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Review

A Structured Engineering Review of Robotic Systems in Craniofacial Surgery: Architecture, Validation, and Accuracy

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Abstract

Robotic technologies are increasingly investigated for craniofacial and dental surgical procedures where sub-millimeter positional accuracy and stable instrument trajectories are essential. This structured review evaluates the current landscape of robotic systems applied to craniofacial surgical interventions and analyzes their technical architectures, validation approaches, and reported surgical accuracy. A structured literature search of PubMed and IEEE Xplore identified 27 studies published between 2015 and 2025 that met predefined inclusion criteria. The included systems were analyzed with respect to robotic control architecture, surgical application domain, validation model, and quantitative performance metrics. To facilitate cross-study interpretation, the review introduces a unified engineering classification framework linking robotic control paradigms, mechanical configurations, and clinical application domains. Most platforms employed master–slave teleoperation, image-guided hybrid control, task-autonomous execution, or cooperative haptic-guided architectures designed to stabilize surgical trajectories and reduce surgeon-dependent variability. Across representative investigations, robotic systems demonstrated entry-point deviations typically ranging from approximately 0.6–1.5 mm and angular deviations between 1.2° and 3.5°, indicating improved reproducibility compared with conventional freehand techniques. Dental implant robotics currently represents the most clinically mature application, whereas sinus, skull base, and microsurgical systems remain largely in experimental or early translational stages. Overall, craniofacial surgical robotics demonstrates substantial potential to enhance surgical precision and procedural standardization; however, broader clinical validation and improved workflow integration remain necessary for widespread clinical adoption.

Keywords: craniofacial robotics; dental implant robotics; surgical robotics; robot-assisted surgery; image-guided surgery

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1. Introduction

1.1. Evolution of Surgical Robotics

Robotic technology has become increasingly prominent in healthcare, supporting applications ranging from prosthetics and rehabilitation to surgical assistance and diag-

nostics [1–6]. One of the key advantages of robotic systems in healthcare is their ability to enhance precision while reducing the risk of human error during procedures.

Additionally, robotic platforms facilitate remote collaboration among medical professionals, enabling specialized care to reach underserved regions. As technology advances, the capabilities of robot-assisted surgery continue to evolve, offering new possibilities for improving patient outcomes. The evolution of surgical robotics has been shaped by decades of interdisciplinary innovation across mechanical engineering, imaging, and computer-integrated surgery [1,3,5–8].

Early robotic systems were developed for industrial automation, but their precision and repeatability soon attracted interest from the medical community. The introduction of the da Vinci Surgical System marked a pivotal moment in minimally invasive surgery and enabled the development of robotic approaches for head and neck procedures such as transoral robotic surgery (TORS) [2,9–12]. Since then, the field has rapidly expanded, with newer platforms incorporating advanced features such as real-time imaging integration, force feedback, and AI-assisted decision support [6,8]. These technological milestones have laid the groundwork for the application of robotics in anatomically complex regions like the craniofacial area, where surgical precision is critical and conventional tools often fall short.

1.2. Clinical Motivation for Craniofacial Robotic Surgery

Surgical robotics has particularly impacted the field of craniofacial and maxillofacial procedures, where precision and control are paramount [1]. The complexity of head and neck anatomy presents challenges for traditional surgical methods, making robotic assistance an attractive option [13,14]. Studies suggest that robotic platforms can improve intraoperative bleeding control and reduce cognitive workload in endoscopic surgeries [15]. Such findings suggest that robotic systems can enhance surgical performance and procedural efficiency compared with conventional approaches [1,16,17].

Precise instrument positioning is particularly critical in craniofacial surgery because the operative field often lies in close proximity to vital neurovascular structures and sensory organs [13]. Small positional deviations during drilling or osteotomy procedures can lead to damage of adjacent anatomical structures, including the infraorbital nerve, maxillary sinus, or cranial base. Consequently, craniofacial procedures frequently require sub-millimeter accuracy and careful trajectory planning [14]. Computer-assisted surgical planning and navigation systems have therefore been widely adopted in cranio-maxillofacial surgery to enhance spatial awareness and reduce the risk of intraoperative error [7,8,18,19]. Robotic platforms extend these capabilities by physically stabilizing instrument trajectories and executing planned movements with high repeatability, which may further improve procedural precision and surgical reproducibility [6]. Figure 1 illustrates examples of medical robotic systems specifically designed for craniofacial surgeries.

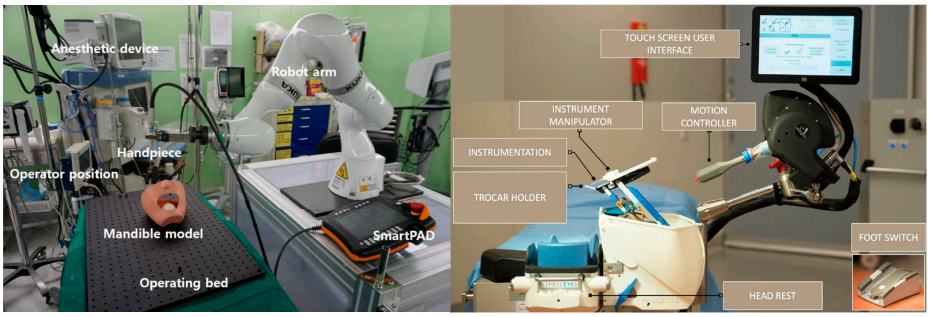

Figure 1. Examples of medical robotic systems. (**left**) An osteotomy robot for mandibular ramus bone harvest adapted from [20] and (**right**) a robotic platform for vitreoretinal surgery adapted from [21].

Craniofacial surgical robotics must operate within a uniquely constrained biomechanical environment. The head and neck region contains dense concentrations of neurovascular structures, narrow anatomical corridors, and rigid osseous boundaries that limit instrument maneuverability [19,22]. Consequently, robotic systems developed for craniofacial procedures frequently incorporate remote center-of-motion (RCM) mechanisms and constrained trajectory planning to maintain stable instrument pivot points and minimize unintended tissue loading [8,23]. Image-guided navigation and robotic actuation must also maintain precise registration between preoperative imaging data and intraoperative anatomical coordinates, as even small deviations can result in clinically significant positioning errors. Previous studies in computer-integrated surgery have emphasized the importance of accurate registration, mechanical rigidity, and trajectory stability when operating near delicate cranial structures [7,8]. These biomechanical and anatomical constraints partially explain why many craniofacial robotic platforms prioritize constrained precision and surgeon-supervised control rather than full autonomy [6].

