

Robotics and navigation systems in periodontal and implant surgery (Review)

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Abstract. Robotics and computer-assisted navigation are increasingly being integrated into digital dentistry, particularly implant surgery, through the combination of three-dimensional imaging, virtual treatment planning, real-time tracking and robotic assistance. However, their clinical role, comparative effectiveness and applicability to periodontal procedures remain incompletely defined. The present narrative review synthesizes current literature on the development, principles, clinical applications, accuracy, limitations and future directions of freehand surgery, static-guided surgery, dynamic navigation, robotic-assisted surgery, artificial intelligence and augmented reality in periodontal and implant surgery. Particular emphasis is placed on distinguishing technical feasibility from clinically validated benefit and differentiating implant-focused evidence from periodontal applications. Static guides facilitate the reproducible transfer of a predefined surgical plan; however, they provide limited intraoperative flexibility. Although dynamic navigation enables the real-time visualization and adjustment of instrument positioning, it remains dependent on registration accuracy, tracking, calibration and operator experience. Robotic-assisted systems demonstrate promising positional accuracy in selected implant workflows; however, available evidence is predominantly implant-focused and characterized by heterogeneous study designs, small clinical cohorts and variable risk of bias. Artificial intelligence and augmented reality may support image interpretation, treatment planning, anatomical visualization and workflow integration, although their clinical effectiveness requires further external validation. Periodontal applications, including flap surgery, root-surface instrumentation, regenerative procedures, connective tissue grafting and microsuturing, remain largely investigational. Current evidence is limited by methodological

heterogeneity, inconsistent accuracy definitions, limited long-term clinical outcomes, operator-related variability, technological costs, learning-curve effects, and inadequate assessment of biological and patient-centered endpoints. Robotics and navigation systems represent promising adjuncts to periodontal and implant surgery, with the strongest evidence currently supporting selected implant applications. Broader periodontal translation will require clinician-supervised development, standardized comparative studies, independent validation, and assessment of biological, functional, economic, and patient-reported outcomes. At present, evidence is stronger for technical accuracy than for long-term clinical and patient-centered benefits.

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1. Introduction

An increasing demand for precision, predictability and minimally invasive approaches is accelerating the use of digital technologies in periodontology and implant dentistry.

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Implant-supported rehabilitation has become a highly predictable treatment modality for replacing missing teeth. The long-term success of implant therapy depends heavily on accurate implant positioning and prosthetically driven treatment planning. An incorrect implant position can compromise aesthetics, biomechanics, oral hygiene and peri-implant tissue health, and can increase the risk of damage to adjacent anatomical structures such as nerves, vessels and the maxillary sinus (1). Traditionally, implant placement has been achieved with a freehand approach on the basis of clinical examination and radiographic assessment. Experienced clinicians can achieve satisfactory results, but freehand surgery is operator dependent and can be associated with positional deviations from the planned implant position (2). Advances in cone-beam computed tomography (CBCT), digital intra-oral scanning and computer-aided design/computer-aided manufacturing (CAD/CAM) technologies have facilitated the development of computer-assisted surgical approaches with the goal of improving implant placement accuracy and reducing procedural variability (3). Computer-assisted implant surgery has evolved considerably over the past two decades. The first attempts to allow clinicians to transfer virtual implant planning into the clinical setting were static surgical guides manufactured using CAD/CAM technology. The static guides improved the accuracy of the surgery, but they were not flexible and did not allow for changes during the surgery. To address these limitations, dynamic navigation systems have been developed that allow real-time tracking and visualization of surgical instruments during the placement of implants (4). Recently, robotic-assisted surgical systems have emerged as innovative developments in implant dentistry. These systems integrate digital treatment planning, navigation technology and robotic control mechanisms to allow the highly accurate placement of the implant. Robotic platforms have already shown promising results in terms of positional accuracy and consistency (5). Artificial intelligence (AI), machine learning and augmented reality (AR) are being increasingly used in digital workflows. These technologies have the potential to lead to improved diagnoses, treatment planning, surgical guidance and post-operative evaluation (5). The integration of robotics, navigation systems and intelligent digital technologies is likely to transform the future of periodontal and implant surgery. The present review aimed to provide a detailed survey of the use of robotics and navigation systems in periodontal and implant surgery covering their development, technological principles, clinical applications, accuracy, benefits, limitations and future perspectives.

2. Literature search methods

Review design and literature search. The present study provides a structured narrative review of the development, principles, clinical applications, accuracy, limitations and future prospects of computer-assisted navigation and robotic systems in periodontal and implant surgery.

A narrative review design was selected as the topic encompasses diverse evidence, including historical reports, technical investigations, laboratory and cadaveric studies, clinical studies, systematic reviews and meta-analyses. The objective was to integrate these different forms of evidence rather than answer a

single narrowly defined intervention question. Accordingly, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were not applied, as this article was not designed as a systematic review or meta-analysis. Nevertheless, methodological transparency and critical interpretation were incorporated to reduce selective reporting and unsupported conclusions. A structured literature search was performed using the PubMed/MEDLINE, Scopus, Web of Science and the Cochrane Library databases. Additional relevant publications were identified by screening the reference lists of key systematic reviews, meta-analyses and landmark studies. The search strategy combined terms related to robotics, computer-assisted surgery, navigation, implant dentistry, periodontology and emerging digital technologies. The principal search terms included the following: ['robotic surgery' OR robotics OR 'robot-assisted surgery' OR 'robotic-assisted surgery' OR 'robot-assisted implant placement') AND ('computer-assisted surgery' OR 'computer-aided implant surgery' OR 'dynamic navigation' OR 'static surgical guide' OR 'image-guided surgery') AND ('dental implant' OR 'implant placement' OR periodont* OR 'periodontal surgery' OR 'periodontal regeneration'].

Additional terms included 'artificial intelligence', 'augmented reality', 'machine learning', 'digital workflow', 'image registration', 'tracking' and 'calibration'. The search period should be specified according to the actual search conducted: January, 2000 to August 2026.

Eligibility criteria. Publications were included when they addressed the historical development, technical principles, accuracy, clinical applications, limitations or future potential of computer-assisted navigation or robotic systems in implant or periodontal surgery. Systematic reviews, meta-analyses, clinical trials, observational studies, technical investigations, laboratory studies, cadaveric studies and relevant conceptual articles were considered.

Publications were excluded if they were unrelated to dental or periodontal surgery, focused exclusively on nonsurgical dental robotics, lacked sufficient methodological information, or consisted of promotional material, conference abstracts or unsupported opinions. Historical and technical publications were retained when they were critical for understanding technological development.

Study selection and evidence synthesis. Relevant articles were selected on the basis of their alignment with the review objectives, methodological transparency and scientific contribution. The literature is organized thematically according to technological evolution, static guidance, dynamic navigation, robotic-assisted surgery, periodontal applications, accuracy, AI, limitations and future directions.

As this was a narrative review, no formal quantitative pooling or meta-analysis were performed. Numerical findings were interpreted within their original methodological context, considering differences in study design, implant location, imaging protocols, registration methods, operator experience and outcome definitions.

When multiple publications addressed the same technology or dataset, preference was given to the most comprehensive and methodologically robust source. Original studies were consulted when detailed information regarding surgical protocols, accuracy measurements or clinical outcomes was needed to avoid double-counting evidence.

Management of conflicting evidence. Conflicting findings were examined in terms of study design, sample size, anatomical site, bone conditions, imaging and registration protocols, operator experience, comparator type and outcome definitions. Greater interpretive weight was given to well-designed prospective clinical studies, transparent systematic reviews and investigations reporting clinically meaningful outcomes.

Findings from *in vitro* or cadaveric studies were primarily used to assess technical feasibility and positional accuracy, whereas clinical studies were prioritized when safety, post-operative morbidity, implant outcomes and patient-centered effects were discussed. When discrepancies remained unresolved, they were reported explicitly rather than selecting only favorable results.

Evidence quality and critical appraisal. A single formal risk-of-bias tool was not applied to all publications as the review included heterogeneous evidence types that require different assessment criteria. Instead, each source was considered in terms of study design, sample characteristics, methodological transparency, comparator appropriateness, outcome validity, follow-up duration, statistical reporting, potential bias, external validity and conflicts of interest.

Technical accuracy outcomes, such as coronal, apical and angular deviation, were distinguished from clinical outcomes including implant survival, peri-implant health, prosthetic complications, morbidity, patient satisfaction and cost-effectiveness. Systematic reviews and meta-analyses were interpreted with attention to heterogeneity, methodological quality and whether reported differences were clinically meaningful.

The quality and transparency of the narrative review were guided by the principles of the Scale for the Assessment of Narrative Review Articles (SANRA), particularly the description of the literature search, adequacy of reference, scientific reasoning and presentation of relevant outcomes (6).

Limitations of the review. The present review has several limitations. Although a structured search strategy was used, the process was not based on a prospectively registered systematic-review protocol, duplicate independent screening or formal risk-of-bias assessment of every included study. Selection bias and publication bias therefore cannot be excluded.

The available literature is also heterogeneous, with substantial variation in imaging workflows, registration and calibration methods, implant sites, surgical protocols, operator experience and outcome definitions. Much of the evidence concerns technical accuracy in controlled experimental settings rather than long-term clinical outcomes. In addition, the terminology related to navigation, robotics and autonomous surgery is inconsistently applied across publications.

Finally, evidence concerning robotic applications in periodontology remains considerably less developed than that concerning computer-assisted implant placement. Accordingly, emerging periodontal applications, AI integration and autonomous surgical functions should be interpreted as investigational unless supported by direct clinical evidence (5).

3. Historical evolution of computer-assisted navigation and robotic systems in implant dentistry

The evolution of computer-assisted and robotic technologies in implant dentistry has been driven by the need to improve the transfer of a prosthetically determined treatment plan to the surgical field. Conventional freehand implant placement remains dependent on the interpretation of imaging by the clinician, three-dimensional anatomical assessment and intra-operative visual and tactile feedback. Although experienced clinicians can achieve predictable outcomes using freehand techniques, implant positioning may be influenced by restricted surgical access, anatomical limitations, operator experience and difficulty maintaining the planned angulation and depth throughout osteotomy preparation. Computer-assisted technologies were therefore developed not to replace clinical judgment, but to improve the consistency of treatment planning and surgical execution (7,8).

From radiographic assessment to three-dimensional digital planning. Early implant planning relies primarily on two-dimensional radiographs and clinical examination. Although these methods provided useful information regarding tooth position and general anatomical relationships, they provided limited representation of three-dimensional bone morphology and could not consistently demonstrate the spatial association between the proposed implant and critical anatomical structures. The introduction of three-dimensional imaging, particularly CBCT, substantially improved the ability to assess available bone, anatomical constraints and prosthetically relevant implant positions (9,10).

The availability of three-dimensional imaging did not resolve the problem of intraoperative plan transfer. A virtual implant position could be planned with considerable precision, yet the final osteotomy could still deviate from that plan during freehand surgery. This distinction between planning accuracy and execution accuracy was central to the subsequent development of computer-aided implant surgery. Digital planning should therefore be regarded as an enabling component of the surgical workflow rather than a complete solution to intraoperative variability (7,8).

