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'Precision Without Proof? A Systematic Appraisal of Robotic-Assisted Dental Procedures: A Narrative Review.

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ABSTRACT :

Background: Robotic systems have moved from laboratory prototypes to cleared clinical devices in dentistry within a decade, led by implant surgery but now extending to endodontics, tooth preparation, autotransplantation, periodontal and orthognathic surgery. Evidence is scattered across specialties and dominated by geometric accuracy endpoints.

Objective: To systematically map and appraise the evidence on robotic-assisted procedures across dental disciplines, with emphasis on accuracy, efficiency, safety, clinical outcomes and level of translational readiness.

Methods: Reported in accordance with PRISMA 2020. PubMed/MEDLINE was searched on 6 November 2026 with 19 discipline-specific strings (610 hits). Systematic reviews, meta-analyses, randomized and non-randomized clinical studies, case series/reports and in vitro/technical studies evaluating a robotic system in any dental procedure were eligible. Risk of bias was assessed using the RoB 2, ROBINS-I, QUIN, and AMSTAR 2 domains, and certainty was rated using GRADE. A narrative synthesis by discipline was performed; pooled estimates were extracted from existing meta-analyses.

Results: Forty-seven records were included (23 evidence syntheses, 24 primary studies). Implantology has the most mature evidence: four independent meta-analyses converged on pooled clinical deviations of 0.60–0.69 mm (coronal), 0.70–0.72 mm (apical) and 1.60–1.68° (angular), with a network meta-analysis of 11 RCTs ranking robotic surgery highest for single-tooth sites. Higher autonomy was associated with greater accuracy in the largest meta-analysis, but operative time was consistently longer. In other disciplines, robots reduced tooth-structure loss in calcified-canal access, improved socket congruence in autotransplantation (angular error 3.81° vs 9.54° freehand) and achieved crown-preparation RMSE of 0.18 mm, but evidence is limited to in vitro work and single-patient reports.

Conclusions: Robotic implant placement is accurate, with low-to-moderate certainty of superiority over static and dynamic guidance. All other applications remain at the feasibility stage. Patient-reported outcomes, long-term survival, cost-effectiveness and safety reporting are the critical evidence gaps.

Keywords: Robotics; Robotic surgical procedures; Computer-assisted implant surgery; Digital dentistry; Systematic review.

Introduction

Dentistry has always been a discipline of millimetres and degrees. Implant position, preparation taper, access-cavity trajectory and osteotomy depth all tolerate very small error, yet they are executed by hand in a confined, wet, moving field with limited visibility. The digital workflow, including cone-beam computed tomography (CBCT), intraoral scanning and virtual planning, has solved much of the planning problem. Static guides and dynamic navigation then tried to solve the transfer problem: moving the virtual plan into the patient. Robotics is the next step in that sequence, replacing or constraining the operator's hand during execution.

Medical robots are best classified by their level of autonomy rather than by brand. Yang and colleagues proposed a six-level scale, from no autonomy (pure tele-manipulation) through robot assistance, task autonomy and conditional autonomy to full autonomy, and argued that regulatory, ethical and legal obligations scale with each step.1 Dental systems now occupy several of these levels: haptic-guided arms (e.g., Yomi) constrain the operator's handpiece along a planned path, while task-autonomous platforms (e.g., Yakebot) execute the osteotomy themselves under clinician supervision.

Early prosthodontic reviews described robotic tooth preparation, implant surgery, complete-denture tooth arrangement, material testing and education as

candidate applications.2 Recent narrative syntheses note that implant robotics now has a substantial clinical literature, whereas restorative, orthodontic and laboratory applications remain largely industrial or experimental, and that geometric endpoints dominate at the expense of clinically decisive outcomes.3,4 No review has yet appraised the full cross-disciplinary landscape against a single evidence hierarchy. This systematic review therefore asks: for patients undergoing dental procedures, how do robotic-assisted techniques compare with conventional freehand or guided techniques in terms of accuracy, efficiency, safety, and clinical outcomes, and how mature is the evidence in each discipline?

Materials and Methods

1 Protocol and reporting

This review was conducted and reported in accordance with the PRISMA 2020 statement.5 The protocol was defined before the search; it was not prospectively registered (see Limitations).

2 Focused question (PICOS)

Table 1. Eligibility framework (PICOS)

Population	Human patients, cadavers, or validated phantom / 3D-printed / typodont models undergoing any dental, oral or maxillofacial procedure
Intervention	Any robotic system (passive, haptic-guided, semi-autonomous, task-autonomous, micro-robotic or humanoid simulator) used to plan, constrain or execute the procedure
Comparator	Freehand technique, static computer-assisted guide (s-CAIS), dynamic navigation (d-CAIS), conventional laboratory technique, or no comparator (single-arm)
Outcomes	Primary: positional / geometric accuracy (coronal, apical, angular deviation; RMSE). Secondary: operative time, tooth / bone volume removed, complications, survival, patient-reported outcomes (PROMs), learning curve, cost
Study design	Systematic reviews ± meta-analysis, umbrella / scoping reviews, RCTs, non-randomized comparative studies, cohorts, case series and case reports, in vitro and technical-validation studies

3 Information sources and search strategy

PubMed/MEDLINE was searched on 6 November 2026 without language restriction; date limits were applied only to strings that returned very large historical yields. Nineteen discipline-specific strings were used (Table 2) combining robot* / robotic surgical procedures [MeSH] with procedure-specific terms. One malformed string that returned 5,420 non-specific hits was discarded and replaced by a narrower string.

