at M3-M4; all three have reached patients. Disinfection is served exclusively by the micro axis at proof-of-concept stage, with no macro-robotic system addressing it. Canal shaping and obturation are shown as stalled rather than unexplored: both were proposed as early as 2006 and pursued repeatedly, but neither has produced clinical validation or a deployed system. The resulting distribution is bimodal - the discrete, pre-plannable tasks at the entry and exit of the workflow have translated into practice, while the continuous, tactile-dependent tasks at its biological core have not.

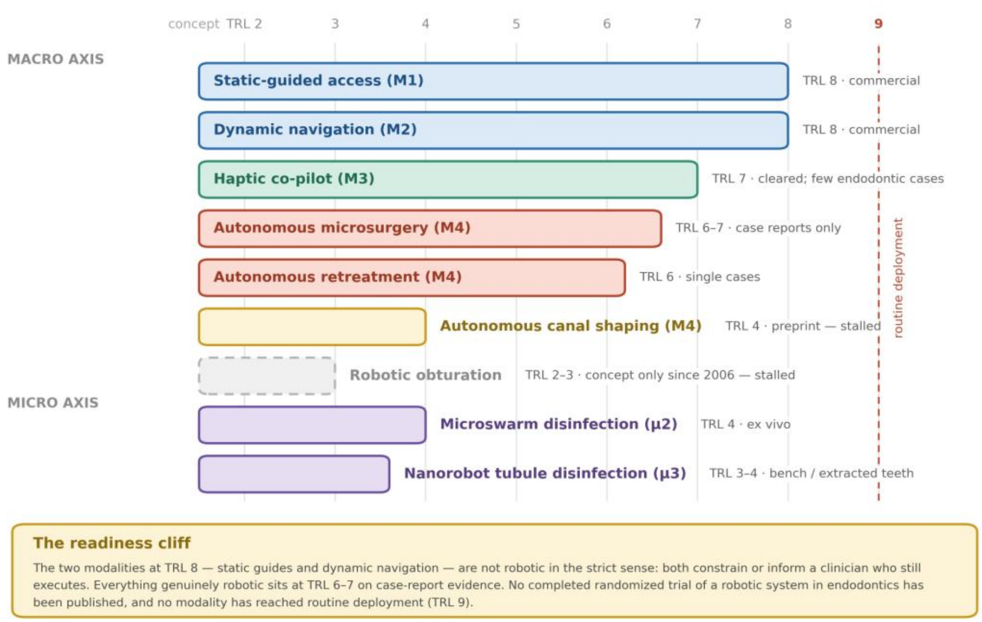

Figure 3: Technology readiness of endodontic robotic modalities. Modalities on both axes plotted against the 1-9 technology-readiness scale. Static-guided access and dynamic navigation reach TRL 8, but neither is robotic in the strict sense: both constrain or inform a clinician who still executes. The haptic co-pilot is regulatorily cleared and clinically deployed (TRL 7) though supported by

few endodontic reports, and autonomous microsurgery and retreatment sit at TRL 6-7 on case-report evidence alone. Below these lies a readiness cliff spanning laboratory validation to demonstration in an operational environment: autonomous canal shaping remains at TRL 4, robotic obturation has not advanced beyond conceptual description in nearly two decades, and microswarm and nanorobotic disinfection remain at TRL 3-4 with no in-vivo human data identified. No modality has reached routine deployment (TRL 9), and no completed randomized trial of a robotic system in endodontics has been published. The inverse relationship between technological maturity and autonomy is the central structural finding of this appraisal.

Robotics in endodontics: an integrative review of autonomy and translational readiness.

Abstract

Background: Existing syntheses of endodontic robotics import autonomy terminology from implant robotics, separate the macro- and micro-robotic literatures, and report performance without appraising the evidence.

Methods: This integrative review searched PubMed to 31 July 2026, supplemented by Google Scholar and citation tracking, purposively selecting 61 records graded on the OCEBM 2011 hierarchy and assigned technology-readiness levels. No human participants or animals were involved; ethical approval was not applicable.