Emergence of static computer-assisted implant surgery. Static computer-assisted implant surgery was developed to transfer the virtual treatment plan to the patient through a patient-specific surgical guide. By restricting the initial drilling direction and, in fully guided protocols, subsequent instrumentation, static guides aimed to reduce deviations in implant position and angulation. Their principal contribution was the standardization of the planning-to-surgery pathway, particularly in cases where prosthetically driven positioning or proximity to anatomical structures required greater positional control (8,11-13).

Nevertheless, static guidance introduced critical trade-offs. Its accuracy depends on the quality of the CBCT and surface-scan data, the accuracy of image registration and guide fabrication, the stability and seating of the guide, and the ability of the clinician to follow the prescribed drilling sequence. In addition, a static guide provides limited flexibility when intraoperative findings differ from those of the

preoperative plan. Restricted mouth opening, posterior access, bone quality, flap management and the need for unanticipated surgical modifications may further reduce its practical advantages (8,11-13).

Accordingly, although static guidance improved the reproducibility of a predefined plan, it did not eliminate the influence of clinical circumstances or technical errors. Its value is therefore greatest when the preoperative plan is reliable, the guide is accurately fabricated and the surgical situation remains sufficiently consistent with the planned workflow (8,11-13).

Transition from static guidance to dynamic navigation. Dynamic navigation emerged partly in response to the limited adaptability of static surgical guides. These systems use optical or electromagnetic tracking to display the real-time position of the surgical handpiece or implant relative to the virtual plan. Unlike static guidance, dynamic navigation allows the clinician to modify the surgical trajectory during the procedure, while maintaining access to updated positional information (7,8,14).

This flexibility may be particularly relevant in anatomically complex cases, limited-access regions or situations in which intraoperative findings require modification of the original plan. Dynamic navigation does not simply transfer the risks associated with static guidance into a more advanced format. It introduces additional dependencies, including accurate patient registration, instrument calibration, uninterrupted tracking, appropriate camera positioning and continuous interpretation of the navigation display (7,8).

Furthermore, dynamic navigation requires the clinician to coordinate attention between the surgical field and the monitor. Consequently, the technology may reduce some forms of positional uncertainty, while increasing the critical role of training, visuomotor coordination and system familiarity. Clinical studies and systematic reviews have reported favorable accuracy outcomes for dynamic navigation (4,15-17); however, differences in navigation platforms, implant sites, registration methods, operator experience and study design limit direct comparisons between investigations (7,8). Reported technical advantages should therefore be interpreted as context-dependent rather than as evidence of universal superiority.

Development of robotic-assisted implant surgery. Robotic-assisted implant surgery represents a further integration of digital planning, tracking, mechanical guidance and, in some systems, automated execution of predefined components of the surgical task. The rationale for robotic assistance is based on the possibility of improving the reproducibility of planned movements and reducing selected forms of operator-dependent variability (11-13,18).

The term 'robotic surgery' encompasses systems with substantially different levels of automation and clinician control. Some platforms provide navigational information, whereas others constrain handpiece movement or assist in maintaining a planned trajectory. Fully autonomous implant placement, in which a robot independently performs the complete surgical procedure without continuous clinician supervision, should not be considered in established routine clinical practice. Current systems

are more appropriately understood as clinician-supervised guidance, movement-restriction or task-assistance technologies (12,18).

The emergence of robotic systems also illustrates why technological sophistication should not automatically be equated with clinical superiority. Robotic performance remains dependent on the accuracy of the digital plan, imaging data, registration, calibration and tracking workflow. In addition, the system must operate within the anatomical and mechanical constraints of the clinical environment. Comparative studies have reported favorable positional accuracy for robotic-assisted implant placement; however, the available evidence includes *in vitro* models, controlled experimental settings and relatively limited clinical cohorts. Systematic reviews have also identified heterogeneity in study design and insufficient evidence for some direct comparisons, particularly between robotic and static-guided approaches (11-13,18).

Thus, although robotic assistance may improve the reproducibility of selected surgical movements, its technical capabilities should not be interpreted as proof of superior implant survival, peri-implant health, prosthetic performance or patient satisfaction. These outcomes require independent clinical evaluation and longer-term follow-up.

Historical progress and the redistribution of surgical risk. The progression from freehand surgery to static guidance, dynamic navigation and robotic assistance should not be interpreted as a linear movement toward error-free surgery. Alternatively, each technological generation has attempted to reduce particular sources of uncertainty, while introducing new technical and operational dependencies (8,11,12,18).

Freehand surgery relies heavily on the experience and intraoperative judgment of the clinician. Although static guidance improves the transferability of a predetermined plan, it reduces intraoperative flexibility. Dynamic navigation provides real-time feedback and adaptability, yet depends on accurate registration, tracking and active operator interpretation. Robotic systems may provide movement assistance or restrictions; however, they remain dependent on the accuracy of the preceding digital workflow and appropriate clinician oversight (7,8,13,18).

The historical development of these technologies therefore represents a redistribution of surgical risks rather than their elimination. Errors may shift from manual angulation and depth control toward imaging artifacts, data fusion, registration, calibration, tracking and software performance or inappropriate reliance on automated guidance. This consideration is particularly critical when systems are compared solely on the basis of their reported positional accuracy (7,8,11-13,18).

From technical feasibility to clinical relevance. Early investigations of computer-assisted implant surgery understandably focused on technical feasibility and positional accuracy. Outcomes, such as coronal deviation, apical deviation and angular deviation provided measurable indicators of how closely the achieved implant position corresponded to the virtual plan. These outcomes remain crucial, particularly in anatomically restricted or prosthetically demanding cases (7,8,11-13,18).

Nevertheless, technical accuracy is only an intermediate outcome. A reduction in positional deviation does not automatically lead to improved implant survival, peri-implant health, prosthetic performance, post-operative morbidity, patient satisfaction or cost-effectiveness. The clinical significance of a numerical difference in deviation also depends on the implant location, bone anatomy, prosthetic requirements, proximity to vital structures and the magnitude of the deviation relative to clinically acceptable limits (11-13,18).

More recent comparative research has attempted to evaluate static, dynamic and robotic approaches within a common analytical framework (19-21). Differences in imaging protocols, surgical workflows, operator experience, implant sites and outcome definitions continue to complicate interpretation. For example, a robotic system demonstrating excellent accuracy in a controlled model may not provide the same magnitude of benefit in routine clinical practice involving patient movement, restricted access or unexpected anatomical findings. Consequently, evidence of improved positional accuracy should be distinguished from evidence of improved clinical effectiveness. The former indicates closer agreement between the planned and achieved implant positions, whereas the latter requires the demonstration of meaningful improvements in safety, efficiency, biological outcomes, prosthetic outcomes or patient experience (11,12,18).

Current interpretation of the historical trajectory. The historical development of computer-assisted and robotic implant surgery is best understood as an expansion of the technological options of the clinician, rather than a replacement of surgical expertise. Static guides, dynamic navigation and robotic assistance may each be advantageous in selected situations; however, their effectiveness depends on appropriate case selection, technical reliability, operator training and integration with sound surgical judgment (7,8,11-13,18).

The central contemporary question is therefore no longer whether digital or robotic systems can improve the agreement between planned and achieved implant positions. Instead, whether these improvements produce meaningful advantages in safety, efficiency, patient-centered outcomes and long-term treatment success that justify their additional cost, complexity and training requirements should be investigated. This distinction provides a critical basis for evaluating the current evidence and defining the future role of robotics in implant and periodontal surgery (11-13,18).

4. Navigation system principles

Navigation systems depend on the integration of advanced imaging, planning software, tracking technologies and real-time feedback processes. The workflow generally begins with the acquisition of CBCT images, which provide detailed three-dimensional information about the anatomy of the patient. Digital intraoral scans are often fused with CBCT data to generate a virtual model that accurately represents hard and soft tissues. Treatment-planning software is used following image acquisition to determine the ideal implant position according to prosthetic requirements, bone availability, and anatomical considerations. Virtual implant placement allows clinicians to evaluate a variety of treatment options

and optimize implant angulation, depth and position prior to surgery (22). An integral part of the navigation technology is registration. Registration establishes a relationship between the actual patient anatomy and the virtual treatment plan. Correct registration is crucial as even minor errors can lead to clinically relevant deviations during surgery (8). During surgery, the positions of the patient, handpiece and surgical instruments are recorded using optical tracking cameras. The navigation software uses reference markers attached to the patient and instruments to determine their exact location in three-dimensional space. The system constantly illustrates the drill path in relation to the planned position of the implant providing the clinician with the opportunity to make adjustments in real-time (4,11). Contemporary navigation systems also provide visual and auditory feedback to help maintain the desired angulation and depth. These features enhance spatial awareness and allow precise implant placement even in anatomically challenging cases (12). The combination of pre-operative planning, accurate registration and real-time tracking forms the foundation of dynamic navigation technology and is important for its clinical efficacy. The principal stages of this integrated digital workflow for image-guided dental and periodontal surgery are schematically illustrated in Fig. 1.

5. Dynamic navigation systems in dental implantology

One of the most prominent technological advancements in the field of implant dentistry is dynamic navigation systems. Unlike static guides that physically constrain surgical instruments, dynamic navigation provides real-time, while maintaining surgical flexibility (14). Several commercially available systems are currently in clinical use, including X-Guide®, Navident® ImplaNav®, DENACAM® and DCARER®(23). These systems use stereoscopic cameras and optical tracking technology to track instrument movement during surgery (13). Clinical studies and systematic reviews have reported relatively minimal positional deviations with dynamic navigation-guided implant placement. Reported mean coronal deviations have generally been ~0.8-1.2 mm, whereas mean angular deviations range from ~2.5° to 4° (14,18,24). These numbers are markedly lower than the typical deviations observed in freehand implant placement and are comparable to static guided surgery accuracy (24). One of the main advantages of dynamic navigation is the ability to alter treatment plans intraoperatively. In contrast to static guides that need to be fabricated before surgery, navigation systems can be used by clinicians to respond to unforeseen anatomic findings or changes in the treatment plan without sacrificing accuracy (14). Dynamic navigation has been found to be particularly beneficial in complex clinical situations, such as immediate implant placement, flapless surgery, multiple implant rehabilitation and the treatment of patients with limited bone volume. The ability to visualize the position of the drill in real-time improves safety by allowing clinicians to avoid critical anatomic structures, such as the inferior alveolar nerve and the maxillary sinus (25). A reduction in operator-dependent variability with navigation-assisted surgery has also been demonstrated in several studies (16,17,26,27). With appropriate training,