Table 2. Representative search strings (PubMed/MEDLINE, 6 Nov 2026)

Implant accuracy (SR)	robot-assisted dental implant accuracy systematic review (2021–)	12
Autonomous implant surgery	autonomous robotic implant surgery dentistry clinical (2020–)	72
Implant RCTs	robotic computer-assisted implant surgery randomized controlled trial accuracy (2022–)	21
Zygomatic / full-arch	robotic zygomatic implant placement accuracy; autonomous robot full-arch edentulous implant immediate loading	21; 1
Tooth preparation	robotic tooth preparation OR robotic crown preparation; automated robotic tooth preparation system accuracy	75; 18
Endodontics	robot endodontic access OR robotic endodontics microrobot root canal	19
Microrobotics	catalytic antimicrobial robots biofilm dental OR magnetic microrobot root canal biofilm	4
Oral & maxillofacial	transoral robotic surgery oral cancer outcomes SR; robot zygomatic OR orthognathic OR fibula reconstruction	34; 129; 45
Periodontics	robot-assisted periodontal OR robotic crown lengthening OR robotic sinus lift (2022–)	18
Orthodontics	robot wire bending orthodontic archwire	3
Complete dentures	robotic complete denture tooth arrangement	5

Education	patient simulation robot dental education OR humanoid patient simulator dentistry	3
General / overview	robotics dentistry review applications (2019–)	130

Full strings with MeSH translations are available from the author. Hit counts include overlaps between strings.

4 Study selection and data extraction

Records were ranked by PubMed relevance, and the top-ranked records for each string (6–12 per string) were screened by title and abstract. Full metadata and abstracts were then retrieved for potentially eligible records. Studies were excluded if no robotic system was used, if the anatomical site was not oral or maxillofacial (e.g., laryngeal transoral surgery), if no robotic outcome data were reported, or if methodological reporting was insufficient to interpret the results. From each record, we extracted the design, setting, sample (patients, implants, teeth, or models), robotic system and autonomy level, comparator, accuracy metrics, time, complications, follow-up, and authors' conclusions.

5 Risk of bias and certainty of evidence

Risk of bias was assessed using the domain structure of RoB 2 for randomized trials,6 ROBINS-I for non-randomized studies,7 the QUIN tool for in vitro dental studies, 8 and AMSTAR 2 for systematic reviews.9 Certainty was rated per outcome and discipline with the GRADE approach.10 Ratings started high for RCT evidence and low for observational evidence, and were downgraded for risk of bias, inconsistency, indirectness (phantom models, surrogate endpoints), imprecision and suspected publication bias.

6 Synthesis

Because the primary studies were heterogeneous in design, robotic platform, measurement protocol and endpoint definition, a new pooled meta-analysis was not undertaken. For implantology, pooled estimates were taken from the published meta-analyses and compared for convergence. All other disciplines were synthesized narratively and placed on an evidence-maturity scale (concept → in vitro → case report/series → comparative cohort → RCT/meta-analysis).

Results

1 Study selection

The 19 strings returned 610 hits. After relevance-ranked screening of 122 titles/abstracts, 55 records were assessed in full, and 8 were excluded (Figure 1). Forty-seven records were included: 23 evidence syntheses or reviews and 24 primary studies (2 RCTs, 7 clinical reports or series, 14 in vitro or technical validation studies, and 1 educational survey). Most primary research came from Chinese academic centres using task-autonomous platforms, and 38 of the 47 records were published in 2025–2026, which shows how fast the field is moving.

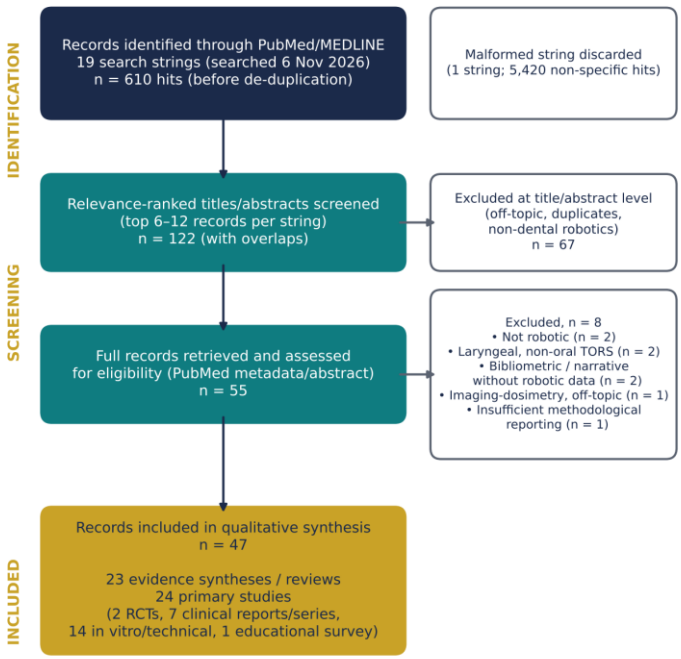


Figure 1. PRISMA 2020 flow diagram of record identification, screening and inclusion.

