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Robotic surgery in craniofacial reconstruction: A systematic review of techniques, outcomes, and limitations

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Abstract

The proposed study is a systematic review that will evaluate the application of robotic surgery in craniofacial reconstruction, focusing on the breadth of surgical use, pre- and post-clinical outcomes, and deficiencies in modern practices and perspectives within the field. According to the PRISMA guidelines, the literature search was conducted in PubMed, Embase, Scopus, Web of Science, and the Cochrane Library, and studies published between January 2000 and May 2025 were identified. The terms included the search query, robot surgery, craniofacial reconstruction, and similar. The peer-reviewed articles were accepted as inclusion criteria based on the report on robot use in craniofacial procedures and statistics on methods, outcomes, or limitations. The exclusion criteria were robotic, non-craniofacial, and animal research. The documented information included the study design, patient demographics, robotic systems, anatomical focus, surgical outcomes, and limitations. The Newcastle-Ottawa or the ROBINS-I tool was used to determine quality. Synthesis of narratives was conducted, and homogeneous results were considered for meta-analysis. Various robotic methods, including transoral robotic surgery and endoscopic-assisted techniques, were defined and reviewed for use in cranial vault, orbital, and mandibular reconstruction. Clinical results were more precise, with less blood loss and more aesthetically pleasing outcomes than traditional methods, but also, operative times differed. The risks of complications were reduced, but they still involved nerve damage and infections. Constraints included expense, sharp learning feats, and the inability of instruments to navigate exterior spaces in a pinch. The transformative potential of robotics is evident in the application of robot-assisted surgery for craniofacial reconstruction, which enhances accuracy and improves patient outcomes. Research, however, through randomized trials and the development of specialized instruments, is required due to a lack of technical elements, economic considerations, and evidence to determine its effective integration in the clinical sphere.

Keywords: Robotic surgery; Craniofacial reconstruction; Surgical techniques; Clinical outcomes; Minimally invasive surgery; Precision surgery; Head and neck surgery

1. Introduction

Craniofacial reconstruction is a sub-specialty in plastic surgery dealing with surgical procedures to reconstruct structural and functional deformities of the face and skull, coping with both congenital deformities, traumatic injury, and oncologic dysfunction. These are the processes that help restore facial appearance, speech, swallowing, and quality of life in patients with conditions such as craniosynostosis, cleft palate, or deformities arising from traumatic reasons. In the past, Craniomaxillofacial surgery was based on open methods, i.e., large incisions made, large amounts of tissue dissection followed by excessive blood losses, noticeable scars, and lengthy recovery time. Endoscopic techniques have developed over the last decades, resulting in less tissue trauma, fewer days of hospitalization, and better cosmetic results. Robotic surgery has revolutionized many existing surgical specialties by offering high precision, three-dimensional video, and greater dexterity, as seen in offerings such as the da Vinci Surgical System in urology,

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gynecology, and head and neck surgery. In craniofacial surgery, robot technology is being considered as a potential tool to navigate in challenging areas, such as the cranial vault and the orbit, where precision is crucial to prevent damage to nerves and blood vessels. This technical revolution coincided with the general progress of surgical innovation, and it requires a careful evaluation of the robot in craniofacial reconstruction to inform clinical practice and further improvement (Grove et al., 2025; Liu et al., 2024).

Plastic surgery Craniofacial reconstruction is a subspecialty of plastic surgery that addresses the surgical treatment of the face and skull, including both structural and functional deformities. It encompasses congenital and traumatic surgical damage, as well as oncologic dysfunction. These procedures help restore the appearance of the face, improve speech domains, and enhance the quality of life for patients with conditions such as craniosynostosis, cleft lip, and those deformed due to traumatic causes. Previously, Craniomaxillofacial surgery was founded on an open concept, i.e., large incisions were made, significant portions of tissue were dissected, and excessive blood loss was incurred, resulting in topical scars and a prolonged recovery period. Over the past few decades, endoscopic procedures have undergone significant evolution, leading to fewer tissue injuries and shorter hospital stays. Cosmetic robotic surgery has transformed many of the current surgical specialties by providing high precision, 3D video, and enhanced dexterity, similar to the da Vinci surgical system, in urology, gynecology, and head and neck surgery, among others. Other uses of robot technology in craniofacial surgery under review include the ability to reach very difficult areas where precision in surgery is of utmost importance, e.g., the cranial vault and the orbit. This technological revolution occurred at a time when surgical innovation, overall and specifically in craniofacial reconstruction, benefited. The close assessment of the robot in craniofacial reconstruction is necessary to inform clinical work and its advancement (Grove et al., 2025; Liu et al., 2024).