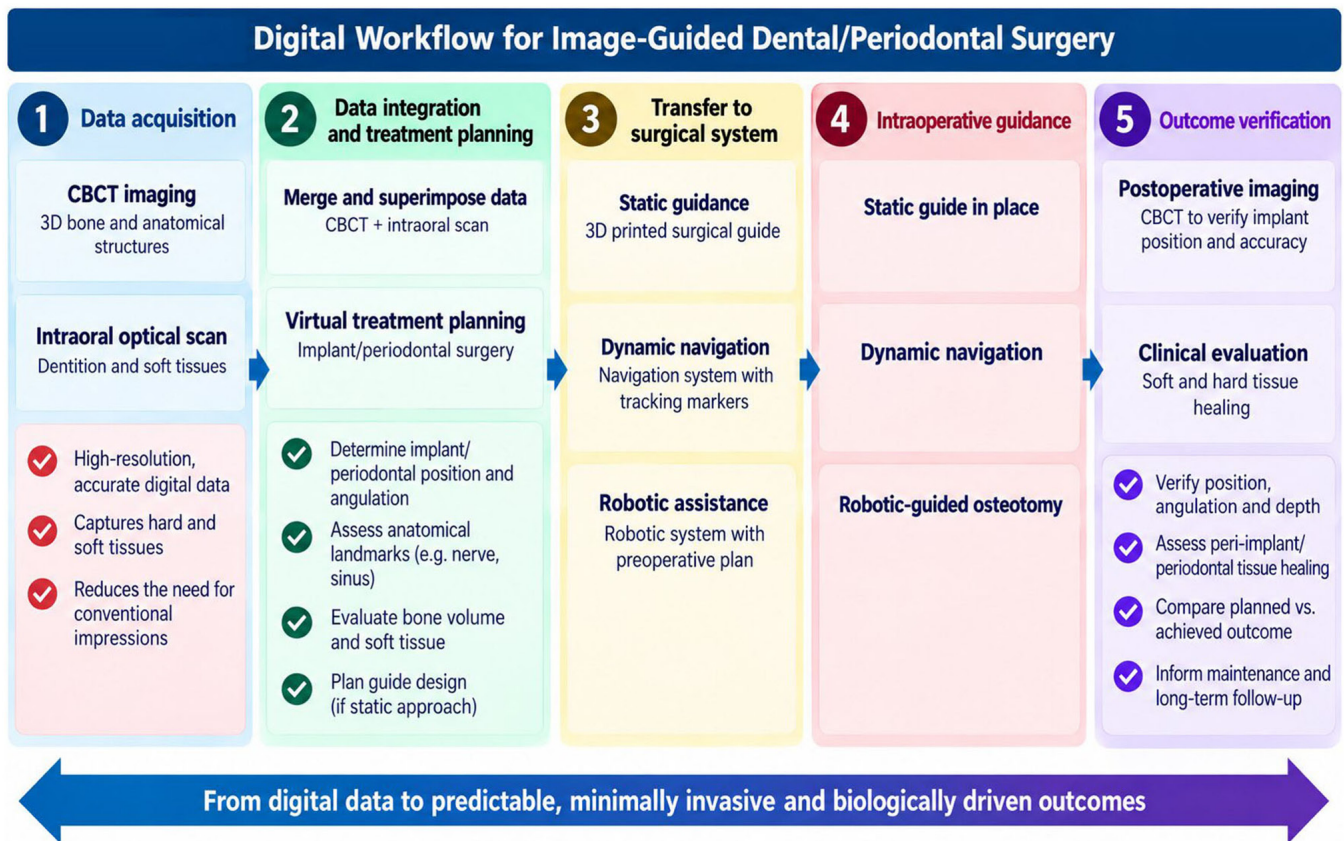


Figure 1. Digital workflow for image-guided dental and periodontal surgery. Schematic representation of the digital workflow, beginning with CBCT and intraoral optical data acquisition, followed by data integration and three-dimensional treatment planning. The planned procedure may then be transferred to a static surgical guide, dynamic navigation system, or robotic-assisted platform for intraoperative guidance. Postoperative imaging and clinical assessment were used to verify the achieved position, surgical accuracy, and subsequent soft- and hard-tissue healing. The figure is a conceptual synthesis of the current digital workflow and is not intended to imply that all technologies are routinely validated for every periodontal procedure (2,4,14,18,20,21,25,31,66,67,80,81,85,86). CBCT, cone-beam computed tomography.

acceptable levels of accuracy can be obtained by clinicians with limited experience with implants (25). There is a learning curve, and proficiency depends on familiarity with digital workflow, registration procedures and navigation protocols (28). Despite its benefits, dynamic navigation has several limitations. Implementation and clinical performance can be affected by high equipment costs, calibration requirements, registration errors and the possibility of tracking interruptions. Increasing evidence supports its use as a reliable and accurate alternative to conventional techniques of implant placement (13,18).

6. Robotic-assisted surgery implantation

Robotic-assisted implant surgery is the latest step in computer-aided dental implant placement. These systems combine digital treatment planning, dynamic navigation and robotic guidance to improve accuracy and consistency during surgery (21). Surgical robots can be broadly categorized into passive, semi-active and active systems. Passive robots are used to guide the motion of the instrument, but do not control it. Semi-active systems provide clinicians with control, yet limit movement beyond preset parameters. Active systems conduct surgical tasks autonomously following preprogrammed instructions, although fully

autonomous dental implant surgery continues to be mostly experimental (29). The majority of the robotic systems currently available in dentistry today are semi-active. Virtual implant planning is followed by the use of a robotic platform to guide clinicians to maintain the planned trajectory during osteotomy preparation. The robot continuously monitors the drill position and provides corrective guidance if any deviations occur (30,31). The first clinical applications of robotic implant surgery have exhibited promising results, with several studies reporting improved positional accuracy compared with freehand techniques (32,33). Recent systematic reviews have demonstrated that compared with conventional methods of implant placement, robotic systems can achieve lower angular, coronal and apical deviations (20,34). Of note, deviations of <2 degrees have been reported, highlighting the marked precision possible with robotic guidance (28,31,35). Robotic systems have several theoretical advantages. Increased accuracy may improve prosthetically driven implant placement, reduce the risk of surgical complications and allow treatment in anatomically complex locations. Furthermore, robotic assistance may reduce operator fatigue and improve the consistency of procedures among clinicians with different levels of experience (28). Another key advantage is the potential integration of robotics with AI and machine learning algorithms. Future

robotic platforms may be able to analyze intraoperative data, identify deviations from treatment plans and provide predictive guidance in real time. Such developments may result in improved surgical outcomes and lower risks of the procedure (28,31,36,37). However, robotic implant surgery faces critical challenges. High acquisition costs, technical complexity, training needs and limited long-term clinical evidence still hinder widespread adoption. Regulatory approval, medico-legal liability and ethical issues are also obstacles that need to be overcome before fully autonomous robotic systems can be considered standard in clinical practice (38-42). Nevertheless, the existing evidence points to robotic-assisted implant surgery as a promising innovation in digital dentistry, which could play an increasingly important role in future implant rehabilitation strategies.

A critical distinction should be made between the accuracy of osteotomy preparation and the accuracy of the final implant position. Osteotomy accuracy refers to the extent to which the prepared osteotomy follows the planned entry point, angulation, depth and trajectory. By contrast, the final implant placement accuracy reflects the deviation between the planned and achieved positions of the inserted implant, including coronal, apical and angular discrepancies. Although accurate osteotomy preparation may contribute to precise implant placement, the two outcomes are not interchangeable. Implant positioning may also be influenced by factors, such as drill deviation, osteotomy enlargement, bone density, implant insertion torque, implant-osteotomy interactions, guide or tracking stability and intraoperative changes (43,44). Therefore, studies reporting osteotomy accuracy should not automatically be interpreted as demonstrating the equivalent accuracy of final implant placement. Where possible, these outcomes should be reported and interpreted separately.

Robotic systems in dentistry can be classified according to the degree of human involvement, the tasks performed and the extent of autonomy. Current platforms range from passive or surgeon-guided systems that provide mechanical stabilization to semi-active and task-autonomous systems capable of executing predefined steps, such as osteotomy preparation or implant placement. This classification is clinically relevant as the term 'robotic surgery' encompasses systems with substantially different capabilities and levels of validation. A summary of the principal categories and their current clinical status in implant and periodontal surgery is provided in Table I.

7. Clinical evidence and systematic reviews evaluating computer-assisted implant surgery

Clinical studies and systematic reviews have evaluated static-guided surgery, dynamic navigation, and robotic-assisted implant placement primarily in terms of positional accuracy, including coronal, apical and angular deviations between planned and achieved implant positions (38-42). The available evidence also provides insight into procedural efficiency, complications and clinical outcomes, although substantial heterogeneity exists in imaging protocols, guidance systems, operator experience, study design, and outcome reporting. A summary of representative clinical studies and systematic reviews, their principal findings, and major methodological limitations is presented in Table II.

8. Technical accuracy vs. clinical effectiveness

Technical accuracy is a key advantage of computer-assisted implant surgery; however, it should not be considered a surrogate for overall clinical effectiveness. Static-guided, dynamic navigation and robotic-assisted workflows generally demonstrate smaller deviations between the planned and achieved implant positions than freehand surgery does, particularly in terms of coronal, apical and angular measurements. Nevertheless, these outcomes primarily assess the accuracy of transferring a virtual plan to the surgical field and do not independently establish improvements in biological healing, peri-implant tissue health, implant survival, or patient satisfaction (2,4,20,29).

A recent systematic review and network meta-analysis of randomized clinical trials evaluating immediate implant placement reported that compared with freehand surgery, static and dynamic computer-assisted approaches improved positional accuracy (29). No significant differences were identified between the different computer-assisted modalities and robotic-assisted surgery was not represented in the included randomized trials (29). Similarly, recent evidence indicates that robotic-assisted implant placement can achieve high positional accuracy; however, the available studies remain predominantly focused on radiographic deviations and include heterogeneous clinical protocols and study designs (20).

Notably, the available clinical evidence suggests that improvements in implant positioning do not consistently translate into superior patient-centered or biological outcomes. Recent international evidence has demonstrated that although computer-assisted implant surgery provides strong evidence for improved placement accuracy, outcomes such as primary implant stability, implant survival, marginal bone loss, peri-implant tissue health, and intra- and post-operative complications are broadly comparable between guided and nonguided approaches. Evidence regarding treatment efficiency and long-term clinical advantages remains limited or inconsistently reported (21). Some aesthetic benefits may be associated with more prosthetically driven implant positioning, particularly in anatomically demanding or aesthetically sensitive cases, but these effects are difficult to separate from case selection, clinician expertise, prosthetic planning, and adjunctive hard- and soft-tissue procedures (21).

The clinical value of computer-assisted surgery therefore depends not only on positional precision, but also on the quality of the initial diagnosis, prosthetically driven planning, anatomical risk assessment, surgical execution, implant design, soft- and hard-tissue management, and maintenance care. A technically accurate implant may still produce an unsatisfactory outcome if the treatment plan is biologically inappropriate, if the implant is placed in an unfavorable restorative position, or if peri-implant tissue deficiencies are not adequately managed. Conversely, minor deviations from the virtual plan may have limited clinical significance when they remain within the anatomical and prosthetic tolerance of the patient.