Results: A dual-axis framework separates a macro scale (M0-M5) for positioning and cutting from a micro scale (μ0-μ3) for disinfection. Translation across seven workflow stages is bimodal: robotics has reached patients at access, microsurgery and retreatment, while shaping and obturation remain preclinical. No completed randomized trial was identified; the most mature modalities are the least autonomous.

Conclusion: The bottleneck is translational rather than conceptual.

Keywords: Endodontics; medical robotics; microrobotics; endodontic microsurgery; technology readiness; surgical autonomy

Introduction

Endodontic treatment is performed within one of the most technically unforgiving operative fields in medicine. The target is a millimeter-scale, three-dimensionally branching space that cannot be directly visualized, approached through a rigid access constrained by the surrounding dentition, and containing anatomy — accessory canals, isthmuses, apical deltas, dentinal tubules — that is simultaneously the source of infection and beyond the reach of the instruments used to treat it. Outcomes accordingly depend heavily on operator skill, and vary with it.

These are precisely the conditions under which robotic assistance might be expected to offer most, and two decades have seen a widening range of approaches applied to endodontic tasks: navigated guidance for access preparation [1,2], haptic co-pilot systems constraining movement within a planned safe zone [3], autonomous arms performing osteotomy and root-end resection [4], and magnetically actuated micro- and nanorobots directed at biofilm beyond the reach of irrigation [5,6]. Two scoping reviews have recently catalogued this literature [7,8].

Yet the existing syntheses share three limitations that this review addresses. First, they characterize autonomy using terminology imported from implant robotics — a passive, semi-active, active tripartition [9] developed for a different operative problem, which compresses a range extending from a static drill guide to a nanorobot in a dentinal tubule. Second, they treat macro-robotic navigation and micro-robotic disinfection as separate literatures, despite both addressing stages of the same workflow. Third, and most consequentially, they report performance in the affirmative register of the source studies without interrogating the design of the studies generating those claims.

This review makes three corresponding contributions: a dual-axis autonomy framework specific to endodontics, distinguishing a macro scale for positioning and cutting from a parallel micro scale for disinfection; a mapping of both axes onto the full endodontic workflow, integrating literatures not previously considered together; and an appraisal of translational readiness through an evidence-hierarchy audit and technology-readiness mapping. It then develops the regulatory, economic, medicolegal, equity, and training dimensions that prior reviews name but do not analyze, and converts the gaps identified into a prioritized research agenda.

Materials and Methods

This review was conducted as an integrative review, selected deliberately over a systematic or further scoping review for two reasons. First, the literature is methodologically heterogeneous to a degree that precludes statistical pooling, spanning case reports, in-vitro and ex-vivo investigations, engineering proof-of-concept work, and preprints. Second, the objective was not to map the literature — which recent scoping reviews have done [7,8] — but to generate three contributions requiring interpretive rather than aggregative synthesis. This review analyzed previously published literature and involved no human participants, human material, human data or animal subjects; institutional review board approval and informed consent were therefore not applicable.

The scope was framed using the Population–Concept–Context structure, borrowed from scoping-review methodology to specify the boundaries of the review; it does not import the exhaustive-screening requirements of that design. The population comprised human teeth, tooth analogues, and the endodontic operative field, in vivo, ex vivo, or in vitro. The concept comprised any application of robotic, autonomous, or micro/nanorobotic technology to an endodontic task. The context comprised all endodontic procedural domains, from diagnosis and planning to microsurgery and retreatment.

A structured search of PubMed combined terms for robotic modality (robot*, robotic-assisted, autonomous, cobot, microrobot*, nanorobot*, dynamic navigation, guided endodontic*, active dental robot*) with terms for endodontic task (endodontic*, root canal, access cavity, apicoectomy, endodontic microsurgery, canal disinfection, retreatment, obturation), supplemented by Google Scholar and by citation tracking of key primary studies and prior reviews. Searches were run without lower date limit and were last updated on 31 July 2026. Yield counts and a flow diagram are not reported, because purposive selection makes a screening cascade misleading.