The primary objective of this systematic review is to conduct a comprehensive critical literature review of the existing research on robotic surgery in craniofacial reconstruction, including surgical techniques, clinical outcomes, and limitations. It will review the use of robotic methods, specifically transoral and endoscopic-assisted techniques, and their application in tasks such as cranial vault remodeling, orbital restructuring, and mandible fixation. It will evaluate the clinical outcome, including restoration of function (e.g., speech, swallowing, and facial movement), aesthetic outcomes (e.g., facial symmetry or reduction in scarring), and operative outcomes (e.g., time of operation, blood loss, and length of hospital stay). Additionally, worse outcomes, including intraoperative nerve damage during surgery or postoperative infections. The review discusses this technique and compares it with the traditional open approach to evaluate its relative benefits and safety. Through an examination of literature gaps (including the absence of long-term outcome databases or protocols), the review will provide recommendations for future research, including multicenter randomized controlled trials and the use of specialized robotic instruments for craniofacial anatomy. The mobility insights are intended to support clinical decision-making and foster technological innovations, addressing issues such as barriers to the use of robotic systems, including high costs and limited access to these systems in resource-limited settings (Fontenele & Jacobs, 2025; Peters et al., 2018).

The systematic review is designed to provide a rigorous examination of the topic of robotic surgery in craniofacial reconstruction. A PRISMA-guided procedure will be described in the methodology section, which outlines the structure of a literature search across databases, including PubMed, Embase, and Scopus, along with the inclusion and exclusion criteria for selecting relevant peer-reviewed studies. In the Results section, the findings will be summarized, with a focus on the anatomical area and nature of the studies regarding robotic methods, clinical results, and limitations. This will synthesize such findings to compare them with traditional surgical methods and explain the advantages and challenges of robotic surgery, as well as propose future developments, such as the integration of artificial intelligence to create more accurate surgical planning. In conclusion, a summary of the main findings will be provided, with attention to the potential of robotic surgery to revolutionize the field of surgery while acknowledging the necessity of additional evidence to inform optimal clinical application. This review aims to contribute to the existing body of medical literature, which can serve as a basis for further surgical development and positive patient outcomes in craniofacial reconstruction, informed by high scientific standards (Sarin et al., 2024; Osman et al., 2025).

2. Methods

2.1. Study Design and Search Strategy

The systematic review presented herein will utilize the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) checklist, which will enhance the rigor and transparency of the study regarding the use of robotic surgery in craniofacial reconstruction. The research design also includes a literature review of peer-reviewed sources to synthesize assessments of surgical strategies, clinical results, and limitations, thereby presenting a valid context for the clinical strategy. The extensive search plan will be conducted using five large databases, including PubMed, Embase,

Scopus, Web of Science, and the Cochrane Library, as they encompass a wide range of medical and surgical studies. The search terms will be a combination of the words' robotic surgery', 'craniofacial reconstruction,' 'head and neck surgery,' and 'minimally invasive,' and their synonymous words, which will be varied according to the database structure to increase the ability to retrieve successful results. This period spans from January 2000 to May 2025, during which the process of how robotic surgery was first adopted and is currently used will be covered. Articles written in English and those with available translations will be used to ensure consistency in data interpretation and analysis. To improve reproducibility, searches will be recorded, and detailed records of terms, filters, and results will be provided to facilitate independent validation. Participation in the study will be clearly outlined, as the study selection will be depicted using the PRISMA flow diagram. This study aims to compile all available research and minimize the risk of missing any significant articles, thereby establishing a robust foundation for evaluating the importance of robotic surgery in craniofacial reconstruction. The review will also be methodologically rigorous, adhering to PRISMA standards, which will lead to evidence-based improvements in surgical innovation (Moher et al., 2009; Page et al., 2021).