2 Taxonomy of dental robotic systems

Dental robots fall into four functional classes (Figure 2; Table 3). Classification by autonomy matters clinically, because the largest meta-analysis found that autonomy level independently predicted accuracy, whereas a smaller one did not.

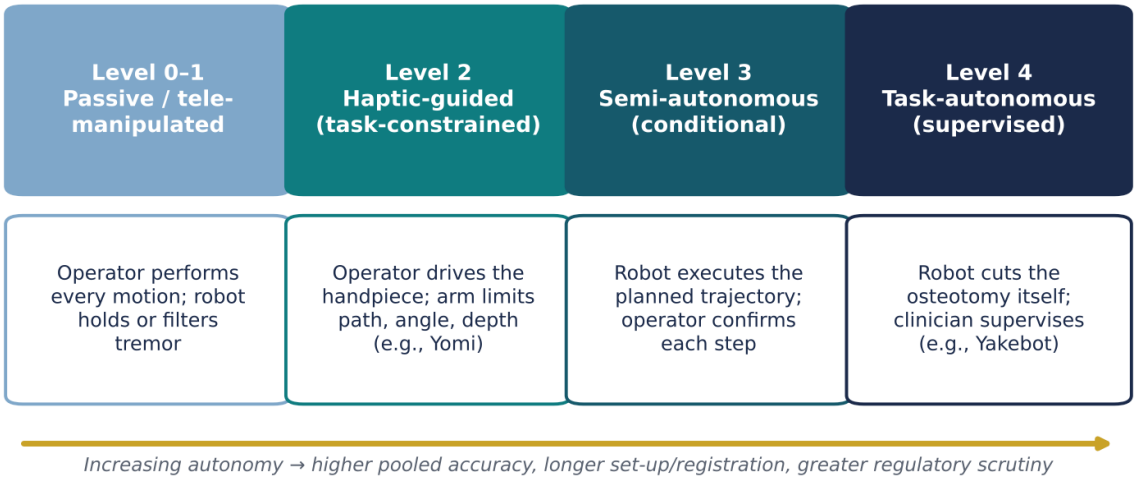


Figure 2. Levels of robotic autonomy as applied to dental procedures (adapted from Yang et al.1).

Table 3. Functional classes of robotic systems identified in the included studies

Haptic-guided (Level 2)	Operator holds and drives the handpiece; arm physically limits position, angulation and depth to the plan	Implant osteotomy; calcified-canal access, fibre-post removal, endodontic microsurgery
Semi- / task-autonomous (Level 3–4)	Arm executes the planned drilling or milling path under optical or mechanical tracking; clinician supervises and can stop	Single-tooth, full-arch and zygomatic implants; post-space; crown preparation; autotransplant sockets; crown lengthening; endodontic microsurgery
Laboratory / manufacturing robots	Industrial manipulators executing CAD-defined bending or positioning	Orthodontic archwire bending; complete-denture tooth arrangement
Tele-operated surgical platforms	Surgeon console with wristed instruments through a single or multiple ports	Transoral robotic surgery for oropharyngeal / oral tumours, sleep surgery
Micro-robots	Magnetically steered catalytic nanoparticle swarms or soft helicoids	Root-canal biofilm disruption and retrieval
Humanoid patient simulators	Robotic manikin reproducing patient movement, speech and reflexes	Pre-clinical communication and emergency training

3 Implantology

1 Pooled accuracy

Implantology is the only discipline with enough data for meta-analysis. Four independent clinical meta-analyses, published between 2024 and 2026 and drawing on 257 to 2,066 implants, gave closely agreeing pooled deviations (Table 4). Figure 3 outlines the workflow on which these estimates depend, and Figure 4 plots them.11–14 The largest (39 studies, 1,227 patients, 2,066 implants) reported 0.68 mm coronal, 0.72 mm apical, and 1.60° angular deviations; task-autonomous and semi-autonomous systems outperformed haptic-guided systems, whereas edentulous span, implant site, and study design had no significant effect.11 In contrast, Luo et al. found no difference between autonomous and semi-active systems but a significant effect of tracking technology, with infrared and visible-light tracking more accurate than mechanical tracking.13 Heterogeneity was very high (I^2 93–96%).