Robotic platforms are also being developed specifically for craniofacial procedures, particularly in dental and maxillofacial surgeries [10,24]. Many of these systems remain relatively large and complex, limiting their clinical practicality. Optimal implant angulation is essential to ensure functional integration, aesthetic outcomes, and long-term biomechanical stability [24], highlighting the value of robotic platforms in enhancing surgical accuracy and consistency. Precise control of force application is crucial for procedures such as tissue retraction and incision; however, the physical workspace required by existing robotic platforms can be restrictive. Research continues to focus on optimizing robotic designs to balance precision with ergonomic efficiency [6].

1.3. Image-Guided and Computer-Assisted Craniofacial Surgery

Image-guided navigation technologies have played a central role in enabling robotic applications in craniofacial surgery [25,26]. Surgical navigation systems integrate preoperative imaging, typically computed tomography or cone-beam CT, with real-time tracking of surgical instruments [27]. This integration allows surgeons to visualize instrument trajectories relative to patient anatomy during the procedure. Navigation systems have been widely applied in cranio-maxillofacial surgery for procedures such as orbital reconstruction, skull base access, and dental implant placement, where millimeter-scale precision is required [7,18,28,29]. Robotic platforms build upon these navigation frameworks by providing mechanically stabilized execution of planned trajectories, thereby reducing surgeon-dependent variability [30].

The convergence of robotic manipulation and image-guided navigation represents an important technological pathway toward improved reproducibility in craniofacial surgery. In dental implant surgery, computer-assisted and robotic guidance have demonstrated improved placement accuracy compared with manual methods [10,11,18,24,31–35]. Image-guided surgical systems have enabled more precise targeting of craniofacial anatomical structures and improved surgical navigation during complex procedures [8,18,29,36]. Despite these advances, the architectural design, validation methodology, and quantitative surgical performance of craniofacial robotic systems have not been systematically analyzed within a unified engineering–clinical framework.

1.4. Emerging Robotic Systems in Craniofacial Surgery

The integration of robotics in craniofacial procedures extends beyond implants, influencing broader surgical fields such as transoral robotic surgery (TORS) for head and neck cancers [4,37]. Meccariello et al. compared TORS with chemoradiation therapy (CRT) for treating oropharyngeal squamous cell carcinoma, reporting that patients undergoing TORS

required lower dosages of cisplatin and radiation [38]. Additionally, robot-assisted surgery has been linked to increased procedural efficiency and improved surgical safety [4,39]. However, some studies emphasize the need for further refinement of surgical protocols to optimize outcomes [37,40]. For instance, Schiroli et al. noted that successful robot-assisted implant placement depends on meticulous preoperative planning and stability of the surgical guide [41].

While robot-assisted surgery has demonstrated significant benefits, challenges remain in adapting these systems for live surgical environments. Many studies evaluating robotic surgical accuracy rely on cadaveric or synthetic models, which lack the unpredictable physiological movements of live patients, such as involuntary twitches or coughing [42,43]. For procedures performed on living subjects, external stabilizing factors were often employed to minimize patient movement, but such methods may not be applicable across all surgical settings. The need for improved patient stabilization and adaptive robotic systems is an area of ongoing research.

To provide an overview of the types of craniofacial robotic systems identified in the literature, the included studies were categorized according to surgical application and primary technical focus. The resulting classification of reported robotic platforms is summarized in Table 1.

Table 1. Classification of included studies by surgical application and technical focus.

Surgical Application	Key Focus Area	References
Dental Implant Surgery	Autonomous Placement Accuracy	[44–46]
	Haptic Guidance Systems	[47,48]
	Hybrid Robotic Systems	[45,49]
	Critical Perspectives	[50]
Maxillofacial & Craniofacial	Transnasal Surgery Planning	[15,51]
	Zygomatic Implant Precision	[46,52]
	Bone Osteotomy	[53]
	Sinus Surgery (master–slave)	[54]
Head & Neck Oncology	Transoral Robotic Surgery (TORS)	[38]
	Skull Base Tumor Treatment	[33]
Microsurgery	Endodontic Surgery	[47]
	Thread Traction Control	[55]
	Endoscopic Tissue Manipulation	[40]
Middle Ear Surgery	Kinesthetic Teaching Systems	[56]
Technical Innovations	Real-Time Instrument Tracking	[57]
	Calibration Error Compensation	[58]
	Robotic Platform Design	[57,59]
	Bone Milling Perception	[39]
Comparative Studies	Robotic vs. Freehand/Navigating	[41,45,60]

Comparative studies between robot-assisted and conventional craniofacial procedures are essential to determine whether robotic technology significantly enhances surgical precision and patient outcomes. He et al. and Liang et al. demonstrated that robotic systems, coupled with advanced mapping algorithms, improved stability and maneuverability in trans nasal surgeries [51]. In soft tissue procedures, Li et al. applied an enhanced framework to the da Vinci Surgical System, achieving precise operations [40]. Similarly, Yoon et al. found that robotic procedures utilizing flexible end-effectors and navigation software improved surgical precision in sinus surgeries [54]. Meanwhile, Fanhao et al. assessed the use of "Remebot" in skull base tumor treatments, concluding that the system was safe, reliable, and stable, though further research is needed on insertion-needle deformation mechanics [33]. These studies highlight the potential of robot-assisted surgery while acknowledging areas for further refinement.

Advancements in robot-assisted surgical systems continue to improve precision and effectiveness, with ongoing efforts to refine surgical protocols. Volumetric compensation techniques, such as those studied by Vicentini et al., have contributed to increased calibration accuracy [58]. Additionally, the incorporation of tracking mechanisms has been shown to enhance surgical precision. Despite these advancements, there remains a need for further research to address the adaptability of robotic systems in dynamic surgical environments.

In specific craniofacial applications, robotic systems have demonstrated measurable improvements in positional accuracy and procedural reproducibility [61]. In middle ear surgery, kinesthetic teaching systems have helped stabilize surgeon movements, improving procedural outcomes [56]. Haptic and robotic guide systems have also been successfully implemented for procedures involving the maxilla and mandible [48], chin [53], microsurgery [55], and endodontics [47]. The use of haptic guidance systems, in particular, has enhanced precision while minimizing human error [62]. Unlike fully autonomous systems, these haptic devices work in conjunction with the surgeon's manual input, allowing greater control while maintaining the benefits of robotic precision.

Overall, the increasing integration of robotics in craniofacial surgery represents a shift toward precision-driven surgical techniques. While robotic systems offer improved accuracy, reduced operative fatigue, and improved patient outcomes, continued research is needed to address challenges related to adaptability, real-time responsiveness, and patient stabilization. The following sections examine the literature surrounding robot-assisted craniofacial procedures, highlighting key advancements, technical challenges, and future directions in the field.

1.5. Technical Architecture of Craniofacial Surgical Robots

While the preceding studies highlight clinical and experimental robotic systems applied to craniofacial procedures, these platforms also differ substantially in their underlying control architectures and mechanical configurations. Understanding these technical differences is important for interpreting reported performance outcomes and translational readiness.