This distinction is particularly relevant when considering the potential application of robotics and navigation in periodontology. Periodontal outcomes depend on factors, such as inflammation control, wound stability, vascularity,

Table I. Classification and current clinical status of robotic systems in implant and periodontal surgery.

Robotic category	Defining characteristics	Representative systems or applications	Current clinical status	Established or reported capabilities	Principal limitations and evidence gaps
Passive or surgeon-guided robotic systems	The robot provides mechanical support, stabilization, or trajectory guidance, while the clinician actively controls instrument movement.	Collaborative robotic platforms; surgeon-guided implant robots; Yomi-type systems in clinician-controlled workflows	Early clinical use for selected implant procedures	May reduce hand tremor, improve instrument stabilization, and support transfer of a digitally planned implant trajectory.	Clinical performance remains dependent on operator control, registration, planning, and system calibration. Evidence is primarily implant-focused, with limited long-term comparative outcomes.
Semi-active or cooperative robotic systems	The clinician positions or guides the robotic arm, while the system assists with trajectory alignment, drilling, depth control, or selected procedural steps.	Remebot; Theta; human-robot collaborative dental implant systems	Early clinical implementation; limited but growing clinical evidence	Supports predefined osteotomy preparation and implant positioning while retaining direct clinician supervision and control.	Requires manual arm positioning, instrument changes, activation, and continuous supervision. Workflow complexity, training requirements, and limited independent validation remain concerns.
Active or task-autonomous robotic systems	The robot executes predefined surgical tasks according to a digital plan, such as osteotomy preparation or implant insertion, within specified safety boundaries.	Selected autonomous implant robots, including systems described in recent robotic implant studies	Limited clinical application; investigational-to-early clinical status	May provide reproducible execution of selected planned tasks and reduce variability associated with manual hand movements.	Autonomy is generally restricted to specific tasks and does not encompass independent diagnosis, treatment planning, intraoperative judgment, or management of unexpected anatomy.
Fully autonomous surgical robots	The system independently performs the complete surgical workflow, including diagnosis, planning, decision-making, execution, and management of unexpected intraoperative events.	No established fully autonomous robotic system for routine dental implant or periodontal surgery	Not clinically established	Conceptually could provide highly standardized surgical execution under predefined conditions.	Major unresolved issues include safety, accountability, anatomical variability, soft-tissue deformation, unexpected bleeding, ethical responsibility, regulatory approval, and reliable failure recovery.

Table I. Continued.

Robotic category	Defining characteristics	Representative systems or applications	Current clinical status	Established or reported capabilities	Principal limitations and evidence gaps
Tele-operated robotic systems	The surgeon controls robotic instruments remotely through a master-slave interface.	Primarily experimental or adapted surgical-robotic concepts; limited dental application	Not established for routine periodontal or implant surgery	May facilitate remote manipulation, magnified visualization, and potential access to restricted surgical fields	Requires reliable communication, force feedback, latency control, specialized infrastructure, and robust safety mechanisms. Dental evidence remains limited.
Robotic systems for implant osteotomy preparation	Robotic assistance is directed mainly toward drill positioning, angulation, depth, and trajectory control.	Robotic implant osteotomy systems, including semi-active and task-autonomous platforms	Most clinically developed robotic application	Can improve the reproducibility of planned osteotomy geometry and implant trajectory in selected cases.	Accuracy does not ensure adequate primary stability, ideal biological positioning, or long-term peri-implant tissue health.
Robotic systems for implant insertion	The robotic platform assists or executes implant insertion after osteotomy preparation.	Integrated robotic implant placement workflows	Early clinical and technology-development stage	May improve control of insertion trajectory and planned implant positioning.	Evidence is limited regarding insertion torque, tactile feedback, implant stability, postoperative complications, and long-term survival.
Robotic systems for periodontal microsurgery	Proposed use for flap manipulation, root-surface instrumentation, microsuturing, graft stabilization, or minimally invasive access.	Experimental or conceptual periodontal robotic applications	Preclinical, conceptual, or investigational	Potentially could improve instrument stability and precision during technically demanding microsurgical procedures.	Periodontal tissues are deformable, inflamed, vascular, and biologically dynamic. Current systems cannot reliably account for tissue displacement, bleeding, wound tension, or biological healing.
Robotic systems for periodontal regeneration	Proposed robotic assistance for membrane placement, biomaterial delivery, graft positioning, or regenerative-site stabilization.	Conceptual robotic regenerative workflows	Conceptual or preclinical; no established clinical standard	Could theoretically support standardized placement of regenerative materials and minimally invasive handling.	Mechanical precision cannot predict vascularization, cell recruitment, wound stability, tissue integration, or periodontal attachment gain. Clinical evidence is currently insufficient.

Robotic systems are classified according to their level of human interaction and task autonomy rather than by manufacturer-specific terminology. The clinical status categories reflect the maturity of the available evidence and should not be interpreted as regulatory approval classifications. The majority of clinically evaluated robotic systems focus on selected implant-placement tasks, whereas fully autonomous surgery and periodontal robotic applications remain unestablished or investigational (28,31,35-37).

Table II. Clinical evidence and systematic reviews evaluating computer-assisted implant surgery.

First author, year of publication	Design	Technology	Sample/comparator	Coronal deviation	Apical deviation	Angular deviation	Follow-up	Main findings	Major limitations	(Refs.)
Vercruyssen, 2014	Narrative review of guided surgery	Static computer-assisted implant surgery	Guided implant placement; comparison with conventional approaches discussed	NR	NR	NR	Not applicable	Reviewed the principles, accuracy, indications, and limitations of guided implant surgery. Emphasized the importance of accurate imaging, planning, guide fabrication, and clinical execution.	Narrative design; no pooled quantitative analysis; evidence largely implant-focused; limited patient-centered outcomes.	(18)
Tahmaseb, 2018	Systematic review and meta-analysis	Static computer-assisted implant surgery	Clinical and laboratory studies of static-guided implant placement	Pooled deviations reported in the original review	Pooled deviations reported in the original review	Pooled deviations reported in the original review	Primarily immediate postoperative assessment	Static guidance generally improved transfer of the virtually planned implant position and demonstrated clinically acceptable accuracy under selected conditions.	Considerable heterogeneity in study design, guide support, implant site, imaging protocols, and deviation reporting; limited long-term clinical outcomes.	(2)
Jorba-García, 2021	Systematic review and meta-analysis	Dynamic computer-assisted implant surgery	Clinical studies evaluating dynamic navigation	NR in summary data	NR in summary data	NR in summary data	Primarily immediate postoperative assessment	Dynamic navigation provided accurate implant placement while allowing intraoperative modification of the planned trajectory. Accuracy was influenced by registration, tracking, calibration, and operator-related factors.	Small and heterogeneous evidence base; variable navigation systems and surgical protocols; limited comparative clinical trials; limited long-term biological outcomes.	(4)
Khaohoen, 2024	Systematic review and meta-analysis of clinical trials	Static, dynamic, and robotic-assisted surgery	67 studies; 5,673 implants; 53 static, 15 dynamic, and 2 robotic studies	Overall: 1.11 mm (95% CI, 1.02–1.19). Static: 1.11 mm; dynamic: 1.18 mm; robotic: 0.81 mm	Overall: 1.40 mm (95% CI, 1.31–1.49). Static: 1.44 mm; dynamic: 1.36 mm; robotic: 0.77 mm	Overall: 3.51° (95% CI, 3.27–3.75). Static: 3.58°; dynamic: 3.51°; robotic: 1.71°	Predominantly immediate postoperative evaluation	Computer-assisted approaches demonstrated measurable accuracy in three-dimensional implant positioning. Robotic-assisted surgery showed the lowest pooled deviations, although it was represented by only two clinical studies. Fully	Robotic evidence was very limited; substantial heterogeneity; mixed study designs and clinical protocols; technical accuracy was not equivalent to improved implant survival, peri-implant health, or patient benefit.	(21)

Table II. Continued.

First author, year of publication	Design	Technology	Sample/comparator	Coronal deviation	Apical deviation	Angular deviation	Follow-up	Main findings	Major limitations	(Refs.)
Sankar, 2025	Systematic review and meta-analysis including clinical and <i>in vitro</i> studies	Robotic-assisted implant surgery compared with freehand, static, and dynamic techniques	Clinical and laboratory studies; exact clinical subgroup values should be extracted from the full text before final submission	Clinical subgroup: extract separately; not reported in the available summary	Clinical subgroup: extract separately; not reported in the available summary	Clinical subgroup: extract separately; not reported in the available summary	Primarily immediate postoperative or model-based assessment	guided protocols were more accurate than pilot-guided protocols in the analyzed comparisons. Evaluated whether robotic assistance improved implant placement accuracy compared with conventional and computer-assisted methods. The review included risk-of-bias assessment using QUIN and JBI tools.	Combined clinical and <i>in vitro</i> evidence; differences in study settings and comparators; limited clinical evidence; possible overinterpretation of statistically significant differences as clinically meaningful.	(20)
Khaohoen, 2025	Systematic review and meta-analysis of clinical robotic studies	Robotic computer-assisted implant surgery	16 clinical studies; 908 implants	0.69 mm (95% CI, 0.61-0.77); $I^2=94\%$	0.72 mm (95% CI, 0.64-0.79); $I^2=93\%$	1.62° (95% CI, 1.34-1.89); $I^2=96\%$	Primarily immediate postoperative assessment	Robotic implant placement demonstrated relatively low pooled deviations in clinical studies. Substantial heterogeneity was observed across all accuracy outcomes.	Very high statistical heterogeneity; differences in robot autonomy, camera systems, dentition, surgical workflows, and operator experience; limited evidence for long-term clinical effectiveness or cost-effectiveness.	(77)
Wu, 2025	Systematic review and network meta-analysis	Robotic, dynamic, static-guided, freehand implant surgery	Clinical and preclinical studies; exact sample size and subgroup extraction should be confirmed from the final publication	NR in available summary	NR in available summary	NR in available summary	Primarily immediate postoperative accuracy assessment	Compared the relative accuracy of robotic, dynamic, static-guided, and freehand implant placement using network meta-analysis.	Network comparisons may be affected by indirectness, differences in study populations, protocols, implant sites, and risk of bias; technical accuracy does not establish clinical superiority.	(66)

Table II. Continued.