Studies were purposively selected if they reported the development, laboratory evaluation, or clinical application of a robotic or micro-robotic technology applied to an endodontic task. Static and dynamically navigated systems were included deliberately, notwithstanding that neither is robotic in the strict sense: they constitute levels M1 and M2 of the macro scale and supply the comparative baseline against which robotic accuracy claims are made. Robotics in non-endodontic disciplines was excluded from the primary evidence base; three such studies were retained as transfer-relevance citations supporting framework derivation only. Reviews and perspectives were retained separately for context, as was one study of haptic simulation for access-cavity training. The corpus comprises 42 primary studies, 3 transfer-relevance studies, 13 reviews, 1 education study, and 2 methodological instruments — 61 records, all cited here. An AI-assisted tool was used for language editing and to cross-check bibliographic details against source articles; all gradings and interpretations are the authors' own and were verified against primary sources.

Data were charted into a matrix capturing author, year, design, robotic modality and scale, endodontic task, comparator, reported outcomes, and setting. Each primary study was assigned a level of evidence using the OCEBM 2011 hierarchy [10]; each modality a technology-readiness level on the standard 1–9 scale, developed for aerospace systems [11] and now widely applied to health technologies. Note that OCEBM 2011 assigns Level 5 to mechanism-based reasoning — bench models, in-vitro work, computational simulation — so Level 5 here denotes preclinical evidence, not expert opinion. The IDEAL framework was considered as an alternative translational lens; OCEBM was retained because it grades the strength of individual studies, which IDEAL does not, and because pairing it with the readiness scale separates evidentiary strength from engineering maturity. Charting was performed by one reviewer and verified by a second, who re-examined every autonomy-level, evidence-grade and readiness assignment against the source articles; discrepancies were resolved by discussion. Because verification followed the initial rating rather than duplicating it independently, no inter-rater agreement statistic is reported.

Results

A dual-axis framework for robotic autonomy in endodontics

Prior syntheses have described robotic endodontic systems using terminology borrowed from implant robotics — passive, semi-active, active [7-9]. This schema compresses the range of autonomy present in contemporary systems and forces two fundamentally different classes of technology onto a single axis. A robotic arm that positions and cuts, and a magnetically actuated microswarm that navigates a fluid-filled canal to disrupt biofilm, represent distinct modes of machine agency. Grading autonomy is established in surgical robotics, where a six-level scale is in general use [12], and has been applied to dental implant robotics, where deployment was found capped at task-autonomous execution [13]. What is absent is an instrument calibrated to endodontics. We therefore propose a dual-axis framework: a macro scale (M0–M5) for positioning and cutting autonomy, and a parallel micro scale (μ0–μ3) for disinfection autonomy (Figure 1).

The macro scale progresses from fully manual operation (M0), through static-guided (M1) and dynamically navigated (M2) modes in which the clinician still executes, to collaborative haptic control (M3) where a robot restricts the operator to a pre-planned safe zone [3,14], and task-autonomous operation (M4) where the robot executes a discrete planned task under supervision [4,15-17]. A fully autonomous mode (M5) is not yet represented in the literature.

The micro scale is necessarily shallower, reflecting the earlier developmental stage of the field. It ascends from conventional irrigation (μ0), through externally driven agents under basic magnetic actuation (μ1), to steerable microswarms capable of directed navigation through confined spaces (μ2) [5,18], and finally to autonomous target-seeking nanorobots able to penetrate dentinal tubules (μ3) [6,19]. That it terminates at fewer levels than its macro counterpart is itself informative.

Crucially, the two axes are not permanently separate. The macro scale addresses a problem of access and precision; the micro scale a problem of reach. A convergence horizon is foreseeable, in which a task-autonomous macro system (M4) delivers an autonomous micro-disinfection payload (μ3) within a single integrated workflow — a direction that may prove more consequential than progress along either axis alone.

Mapping robotics across the endodontic workflow

Positioning each robotic modality within the clinical sequence of endodontic treatment reveals an uneven distribution of technological maturity across seven stages: diagnosis and planning; access and canal location; canal shaping; disinfection; obturation; endodontic microsurgery; and retreatment (Figure 2).