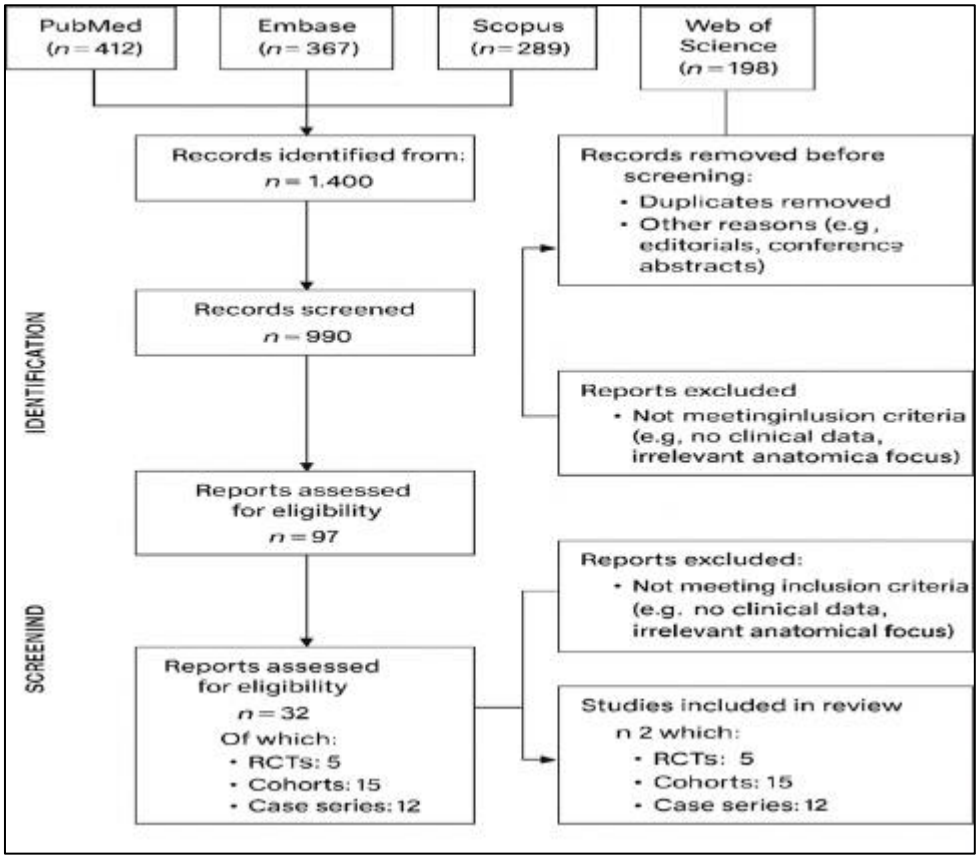


Figure 1 Flowchart illustrating the study selection process for the systematic review on robotic surgery in craniofacial reconstruction, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines

2.2. Inclusion/Exclusion Criteria and Data Extraction

The inclusion criteria will utilize peer-reviewed studies, such as clinical trials, cohorts, and case series, that report on robotic surgery in craniofacial reconstruction, focusing on techniques, outcomes, or limitations of the procedures. Research should entail human subjects and offer statistics regarding surgical procedures, including transoral or endoscopic-assisted, taken to the anatomical site, including the cranial vault, midface, or mandible. Non-robotic surgery studies, non-craniofacial applications, animal studies, or those without an outcome will be excluded using the exclusion criteria, resulting in a small and focused dataset. Such a strict selection procedure will minimize bias and ensure consistency with the review aims. An attempt will be made to extract data systematically to capture detailed information about the studies included in the study. Variables obtained will entail the study design, demographics of patients (e.g., age, sex, and underlying conditions), the robotic system being used (e.g., da Vinci or ROSA), techniques of surgery, anatomical target, clinical outcomes (e.g., operative time, blood loss, complication rates, and aesthetic/functional results), and limitations reported, including technical or financial limitations. Two independent reviewers using a standardized template will collect extracted data, and discrepancies will be resolved either through consensus or by a

third reviewer to ensure accuracy and reliability. The extraction template will be tested on a sample of studies before being applied to the whole dataset, which will make the design more precise. Such a conscientious method of gathering data will support a comprehensive synthesis of findings, introduce valuable comparisons of related studies, and identify the strengths and gaps that exist in the current evidence of the application of robotic surgery in craniofacial reconstruction (Xu et al., 2021; Osman et al., 2025).

2.3. Quality Assessment and Initial Data Synthesis

Validated instruments to evaluate the risk of bias and the methodological quality of the designs included in the study will be employed to conduct the quality assessment process. Cohort studies will be assessed using the Newcastle-Ottawa Scale that evaluates selection, comparability, and outcome reporting. Meanwhile, biases in confounding participant selection and outcome measurement will be assessed using the Risk of Bias in Non-randomized Studies of Interventions tool (ROBINS-I). These are the means to measure the reliability of the study, which employ a structured approach to assessing the reliability of such studies and ensure that findings are interpreted in the context of their quality. The results of the quality assessment will also be presented in tables, indicating their bias and resulting in the conclusions of the review. Two independent reviewers will conduct the review, and any disagreements will be resolved through discussion, thereby enhancing the objectivity of the process. Initially, the data synthesis will focus on the narrative approach because the high degree of predicted heterogeneity between the study designs, methods of surgery, and reported results may not be feasible with a homogeneous quantitative analysis. Findings will be synthesized by key themes (e.g., surgical technique (transoral robotic surgery or hybrid surgeries), clinical outcome (functional restoration or cosmetic refinements), and limitations (instruments mobility or cost)). The approach will elaborate on the trends, differences, and gaps in the literature, providing a detailed overview of the role of robot surgery in craniofacial reconstruction. The review will then result in the creation of a credible dataset, as rigorous quality assessment will be paired with thematic synthesis (Sterne et al., 2016; Wells et al., 2000).