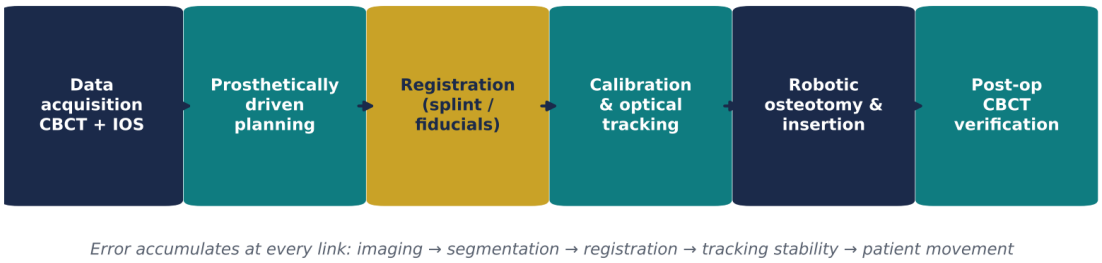


Figure 3. Clinical workflow of robotic computer-assisted implant surgery (r-CAIS). Achieved accuracy reflects the whole chain, not the robot alone.

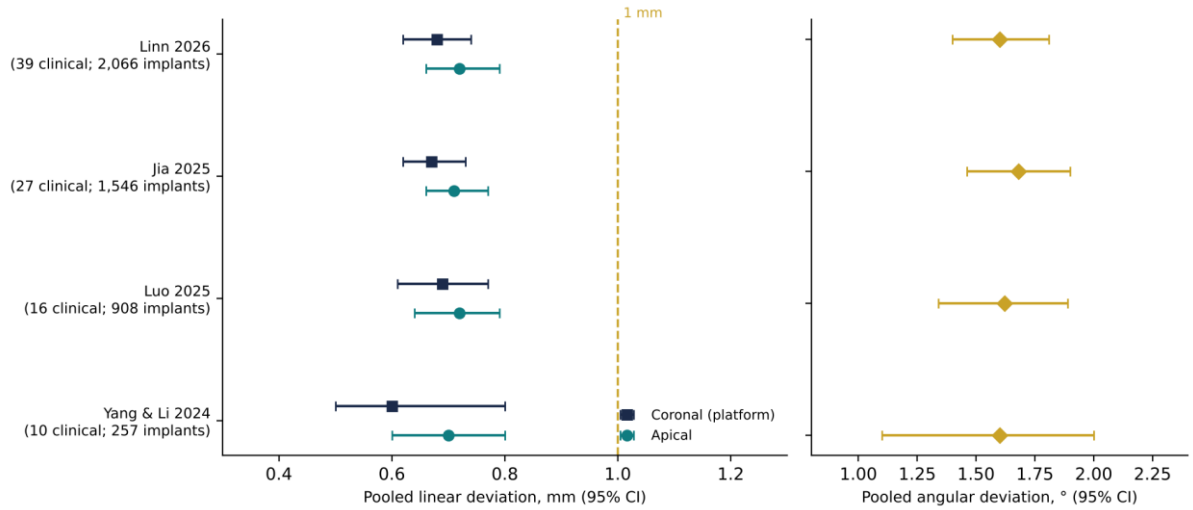


Figure 4. Pooled clinical accuracy of robotic implant placement reported by four independent meta-analyses (95% confidence intervals). Dashed line marks the 1 mm threshold.11–14.

Table 4. Evidence syntheses on robotic implant accuracy

Linn 2026[11]	39 clinical; 1,227 pts; 2,066 implants	0.68 mm / 0.72 mm / 1.60°	Autonomy level significant; task-autonomous > haptic
Jia 2025[12]	27 clinical; 983 pts; 1,546 implants	0.67 mm / 0.71 mm / 1.68°	r-CAIS more accurate than freehand, s-CAIS and d-CAIS; one adverse event
Luo 2025[13]	16 clinical; 908 implants	0.69 mm / 0.72 mm / 1.62°	Tracking type significant; autonomy and dentition NS
Yang & Li 2024[14]	10 clinical (257 implants) + 11 in vitro (809)	Clinical 0.6 mm / 0.7 mm / 1.6°	In vitro: robot < CAIS for all three deviations
Khaohoen 2024[15]	67 articles (all CAIS)	Robot 0.81 mm / 0.77 mm / 1.71°	Robot lowest deviation among CAIS modalities
Pisla 2025[16]	43 studies (7 RCT, 10 NRS, 26 in vitro); >4,000 implants	Global linear: robot <1 mm; d-CAIS ~1.0; s-CAIS ~1.3; freehand ~1.8 mm	Tight error clusters; comparative data insufficient to claim superiority
Ravipati 2024[17]	13 in vitro	0.72 / 0.86 mm / 1.47°	Favours robot over CAIS
Jain 2023[18]	5 in vitro (3 pooled)	MD vs d-CAIS: −1.22° angular	Angular advantage significant; linear NS
Mehta 2025[19] **(umbrella)**	8 SRs; 5,130 implants	SMD coronal −0.97	Better apical and angular; coronal mixed
Alqutaibi 2026[20]	36 clinical (2020–2026)	Mostly <1 mm; angular <2°	Complications infrequent; survival ~100% short-term; time ↑
Mahardawi 2026[21] **(NMA)**	11 RCTs, single-tooth delayed	Robot ranked first	Apex vs s-CAIS −0.42 mm; angle vs s-CAIS −1.65°, vs d-CAIS −1.26°; certainty very low–moderate

Deviations listed as coronal / apical / angular. NS, not significant; NRS, non-randomized study; NMA, network meta-analysis; SMD, standardized mean difference.