The diagnosis and planning stage functions as a shared substrate rather than a robotic act in itself. Artificial-intelligence systems detect root and canal anatomy and convert cone-beam and intraoral scan data into the operative plan [20,21] that every downstream robotic level executes; its accuracy bounds everything that follows.

Robotic evidence is densest at the access and canal location stage, spanning the full macro axis from static guides (M1) [1,22-25] through dynamic navigation (M2) [2,26-34] to autonomous robotic drilling of calcified canals (M4) [35,36]. This concentration is unsurprising: access is a discrete, geometrically well-defined task amenable to preoperative planning, and it is where guided endodontics originated [1].

Canal shaping and obturation present a more complex picture, and one frequently mischaracterized. These stages are not unexplored; they were among the earliest targets of endodontic robotics. A conceptual micro-robot proposing automated probing, drilling, filing, cleaning and filling was described as early as 2006 [37], a vision-guided system for canal filing followed in 2010 [38], and further conceptual micro-robots were proposed thereafter [39]. More recently, a six-degree-of-freedom hybrid position/force-control system has been reported for canal shaping [40].

What distinguishes these stages is not absence of effort but absence of translation. This line of work remains confined to conference proceedings, preprints, and preclinical prototypes; within the databases searched we identified no clinical case reports, no in-vivo validation, and no commercially deployed system arising from it. The qualification matters more here than elsewhere, because much of this engineering literature is indexed in IEEE Xplore and Scopus rather than the biomedical databases searched. Over the same two-decade window access preparation and microsurgery progressed from concept to documented treatment of patients, whereas shaping and obturation did not — a translational failure rather than a conceptual oversight.

The reasons are plausibly intrinsic to the tasks. Access preparation and osteotomy are discrete, geometrically bounded operations specifiable in advance from volumetric imaging — precisely the conditions under which pre-planned robotic execution excels. Canal shaping is a continuous, adaptive process dependent on tactile feedback and real-time interpretation of changing dentine resistance, while obturation demands handling deformable materials within an irregular three-dimensional space. Whether this reflects a temporary limitation or a fundamental mismatch remains an open question.

Disinfection is unique in being served entirely by the micro axis, and its operating principle differs fundamentally from that of the macro systems. A device of micrometer scale can carry neither motor nor power source, and is actuated externally: iron-oxide particles are driven, steered and retrieved by an applied magnetic field [5,18]. Reported systems disrupt biofilm by catalytic generation of reactive oxygen species [5,19], mechanical disruption by bristle-like or helical structures [18,41], or localized magnetic hyperthermia [6].

This clarifies why the axes are complementary rather than competing. Isthmuses, apical deltas and, above all, dentinal tubules are dimensionally inaccessible to any file that could be manufactured [6] — the constraint is physical scale, not engineering refinement. We identified no macro-robotic system addressing disinfection, and no micro-robotic system addressing the cutting stages.

The second dense cluster appears at endodontic microsurgery and retreatment, where collaborative haptic (M3) and task-autonomous (M4) systems perform osteotomy, root-end resection, fiber-post removal, and fractured-file retrieval [3,4,15-17,42-50] — tasks whose precision demands exceed comfortable human limits, particularly in anatomically constrained posterior regions.

The overall pattern is one of bimodal concentration. Robotics has translated into practice at the entry (access) and exit (surgery, retreatment) points of the workflow — the discrete, pre-plannable tasks. The biological core is addressed only partially: disinfection exclusively on the micro axis at proof-of-concept stage, while shaping and obturation have been attempted repeatedly but never left the laboratory.

Translational readiness: evidence and technological maturity

The preceding sections describe what robotic systems can do. This section asks a different question: on what strength of evidence, and at what stage of technological maturity, do those capabilities rest? Existing reviews report robotic performance in the affirmative register of the source studies without interrogating its evidentiary basis.