In addition to procedural categorization, the reviewed robotic systems can also be understood through a technical classification framework. This framework facilitates comparison across diverse robotic systems by consistently linking control strategies, mechanical configurations, and clinical applications within a unified analytical structure. The descriptions are intended to balance technical accuracy with accessibility for both engineering and clinical audiences. From a control perspective, platforms applied to craniofacial surgery generally fall into three broad architectures: master–slave teleoperation, image-guided hybrid systems, and task-autonomous systems. Master–slave configurations, such as those used in sinus and maxillary applications [54], emphasize tremor reduction and remote center

of motion (RCM) stability. Image-guided hybrid systems integrate preoperative planning and navigation constraints with robotic actuation to enhance positional accuracy [45,49]. Task-autonomous platforms, particularly in dental implant placement, execute preplanned drilling sequences under supervisory control [46,52]. Cooperative or haptic-guided systems maintain direct surgeon manipulation while enforcing geometric constraints to reduce deviation [47,48]. This technical stratification reveals that most craniofacial robotic platforms prioritize constrained precision rather than full autonomy.

Mechanical configuration further differentiates these systems. Serial manipulators incorporating RCM mechanisms are frequently employed in transnasal and endoscopic procedures to maintain stable pivot points [51,54]. In contrast, parallel or hybrid kinematic systems, including Stewart-platform-based architectures, are more commonly observed in dental implant robotics, where stiffness and micrometer-scale accuracy are critical [49,63]. Flexible or tendon-driven systems are utilized in applications requiring navigation through confined anatomical corridors [16,64]. These design patterns reflect the biomechanical demands of craniofacial anatomy and underscore the importance of structural rigidity, constrained motion, and registration stability in this domain.

To better contextualize the diversity of robotic platforms identified in the literature, the reviewed systems can be categorized according to their control architecture and level of autonomy. These architectures reflect different strategies for integrating robotic actuation with surgeon control and image guidance. Table 2 summarizes the primary robotic system paradigms observed across craniofacial surgical applications. The structured methodology and consistent extraction of technical and performance variables further enable systematic and reproducible comparison across studies despite variability in reporting formats. This review introduces a unified engineering classification framework that relates robotic control architecture, mechanical configuration, and surgical application domains in craniofacial surgery.

This classification highlights the diversity of robotic approaches across craniofacial surgical domains, ranging from implant placement systems to microsurgical robotic platforms. Importantly, most craniofacial robotic systems prioritize constrained precision and trajectory stability rather than full surgical autonomy, reflecting the safety-critical nature of operations in the head and neck region [65,66]. By integrating engineering system architecture analysis with reported surgical accuracy metrics and validation models, this review aims to provide a comprehensive overview of the current technological maturity of craniofacial surgical robotics.

While prior review articles have examined surgical robotics and related navigation technologies, most have focused on individual clinical applications, specific subspecialties, or enabling technologies such as image guidance and navigation systems. These studies provide valuable clinical or technical insights but typically do not integrate robotic control architecture, validation methodology, and quantitative performance metrics within a unified analytical framework. Moreover, few reviews explicitly compare robotic systems across craniofacial domains using consistent engineering criteria or assess translational maturity in relation to validation models and reported accuracy.

Accordingly, a gap remains in the literature for a structured, cross-disciplinary synthesis that links system architecture, validation approaches, and surgical performance metrics. This review addresses this gap by systematically identifying relevant studies and applying a unified engineering–clinical framework to enable consistent comparison and interpretation across diverse craniofacial robotic platforms.

Table 2. Technical classification of robotic systems used in craniofacial surgical procedures.

Robotic Architecture	Control Strategy	Typical Applications	Key Technical Characteristics
Master–slave teleoperation	Surgeon-controlled robotic manipulation with motion scaling and tremor filtering	Sinus surgery, transnasal procedures	Remote center of motion (RCM) constraints, improved dexterity, tremor suppression
Image-guided hybrid systems	Preoperative imaging and navigation integrated with robotic actuation	Dental implant placement, skull base procedures	Registration between imaging and robot coordinate frames enables precise trajectory execution
Task-autonomous robotic systems	Robot executes preplanned surgical steps under supervisory control	Dental implant drilling and placement	Automated trajectory following, high positional repeatability
Cooperative or haptic-guided systems	Surgeon manipulates instrument while robot enforces geometric constraints	Endodontic surgery, implant guidance	Shared control architecture maintains surgeon input while reducing deviation
Flexible or continuum robotic systems	Cable-driven or tendon-driven manipulators navigating constrained anatomical spaces	Skull base and endoscopic procedures	High dexterity in confined surgical corridors

The objective of this review is to systematically evaluate the current landscape of robotic systems applied to craniofacial procedures, synthesize reported performance outcomes, and identify technical and translational challenges that may influence future development and clinical integration [67,68]. To guide this review, the following research questions are considered: (RQ1) What robotic control architectures are currently used in craniofacial and dental surgery? (RQ2) How are these systems validated across experimental and clinical settings? (RQ3) What levels of surgical accuracy are reported across different robotic approaches? Figure 2 summarizes the conceptual relationships between robotic control paradigms, mechanical architectures, and their typical surgical applications in craniofacial procedures. To systematically characterize the technical architectures, validation approaches, and performance outcomes reported in craniofacial surgical robotics, a structured literature review methodology was implemented [69,70].

Unlike prior reviews that primarily focus on individual clinical applications or navigation technologies, this review systematically integrates robotic system architecture, validation methodology, and quantitative surgical accuracy metrics [65,69,71,72]. In particular, this review systematically analyzes robotic control architectures, including master–slave, hybrid, and autonomous systems, to facilitate comparison across different robotic platforms. This combined engineering–clinical framework enables a clearer assessment of the technological maturity and translational readiness of craniofacial surgical robotics. The primary contribution of this review is the integration of robotic system architecture, validation

methodology, and quantitative surgical performance into a unified engineering–clinical framework that enables cross-disciplinary interpretation and comparison.