First author, year of publication	Design	Technology	Sample/comparator	Coronal deviation	Apical deviation	Angular deviation	Follow-up	Main findings	Major limitations	(Refs.)
Nava, 2026	Systematic review and network meta-analysis	Static, dynamic, and robotic guidance for immediate implant placement	18 studies; 780 immediately placed implants; 6 RCTs, 2 prospective case series, 7 retrospective case series, and 3 retrospective studies	Extract from full text; available summary emphasizes angular outcomes	Extract from full text	Compared with freehand, angular deviation decreased by 3.36° with robotic, 2.66° with dynamic, 1.73° with half-guided static, and 1.85° with fully guided static protocols	Immediate implant placement; primarily postoperative accuracy assessment	Guided protocols were associated with improved angular accuracy compared with freehand placement in immediate implant placement. The findings suggest potential benefits in anatomically demanding immediate implant workflows.	Mixed evidence levels, including case series and retrospective studies; indirect comparisons; limited long-term implant and peri-implant tissue outcomes; immediate implant findings may not generalize to all clinical situations.	(29)
Alqutaibi, 2023	Scoping review of clinical robotic studies	Robotic computer-assisted implant surgery	27 studies; 983 patients; 1,546 implants	0.67 mm (95% CI, 0.62-0.73)	0.71 mm (95% CI, 0.66-0.77)	1.68° (95% CI, 1.46-1.90)	Primarily immediate postoperative accuracy assessment	Robotic computer-assisted implant surgery demonstrated high positional accuracy across clinical studies and showed higher accuracy than freehand, static, and dynamic techniques in comparative analyses.	The evidence remains predominantly accuracy-based; study heterogeneity, cost, learning-curve effects, limited independent validation, and uncertain clinical relevance of small numerical differences remain important concerns.	(36)

Clinical evidence indicate that computer-assisted implant surgery can improve the reproducibility of implant positioning relative to freehand approaches, particularly when a fully guided workflow is used. Across the available literature, reported deviations are generally within clinically manageable ranges; direct comparisons between studies are complicated by differences in imaging protocols, guide support, registration methods, implant sites, operator experience, and accuracy definitions. Recent clinical meta-analyses have demonstrated relatively low pooled coronal, apical, and angular deviations, but these findings should be interpreted cautiously because the evidence remains heterogeneous and is largely based on immediate postoperative accuracy rather than long-term implant survival, peri-implant tissue stability, biological outcomes, or patient-reported benefit.

tissue thickness, flap adaptation, root-surface characteristics, patient-related healing responses and regenerative potential. These biological variables cannot be predicted solely from the accuracy of instrument positioning (45-47). Consequently, evidence demonstrating improved implant placement accuracy should not be directly extrapolated to periodontal flap surgery, root-surface instrumentation, connective tissue grafting, microsuturing, or periodontal regeneration.

Future investigations should evaluate computer-assisted surgery as part of the complete treatment pathway, rather than as an isolated accuracy-enhancing procedure. The relevant outcomes should include postoperative morbidity, treatment time, complications, prosthetic and aesthetic outcomes, marginal bone and soft-tissue stability, implant survival, patient-reported outcomes, cost-effectiveness and long-term maintenance requirements. Such studies would clarify whether improved technical precision produces clinically meaningful benefits and identify the patient groups and procedural contexts in which these technologies provide the greatest value. Evidence of improved positional accuracy should be distinguished from evidence of improved clinical effectiveness. The former indicates closer agreement between the planned and achieved implant positions, whereas the latter requires demonstration of meaningful improvements in safety, efficiency, biological outcomes, prosthetic outcomes, or patient experience. A comparative overview of freehand surgery, static-guided surgery, and dynamic navigation in dental and periodontal procedures is presented in Fig. 2.

9. Robotics in periodontal surgery: Current evidence, translational potential and research gaps

Compared with implant placement, the application of robotics in periodontal surgery remains substantially less developed. The majority of the available evidence concerning dental robotics has focused on implant osteotomy and implant positioning, whereas periodontal procedures involve additional biological and technical challenges, including manipulation of deformable soft tissues, preservation of vascularity, root-surface instrumentation, wound stabilization and regeneration of multiple periodontal tissue (31,36,37,48). Therefore, the accuracy outcomes reported for robotic implant placement cannot be directly extrapolated to periodontal microsurgery or regenerative procedures.

Several periodontal interventions could theoretically benefit from robotic assistance, including minimally invasive flap design, access to intrabony defects, root-surface instrumentation, membrane or scaffold placement, connective tissue graft positioning and microsurgical suturing. These applications should currently be regarded as conceptual or investigational, rather than as having established clinical indications. The ability of a robotic system to reproduce a predefined movement does not necessarily demonstrate improved periodontal healing, connective tissue attachment or long-term tooth retention (35,48,49).

Periodontal regeneration. Robotic assistance may eventually support the standardized placement of membranes, scaffolds or biomaterials within periodontal defects. Three-dimensional imaging and digital planning could assist in individualized

defect assessment, while robotic or semi-active instruments might improve the positioning of regenerative materials in anatomically complex sites.

Nevertheless, periodontal regeneration is not simply a problem of spatial accuracy. Clinical outcomes depend on defect morphology, wound stability, blood supply, cellular recruitment, exclusion of epithelial migration, biomaterial characteristics and host-related factors (46,49-53). Current evidence supporting periodontal regeneration primarily concerns surgical techniques, guided tissue regeneration, enamel matrix derivatives and grafting materials rather than robotic delivery systems. Consequently, improved membrane or scaffold positioning would not, by itself, establish enhanced periodontal ligament, cementum or alveolar bone regeneration (46,49-53).

Future studies should determine whether robotic assistance improves clinically relevant outcomes such as probing-depth reduction, clinical attachment-level gain, radiographic defect fill, wound stability, postoperative morbidity and long-term tooth retention. At present, direct evidence supporting these benefits is insufficient (48,49).

Periodontal microsurgery and soft-tissue procedures. Periodontal microsurgery and mucogingival procedures may appear suitable for robotic assistance as they involve delicate movements and require accurate tissue handling. Potential applications include connective tissue graft positioning, flap advancement, papilla reconstruction and microsuturing. The success of these procedures depends not only on movement precision but also on tissue thickness, elasticity, vascularity, flap tension, graft adaptation and wound stability (54-59).

Unlike implant placement, where the target trajectory can be defined relative to relatively stable anatomical landmarks, periodontal soft tissues deform during retraction, incision and suturing. Pre-programmed or mechanically constrained movement may therefore be unsuitable if it cannot respond to tissue resistance or unexpected anatomical changes. Robotic assistance may ultimately be more useful for instrument stabilization, tremor reduction or motion scaling than for autonomous execution of complete periodontal procedures (35,49,60,61).

Evidence from periodontal microsurgery has demonstrated that magnification and minimally invasive techniques may improve visualization and facilitate delicate tissue handling; however, these benefits should not be automatically attributed to robotic technology (56-59). Moreover, systematic reviews have reported variability in the clinical advantages of microsurgical approaches, particularly for patient-centered outcomes, emphasizing that technical refinement does not always translate into clearly superior clinical results (55-57).

Root-surface instrumentation and periodontal debridement. Robotic or navigational assistance could theoretically support selective root-surface instrumentation by integrating three-dimensional imaging with instrument tracking. Such systems may improve access to complex root morphologies or assist in the controlled removal of calculus and contaminated root-surface deposits.

This application presents substantial challenges. CBCT cannot reliably identify all clinically relevant deposits, whereas inflammation, calculus, soft-tissue coverage and bleeding may

Comparison of Freehand, Static Guided and Dynamic Navigation Systems in Dental/Periodontal Surgery			
Surgical approach	Freehand Surgery	Static Guided Surgery	Dynamic Navigation
	Surgeon's experience and anatomical landmarks	Pre-fabricated surgical guide (guide in place)	Real-time tracking and navigation
 Principle	Conventional drilling based on surgeon's anatomical judgment	Guided drilling through a pre-fabricated surgical guide based on a digital plan	Real-time tracking of instruments relative to patient anatomy using optical tracking
 Typical setup	Conventional surgical instruments	3D printed guide with metal or plastic sleeves	Tracking camera, reference markers, navigation software and instrumentation
 Intraoperative flexibility	High	Limited (fixed to guide design)	High (real-time adjustments possible)
 Reported accuracy	Lower (greater deviation)	High	High (comparable to static guidance)
 Line of sight required	No	No	Yes (uninterrupted line of sight)
 Learning curve	Short	Short to moderate	Moderate
 Cost	Lower	Moderate (guide fabrication)	Higher (equipment and software)
 Advantages	Simple, widely available, no additional equipment	Reproducible, reduces operator variability, useful for complex cases	Real-time control, intraoperative flexibility, no guide fabrication
 Limitations	Greater risk of deviation, operator-dependent	No intraoperative changes, potential fit issues, requires guide fabrication	Higher cost, requires training, line-of-sight dependent, potential tracking errors
 Common applications	Routine dental and periodontal surgery	Implant placement, osteotomy preparation, periodontal and regenerative procedures (with guide adaptation)	Implant placement, complex cases, revision surgery, selected periodontal and regenerative procedures


Increasing technological complexity and intraoperative flexibility


Figure 2. Comparison of freehand surgery, static-guided surgery, and dynamic navigation in dental and periodontal procedures. Comparison of the three surgical approaches according to their operating principles, typical equipment, intraoperative flexibility, reported accuracy, line-of-sight requirements, learning curve, cost, advantages, limitations and common clinical applications. Freehand surgery relies primarily on the anatomical knowledge and intraoperative judgment of the clinician. Static-guided surgery transfers a digitally planned trajectory through a prefabricated surgical guide, whereas dynamic navigation provides real-time tracking and visual guidance of surgical instruments. The figure illustrates general functional differences and should not be interpreted as evidence of the universal superiority of one approach, particularly for periodontal procedures (2,4,11,14,18,25,65).

alter the relationship between the radiographic anatomy and the actual root surface. Effective periodontal instrumentation also requires tactile feedback to distinguish calculus, cementum, dentin and soft tissue (60-62). Excessive mechanical control without adequate tactile interpretation could increase the risk of unnecessary root-surface removal or soft-tissue injury.

Accordingly, robotic periodontal instrumentation should currently be regarded as a research possibility, rather than a validated replacement for clinician-performed debridement (48,49,62). Future systems would require reliable tactile sensing, tissue recognition, adaptive control and safety limits, followed by clinical comparison with established instrumentation protocols (35,49,60,61).

Evidence maturity of the proposed periodontal applications. The classification of robotic and navigation-related applications in periodontology according to the maturity of available evidence is presented in Table III. The current evidence should be interpreted according to the maturity of each proposed application: The presence of a plausible technical workflow should not be interpreted as evidence of clinical efficacy. A proposed robotic application should be described as clinically beneficial only when supported by appropriately designed human studies evaluating periodontal and patient-centered outcomes.

Translational barriers and research priorities. Several factors currently limit the translation of robotics into periodontal practice. Periodontal procedures are highly individualized and require real-time adaptation to tissue quality, inflammation, bleeding and defect morphology. In addition, soft tissues are deformable and difficult to register accurately using static three-dimensional datasets. Treatment success is determined by biological healing and tissue integration, neither of which can be predicted solely from instrument positioning (35,51,52).

Early research should therefore focus on clinician-supervised and semi-active applications, such as instrument stabilization, motion scaling, navigation-assisted access, digitally planned placement of regenerative materials and assistance with microsuturing. These applications should progress through laboratory validation, and cadaveric studies where appropriate and carefully designed clinical trials are performed (48,56).

Clinical investigations should include periodontal-specific outcomes, such as clinical attachment-level gain, probing-depth reduction, gingival recession, soft-tissue thickness, wound stability, postoperative pain, patient satisfaction and long-term tooth retention. Technical accuracy should be reported as a complementary endpoint rather than the sole indicator of success (38,62,63).