Classified by study design, the primary corpus is dominated by preclinical and anecdotal evidence. Approximately half of the included studies are in-vitro, ex-vivo, or cadaveric investigations on extracted teeth, printed models, or jaw specimens (OCEBM Level 5), the dynamic-navigation literature particularly so [24-33,46]; a further substantial block comprises single case reports and small case series (Level 4). Most consequentially, we identified no completed randomized controlled trial of a robotic system in endodontics. A protocol for a randomized trial of dynamic navigation in microsurgery has been registered [51], but dynamic navigation is a guidance rather than a robotic modality. The absence is not attributable to infeasibility: a randomized trial of a haptic collaborative robot has been conducted in implant dentistry [52]. That no equivalent exists in endodontics is a gap, not an impossibility.

This distribution has direct interpretive consequences. Claims of robotic superiority, which recur throughout the secondary literature, rest almost entirely on in-vitro deviation metrics and uncontrolled single cases. The strongest comparative evidence is summarized in Table 1 [2,53,54]: genuinely informative, and consistently significant, but conducted throughout on printed jaw models or extracted teeth.

Note the ordering implied by these data: guidance outperforms freehand, and robotic guidance outperforms non-robotic guidance, on every accuracy metric reported — though not on overall operative time, which is longer for the robotic system. What this is not is evidence of clinical benefit. Accuracy and benefit are not the same quantity, and the literature has tended to treat them as though they were. The advantage is moreover not cost-free: superior precision is offset by longer setup and registration, higher cost, and reduced intraoperative adjustability [55]. We identified no study reporting healing rates, tooth survival, or patient-centered endpoints for robotic versus conventional treatment, mirroring the wider dental-robotics literature, in which clinical validation has been judged low and cost-efficiency data lacking [56].

A further caution concerns provenance. A substantial proportion of the autonomous-robotic clinical reports originate from a small number of groups working with a single platform, and should be read as successive outputs of one developmental program rather than independent replications; the platform originated in implant dentistry [57].

Mapping each modality onto the technology-readiness scale reveals a pronounced discontinuity (Figure 3). Static guides and dynamic navigation are genuinely mature (TRL 8): commercially available, in routine use, and supported by the largest body of comparative data [2,26-32,45-50,58]. Neither, however, is robotic in the strict sense — both constrain or inform a clinician who still executes.

The haptic co-pilot modality (TRL 7) is regulatorily cleared and clinically deployed, though its endodontic application rests on few reports. A controlled in-vitro pilot has now compared robot-assisted haptic guidance against freehand across calcified-canal access, fiber-post removal and microsurgery, reporting significant reductions in operative time and tooth structure removed in all three [14] — the first comparative peer-reviewed evidence for the modality, and still preclinical. Autonomous systems for microsurgery and retreatment sit at TRL 6–7, on case reports alone.

Below this lies a readiness cliff. The interval it spans — laboratory validation (TRL 4) to demonstration in an operational environment (TRL 7) — is the zone the innovation literature terms the translational "valley of death", and that the biological core of endodontics sits precisely within it is the central structural finding of this appraisal. Autonomous canal shaping remains at TRL 4, reaching peer-reviewed publication without clinical validation [40]; robotic obturation has not advanced beyond conceptual description (TRL 2–3) in nearly two decades [37,39]. An independent systematic review grading dental robotic initiatives by readiness identified only four endodontic articles, none exceeding TRL 2 — the lowest of any dental discipline surveyed [56]. Microswarm and nanorobotic disinfection remain at TRL 3–4 [5,6,18,19], with no in-vivo human data identified; the obstacles are common to surgical nanorobotics generally [59].

Two conclusions follow. First, the modalities that are most mature are the least autonomous — a pattern inverting the emphasis of much secondary literature. Second, the field's principal bottleneck is not conceptual but translational: capability has been demonstrated at every level of both axes, yet the transition to controlled clinical validation has occurred nowhere.

Discussion

Under-addressed dimensions

The regulatory question is repeatedly named as a barrier but never analyzed, and analysis reveals a structural problem. Existing dental robots occupy a category built for assistive devices — the haptic co-pilot cleared for dental use is regulated on the logic that a licensed clinician remains the operator [3]. Autonomous systems break that logic: when a robot executes an osteotomy under supervision but not direct manual control, it is no longer merely assisting, yet no dental-specific framework distinguishes supervised autonomy from assistance. The same constraint is documented in implant robotics [13]. Sponsors cannot design pivotal studies against criteria that do not exist; regulatory science is therefore a prerequisite for, not a consequence of, clinical translation.