3.2 Randomized controlled trials

Two well-reported RCTs show that the robotic advantage is real but smaller than single-arm data imply. In a three-arm trial of 45 posterior single-tooth sites, robotic surgery yielded platform/apex/angular deviations of 1.1 mm/1.5 mm/4.7°, compared with 1.3 mm/1.9 mm/5.5° for dynamic navigation and 1.1 mm/2.0 mm/6.2° for static guides. Only the mesiodistal component differed significantly; the robot exhibited a near-zero systematic error, whereas the guided methods showed a centrifugal error pattern. Static guides gave shorter surgery and better quality of life at day 3.22 In a 40-patient trial comparing an autonomous robot with dynamic navigation using the same optical tracking system, angular deviation was lower with the robot (1.01° vs 1.78°, $p < 0.01$), linear deviations did not differ, and surgery took longer (21.5 vs 14.3 min). Pain, oedema, complications and early success were

comparable.23

3.3 Complex implant indications

In a full-arch case series (3 patients, 5 arches, 28 implants) placed flapless with an autonomous robot for immediate loading, mean deviations were 0.91 mm coronal, 1.01 mm apical and 1.21°. These were significantly better than historical s-CAIS data, and 80% of prefabricated provisional prostheses were delivered as planned.24 Zygomatic implants, with trajectories over 40 mm, are a stringent test. Clinically, eight zygomatic implants in hemimaxillectomy patients deviated 1.97 mm at entry and 1.79 mm at exit (1.92°), with improved OHIP-14 scores over 2–15 months.25 In vitro, a fully autonomous system achieved 0.87 mm neck, 1.26 mm apex and 1.22° angular deviation, but 8 of 40 planned sites cracked the resin model, a reminder that bone-analogue behaviour limits extrapolation.26 A mixed-reality scoping review observed that augmented reality alone did not surpass freehand zygomatic placement, and accuracy improved only when robotic stabilisation was added.27

4 Prosthodontics and restorative dentistry

A scoping review identified 18 prosthodontic robotic studies: 10 in vitro tooth-preparation studies (complete crowns and veneers) on phantom models and 8 on complete-denture tooth arrangement. None was a clinical trial.28 Recent work has advanced the field in three ways. First, an automated system for posterior full-crown preparation yielded lower root-mean-square error than a step-by-step guide overall (0.18 vs 0.33 mm), at the chamfer (0.12 vs 0.30 mm), and on the occlusal surface, and required less time (350 vs 584 s).29 Second, because enamel and dentine differ in hardness, constant-force control is a precondition for safe robotic cutting: a force-adaptive model-predictive controller held a 5 N target within ±1.1 N under vibration, with the shortest rise time (0.76 s).30 Third, the first clinical report of autonomous post-space preparation achieved 0.6° angular, 0.21 mm coronal and 0.33 mm apical deviation. This allowed a 3D-printed zirconia post-and-core to be designed in advance and cemented in the same visit.31

For complete dentures, multi-manipulator tooth-arrangement robots with an automatic dental-arch generator have reached prototype stage. They show 0.12 mm repeatability in the drive slipways but single-point errors of up to 1.83 mm, and they have not been clinically tested.32,33 At the interface with reconstruction, a robot-assisted 'jaw-in-a-day' protocol combining mandibular resection, fibula or iliac reconstruction and immediate implant-supported provisionalisation achieved 1.17° angular and <0.5 mm linear implant deviation in five patients.34

Prosthodontic perspective

- Robotic accuracy is only as good as the plan: prosthetically driven planning, accurate scan–CBCT registration and splint stability decide the final error, not the arm alone.[4,22]
- Sub-millimetre implant transfer makes prefabricated, same-day full-arch and post-and-core restorations practical, which is the most concrete prosthodontic benefit so far.[24,31]

Robotic tooth preparation is technically mature in vitro but needs clinical validation of marginal adaptation, pulpal temperature, soft-tissue protection and patient tolerance of intraoral fixation.[28–30]

5 Endodontics

Pulp-canal obliteration is the clearest indication for the use of robotics in endodontics. In 192 3D-printed calcified-canal models, robot-assisted access was the most accurate of four methods (angular deviation 1.31°). It was also the fastest (about 12 s of drilling), removed the least tooth material, and allowed novice operators to reach expert-level performance.35 An autonomous system located 95.7% (88/92) of calcified canals with 0.35 mm coronal, 0.47 mm apical and 1.17° angular deviation, leaving 1.24 mm of residual dentine at the drilling end.36 With a haptic-guided arm, a resident working on extracted teeth reduced both operative time and the volume of tooth removed, compared with freehand work by the same resident and by an experienced endodontist. This held for calcified-canal access, fibre-post removal and root-end resection, and the robot also produced smaller bevel angles.37