Table III. Classification of robotic and navigation-related applications in periodontology according to the maturity of available evidence.

Periodontal application	Potential role of robotics or navigation	Current evidence status	Evidence interpretation and principal limitations
Periodontal flap surgery and minimally invasive access	Guidance of incision design, flap elevation, instrument positioning, and minimally invasive access to periodontal defects.	Conceptual/investigational	No established clinical evidence demonstrates that robotic guidance improves periodontal attachment gain, pocket reduction, wound healing, or long-term tooth retention. Soft-tissue mobility, bleeding, and anatomical variability remain major challenges
Root-surface instrumentation and debridement	Potential guidance of ultrasonic, rotary, or micro instrument positioning during subgingival debridement and root-surface preparation.	Preclinical/conceptual	Root morphology, calculus distribution, tissue interference, and the need for tactile feedback make automation challenging. Evidence supporting superior clinical periodontal outcomes is currently lacking.
Periodontal microsuturing	Assistance with needle positioning, suture placement, knot tying, and reproducible wound closure.	Conceptual/early experimental	Microsuturing requires adaptation to tissue thickness, tension, mobility, and wound geometry. Robotic feasibility does not establish improved wound stability, healing, or clinical attachment outcomes.
Connective tissue grafting and periodontal plastic surgery	Potential assistance with graft harvesting, graft positioning, flap manipulation, and microsuturing.	Investigational	Current clinical benefits reported for periodontal microsurgery largely relate to magnification and minimally invasive techniques rather than robotic systems specifically. Evidence for robotic superiority in root coverage or soft-tissue stability remains insufficient.
Periodontal regeneration of intrabony defects	Potential assistance with defect access, debridement, membrane or biomaterial positioning, and precise wound closure.	Conceptual/preclinical	Regenerative outcomes depend on defect morphology, blood-clot stability, biomaterial selection, wound closure, and biological healing.
Furcation defect management	Potential guidance of access, debridement, regenerative material placement, or microsuturing in anatomically restricted furcation areas.	Conceptual/investigational	Robotic accuracy alone cannot ensure periodontal ligament, cementum, or bone regeneration. Complex root anatomy, restricted access, and variable defect morphology may limit robotic implementation. Procedure-specific clinical evidence is currently lacking.
Periodontal maintenance and supportive therapy	Possible navigation-assisted localization of residual deposits or guidance of targeted instrumentation.	Conceptual/future application	The clinical value of automated or guided maintenance remains uncertain, particularly regarding treatment efficiency, patient comfort, disease recurrence, and long-term periodontal stability.
AI-assisted periodontal assessment and treatment planning	Automated detection of bone loss, periodontal defects, tooth morphology, and risk-related imaging features to support treatment planning.	Early clinical/investigational	AI may assist image interpretation and risk stratification, but performance depends on training datasets, image quality, external validation, and clinical oversight. AI-generated assessments should not replace comprehensive clinical examination.
Augmented- or mixed-reality assistance in periodontal surgery	Overlay of anatomical information, treatment plans, or surgical guidance onto the operative field.	Preclinical/early feasibility	Registration drift, limited field-of-view accuracy, optical obstruction, and mismatch between virtual images and mobile soft tissues may restrict reliability in periodontal surgery.

Table III. Continued.

Periodontal application	Potential role of robotics or navigation	Current evidence status	Evidence interpretation and principal limitations
Fully autonomous periodontal surgery	Independent execution of incision, instrumentation, suturing, or regenerative procedures based on a preoperative digital plan.	Not clinically established	Periodontal tissues are deformable and biologically dynamic, and procedures require continuous clinical judgment and tactile assessment. Fully autonomous periodontal surgery remains a future research concept rather than a routine clinical application.
Of note, 'Early clinical' indicates limited human or feasibility evidence; 'preclinical' refers to laboratory, simulation, or animal research; and 'conceptual' indicates a proposed application without adequate procedure-specific clinical validation. Evidence relating to conventional periodontal microsurgery or regenerative therapy should not be interpreted as direct evidence for robotic systems unless robotics or navigation is specifically evaluated (35,46,51,52,54-58,62,63).			

Overall, robotics may eventually enhance selected periodontal procedures; however, the current role of robotics remains exploratory. The strongest available evidence concerns computer-assisted implant positioning, whereas the use of robotics in periodontal soft-tissue surgery, root-surface instrumentation and regeneration requires independent validation. These applications should therefore be presented as promising research directions rather than established clinical modalities (48,52,53).

10. Potential indications and contraindications for computer-assisted and robotic technologies in periodontal and implant surgery

The potential indications and contraindications of computer-assisted and robotic technologies should be interpreted cautiously, as their clinical applicability varies according to the procedure, platform, anatomical conditions and available supporting evidence. Rather than representing universally established criteria, the considerations summarized in Table IV (48,52,53) are intended to highlight situations in which these technologies may be considered, as well as circumstances that could limit their reliability or clinical usefulness. This distinction is particularly relevant for periodontal applications, where evidence remains limited and the effects of tissue mobility, bleeding, and intraoperative anatomical changes may reduce the direct applicability of implant-related experience.

Clinical accuracy and results. The main reason for using navigation and robotic technology in periodontal and implant surgery continues to be accuracy. Accurate implant positioning is necessary to obtain optimal aesthetic, functional and biological results. Deviations from the planned implant position can compromise prosthetic design, increase biomechanical complications and contribute to peri-implant disease (2). A number of clinical studies have assessed the accuracy of dynamic navigation systems (11,17,64). Studies have repeatedly demonstrated less angular, coronal and apical deviation with respect to freehand implant placement. Dynamic navigation provides a continuous view of the drill position and trajectory, enabling clinicians to make real-time adjustments and stay within the surgical plan (4,19,65). Robotic-assisted implant surgery has demonstrated even higher levels of accuracy in several recent studies. Systematic reviews have demonstrated that compared with freehand and static-guided techniques, robotic systems tend to have lower positional deviations (20,66). The robotic platform aids in maintaining the planned trajectory during the preparation for osteotomy and reduces the impact of inadvertent hand movements (20,21,23,66,67). Improved surgical accuracy may lead to beneficial clinical outcomes. Proper implant positioning may lead to desirable emergence profiles, improve prosthetic design, facilitate the maintenance of oral hygiene and reduce the likelihood of injury to adjacent anatomical structures. Moreover, accurate implant placement leads to favorable stress distribution and may enhance the long-term stability of peri-implant tissues (28,51). Previous studies have reported excellent short-term survival rates for implants placed with dynamic navigation and robotic

Table IV. Potential indications and limitations of computer-assisted and robotic technologies in periodontal and implant surgery.

Category	Potential indications or considerations
Potential indications	Complex implant placement requiring prosthetically driven positioning; anatomically restricted sites; procedures where enhanced visualization, planning, or instrument guidance may improve workflow; selected research applications in periodontal microsurgery, soft-tissue grafting, and regenerative procedures.
Patient selection considerations	Adequate preoperative imaging; stable reference structures; sufficient mouth opening and surgical access; ability to obtain reliable CBCT-IOS registration; and a treatment plan suitable for digital guidance.
Relative contraindications or limitations	Unstable teeth or reference markers; extensive movement of soft tissues; inadequate imaging quality; severe artefacts; inability to achieve reliable registration; restricted access; uncontrolled bleeding or poor visibility; and insufficient space for the guide, tracking system, or robotic instruments.
Situations requiring caution	Procedures involving highly mobile or deformable periodontal tissues, substantial intraoperative anatomical changes, unpredictable bleeding, complex regenerative defects, or situations in which tactile feedback and continuous clinical adaptation are essential.
Operational contraindications	Inability to calibrate or verify the system, tracking failure, software or hardware malfunction, inadequate operator training, lack of a safe conventional alternative, or failure to maintain appropriate data security and system integrity.

These considerations are intended to support clinical selection and should not be interpreted as universally validated indications or formal absolute contraindications, particularly for emerging periodontal applications (2,4,19,21,28,29,51,54,55,65,87). CBCT, cone-beam computed tomography; IOS, intraoral scan.

guidance (32,66). Although long-term outcome data remain limited, the available evidence points to clinical outcomes that are comparable to or even better than those of conventional implant placement techniques (23,65). It is important to realize that numerous factors other than surgical accuracy determine implant success. Patient-related factors, systemic health, bone quality, prosthetic design, maintenance therapy and clinician experience continue to influence treatment outcomes (2,54,55). Therefore, navigation and robotic technologies should be considered tools that support, not replace, sound clinical judgment.

11. Critical appraisal of current evidence

Although systematic reviews and meta-analyses generally support the technical feasibility and high positional accuracy of computer-assisted implant surgery, the strength of the evidence should be interpreted in light of methodological heterogeneity. Studies evaluating dynamic navigation and robotic-assisted implant placement differ in design, implant location, bone characteristics, surgical protocols, registration methods, imaging workflows and operator experience. Consequently, reported deviations cannot always be directly compared across studies or generalized to all clinical situations (4,19,20,23,66-68).

Comparative evidence suggests that robotic-assisted, dynamic-navigation and static-guided approaches can achieve favorable positional accuracy under selected conditions. Differences in pooled estimates should not automatically be interpreted as evidence of clinically meaningful superiority. The relative performance of each technology may depend on

the specific surgical workflow, degree of movement restriction, registration accuracy and operator familiarity with the system (20,21,65,66).

A further limitation is that an ample amount of the available literature focuses on technical endpoints, including coronal, apical and angular deviations, rather than patient-centered outcomes. Although improved positional accuracy may facilitate prosthetically driven implant placement and help avoid anatomical structures, it does not independently improve long-term implant survival, peri-implant tissue health, prosthetic complications, postoperative morbidity, patient satisfaction or cost-effectiveness. These outcomes are influenced by multiple patient-, implant-, prosthetic- and maintenance-related factors (2,19-21,23,28,55,66).

Evidence for robotic applications in periodontal surgery remains substantially less developed than that for computer-assisted implant placement. Proposed applications in periodontal regeneration, mucogingival surgery, connective tissue grafting and tissue-engineered scaffold placement should therefore be distinguished from established clinical applications. At present, these areas represent emerging or investigational possibilities rather than validated alternatives to conventional periodontal microsurgery.

Overall, the current evidence supports the use of navigation and robotic technologies as tools that may improve surgical guidance and positional accuracy in appropriately selected implant cases. Nevertheless, the clinical significance of these technical improvements, their cost-effectiveness and their potential benefits in periodontal surgery require further prospective clinical investigation with standardized outcome measures and longer follow-up.

12. AI and augmented/mixed reality in periodontology

AI, digital planning software, navigation systems and autonomous robotic control represent distinct technological levels. Diagnostic AI analyses clinical or imaging data, whereas planning software supports treatment design and navigation systems provide real-time procedural guidance. Autonomous control involves the performance of selected surgical actions with limited direct human intervention. Evidence supporting diagnostic AI or digital planning should therefore not be interpreted as evidence for autonomous periodontal surgery (35,69,70).