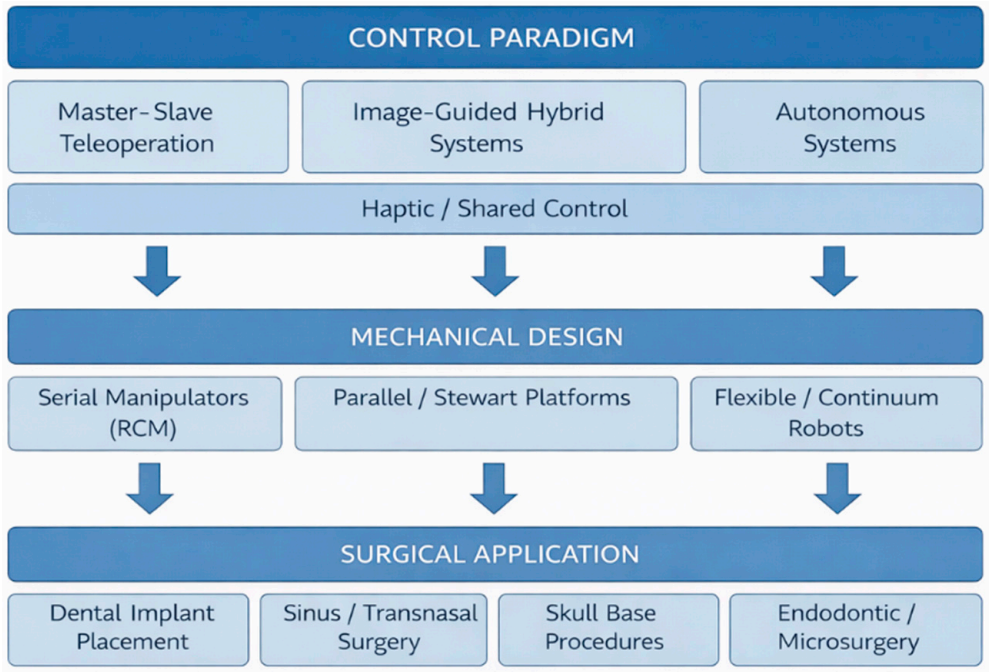

Figure 2. Conceptual classification of craniofacial surgical robotic systems. Framework illustrating relationships between robotic control paradigms, mechanical architectures, and surgical applications in craniofacial procedures.

2. Materials and Methods

This structured review was conducted using a systematic literature search strategy informed by PRISMA 2020 guidelines [73] (see Supplementary Materials). A predefined search strategy, explicit inclusion and exclusion criteria, and sequential screening procedures were implemented to ensure a structured and reproducible study selection process. Given the interdisciplinary nature of craniofacial surgical robotics, which spans both biomedical and engineering domains, methodological adaptations were applied to accommodate heterogeneous study designs and reporting standards [70]. Due to substantial heterogeneity in validation models, experimental designs, and outcome definitions, a qualitative synthesis approach was adopted rather than statistical meta-analysis. No automation tools were used in the screening process. This review was not prospectively registered.

2.1. Information Sources and Search Strategy

A structured literature search was conducted on 14 October 2025, to identify studies describing robotic systems directly applied to craniofacial surgical procedures. Two electronic databases were searched: PubMed and IEEE Xplore. PubMed was selected to capture clinical and biomedical publications, while IEEE Xplore was included to identify engineering-oriented robotic system developments that may not appear in traditional medical databases.

These databases were selected to capture both clinical biomedical publications and engineering-focused robotic system development studies, which are often indexed in separate academic repositories. Because craniofacial surgical robotics spans both biomedical and engineering disciplines, PubMed and IEEE Xplore together provide broad coverage of the relevant literature. Although additional databases such as Scopus or Web of Science may include related publications, preliminary searches indicated substantial overlap with PubMed-indexed biomedical studies and IEEE engineering conference proceedings. There-

fore, these databases were considered sufficient to capture the majority of clinically and technically relevant publications in this field.

The search strategy combined anatomical descriptors ("cranial," "head," "facial," "oral," and "dental") with procedural terminology ("surgery") and robotic system keywords ("robot," "robotic," or "robot-assisted"). Searches were conducted using article title, abstract, and keyword fields as supported by each database. Boolean operators were used to ensure inclusion of craniofacial surgical contexts while excluding unrelated robotic domains such as humanoid robotics or augmented-reality navigation systems without robotic actuation.

The core search structure was: ("craniofacial" OR "head and neck" OR oral OR dental OR maxillofacial) AND (surgery OR surgical) AND (robot OR robotic OR robot-assisted) AND (navigation OR guidance OR positioning OR tracking OR assistance). The inclusion of navigation- and guidance-related terms (e.g., "navigation," "guidance," "positioning," "tracking," and "assistance") was intentional to ensure that retrieved studies involve robotic systems with explicit control, guidance, or execution capabilities in surgical contexts. This constraint was applied to maintain consistency within the analytical framework of the review, which focuses on systems that actively influence surgical trajectory or execution. Consequently, studies involving robotic technologies without defined guidance or control mechanisms may be underrepresented.

Search strings were adapted to the syntax of each database. No database filters were applied beyond language (English) and publication date (1 January 2015 through 14 October 2025). The date restriction was selected to reflect contemporary robotic systems incorporating image guidance, navigation integration, and advanced control architectures.

2.2. Inclusion and Exclusion Criteria

Studies were included if they: (1) Described robotic systems applied to craniofacial, dental, or maxillofacial surgical procedures; (2) Reported system design, implementation, or experimental validation; (3) Were published in peer-reviewed journals or conference proceedings. Studies were excluded if they: (1) Did not involve active robotic actuation in surgical tasks; (2) Focused solely on virtual simulation, augmented or virtual navigation without robotic execution, or non-surgical robotic applications; (3) Were review articles, editorials, or abstracts without full text.

2.3. Study Selection Process

The initial search yielded 45 records, comprising 43 articles from PubMed and 2 from IEEE Xplore. All records were exported and screened manually, and no duplicate records were identified across the databases. Titles and abstracts were reviewed to exclude articles not directly involving robotic systems performing or assisting craniofacial, dental, or maxillofacial surgical procedures. Full-text articles were subsequently assessed for eligibility based on the predefined inclusion and exclusion criteria. Study selection was conducted through sequential screening of titles, abstracts, and full-text articles based on predefined eligibility criteria. After application of all criteria, 27 studies were retained for final analysis. Screening and eligibility assessment were performed through manual review of titles, abstracts, and full-text articles. The study selection process followed PRISMA 2020 guidelines and is summarized in Figure 3.