In endodontic microsurgery, a first clinical report used an autonomous robot on a maxillary first molar with a descended sinus floor. The robot located a lateral-window fenestration, performed the osteotomy and made a 15 mm buccal-to-palatal root-end resection with real-time depth, angle and force monitoring, and the patient was asymptomatic at 6 months.38 Contemporary reviews regard guided (static, dynamic or robotic) microsurgery as most useful for small, isolated lesions near critical structures, where microscope-based success already reaches 91–94%.39,40 AI-driven planning (automated landmark detection and drill-path generation in about 4 min) is emerging as the upstream partner to robotic execution.41

At the micro-scale, catalytic antimicrobial robots built from iron-oxide nanoparticles kill, degrade and remove biofilm under magnetic control,42 and radiopaque soft helicoid microrobots have been steered inside root canals ex vivo with microscale precision.43 These remain proof-of-concept platforms.44

6 Oral and maxillofacial surgery

Tooth autotransplantation. A geometry-matched recipient socket is the critical step in autotransplantation. In 120 resin models, robot-assisted preparation yielded smaller coronal deviation (0.49 vs 0.63 and 0.69 mm) and much smaller long-axis angular error (3.81° vs 6.10° template-guided and 9.54° freehand), as well as the shortest preparation time (5.6 min).45 Autonomous non-linear, surface-conforming milling improved full-depth fidelity, particularly for double-rooted donors.46 The first clinical proof of concept of supervised autonomous socket milling for a mandibular molar showed no complications.47

Orthognathic and reconstructive surgery. A PROSPERO-registered systematic review of 18 oral and maxillofacial studies found mean implant deviations of < 1 mm and < 3° and comparable or better functional outcomes for transoral oncologic surgery. GRADE certainty was moderate to low.48 A scoping

review of 35 orthognathic publications found mostly phantom, cadaver or animal work. Robots improved plan-to-execution transfer for maxillary positioning and linear osteotomies, but performance was comparable to, not better than, established digital techniques.49

Transoral robotic surgery (TORS). For head-and-neck lesions, the single-port platform has been evaluated in 14 studies of 479 patients. There were no conversions to multiport or open surgery; the pooled operative time was 58 min, and bleeding was the most common complication. All evidence was non-randomized.50

7 Periodontics

Autonomous buccal alveolar bone reduction for anterior crown lengthening was performed as planned, with a 0.39 mm apical-midpoint deviation in typodont models. However, the robot breached the planned root clearance in 4 of 36 reduction volumes, by up to 0.65 mm, which is a direct root-surface safety signal.51 A pilot clinical report described robot-reconstructed alveolar sockets for intentional root-oriented replantation of periodontally hopeless teeth, with improved stability, probing depth and bleeding at 3 months.52

8 Orthodontics, education and adjunct technologies

Robotic archwire bending is in established commercial use. It addresses the stiffness and super elasticity that make manual bending slow and error-prone, but published evidence consists of narrative reviews without comparative clinical trials on treatment duration or finishing quality.53 In education, a humanoid robotic patient (SIMROID) that reproduces patient movements and unexpected reactions was rated 4.05–4.70 out of 5 by 112 students. This measures satisfaction only, not competence transfer.54 Across procedures, augmented and mixed reality act as visualisation aids, and AI has so far been confined to segmentation, registration and planning rather than intraoperative execution.27