AI applications in periodontology exhibit potential for radiographic bone-loss assessment, periodontal classification, risk prediction and treatment-planning support. Their performance depends on training-data quality, annotation standards, disease characteristics and validation methods. Studies use retrospective or single-center datasets, and external validation remains limited. Consequently, performance may vary across populations, disease severities, scanners, CBCT devices, imaging protocols and clinical settings (69,71).

Explainability and clinician oversight remain essential, particularly when AI outputs influence diagnosis or treatment decisions. Algorithmic bias may also occur when datasets underrepresent specific demographic groups, geographic populations, disease presentations, or imaging conditions. AI-generated results should therefore be interpreted alongside clinical examination and conventional diagnostic findings, with final responsibility retained by the treating clinician (71-73).

AI and AR/MR technologies also raise concerns regarding patient-data privacy, cybersecurity, accountability, informed consent and compliance with applicable medical-device regulations. CBCT scans, intraoral scans, photographs and treatment plans require appropriate security, access control, and transparent data governance (72-74).

AR/MR systems may display virtual anatomical structures or treatment plans within the visual field of the clinician. Their periodontal applications remain limited, with potential challenges including registration drift, tracking errors, optical obstruction, a restricted field of view, and mismatch between virtual overlays and mobile or deformable periodontal tissues. Thus, the potential of AI and AR/MR should not be equated with demonstrated improvements in periodontal healing, clinical attachment gain, regenerative outcomes, patient safety, or long-term tooth retention. Their current role is best regarded as adjunctive or investigational, pending robust prospective validation and evidence of meaningful clinical benefit (75,76).

13. Limitations, challenges and technology-specific evidence gaps

Technical limitations of computer-assisted and robotic workflows. The technical limitations affecting computer-assisted and robotic workflows in periodontal and implant surgery are summarized in Table V (2,4,19,77). The clinical implications of robotics and navigation systems should be interpreted according to the specific function and maturity of each technology. Static guides, dynamic navigation, robotic systems, AI, AR, and haptic interfaces are not interchangeable. They differ in how they transfer digital information to the operative field,

the type of error they are designed to reduce, and the degree of dependence on the surgeon. Furthermore, the evidence base is uneven. The majority of comparative studies evaluate implant placement accuracy, whereas direct clinical evidence for robotic periodontal flap surgery, root-surface instrumentation, periodontal regeneration, connective tissue grafting, and microsuturing remains limited. Consequently, improvements in geometric accuracy should not automatically be interpreted as evidence of improved periodontal healing, tooth retention, or patient-reported outcomes (2,4,19,77).

Static computer-assisted surgery. Static computer-assisted surgery uses a digitally designed surgical template to transfer a virtually planned implant position to the operative field. Its principal function is to constrain the drilling trajectory and, in fully guided workflows, control the angulation and depth of osteotomy preparation. This can reduce the dependence on freehand spatial estimation and improve the reproducibility of implant positioning (2,4).

The accuracy of static guidance depends on the quality of CBCT imaging, segmentation, prosthetic planning, template fabrication, guide support, sleeve-drill tolerance and intra-operative seating. Errors may be introduced during image acquisition, virtual planning, manufacturing, or placement of the guide. Tooth-supported guides may provide relatively stable support, whereas mucosa-supported guides are susceptible to tissue compressibility and movement. Bone-supported guides may require additional surgical exposure and may be inconsistent with minimally invasive treatment objectives (2,4,21).

Static guides also have limited intraoperative adaptability. Once fabricated, they cannot readily accommodate unexpected anatomical findings, changes in prosthetic requirements, inadequate bone quality, or a need to modify the planned trajectory. The guide may reduce visibility, interfere with irrigation, and complicate treatment in posterior regions or patients with restricted mouth opening. Importantly, a guide can accurately reproduce an inappropriate plan; it does not independently assess biological suitability, prosthetic emergence, bone quality, or the risk of anatomical injury (2,4).

The majority of studies on static guidance report implant deviation rather than long-term peri-implant tissue stability, implant survival, postoperative morbidity, or patient-centered outcomes. Therefore, static guidance should be understood as a tool for improving the execution of a preoperative plan rather than as an independent determinant of treatment success.

Dynamic navigation. Dynamic navigation provides real-time visual feedback regarding the position of the surgical instrument relative to the planned trajectory. Unlike static guides, it allows clinicians to modify the osteotomy path during surgery and may be useful when intraoperative adaptation is needed. Its performance depends on accurate patient registration, calibration, handpiece tracking, maintenance of the tracking field, and effective integration of the navigation display into the surgical workflow (4,19,65,77).

The principal limitation of dynamic navigation is that it remains operator-dependent. Registration errors, movement of tracking markers, calibration inaccuracies, instrument replacement, optical obstruction, tracking loss and display latency may reduce accuracy. Surgeons must also divide

Table V. Technical limitations affecting computer-assisted and robotic workflows in periodontal and implant surgery.

Technical domain	Specific limitations and clinical implications
Registration and calibration	Accurate registration depends on stable fiducial or reference markers and reliable identification of anatomical landmarks. Marker movement or instability can generate registration errors and compromise the relationship between the virtual plan and the patient. Inaccurate calibration of the handpiece, drill, robotic arm, or instrument tip may introduce deviations into the planned surgical trajectory.
Patient movement and tracking	Patient movement or displacement of the reference array may invalidate registration. Dynamic navigation may also be affected by tracking interruption, optical obstruction from the surgeon's hands, instruments, retractors, blood, or saliva, and loss of the camera's line of sight. These problems may require repeated registration and increase procedural time.
Imaging and data-fusion errors	CBCT resolution, voxel size, patient movement, metallic artifacts, scatter, and reconstruction parameters may influence anatomical identification and planning accuracy. Additional errors may occur during CBCT-intraoral scanner (IOS) registration because of incomplete scans, stitching inaccuracies, reflective surfaces, saliva, mobile teeth, or inadequate stable reference structures.
Soft-tissue mismatch	Digital datasets may not accurately represent soft-tissue position during surgery. Differences between the scanned anatomy and the tissues after retraction, flap elevation, inflammation, edema, or manipulation may reduce the reliability of digitally transferred plans.
Intraoperative anatomical changes	Virtual planning represents anatomy at the time of imaging and may not fully reflect intraoperative soft-tissue position. This is particularly relevant in periodontal surgery, where bleeding, tissue tension, flap elevation, and retraction can alter the surgical field and limit direct extrapolation from implant-related navigation data.
Clinical access and visibility	Posterior regions, limited mouth opening, restricted interarch space, and interference from the cheeks or tongue may limit access for cameras, robotic arms, reference arrays, guides, and handpieces. Saliva, blood, irrigation, retractors, and soft-tissue displacement may further compromise visibility, tracking, or instrument access.
Training and learning curve	Effective use requires competency in digital planning, registration, calibration, navigation or robotic interfaces, error recognition, and contingency management. Operator experience may influence workflow efficiency and accuracy, particularly during early adoption. Training should include supervised use and the ability to revert safely to conventional surgery when technical problems occur.
Cost and maintenance	Implementation involves acquisition of the platform, imaging and scanning equipment, software licenses, calibration devices, consumables, service contracts, upgrades, and staff training. Periodic maintenance and calibration are necessary to preserve system reliability, while evidence regarding long-term cost-effectiveness remains limited.
Data governance and cybersecurity	Integration of CBCT data, IOS files, treatment plans, cloud-based platforms, and robotic systems introduces risks related to unauthorized access, insecure data transfer, software vulnerabilities, and alteration of digital treatment files. Secure authentication, encryption, access control, audit trails, validated software updates, and clinician verification of automated outputs are therefore necessary.

These limitations may occur independently or cumulatively across imaging, planning, registration, calibration, tracking and surgical execution (4,7,77,88) CBCT, cone-beam computed tomography.

attention between the operative field and the navigation screen, potentially increasing the cognitive workload. Consequently, dynamic navigation does not eliminate human error but transfers some sources of error from freehand spatial estimation to registration, tracking, calibration, visual interpretation and human-computer interaction (4,19,65,77).

Evidence from implant surgery suggests that compared with freehand placement, dynamic navigation can improve positional accuracy. Nevertheless, performance is influenced

by operator experience, the learning curve, anatomical access and the complexity of the surgical site (11,78,79). In periodontal surgery, these limitations may be amplified as the target structures are not always rigid or stable. Flap reflection, retraction, bleeding, tissue displacement and changes in the operative field can compromise the reliability of registration on the basis of preoperative anatomy. Therefore, the accuracy demonstrated in rigid implant osteotomy models should not be directly extrapolated to periodontal soft-tissue procedures (51,54).

Robotic-assisted surgery. Robotic-assisted systems combine digital planning with mechanical guidance, tracking, motion control, and, in some platforms, haptic or movement-constraining functions. Depending on the system, the robot may guide the instrument along a planned trajectory, restrict movement beyond predefined boundaries, reduce tremor, or support shared control between the surgeon and the robotic arm (35,80).

The strongest current evidence concerns robotic-assisted implant placement. Recent systematic reviews and meta-analyses have reported more favorable coronal, apical and angular accuracy with respect to freehand surgery and, in selected analyses, compared with dynamic navigation or static guidance (2,4,19,77). These findings require cautious interpretation. The available literature includes a substantial proportion of *in vitro* studies, small clinical cohorts and nonrandomized comparisons. A recent systematic review comparing robotic, static and dynamic implant surgery identified only a limited number of clinical studies and reported a high risk of bias in several included investigations (77). Another review concluded that although robotic systems may demonstrate improved accuracy, the clinical significance of relatively small geometric differences remains uncertain (19).

Robotic precision is also dependent on the accuracy of the CBCT data, segmentation, virtual planning, patient registration, robotic-arm calibration, mechanical stability, tracking and software performance. A robot can reproduce a planned trajectory consistently, but cannot correct an inaccurate image, faulty segmentation, incorrect registration, or an inappropriate treatment plan. Thus, robotics may reduce execution error while leaving diagnostic and planning errors unresolved (35,77,80).

Practical limitations include high acquisition and maintenance costs, proprietary hardware and software, dedicated training requirements, technical support needs, additional setup time, and uncertain cost-effectiveness. The economic justification for robotic systems remains unclear as only a limited number of studies have examined whether improved accuracy translates to shorter procedures, fewer complications, better long-term outcomes, or improved patient satisfaction (2,4,19,35,77).

Specific challenges in periodontal surgery. The translation of robotics from implant placement to periodontal surgery is more complex. Implant osteotomy preparation generally involves a defined trajectory within relatively rigid tissues. By contrast, periodontal surgery involves deformable soft tissues, inflammatory changes, bleeding, irregular root morphology, variable flap positions, and biologically active wound surfaces (35,51,54).

Robotic assistance has been proposed conceptually for minimally invasive flap access, intrabony defect debridement, membrane or scaffold positioning, connective tissue graft placement and microsuturing. These applications require more than geometric control. The system would need to recognize soft-tissue boundaries, accommodate tissue deformation, preserve vascularity, respond to tissue tension, and support wound stability. These requirements are not adequately addressed by conventional image-based navigation or trajectory control (35,51,55).