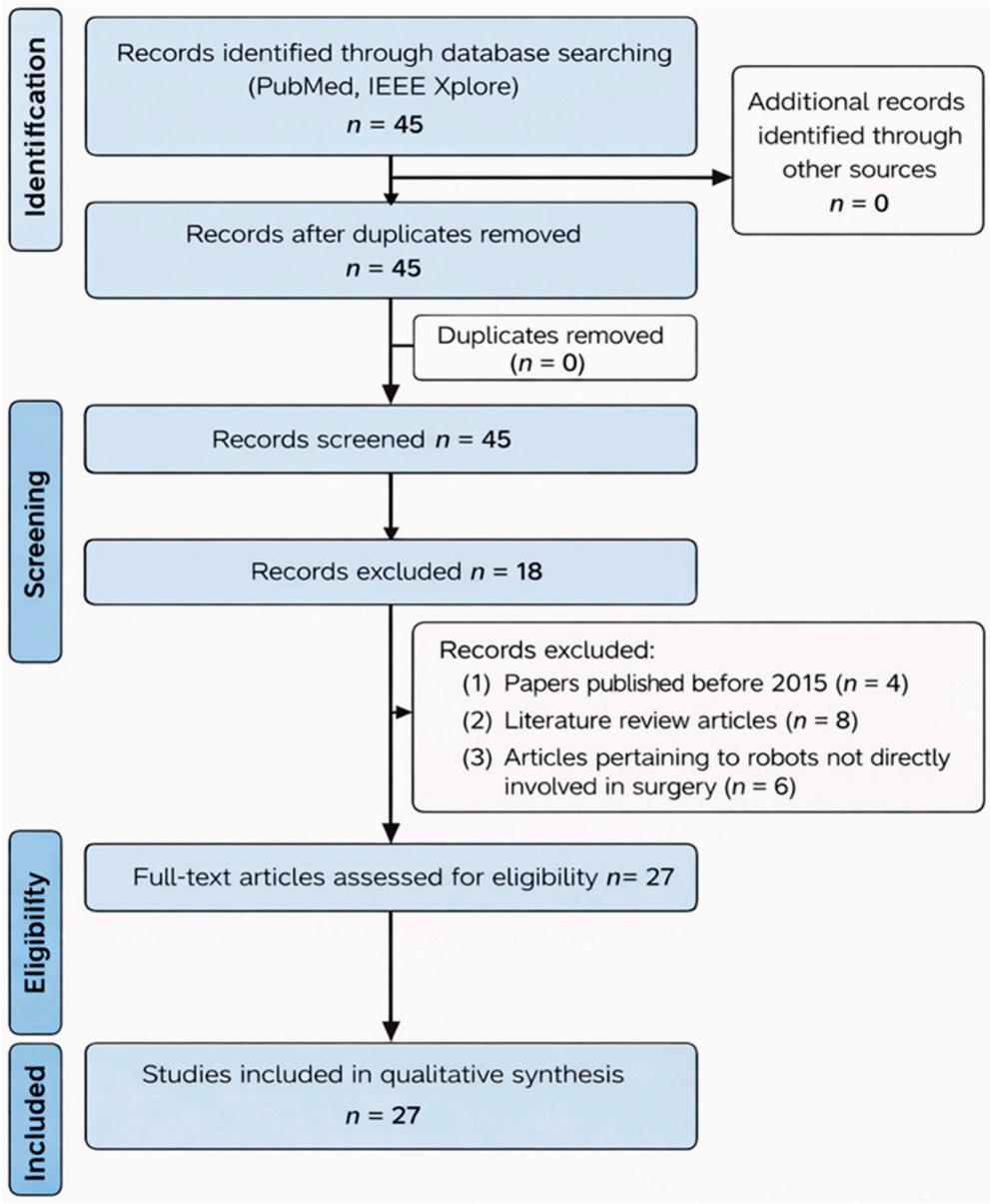

Figure 3. PRISMA 2020 flow diagram of study selection. Records were identified through database searching, screened based on titles and abstracts, and assessed for eligibility through full-text review, resulting in 27 studies included in the final analysis.

2.4. Data Extraction

For each included study, key information was extracted regarding robotic system architecture, surgical application, validation model (in vitro, cadaveric, or clinical), and reported performance metrics. When available, quantitative accuracy measures such as entry-point deviation, angular deviation, and trajectory stability were recorded to facilitate cross-study comparison. Because reporting formats differed across studies, extracted metrics were summarized descriptively rather than pooled for statistical meta-analysis due to heterogeneity in study design, validation models, and outcome reporting [74].

2.5. Risk of Bias and Data Synthesis

Because the included studies consist primarily of heterogeneous engineering validation experiments and early translational investigations rather than randomized clinical trials, conventional clinical risk-of-bias assessment tools were not applied. Instead, study quality was interpreted using a structured qualitative appraisal framework considering val-

idation model (in vitro, cadaveric, or clinical), degree of experimental control, and reporting of quantitative performance metrics. This approach enables consistent interpretation of methodological rigor across diverse study designs while acknowledging the limitations of applying traditional clinical appraisal tools to engineering-focused research [70,75]. This structured qualitative appraisal approach is consistent with systematic review methodologies applied to heterogeneous preclinical and engineering-focused studies, where conventional clinical risk-of-bias tools are not directly applicable.

3. Results

The 27 included studies were analyzed with respect to robotic system architecture, validation methodology, and quantitative surgical accuracy metrics to characterize the technological maturity of craniofacial robotic systems. The Section 3 synthesizes quantitative performance metrics reported across the included studies rather than presenting newly generated experimental data. The relatively small number of studies reflects the emerging nature of craniofacial surgical robotics, where many systems remain in early engineering or translational development stages. Dental implant robotics represented the most clinically mature application, whereas sinus, skull base, and microsurgical systems remain primarily in experimental or early translational stages.

The methodological characteristics of the literature indicate that the field remains largely focused on technical validation. Of the 27 included studies, the majority were conducted under controlled laboratory conditions. In vitro investigations accounted for a substantial portion of the corpus [45,46,52], while cadaveric validation studies were also common [41,54]. A smaller subset involved limited clinical implementation, primarily in dental implant applications [44,54,76]. No randomized controlled trials were identified.

Across the selected literature, robotic platforms were generally categorized into several architectural paradigms. Master–slave teleoperation systems were frequently employed in sinus and transnasal procedures, emphasizing remote center-of-motion (RCM) stability and tremor suppression [51,54]. Image-guided hybrid systems integrated preoperative imaging and navigation constraints with robotic actuation to enhance positional accuracy [49,52,53,76]. Task-autonomous systems were predominantly observed in dental implant placement, where preplanned drilling trajectories were executed under supervisory control [15,52,76]. Cooperative or haptic-guided systems preserved surgeon manipulation while enforcing geometric constraints to reduce deviation and improve repeatability [47,48]. Although autonomy levels varied, most systems prioritized constrained precision rather than complete independent execution.

Despite heterogeneity in reporting formats, quantitative performance improvements were consistently observed. In dental implant robotics, reported entry-point deviations typically ranged between approximately 0.6 and 1.5 mm, with angular deviations frequently reported between 1.2° and 3.5° in both experimental and pilot clinical settings [44,45,60]. Comparative studies demonstrated reduced variability relative to freehand or static computer-assisted techniques [60]. Autonomous systems also showed improved reproducibility across operators with differing experience levels, suggesting a potential role in procedural standardization [44]. Zygomatic implant placement, involving deeper and more complex trajectories, demonstrated slightly greater deviation ranges but maintained improved consistency compared to navigation-only approaches [46,52]. Hybrid systems employing Stewart-platform architectures achieved high mechanical stiffness and micrometer-scale stability under laboratory conditions [49].