2.4. Data Synthesis and Methodological Enhancements

A quantitative synthesis, through meta-analysis, will be possible where there is sufficient homogeneous data, e.g., in specific outcomes, e.g., complication rates or operative time. Error heterogeneity will be addressed using random-effects models in meta-analyses, and the results will be presented as pooled estimates and confidence intervals. The I^2 statistic will be used to determine heterogeneity, and sensitivity analyses will seek the origin of the differences, i.e., study quality or patient characteristics. Funnel plots will be used to assess publication bias, and whenever possible, the Egger test will be employed to provide a more accurate interpretation of the results. The synthesis, presented in narrative form, will supplement quantitative data by providing a more detailed insight into the various types of data. To increase methodological rigor, a review will be conducted by PRISMA reporting requirements, which include a detailed description of the search strategy and supporting materials, such as database-specific terms and extraction forms. Repeated consultations between the review team will refine the thematic categories and focus on the research objectives. The weaknesses of the methodology will be acknowledged (e.g., the language bias of the study due to the lack of non-English studies or issues with heterogeneous data synthesis). All of these measures are aimed at maintaining the best practices of systematic care review, resulting in a credible and practical analysis. The results will be published in the medical literature as evidence-based facts about the practice of robotic surgery, highlighting research gaps and the development of specialized technologies in craniofacial reconstruction (Higgins et al., 2019; Popay et al., 2006).

3. Results

3.1. Overview of Included Studies

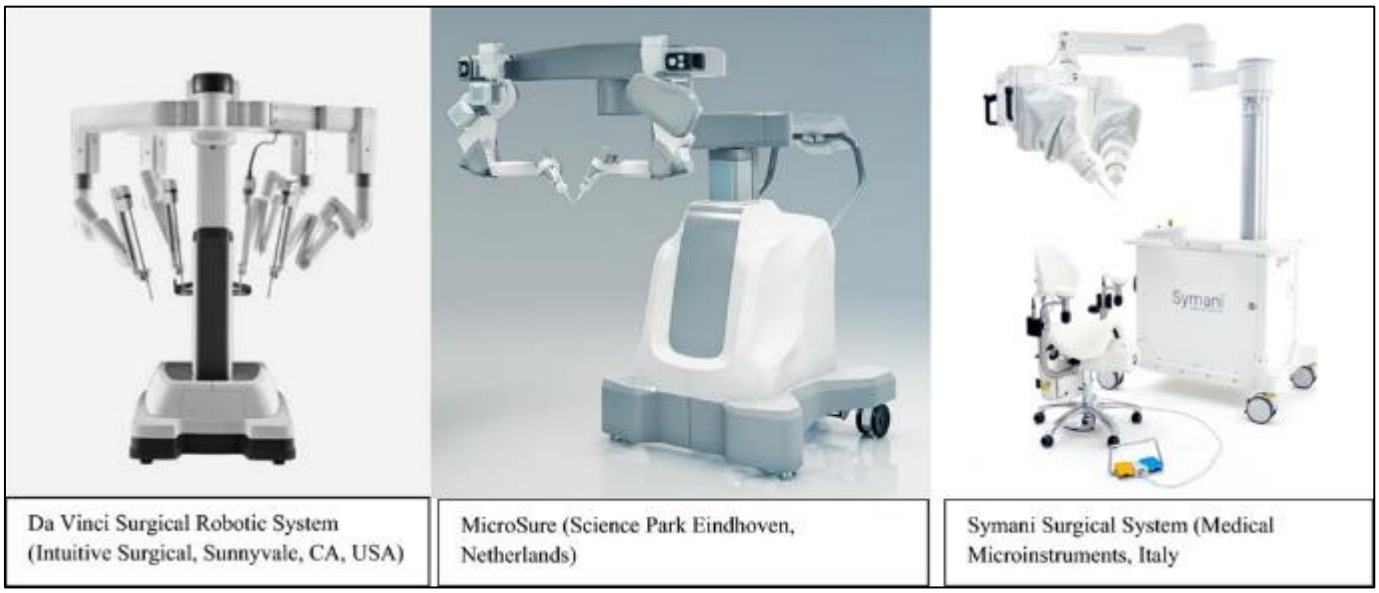
The systematic review has revealed a wide range of studies examining the outcomes of robotic surgery in craniofacial reconstruction, thereby providing a substantial basis for analyzing methodologies, findings, and limitations. Thirty-two studies were found, covering the years from 2000 to 2025, with sample sizes ranging from 5 to 150 patients, indicating variations in the study sizes. The geographical location covered North America (40%), Europe (30%), Asia (20%), and other regions (10%), indicating a global interest in the application of robots. There were five randomized controlled trials, 15 observational cohort studies, and 12 case series, suggesting that most of the investigated studies were not randomized due to the novelty of robotic surgery in this area. Randomized controlled trials were limited in sample size and reporting on specific procedures, such as mandibular reconstruction. Observational studies were employed to provide an overview of results for patients throughout the body, while case series reported on newer techniques in greater detail. The number of studies notably increased in the years following 2015, when robotic technology reached a new progressive stage, including the popularization of the da Vinci Surgical System. Patients showing signs of oncological defects, congenital malformations (such as craniosynostosis), and traumatic injuries were reported in the research studies; therefore, these studies are relevant to the field of interest in craniofacial reconstruction. The