Furthermore, periodontal regeneration depends on biological factors, such as defect morphology, blood supply, wound stability, space maintenance, inflammatory regulation and cellular responses. These outcomes cannot be predicted from the accuracy of robotic positioning alone (19,71). Robotic periodontal applications should therefore currently be regarded as investigational or translational research opportunities rather than established clinical indications.

AI and automated image interpretation. AI can assist with the segmentation of teeth, roots, alveolar bone, periodontal defects, anatomical landmarks and implant-related structures. It may also support treatment planning, image registration, risk assessment and the identification of anatomical constraints. Its primary role is therefore information processing and decision support rather than direct surgical execution (5,69,71).

AI performance depends heavily on the quality and representativeness of the training data. Algorithms may perform differently across CBCT devices, voxel sizes, image artifacts, patient populations, dentition patterns and degrees of periodontal destruction. Metallic restorations, missing teeth, severe bone loss and distorted anatomy may reduce segmentation reliability. High performance in a curated dataset may not translate to equivalent performance in routine clinical practice (5,69,71).

AI systems may also reproduce biases in their training data and generate apparently confident but clinically incorrect outputs. External validation, calibration, transparent reporting, and assessment of failure cases are therefore essential. In periodontology, automated identification of bone loss does not necessarily establish disease activity, prognosis, or appropriate regenerative treatment. Similarly, an algorithmic treatment recommendation cannot replace periodontal examination, clinical attachment measurements, patient preferences, or professional judgment (5,69,71,72).

The principal evidence gap is whether AI-supported planning improves clinically meaningful outcomes rather than merely reducing planning time or increasing segmentation accuracy. Future studies should report external validation, subgroup performance, calibration, clinically relevant errors and the effect of AI assistance on treatment decisions (5,69,71,72).

AR and mixed-reality systems. AR and mixed-reality systems overlay digital information onto the visual field of the patient or clinician. Their intended functions include improving spatial orientation, displaying anatomical structures, and reducing the need to shift attention between the operative field and an external monitor (81,82).

Their limitations include registration error, display latency, optical distortion, a restricted field of view, occlusion, head movement and instability of the virtual overlay. Even small alignment errors may be clinically important when working near vital anatomical structures. Visual distraction and information overload may also impair rather than improve workflow.

The current value of AR in dentistry is more strongly supported for education, visualization, and procedural orientation than for improved periodontal outcomes. In periodontal surgery, tissue displacement during flap reflection or retraction may cause the virtual overlay to become misaligned with the

actual anatomy. Accordingly, AR should currently be viewed primarily as an adjunct to planning and orientation rather than as an independent guarantee of surgical precision (81,82).

Haptic and force-feedback technologies. Haptic systems aim to provide tactile information or constrain instrument movement according to predefined anatomical or procedural boundaries. This is potentially relevant to dentistry as tactile feedback contributes to the recognition of root contours, tissue resistance, bone density, and instrumentation endpoints (60,61).

Reproducing biological tactile sensation is technically challenging. Periodontal tissues vary in compliance, inflammation, fibrosis and anatomical structure. A force-feedback system calibrated using simplified models may not accurately reproduce clinical tissue behavior. Appropriate force thresholds may also differ across patients, anatomical sites, instruments, and procedural stages (60,61).

Haptic guidance may assist with motion control or boundary awareness; however, it should not be assumed to reliably identify calculus, distinguish healthy from diseased root surfaces, or determine when debridement is biologically adequate. Robotic root-surface instrumentation remains an early-stage research concept requiring validation in clinically representative models before clinical adoption can be considered (46,53).

Robotics in periodontal regeneration and microsurgery. Periodontal regenerative procedures differ fundamentally from implant placement because their outcomes depend on wound stability, defect morphology, vascularity, biomaterial properties, soft-tissue management and biological healing. Minimally invasive and microsurgical approaches may improve access and tissue handling; however, these benefits should not be automatically attributed to robotics (51,55,83).

A robotic system could theoretically assist with access to intrabony defects, membrane placement, graft stabilization, or microsuturing. Nevertheless, a system that positions a membrane accurately may not be able to maintain adaptation, avoid dead space, preserve vascularity, or respond to unexpected flap tension. Similarly, robotic suturing may improve needle trajectory consistency but cannot independently determine the appropriate suture tension, tissue choice, or biological suitability of wound closure.

Systematic reviews of periodontal microsurgery and regenerative treatment have demonstrated that clinical outcomes are influenced by case selection, defect characteristics, operator expertise, surgical technique, and biological healing. They also reveal variation in study designs, outcome measures, and certainty of evidence. Robotics should therefore be evaluated as an enabling adjunct rather than as a replacement for periodontal surgical judgment or biological principles (51,55,83,84).

Cross-cutting methodological and translational limitations. The available evidence is limited by heterogeneity in study design, imaging protocols, registration methods, accuracy definitions, surgical workflows and outcome assessment. Studies have variously reported coronal, apical, angular, depth, or three-dimensional deviations, rendering direct comparison difficult (2,4,77). The literature also includes *in vitro* models, small clinical cohorts, retrospective studies and non-randomized comparisons, which may not reproduce

patient movement, bleeding, soft-tissue deformation, or intra-operative decision-making (19,67,77).

The risk of bias, inconsistent reporting of operator experience, learning-curve effects, and limited independent validation further restrict the certainty of the conclusions (19,77,77). Moreover, the majority of studies focus on technical accuracy, rather than clinically meaningful outcomes such as post-operative morbidity, peri-implant tissue stability, periodontal attachment gain, tooth retention, long-term implant survival, or patient-reported outcomes (2,4,19,67,77). A more accurate trajectory does not necessarily translate into superior biological or patient-centered outcomes.

External validity is particularly problematic when implant-related findings are extrapolated to periodontal surgery. Periodontal procedures involve deformable and inflamed tissues, bleeding, variable flap positioning, irregular root surfaces and biologically dynamic wound healing. Therefore, implant accuracy data cannot be directly applied to robotic periodontal flap surgery, root-surface instrumentation, connective tissue grafting, or periodontal regeneration.

Additional barriers include high acquisition and maintenance costs, proprietary systems, technical support requirements, training needs, workflow integration and uncertain cost-effectiveness. Future research should use standardized accuracy definitions, prospective multicenter designs, independent outcome assessments, transparent reporting of operator experience, and longer follow-up. Studies should prioritize periodontal- and implant-specific clinical outcomes rather than technical precision alone (2,4,19,67,77).

Overall critical interpretation. The current evidence supports a graded interpretation of these technologies. Static guides and dynamic navigation have established roles in selected implant workflows, although their performance depends on planning quality, guide stability, registration, tracking, and operator factors. Robotic systems demonstrate promising technical precision; however, clinical evidence remains less mature and does not yet establish universal superiority or cost-effectiveness. AI, augmented reality, haptic technologies, and robotic periodontal applications remain primarily adjunctive, developmental, or investigational (2,4,19,77).

The central limitation is the gap between technical feasibility and demonstrated biological or patient-centered benefit. Successful translation into periodontology will require systems capable of accounting for deformable tissues, inflammatory status, tactile feedback, wound biology and the dynamic nature of periodontal healing. Until such evidence becomes available, robotics and navigation should be presented as technologies that may enhance selected components of clinical care rather than as replacements for diagnosis, surgical judgment, or established biological treatment principles (14,21,35,36,51,54,59,77,85,86).

14. Conclusion and future directions

The future of robotics and navigation systems in periodontics and implant dentistry will be closely tied to the continued evolution of AI, machine learning, digital imaging and robotic engineering. These technologies are expected to further improve the precision, efficiency and predictability of surgical

treatment (80,82). AI is likely to play an increasingly critical role in diagnosis and treatment planning. In the future, radiographic data may be automatically analyzed to determine bone quality, identify anatomic landmarks, and generate optimized implant treatment plans with minimal operator intervention (80,85). Machine-learning algorithms may also assist in risk assessment by predicting implant success, the susceptibility to peri-implant disease and patient-specific treatment outcomes. Such capabilities may enable truly personalized implant therapy (85,86). AR technologies are expected to evolve rapidly and may eventually allow clinicians to visualize surgical plans directly through smart glasses or in head-mounted displays. This capability could eliminate the need for external monitoring and enhance ergonomics during navigation-guided surgery. Future robotic systems might evolve from semi-active assistance to higher levels of autonomy. While complete autonomy in implant surgery remains a long-term goal, the ongoing advances in sensor technology, AI and robot control systems are steadily pushing the boundaries of surgical robotics toward more complex capabilities. Digital workflows will also continue to grow in periodontology. Intraoral scanners, CBCT imaging, AI, navigation systems, and robotic technologies may be combined to create seamless digital treatment pathways that improve efficiency and clinical outcomes. As the cost of technology decreases and clinical evidence continues to accrue, robotics and navigation systems will likely become more affordable and used more widely. Their implementation in periodontal and implant practices may eventually result in more accurate, minimally invasive and patient-centered treatment strategies (21,31,35).

In conclusion, the use of robotics and navigation systems represents a major step forward in modern periodontal and implant surgery. These systems have improved surgical precision, and procedural predictability and have decreased operator-dependent variability by combining digital imaging, virtual treatment planning, real-time tracking technologies and robotic assistance. Dynamic navigation systems have become reliable clinical tools that provide both high accuracy and intraoperative flexibility, whereas the use of robot-assisted implant surgery is the latest evolution in computer assisted dental procedures. Current evidence suggests that these technologies may improve implant placement accuracy and favor minimally invasive treatment approaches. The implementation of such technologies in routine practice is still restricted because of limitations such as costs, technical complexity, training needs and the absence of long-term clinical evidence. The future of periodontal and implant surgery is expected to be influenced by the growing incorporation of AI, machine learning, AR and advanced robotic technologies. These innovations may enhance treatment planning, optimize surgical execution, and improve patient outcomes. As technology evolves and more clinical data accumulates, robotics and navigation systems will play an increasingly important role in delivering accurate, personalized and minimally invasive periodontal and implant therapy.

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Authors' contributions

DK was involved in the conceptualization of the study, and in the study methodology, literature search, investigation, the writing of the original draft of the manuscript, in the writing, reviewing and editing of the manuscript, as well as in visualization and project administration. MS was involved in the literature search, investigation, critical revision of the manuscript, in the writing, reviewing and editing of the manuscript and in the validation of findings obtained from the literature. SUN was involved in the study supervision, in the conceptualization of the study, in the critical appraisal of the scientific content, and in the writing, reviewing and editing of the manuscript. All the authors have read and approved the final version of the manuscript and agree to be accountable for all the aspects of the work. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Use of artificial intelligence tools

During the preparation of this work, the authors utilized OpenAI's ChatGPT and Microsoft Copilot and Notebook LM to generate summaries of research articles. Tables and figures related to the topic were then created. These summaries were evaluated by comparison to manually written summaries by experts in the field. Rubriq was also utilized for language editing. Subsequently, the authors revised and edited the content produced by the AI tools as necessary, taking full responsibility for the ultimate content of the present manuscript.

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