It is important to note that accuracy metrics reported across studies are not fully standardized. Some studies report entry-point deviation, others report target (apex or vertex) deviation, and others report angular deviation. Because these metrics are influenced

by measurement protocols, anatomical references, and validation models, direct quantitative comparisons across studies should be interpreted cautiously. Reported values are therefore best understood as indicative performance ranges rather than strictly comparable benchmarks.

Across studies, variations in measurement protocols, anatomical reference definitions, imaging modalities, and validation models further limit direct comparability of reported accuracy values. Experimental conditions range from synthetic models to cadaveric specimens and early clinical studies, contributing to heterogeneity in reported outcomes. Nevertheless, the consistent observation of sub-millimeter entry-point accuracy across multiple robotic platforms suggests that robotic actuation can reduce variability associated with manual surgical execution and improve procedural reproducibility in precision-dependent craniofacial interventions. To facilitate comparison, principal quantitative accuracy metrics are summarized in Table 3 alongside key system characteristics.

Table 3. Representative quantitative accuracy metrics reported for robotic craniofacial surgical systems.

Study	Surgical Application	Validation Model	Entry-Point Deviation	Angular Deviation	Key Finding
Tao et al., 2023 [45]	Dental implant placement	In vitro	~0.7–1.0 mm	~2.0–3.0°	Hybrid image-guided robotic system improved placement accuracy compared with manual approaches
Wang et al., 2024 [44]	Dental implant placement	Pilot clinical study	~0.8–1.3 mm	~2.5–3.5°	Autonomous robotic system demonstrated high reproducibility across clinical cases
Chen et al., 2025 [46]	Zygomatic implant placement	In vitro	~1.2–1.6 mm	~3.0–3.8°	Robotic system showed improved accuracy compared with navigation-only techniques
Su et al., 2024 [60]	Implant placement comparison	In vitro	~1.0–1.4 mm	~2.5–3.5°	Robot-assisted placement reduced variability relative to freehand and static guides
Li et al., 2023 [76]	Implant placement in edentulous patients	Retrospective clinical series	~0.9–1.5 mm	~2.0–3.2°	Autonomous system enabled consistent implant placement in complex anatomical conditions
Deng et al., 2023 [52]	Zygomatic implant robotic drilling	In vitro	~1.2–1.8 mm	~3.0–4.0°	Semi-autonomous robotic drilling demonstrated improved trajectory consistency

Although reporting formats varied across publications, most studies evaluated entry-point deviation and angular deviation relative to preoperative planning trajectories. Across experimental and pilot clinical investigations, robotic systems generally demonstrated sub-millimeter positional deviations and angular deviations within a few degrees, indicating substantial improvements in reproducibility compared with traditional freehand approaches. These findings should be interpreted in the context of study heterogeneity, variability in measurement protocols, and limited availability of high-level clinical validation. Representative quantitative accuracy metrics are summarized in Table 3 to illustrate typical performance ranges across studies.

In sinus and transnasal applications, evaluation focused less on implant deviation metrics and more on trajectory planning and RCM stability. Robotic path-planning algorithms improved maneuverability within constrained anatomical corridors [51], and dual master–slave systems demonstrated stable sinus access with enhanced positional control [54]. Skull base applications, including automatic radioactive seed placement systems, demonstrated feasibility in phantom models, though validation under dynamic clinical conditions remains limited [33].

Additional studies addressed calibration, perception, and tracking challenges inherent to image-guided robotic surgery. Calibration error analysis and compensation strategies were reported in multi-robot surgical platforms [58], highlighting the importance of systematic error management. Machine learning-based perception frameworks demonstrated high accuracy in recognizing bone milling states [39], while vision-based instrument tracking systems achieved strong detection performance but exhibited latency limitations that may restrict real-time responsiveness [57].

Overall, while technical precision improvements are consistently reported, the evidence base remains weighted toward engineering validation. Most studies were conducted in vitro or in cadaveric models, allowing controlled measurement of deviation but not fully replicating physiological motion, bleeding, or intraoperative variability. Reports of statistical dispersion, long-term clinical outcomes, workflow integration, and cost-effectiveness remains limited. The literature therefore reflects a field in translational progression, with dental implant robotics demonstrating the highest level of clinical integration [44,76], while sinus and skull base robotic systems remain in earlier stages of adoption. These findings highlight a clear translational gap between engineering validation and large-scale clinical adoption.

4. Discussion

The results of this structured review highlight several consistent trends across the literature regarding system architecture, validation maturity, and reported surgical accuracy. Although numerous robotic platforms have been proposed for craniofacial procedures, their translational maturity varies considerably across applications. Dental implant robotics currently represents the most clinically advanced domain, with several systems progressing beyond experimental validation. Dental implant robotics demonstrates relatively higher clinical maturity due to structured workflows and well-defined trajectories, whereas sinus and skull base applications remain in earlier translational stages due to anatomical complexity and validation challenges. In contrast, robotic platforms developed for sinus, skull base, and microsurgical applications remain largely in early engineering or translational stages. Collectively, the reviewed studies demonstrate that robotic assistance can improve procedural accuracy, consistency, and trajectory stability in craniofacial surgery. In addition to summarizing reported surgical performance, this review provides a unified engineering classification framework that links robotic control architecture, mechanical configuration, and validation maturity across craniofacial surgical applications.

The findings of this review address the research questions by demonstrating that (RQ1) craniofacial robotic systems primarily employ master–slave, hybrid, and task-autonomous control architectures; (RQ2) validation is predominantly conducted through in vitro and cadaveric models with limited clinical translation; and (RQ3) reported surgical accuracy achieves sub-millimeter precision, although results remain heterogeneous across studies.

Taken together, the reviewed studies indicate that robotic systems consistently achieve sub-millimeter positional accuracy and reduced angular deviation compared with conventional techniques, particularly in dental implant applications where trajectory constraints and preoperative planning are well defined. However, most investigations remain focused on technical performance metrics rather than long-term clinical outcomes. This distinction underscores the current transitional phase of craniofacial robotics, where engineering validation precedes comprehensive clinical validation.

An important observation emerging from this review is the rapid convergence of surgical robotics, computer-integrated surgery, and intelligent sensing technologies. Many modern craniofacial robotic platforms integrate navigation systems, perception algorithms, and cooperative control architectures. This convergence suggests that future craniofacial surgical robots will increasingly function as integrated surgical intelligence systems rather than purely mechanical manipulators, combining robotic precision with intelligent sensing and decision support.