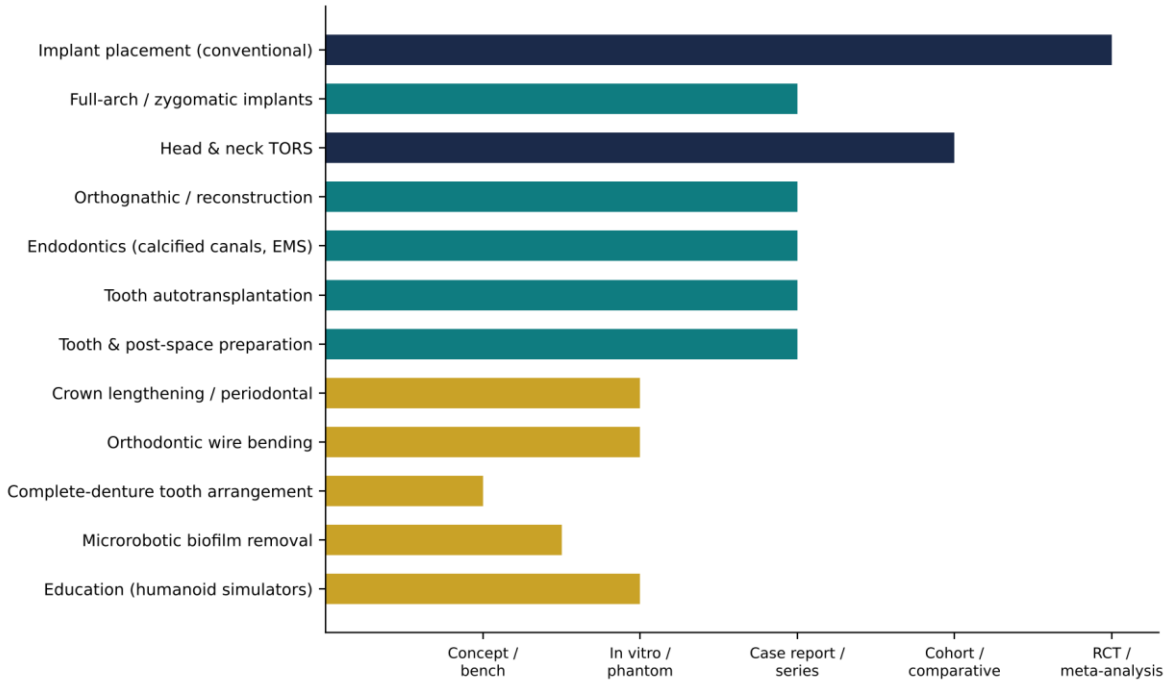


Figure 5. Evidence-maturity map of robotic applications in dentistry. Navy: comparative clinical evidence; teal: case reports/series; gold: in vitro or concept only.

Table 5. Summary of robotic applications by discipline

Implant placement	Pooled ~0.7 mm / ~1.6°; superior to freehand; ranked first in RCT NMA[11–23]	Very high heterogeneity; short follow-up; longer surgery	Clinical use
Full-arch / zygomatic implants	0.9–2.0 mm; same-day prefabricated prostheses[24–26]	Tiny series; model cracking in vitro	Early clinical
Tooth / post-space preparation	Crown RMSE 0.18 mm; post 0.6°[29,31]	Phantom models; one clinical report	Pre-clinical
Endodontics	95.7% calcified canals located; less tooth loss; EMS case[35–38]	In vitro + single cases	Pre-clinical / early clinical
Autotransplantation	Angular error 3.81° vs 9.54° freehand[45–47]	One clinical proof-of-concept	Early clinical

Crown lengthening / periodontal	0.39 mm AMD[51,52]	Root-contact events 4/36	Pre-clinical
Orthognathic / reconstruction	Plan transfer comparable to digital methods[34,48,49]	Mostly cadaver / phantom	Feasibility
TORS	No conversions; 58 min; bleeding main complication[50]	Non-randomized; mixed indications	Clinical use (H&N)
Orthodontic wire bending	Commercially deployed[53]	No comparative trials	Laboratory use
Complete-denture tooth arrangement	0.12 mm repeatability; 1.83 mm max error[32,33]	Prototype only	Concept
Microrobotics	Biofilm kill-degrade-remove in canals ex vivo[42–44]	No in vivo data	Concept
Education	High satisfaction with humanoid simulator[54]	No competence outcomes	Adjunct

9 Risk of bias and certainty of evidence

The two implant RCTs had low to some concerns about risk of bias. Neither could blind operators, but both used blinded outcome assessment or objective CBCT superimposition.22,23 Non-randomized implant studies were mostly single-arm series with selected patients and developer-affiliated centres, giving moderate to serious risk under ROBINS-I. The in vitro studies used standardised printed models, which helps internal validity, but resin does not reproduce bone density, saliva, bleeding, patient movement or limited mouth opening, so indirectness is high. Among the meta-analyses, only some reported registered protocols or GRADE ratings.21,48 Table 6 summarises certainty by outcome.

Table 6. GRADE summary of findings (reviewer judgements)

Implant accuracy vs freehand	RCTs + many cohorts	⊕⊕⊕◯ Moderate	Inconsistency ($I^2 > 90\%$)
Implant accuracy vs s-CAIS / d-CAIS	11 RCTs (NMA) + cohorts	⊕⊕◯◯ Low	Inconsistency between RCTs; imprecision
Operative time (longer with robot)	RCTs + reviews	⊕⊕⊕◯ Moderate	Learning-curve confounding
Implant survival, complications, PROMs	Short-term cohorts	⊕◯◯◯ Very low	Short follow-up; selective reporting
Full-arch / zygomatic accuracy	Case series + in vitro	⊕◯◯◯ Very low	Risk of bias; imprecision
Tooth / post-space preparation	In vitro + 1 case	⊕◯◯◯ Very low	Indirectness; imprecision
Endodontic access / microsurgery	In vitro + cases	⊕◯◯◯ Very low	Indirectness; imprecision
Autotransplantation socket fit	In vitro + 1 case	⊕◯◯◯ Very low	Indirectness
Orthognathic / TORS outcomes	Non-randomized	⊕⊕◯◯ Low (TORS) / ⊕◯◯◯ (orthognathic)	Observational; heterogeneity
Orthodontic, denture, micro-robotic, education	Reviews, prototypes	Not gradable	No clinical comparative data

Discussion

1 Principal findings

This review shows a two-speed field. Robotic implant placement now rests on more than 60 clinical studies, two well-conducted RCTs, a network meta-analysis, and an umbrella review, which consistently show sub-millimetre linear and under-2° angular accuracy.11–23 Everything else, such as tooth preparation, endodontics, autotransplantation, crown lengthening, orthognathic surgery, denture fabrication and microrobotics, is at proof-of-concept or

early clinical stage, typically with one research group, one platform and fewer than ten patients (Figure 5). Both the opportunity and the risk follow from this gap: the clear technical success of implant robotics is now being extended to procedures with very little clinical evidence.