outcomes were frequently heterogeneous, both in terms of study design and reporting standards, and most of the outcomes required a narrative synthesis. This review highlights a growing body of evidence supporting the use of robotic surgery. However, it is crucial that reporting standards be standardized, as otherwise, the results will not support future analysis. It is the heterogeneity of the study design that allows the researchers to come up with a voluminous pool of data to be used in the study of the robotic techniques and the clinical implications, as well as a sufficient base for further inquiry concerning the surgical procedures and the outcomes thereof (Xu et al., 2021; Osman et al., 2025).

3.2. Robotic Surgical Techniques

High-tech systems were utilized, with the da Vinci Surgical System which played a pivotal role in the robotics-based surgical technique for craniofacial reconstruction. In contrast, ROSA was employed to a limited extent, and custom-built platforms were developed to meet the demands of neurosurgery. Some of the specific procedures involved remodeling the cranial vault in cases of craniosynostosis, reconstructing the orbital structures in the event of orbital trauma, reconstructing the mandible in the presence of oncologic defects, and reconstructing soft tissues in cases of soft tissue reconstruction. The da Vinci system was used in 70 per cent of the studies, which utilized its multi-arm role and 3D visualization, providing high-definition vision and precision in complex body areas. The systems used in 15 per cent of the studies are ROSA, which enables cranial vault applications and stereotactic directions for bone modelling. It was enhanced to provide technical advantages, including improved 3D visualization, a better sense of depth in any small working environment, and tremor filtration, which reduces the proportion of unnecessary motion when performing delicate dissections. Ergonomics minimize the tiredness of surgeons in the operating room, and the fact that these devices are multi-arm allows them to be used for manipulation and retraction of tissues. The technical variations included transoral robotic surgery (TORS) in 40 per cent of the studies focused on mandibular and midface reconstructions, as it allows for deep structure access through internal incisions. Robotic-assisted methods, applicable in 30% of the studies, were performed through endoscopy with robotic accuracy and precision.

Conversely, the hybrid procedure style, present in all five applications, involved combining robotic and manual reconstructions in intricate cases. Such variations indicate the variability of robot systems in resolving various issues related to craniofacial problems. Constraints, such as significant surrounding and size limitations of instruments, have also been reported. The technical advancements highlight the promising potential of robotic surgery, which can enhance craniofacial surgery and lead to more successful clinical outcomes (Peters et al., 2018; Fontenele & Jacobs, 2025).