4.1. Robotic Assistance in Dental Implant Procedures

Robotic and computer-guided assistance in dental implant procedures has been widely studied, particularly regarding improvements in placement accuracy and reproducibility [10,11,18,24,31,32]. Chen et al. compared the accuracy of zygomatic implant placement using a task-autonomous robotic system versus a dynamic navigation approach. Their study demonstrated that the robotic system provided superior precision in vitro, reducing deviations in implant placement [46]. Similarly, Li et al. examined the accuracy of autonomous robotic surgery for dental implant placement in fully edentulous patients. The retrospective case series study found that robotic assistance significantly enhanced surgical precision and reliability, supporting its use in complex implant cases [76]. Further research from Tao et al. investigated a novel image-guided hybrid robotic system for dental implant placement. Their findings reinforced previous results, highlighting that robotic guidance improved placement accuracy compared to freehand methods [60]. These studies collectively suggest that robotic systems provide a reliable and precise alternative to traditional implant placement techniques.

4.2. Expanding Applications of Robotics in Oral Surgery

Beyond dental implant procedures, robotic systems have also been applied to zygomatic implant placement and endodontic microsurgery. Research by Chen et al. examined the role of task-autonomous robotic assistance in zygomatic implant placement and found that it outperformed dynamic navigation methods in accuracy [46]. Additionally, Isufi et al. presented a case report on robot-assisted and haptic-guided endodontic surgery, highlighting improved precision and a reduction in intraoperative errors [47]. Su et al. further explored the impact of robotic assistance on endodontic microsurgery, reporting enhanced accuracy and reduced operation time, which contributed to greater efficiency in clinical settings [60]. These findings underscore the versatility of robotic systems in oral surgery and their potential to optimize both surgical precision and efficiency.

4.3. Consistency and Reliability of Robot-Assisted Surgery

One of the major advantages of robot-assisted surgery is its ability to standardize procedures and enhance consistency across different experience levels. Wang et al. conducted a study to assess the precision and reliability of robot-assisted implant surgery, finding that robotic guidance significantly reduced variability in implant placement among surgeons with varying levels of experience. The study also highlighted a steep yet consistent learning curve for robotic implant surgery, suggesting that such systems could contribute to procedural standardization and improved clinical predictability. Additionally, quantitative analysis revealed minimal deviations in implant placement, reinforcing the reliability of robot-assisted techniques in dental surgery [44]. These findings indicate that robotic systems can help mitigate skill-related variability, ensuring more consistent surgical outcomes.

Another important implication of robot-assisted surgery involves surgical education and training. Traditional craniofacial procedures require extensive manual experience to achieve consistent implant positioning and trajectory control. Robotic systems may partially reduce this learning barrier by providing guidance constraints, trajectory stabilization, and real-time feedback during surgical execution. Some robotic platforms also incorporate kinesthetic teaching or demonstration modes, allowing experienced surgeons to record optimal trajectories that can later be reproduced by the robotic system [56]. Such capabilities could contribute to more standardized surgical training and potentially shorten the learning curve associated with complex craniofacial procedures.

4.4. Technical Challenges in Robotic Surgery

Despite the benefits of robot-assisted surgery, several technical challenges remain, particularly in real-time responsiveness and system design. Lin et al. investigated automation in laparoscopic instrument tracking and found that while the system achieved high precision (recall rate of 0.83), its detection time exceeded 5000 ms, making it too slow for real-time surgical applications [57]. Similarly, Rosen et al. developed a rotoscope with 12 degrees of freedom for minimally invasive surgery. Their study addressed key design considerations, such as reducing cable friction and improving system durability, to enhance surgical performance [16]. These challenges highlight the need for further technological advancements to improve the real-time responsiveness and mechanical reliability of robotic surgical systems.

From an engineering perspective, achieving reliable robotic performance in craniofacial surgery requires precise integration of mechanical stiffness, sensor feedback, and control algorithms capable of compensating for physiological motion. Small positional errors can translate into clinically significant deviations when operating near critical neurovascular structures [6,77]. This heterogeneity in reported metrics further limits direct cross-study comparison and highlights the need for standardized evaluation protocols in future work.

4.5. Autonomy in Robotic Surgery

The level of autonomy in robotic surgical systems varies, ranging from semi-autonomous assistance to fully autonomous execution. Dibart et al. described the YOMI platform, which employs a tracking arm and intraoral splint for dental implant procedures, allowing guided yet surgeon-controlled interventions [50]. More advanced robotic systems, such as the semi-autonomous two-stage dental robot examined by Deng et al., are designed to perform sequential drilling procedures with minimal human intervention [52]. Additionally, Feng et al. introduced an image-guided hybrid robotic system that utilizes a Stewart platform for enhanced precision in dental implant placement [49]. These studies suggest

that as robotic systems evolve, increasing levels of autonomy may further improve surgical efficiency and precision.

4.6. General Benefits of Robotics in Surgery

Robot-assisted surgery offers several measurable advantages including motion scaling, tremor filtering, improved dexterity, and enhanced visualization during complex procedures [1,3,6,17,78]. These characteristics contribute to improved procedural precision, surgeon ergonomics, and potentially faster postoperative recovery. Additionally, robotic systems may improve surgeon ergonomics and reduce fatigue during complex procedures [1,17,36]. This increased efficiency not only improves patient care but also enhances overall workflow in surgical settings. These benefits highlight the growing role of robotics in modern surgical practice, particularly in complex and precision-dependent procedures.

4.7. Engineering Design Considerations for Craniofacial Surgical Robots

Robotic systems designed for craniofacial surgery must satisfy a unique combination of mechanical and control requirements. Unlike abdominal surgical robots, which operate within relatively large workspaces, craniofacial robotic systems must function within compact anatomical regions where even small mechanical deflections can affect surgical outcomes. As a result, system stiffness, calibration accuracy, and kinematic constraint mechanisms play a critical role in determining overall performance. Parallel and hybrid kinematic architectures are often used in dental implant robotics because they provide high structural rigidity and positional repeatability. In contrast, flexible or continuum manipulators are frequently explored for skull base and sinus applications, where instruments must navigate curved anatomical pathways. These design strategies reflect the broader engineering challenge of balancing dexterity with stability in surgical robotics. Previous studies in medical robotics have emphasized that surgical robot architectures must be tailored to specific anatomical tasks, with careful consideration of kinematic constraints, sensing capabilities, and surgeon interaction models [6,77].

4.8. Broader System-Level Considerations

Beyond procedural accuracy, craniofacial robotic systems must be evaluated within biomechanical, ergonomic, and translational contexts. The head and neck region presents complex anatomical constraints, including limited access corridors and proximity to critical neurovascular structures. Maintenance of a stable remote center of motion is particularly important in transnasal and sinus applications to prevent unintended tissue stress [51,54]. Bone density heterogeneity also influences drilling mechanics and implant stability, and perception-based monitoring frameworks have been proposed to enhance intraoperative feedback during bone milling [39]. Human factors similarly influence clinical integration. Robotic systems have been shown to reduce variability between operators of differing experience levels [44], suggesting potential benefits in procedural standardization. However, workflow complexity increases due to imaging registration and calibration requirements. Haptic-guided systems attempt to balance surgeon control with robotic constraint enforcement [47,48], potentially improving usability and confidence.