2 Accuracy is necessary but not sufficient

A difference of 0.3–0.5 mm or 1–2° between robotic and guided placement is statistically robust but rarely changes the clinical result in a routine single posterior site. The RCT data show that the benefit is mainly a reduction in systematic error and in outlier risk, not a dramatic change in mean error.22 The clinically meaningful gains are therefore likely to be in situations where small errors have large consequences: proximity to the inferior alveolar nerve or sinus, narrow ridges, flapless full-arch work with prefabricated prostheses, zygomatic trajectories, calcified canals, and teeth with little remaining dentine.24,25,35,38 Future trials should enrol these patients rather than straightforward single-tooth cases, and should measure patient-centred outcomes such as nerve injury, perforation, prosthesis-fit failure and retreatment instead of geometric deviation alone.3

3 The autonomy–accuracy–time trade-off

The meta-analyses conflict on whether autonomy improves accuracy. The largest found that it does,11 but an earlier one found that tracking technology mattered more.13 The two findings are compatible if accuracy is viewed as a property of the whole workflow (Figure 3): imaging resolution, segmentation, registration splint stability, tracking line-of-sight and patient movement each add error before the robot moves.4 What is consistent is the time cost. Registration, calibration, and verification prolonged surgery in RCTs and reviews,20,22,23 and static guides led to shorter surgery and faster early recovery.22 Whether this cost decreases with experience, and whether it is balanced by fewer complications, has not been studied.

4 Safety, regulation and accountability

As autonomy increases, responsibility shifts from the operator's hand to the system's design, software and validation.1 Two safety signals in this review show why reporting must change. Resin models cracked during autonomous zygomatic drilling,26 and autonomous crown lengthening breached the planned root clearance in about 11% of volumes.51 Both are exactly the low-frequency, high-consequence events that small series and accuracy-only endpoints will miss. Standardised adverse-event reporting, device registries, and documentation of emergency-stop and manual-override events should be made reporting requirements. Informed consent should also tell patients that the procedure is robot-executed and explain the fallback plan.

5 Cost, access and the Indian context

Cost is repeatedly named as the main barrier, and formal cost-effectiveness analyses are almost absent.3 For teaching hospitals in low- and middle-income settings, the realistic near-term roles are (i) referral-centre use for high-risk implant, zygomatic and reconstructive cases, (ii) shared-platform models across departments, so prosthodontics, oral surgery, periodontics and endodontics can all use the same task-autonomous arm, and (iii) structured simulation training. Robotic guidance narrowed the novice–expert gap in calcified-canal access,35 which raises a teaching question: should robots be used to train hand skills, or do they replace those skills?

6 Limitations of this review

This review has important limitations. Only one database was searched, and screening was relevance-ranked rather than exhaustive, so eligible studies from Embase, Scopus, Web of Science and the grey literature may have been missed. Selection and extraction were performed by a single reviewer without duplicate verification, and the protocol was not registered on PROSPERO. Implant estimates were taken from overlapping meta-analyses that share primary studies, so their agreement partly reflects shared data rather than independent replication. Finally, the field is changing month by month: 38 of the 47 included records were published in 2025–2026. Before journal submission, the search should be extended to at least three databases with dual independent screening, PROSPERO registration and formal RoB 2/ROBINS-I/QUIN tables per study.

7 Research agenda

1. Multicentre RCTs in high-risk implant indications (atrophic ridges, full-arch immediate loading, zygomatic) with nerve-injury, perforation and prosthesis-fit endpoints.
2. Core outcome set for dental robotics: accuracy (standardised CBCT superimposition), time including set-up, adverse and near-miss events, PROMs, 5-year survival and cost.
3. First-in-human comparative trials for robotic tooth preparation (marginal fit, pulpal temperature, tissue damage) and calcified-canal management.
4. Learning-curve studies separating operator experience from platform effect.
5. Health-economic modelling for shared institutional platforms in public dental hospitals.
6. Integration studies of AI-generated planning with robotic execution, with independent validation.27,41

Conclusions

- Robotic implant placement consistently achieves about 0.7 mm linear and 1.6° angular accuracy. It is more accurate than freehand surgery (moderate certainty) and probably more accurate than static or dynamic guidance (low certainty), at the cost of longer surgery.
- Robotics outside implantology—tooth and post-space preparation, endodontic access and microsurgery, autotransplantation, crown lengthening, orthognathic surgery, denture fabrication and microrobotics—is technically promising but remains at the in vitro or single-case stage (very low certainty).
- The decisive gaps are clinical, not geometric: long-term survival, complications, patient-reported outcomes, learning curves and cost-effectiveness.

For prosthodontists, the main present value of robotics is predictable transfer of a prosthetically driven plan, which makes same-day prefabricated restorations practical in complex cases.

Clinical significance

Clinicians considering robotic platforms should expect reliable gains in implant precision and consistency, especially near critical anatomy, alongside

longer chairside setup times and substantial capital costs. Applications in other disciplines should currently be regarded as investigational and offered only within research or carefully consented protocols.

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