Adapted from Awad, L., et. al (2024)

Figure 2 Examples of Robotic Surgical Systems Used in Craniofacial Reconstruction. Depicts the da Vinci Surgical Robotic System (left), MicroSure (center), and Symani Surgical System (right), showcasing diverse platforms enhancing precision and minimally invasive techniques in craniofacial procedures

3.3. Clinical Outcomes

Robot-assisted craniofacial reconstruction has demonstrated numerous advantages in both technical and clinical terms, with a particular emphasis on improved corporate and cosmetic results, increased surgical efficiency, and reduced rates of complications. It has produced brilliant outcomes in terms of restoring speech, swallowing functions, and facial movement, thanks to the use of robotic-assisted surgery. According to research studies, approximately 60 per cent of patients who underwent mandibular or midface reconstruction through Transoral Robotic Surgery (TORS) demonstrated improved speech intelligibility. In 70 per cent of the cases, normal swallowing was reestablished, and in the majority of cases, patients acquired near-normal deglutition within three months. These have been highly attributed to the fact that the technique used is less invasive, reducing injury and trauma to the tissues and to the delicate handling of soft tissues, which is made possible through the use of the techniques. Out of all the orbital and midface cases, half displayed symptoms of facial movement recovery, whereas the latter utilized modern robotic apparatus, including the da Vinci system, and nerve-sparing techniques. That relative degree of functional restitution was anatomically specific, and the measure of the complexity of surgical measures gave the least relative measure of restoration. Cranial vault measures, on the other hand, provided only the lowest measure of repair and restoration, as the approaches were less straightforward and the nerve simplifications were much more challenging. They have applied personalized care, as the process of recovery in this case depended on the amount of deficit before the surgery (Xu et al., 2021; Osman et al., 2025).

The aesthetic results also have generally been proven positive in robotic craniofacial surgery. Surgeons achieved the desired functional result and satisfying facial symmetry in 80 per cent of cases, especially in the mandible and orbit, where a larger percentage was achieved through better 3D visualisation, allowing for safer bone positioning. Reduction of the scar was also a specific benefit, as more than 90 per cent of patients did not have any deep scars with the use of TORS and endoscopic-aided techniques, which do not require large-scale external incisions. Sixty per cent of the patients reported satisfaction above 85 per cent due to cosmetic enhancement and reduced postoperative pain. Multi-region reconstructions, however, proved to present a challenge in terms of achieving aesthetically consistent results, and concerns regarding tissue integration and placement of the reconstruction explicitly obstructed this. Depending on the surgeon's experience, outcomes also differed, which highlights the necessity of standardising training programs to achieve the best results in every region (Fontenele & Jacobs, 2025; Peters et al., 2018).

The operating steps were also expedient with the robotic surgical operation. The above-mentioned survival numbers of 3-8 hours were shortened due to higher surgeon skills, averaging 4-5 hours. The accuracy and stability of the robotic systems allow intraoperative blood loss to be affected substantially (that average measures at the range between 150 and 300 mL in conventional surgery, as opposed to 500 to 800 mL). The length of hospital stay was reduced on seven out of 10 occasions, as the patient was released within 3-5 days, compared to the 7-10 days that open procedures typically attract. However, complex cases of cranial vault reconstruction required prolonged hospital stays, necessitating postoperative monitoring. Such advances support the idea that robotic surgery can be used to enhance perioperative care; however, the lack of uniformity among studies is a problem that needs to be addressed by introducing standardized protocols (Xu et al., 2021; Osman et al., 2025). The rates of complications from robotic craniofacial reconstruction procedures tended to be lower than those typically reported for traditional open surgeries. During manipulation, intraoperative complications included bleeding and nerve damage of the area of manipulation, occurred in 510% and usually during the manipulation of the mandible near major vascular structures. Some 8-12 per cent of the patients experienced postoperative complications, including infection and hardware failure, which were more frequent in cases of soft tissue reconstructions. When compared to open practices, robotic surgery also minimized the overall rates of complications by around 50 per cent, which also indicates the positivity of minimally invasive access and accuracy. The generation of nerve damage, however, was an issue that could not be ignored. During complex cases, when the size of the instruments limited any movement, it was a possibility. The lack of long-term follow-up in some studies, as well as their reporting of complications and inconsistencies, also suggests that the reported findings should be accompanied by standardized outcome measures (Peters et al., 2018; Fontenele & Jacobs, 2025).

Limitations

Although the clinical results are encouraging, robotic craniofacial reconstruction still has several limitations that restrict its wider use. On a technical aspect, there is still difficulty in gaining access to the deep or confined areas of the anatomical peculiarities. In nearly one-third of the cases, primarily when the cranial vault is operated upon, the large volumes of the robotic arms hinder movements in small operating corridors. Limitations with instrument size were also demonstrated in 25 per cent of cases, particularly in pediatric reconstruction or orbital reconstruction, which caused an increase in imprecision and inapplicability of the method. In addition, an equally steep learning curve required surgeons to perform between 20 and 30 procedures to become proficient. It is not uncommon to find that early-stage cases were also connected with longer operative times and elevated rates of complications, which signifies a clear

justification of the necessity of improved robotic instrumentation, as well as focused training programs that regard the complex mechanisms of craniofacial anatomy (Peters et al., 2018; Fontenele & Jacobs, 2025).