Cost is universally cited as a barrier and never quantified. We identified no published study modeling the cost-effectiveness of robotic endodontics, and the absence is consequential, because the economic case is not self-evident in either direction. The capital stack is substantial — platform, cone-beam imaging, intraoral scanning, planning software — and against it sit potential offsets: reduced procedural time, fewer retreatments if accuracy gains translate into outcome gains, and expansion of the treatable case mix [15,16]. Whether these close the gap depends on parameters nobody has measured. Until a break-even analysis is published, "too expensive" and "worth the investment" remain assertions rather than findings.

Existing reviews resolve the liability question by assertion — the clinician remains responsible. This is true under current regulation but insufficient as analysis, because it does not survive contact with the autonomous case. If a robot executes a pre-planned osteotomy and the resection deviates, the causal chain has at least four candidate origins: a segmentation error in the imaging, a path error in the planning software, an execution or registration error in the robot, or inadequate plan review. The clinician is liable in each case under current doctrine, yet in only one did the clinician's own act cause the harm. This is the accountability gap that autonomy introduces and assistive devices do not: responsibility is retained for a decision chain that can no longer be fully inspected. Pilots are trained to interrogate and override automation; no equivalent competency framework exists for clinicians supervising a dental robot [60].

Every review warns that robotic endodontics may remain confined to specialty and academic centres. The warning is correct but under-examined. If robotics is primarily a precision technology, it will concentrate where precision is already highest and widen rather than narrow the gap between populations. A second reading is rarely articulated: several reported systems are explicitly framed as reducing dependence on operator expertise [16,43]. If that framing is even partially correct, robotics is also a skill-substitution technology, and its most consequential application may lie where specialist endodontists are scarcest. These readings imply opposite deployment strategies, and the literature does not distinguish between them: we identified no report of a robotic system evaluated by a non-specialist operator, in a non-academic setting, or in a health system with limited endodontic capacity.

Adoption presupposes clinicians able to plan, supervise, and troubleshoot these systems, yet we are aware of no such training pathway within established endodontic curricula. The assumption that haptic and virtual-reality simulators will fill the role is doubtful on two grounds. First, in a trial of a haptic simulator for access-cavity training, students trained under full virtual-reality immersion performed worse than those using a less immersive configuration [61]. Second, such simulators train manual execution — the skill robotic systems are designed to supplant. Supervising an autonomous system demands competencies different in kind: verifying a computed plan, recognizing failure modes, and knowing when to abort.

A research agenda

The gaps identified across this review are not evenly urgent. They are ordered in Table 2 by the degree to which resolving them would unblock the others.

Limitations

Several limitations should be acknowledged. Study selection was purposive rather than exhaustive, consistent with the integrative design but entailing a risk of selection bias, since studies were chosen partly for their bearing on the conceptual architecture developed here. The primary search was conducted in PubMed with supplementary Google Scholar and citation tracking; Scopus, Web of Science, and IEEE Xplore were unavailable, so the engineering literature may be incompletely captured. Autonomy and readiness assignments involve interpretive judgement that other investigators might exercise differently; they were verified by a second reviewer but not independently duplicated, so no agreement statistic is available. Only English-language sources were included. Statements regarding the absence of particular evidence should be read as claims about what this search identified, not as assertions that no such work exists.

Conclusion

Robotics has entered endodontic practice, but unevenly and on thinner evidence than the surrounding enthusiasm suggests. The dual-axis framework distinguishes the positioning and cutting systems that have advanced furthest clinically from the micro-robotic disinfection systems that remain at proof-of-concept, and mapping both onto the workflow reveals a bimodal pattern: robotics has translated at the entry and exit of the endodontic sequence while leaving its biological core largely unaddressed. Shaping and obturation were not neglected — they were attempted early and repeatedly, and never reached the clinic.