Economic, regulatory, and translational considerations remain central to the broader adoption of surgical robotics in clinical practice [60,77,79]. However, comprehensive cost-effectiveness analyses remain limited.

Dental implant robotics appears to represent the most mature translational application [44,76], whereas skull base and sinus robotic systems remain in earlier developmental stages [33]. Sustained integration into routine clinical practice will likely depend on long-term outcome validation and workflow efficiency improvements.

An important characteristic of many contemporary craniofacial robotic systems is the emphasis on cooperative human–robot interaction rather than full automation. Shared-control architectures allow surgeons to maintain direct manipulation of surgical instruments while robotic systems enforce geometric constraints that prevent deviation from planned trajectories. This cooperative paradigm is particularly advantageous in safety-critical surgical domains, where maintaining surgeon authority over decision-making remains essential. As sensing technologies and control algorithms continue to evolve, future craniofacial robotic systems are likely to incorporate more sophisticated human–robot collaboration frameworks that combine surgeon intuition with robotic precision [77,79].

4.9. Translational Barriers to Clinical Adoption

Despite promising technical performance, several translational barriers continue to limit the widespread clinical adoption of craniofacial robotic systems. One challenge involves workflow integration within existing surgical environments. Robotic systems require imaging acquisition, patient registration, calibration procedures, and system setup that can increase overall procedure time if not carefully optimized. Regulatory approval processes also represent a significant barrier, as surgical robots must demonstrate safety, reliability, and clinical benefit before widespread deployment. Economic considerations further influence adoption, as hospitals must evaluate capital costs, maintenance requirements, and potential improvements in surgical outcomes when determining whether to invest in robotic platforms. Previous analyses of surgical robotics have highlighted that successful translation from engineering prototypes to clinical tools requires not only technical accuracy but also demonstrated cost-effectiveness, surgeon acceptance, and workflow efficiency [79]. Addressing these translational factors will be essential for expanding the role of robotics in craniofacial surgery.

4.10. Limitations

Several limitations should be considered when interpreting the findings of this review. First, the literature search was restricted to publications between 2015 and 2025 and to English-language articles, which may have excluded relevant studies. Although the selected databases provide broad coverage of biomedical and engineering literature, some relevant studies indexed elsewhere may not have been captured. Second, the available literature is heavily concentrated on dental implant robotics, limiting broader generalization to other craniofacial procedures such as sinus, skull base, or microsurgical applications. Third, significant heterogeneity exists in how studies report accuracy metrics, including entry-point deviation, apex deviation, and angular error, which makes direct comparison between robotic systems challenging. Finally, most studies were conducted in vitro or using cadaveric models, with relatively few clinical investigations, indicating that the field remains in an early translational stage.

The search strategy intentionally incorporated navigation- and guidance-related terminology to ensure inclusion of systems with explicit robotic control. While this supports consistency within the analytical framework, it may introduce bias toward navigation-oriented systems and underrepresent studies using alternative terminology or non-navigation-based robotic approaches.

In addition, the engineering-oriented nature of the literature results in heterogeneous reporting of experimental protocols, accuracy metrics, and validation environments, which limits the ability to perform standardized meta-analysis or direct statistical comparison across studies.

4.11. Future Directions in Craniofacial Surgical Robotics

Future research in craniofacial surgical robotics is expected to focus on integrating artificial intelligence, advanced sensing technologies, and adaptive control strategies to enhance surgical precision and safety. Future research should prioritize standardized evaluation protocols, multicenter clinical validation, real-time motion compensation, and improved integration into surgical workflows to support broader clinical adoption. Recent studies have explored machine learning-based perception frameworks capable of identifying surgical states, recognizing bone–tool interaction patterns, and detecting deviations from planned trajectories during robotic procedures [39,77]. These approaches may allow robotic systems to provide real-time feedback and decision support, improving situational awareness and enabling more intelligent surgical assistance.

Another important research direction involves the development of motion-compensation strategies to address physiological patient movement during live surgical procedures. Many robotic systems are currently validated under static laboratory conditions; however, intraoperative factors such as respiration, tissue deformation, and involuntary patient motion can introduce positioning errors. Integration of real-time tracking systems, predictive motion models, and closed-loop robotic control may allow future surgical robots to dynamically adjust trajectories and maintain sub-millimeter targeting accuracy in dynamic clinical environments.

Advances in multimodal sensing and human–robot interaction are also expected to shape the next generation of craniofacial surgical robots. The incorporation of force sensing, haptic feedback, and vision-based navigation may enhance surgeon awareness of tissue interaction and improve intraoperative control. Rather than pursuing full surgical autonomy, many emerging systems emphasize cooperative or shared-control paradigms in which robotic platforms provide geometric constraint enforcement and precision stabilization while surgeons retain direct decision-making authority [6,77]. Such human–robot collaboration frameworks may help balance safety, precision, and clinical usability.

Collectively, these developments suggest that future craniofacial robotic systems will increasingly combine intelligent perception, adaptive control, and cooperative interaction models. Continued interdisciplinary collaboration among surgeons, engineers, and computer scientists will therefore be essential to translate these technological advances into clinically robust surgical platforms. Potential publication bias and the predominance of early-stage validation studies may influence the observed performance trends.

5. Conclusions

Robotic systems are increasingly applied to craniofacial procedures, particularly in dental implant placement where clinical implementation is already emerging. The reviewed literature consistently demonstrates improved positional accuracy and procedural reproducibility compared with freehand approaches. However, the evidence base remains dominated by in vitro and cadaveric validation studies, with limited prospective clinical trials. Future development should prioritize motion compensation, real-time tracking integration, and standardized reporting of deviation metrics to enable meaningful cross-platform comparison. As sensing technologies, motion-compensation strategies, and cooperative control frameworks continue to evolve, craniofacial surgical robotics is likely to transition from experimental research platforms toward clinically integrated robotic platforms capable of delivering standardized, high-precision craniofacial surgical interventions. Continued interdisciplinary collaboration between surgeons, robotics engineers, and computer scientists will be essential to translate current experimental systems into robust clinical platforms. Establishing standardized reporting metrics and multicenter

clinical validation studies will be critical for accelerating the clinical adoption of craniofacial surgical robotics.

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Abbreviations

The following abbreviations are used in this manuscript:

TORS	Transoral Robotic Surgery
RCM	Remote Center of Motion
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
CT	Computed Tomography
DOF	Degrees of Freedom

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