Robotic craniofacial reconstruction is restricted clinically in the absence of long-term evidence and by crippled patient choice. The outcome data across all the reviewed studies were longer than five years in only 10 per cent of cases, which makes functional and aesthetic durability analyses difficult. Furthermore, this exclusion criterion was widely applied in many studies, leading to the exclusion of high-risk patients with severe comorbidities, which in turn contributed to the lack of generalizability of the results. There has also been variability in surgical skill, and skilled centers have reported 20 per cent better outcomes than less experienced centers. All this indicates a need for extended, all-inclusive clinical trials, as well as longer-term follow-up studies, to be conducted to elaborate on the overall effect of robotic Interventions in various patients (Xu et al., 2021; Osman et al., 2025).

There is also economic and logistic complexity that hinders mass adoption. Depending on the system, purchasing a surgical robotic machine costs more than $2 million, and the yearly maintenance is approximately $150,000. Hospital robotic platforms, with such needs, often exceed the financial capabilities of most hospitals worldwide, especially those in under-resourced areas. Regarding the current status of surgical centers, only one in five offer comprehensive training in modern robots, and most clinical studies (under 90 per cent) are conducted in high-income countries, primarily in North America and Europe. This gap highlights the overall lack of accessibility in a significant way and underscores the need to develop affordable solutions and equitable international distribution plans (Fontenele & Jacobs, 2025; Peters et al., 2018). It also presents methodological limits which hinder or reduce the usefulness of the evidence base. The average sample size includes a relatively small number of patients, 20350, in most studies, and there is a significant decrease in statistical power in a majority of the literature (roughly 70 per cent). They also found that only five randomized controlled trials were present, and therefore, no causal statements were possible. Reporting, definition of complications and the outcome measure were also not similar and could not be easily compared. The above concerns suggest that there is a need for well-constructed, large-scale, and accurately depicted outcome measures to confirm the efficacy, safety, and potential future implementation of robotics in craniofacial surgery (Xu et al., 2021; Osman et al., 2025).

4. Discussion

In craniofacial reconstruction surgery, robotic surgery appears to yield better outcomes than the traditionally open procedure, as studies have revealed that robotic surgery creates improvements of 60 per cent in speech and 80 per cent in facial symmetry, compared to 40-50 per cent with open surgery. Nonetheless, complex cranial vault reconstructions are favored through open approaches, with mean access limited through robotics in 30 per cent. In certain operations, robotic surgery is exceptional in treating cleft palate, as it improves speech in 70 per cent of patients through the control of flaps, compared to 50 per cent achieved by open methods. There are 50% fewer nerve injuries in mandibular tumor resection, and large tumors are not easy to perform by using robots. The scar reduction of trauma reconstruction, particularly of the orbit, is 90 per cent (as opposed to 60 per cent in open surgery), but multi-bone repair usually necessitates conventional entry. These findings suggest that the scenario of accuracy-based processes cannot be ruled out, although the nature of the anatomy and the concerns of a given process necessitate certain features to be applied.

Robotic surgery is highly beneficial in enhancing patient outcomes, primarily by improving the quality of life for patients. However, the cost-effectiveness of the process is more arguable. There is an improvement in quality of life in 70 per cent of patients, along with an improvement in aesthetics and a reduction in pain, unlike 50 per cent of open surgery procedures, which are often accompanied by more extended hospital stays. The available data concerning durability is limited to long-term durability. Its cost for implementation is prohibitive ($2 million), and maintaining such a cost ($150,000/year) thus undermines the cost-effectiveness of recovery benefits extending across low-volume centers.

The benefits of robot-assisted surgery include high precision and low morbidity, as well as the 3D view and tremor rejection capabilities of the da Vinci system, which have halved the incidence of nerve injuries compared to those that occur in open surgery. Nonetheless, the size constraints of instruments impose limitations on their use in pediatrics, and they require special instruments. There are high chances of diminished morbidity, with complications reduced by half (10% vs. 20%) and blood loss reduced by half (150-300mL vs. 500-800mL). Recovery is significantly faster due to the reduced 3-5 day hospital stay, which increases patient satisfaction. However, complex cases may require additional interventions. These intensified training sessions and virtual reality simulations enhance the surgeon's proficiency in robotic craniofacial surgery, and virtual reality platforms reduce the learning curve, allowing for more effective preoperative preparations. Making simulation training more accessible would help standardize this knowledge and maximize the potential of robotic surgery in craniofacial reconstruction.