The appraisal of readiness yields the review's most consequential finding: the modalities that are most technologically mature are the least autonomous, and we identified no completed randomized trial of a robotic system in endodontics. Capability has outrun validation at every level of both axes. The task before the field is therefore not primarily one of invention. It is the unglamorous work of controlled trials with endpoints that matter to patients, independent replication, regulatory definition, and economic modeling.

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Tables

Table 1: Comparative accuracy evidence across guidance modalities (all in vitro)

Study	Design	Comparison	Outcomes measured	Direction of finding
Huth et al. 2024 [2]	In vitro, 3D-printed teeth (n=144)	Freehand vs dynamic vs static	Angular deviation, access cavity	Freehand 9.53°; dynamic 2.82°; static 1.12°. Guidance of any kind markedly outperforms freehand.
Chen et al. 2024 [53]	In vitro, 72 teeth, 3 standardized jaw-model sets	Robotic (RA-EMS) vs dynamic vs static	Platform deviation; angular deviation; resection angular deviation; operation time	Robotic significantly more accurate than both dynamic and static on platform, angular and resection angular deviation, and than dynamic on resection-length deviation ($P<.05$). Angular deviation 0.84 ± 0.37° (robotic) versus medians of 6.68° (dynamic) and 6.25° (static). Operation time shortest for static (20.0 s), then robotic (52.0 s), then dynamic (134.9 s).
Liu et al. 2025 [54]	In vitro	Robotic system vs dynamic navigation	Accuracy; registration, drilling and overall treatment time	Robotic significantly more accurate on global platform deviation (0.33 ± 0.10 vs 0.50 ± 0.22 mm, $P=.009$), apex deviation (0.41 ± 0.12 vs 0.90 ± 0.19 mm) and angular deflection (1.84 ± 0.50° vs 4.49 ± 1.41°, both $P<.001$). Drilling time shorter (85.8 vs 136.1 s) but registration longer (102.2 vs 32.7 s), so overall surgical time longer for the robot (188.0 vs 168.8 s, $P<.001$).

All three studies were conducted on 3D-printed jaw models or extracted teeth. Chen et al. report angular deviation for the comparator arms as medians; robotic values are mean ± SD. RA-EMS, robot-assisted endodontic microsurgery system.

Table 2: Prioritized research agenda, ordered by the degree to which resolving each gap would unblock the others

Priority	What is needed	Why it matters
1	Controlled clinical trials with patient-centered endpoints — feasibility/safety trials first, then outcome trials powered on healing, tooth survival, and morbidity.	Every claim of clinical benefit rests on in-vitro deviation metrics and uncontrolled cases. Nothing else in this agenda substitutes for it.
2	Independent replication outside the originating research groups, on different platforms and in different health systems.	Much of the autonomous-robotic literature is the output of one developmental program; replication is what converts it into evidence.
3	Determining why shaping and obturation have not translated — testing whether these are harder engineering problems or categorically ill-suited to pre-planned execution.	Would tell the field whether to invest in the middle of the workflow or concentrate deliberately at its ends.
4	Moving micro-robotic disinfection toward in-vivo evidence: biocompatibility, particle clearance, actuation in an intact patient, and efficacy against sodium hypochlorite in vivo.	Current evidence is ex-vivo; the threshold test is comparison against standard irrigation in vivo.

5	Economic modeling — a break-even analysis with explicit assumptions and sensitivity analysis.	Converts the cost barrier from assertion into parameter, and could be produced now from available data.
6	Regulatory science defining the evidence requirements for supervised-autonomous dental devices.	Pivotal trials cannot be designed against criteria that do not exist.
7	Testing the skill-substitution hypothesis — evaluating a robotic system operated by general practitioners in a setting without specialist coverage.	Determines whether robotics concentrates or extends capability, which decides its equity implications.
8	Competency frameworks for supervising autonomy, and standardized accuracy reporting.	Current simulators train the skill robots replace, not the skill supervision requires.

Priorities are ordered by the degree to which resolving each would unblock the others, not by ease of execution.