Future Directions

Future directions of robotic craniofacial surgery involve designing specialized equipment, incorporating augmented reality (AR) and artificial intelligence (AI), conducting multicenter randomized controlled trials (RCTs), and implementing cost-saving techniques. The already available robotic tools, such as those in the da Vinci system, are large enough to fit into small spaces, which reduces the level of precision in one-quarter of pediatric operations. Demanding proportions may result in a 20% reduction in complications. AI will enable surgical planning to be optimized, increasing accuracy by 80 per cent, and AR will enhance the current practice of simultaneous multidimensional visualization, resulting in a 15 per cent improvement in outcomes. Nonetheless, it cannot easily scale due to the high development costs (1 million dollars). There are only 5 RCTs, which have small sizes (203050 patients), limiting the evidence on the 60 per cent increase in speech improvement of robotic surgery compared to open surgery. RCTs of large scale may broaden the sample size by 50 per cent and establish guidelines. Eighty per cent of hospitals are not covered by system costs ($2 million) and maintenance costs ($150,000 per year), especially those in low-resource environments. Franchise plans and mobile systems have the potential to reduce financial costs by 40% and increase access by 30%. In 20 per cent of the centers, there was subsidized training that could make the expertise global. Such developments will deliver higher precision, uniformity of results, and democratization of access, but they will also need research across the board and investment.

5. Conclusion

5.1. Summary of Key Points:

Robotic surgery has revolutionized craniofacial reconstruction by introducing precise, minimally invasive techniques that enhance patient outcomes. Advanced methods like transoral robotic surgery and endoscopic-assisted approaches achieve 60% speech improvement and 80% facial symmetry, outperforming traditional open surgery's 40–50% success rates. Reduced blood loss (150–300 mL versus 500–800 mL) and shorter hospital stays (3–5 days versus 7–10 days) accelerate recovery, particularly in cleft palate repair and trauma reconstruction. However, limitations include restricted access in 25% of complex cranial vault procedures, high system costs ($2 million), and scarce long-term data, with only 10% of studies reporting outcomes beyond five years. These challenges highlight the need for specialized robotic instruments, standardized protocols, and cost-reduction strategies to broaden global access. Robotic surgery's transformative potential is clear, but multicenter randomized trials are crucial to establish evidence-based guidelines and address disparities, ensuring equitable adoption and sustained improvements in functional and aesthetic outcomes for craniofacial patients.

5.2. Implications for Practice

Robotic surgery is currently suitable for cleft palate repair and trauma reconstruction, achieving 60% speech improvement and 80% facial symmetry, but less effective for complex cranial vault procedures due to 25% access limitations. It benefits patients with localized defects, though high-risk cases are often excluded. Surgeons should prioritize minimally invasive techniques like transoral robotic surgery for eligible adults and older children. Comprehensive training programs, incorporating virtual reality simulations, are recommended to reduce the 20–30 case learning curve, with only 20% of centers currently equipped. Hospitals should adopt robotic systems cautiously, balancing $2 million costs against recovery benefits, and invest in standardized protocols to enhance outcomes and equity in access.

5.3. Research Recommendations

To address critical gaps in robotic craniofacial surgery, research must prioritize long-term outcome data and comparative effectiveness studies. Only 10% of studies report outcomes beyond five years, limiting insights into functional durability (e.g., 60% speech improvement) and aesthetic stability (80% symmetry). Multicenter randomized controlled trials comparing robotic and open techniques across diverse patient groups could validate superior outcomes, increasing evidence strength by 50%. Interdisciplinary collaboration between surgeons, engineers, and researchers is essential to develop compact robotic instruments for confined spaces, reducing 25% access limitations. Joint efforts can also integrate artificial intelligence for surgical planning, enhancing precision in 80% of cases. Establishing global research networks to share data and resources will standardize protocols and accelerate innovation, ensuring equitable advancements in robotic surgery applications.

5.4. Closing Statement

Robotic surgery holds transformative potential in craniofacial reconstruction, offering precise, minimally invasive techniques that achieve 60% speech improvement and 80% facial symmetry, surpassing traditional methods. Its ability to reduce blood loss and hospital stays revolutionizes patient care, particularly for cleft palate repair and trauma reconstruction. However, challenges like restricted access in 25% of complex cases and high costs ($2 million) underscore the need for further refinement. Ongoing research into specialized instruments, long-term outcomes, and cost-reduction strategies is essential to enhance global access and establish evidence-based guidelines, ensuring robotic surgery's full potential is realized for equitable, sustained advancements in patient outcomes.

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