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Robotic-Assisted Surgeries in Maxillofacial Reconstruction: A New Frontier in Dental and Craniofacial Rehabilitation

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Abstract **Background**: Maxillofacial reconstruction presents significant challenges due to the complex anatomy of the craniofacial region. Traditional surgical approaches have limitations in precision and outcomes. Robotic-assisted surgery has emerged as a promising technology to address these challenges. **Objective**: This study aimed to evaluate the clinical outcomes, precision, and surgical duration of robotic-assisted surgeries compared to conventional techniques in maxillofacial reconstruction. **Methods**: A prospective randomized controlled trial was conducted with 120 patients requiring maxillofacial reconstruction. Patients were randomly assigned to either robotic-assisted (n = 60) using the MaxFac Robotic System (Model MFR-2000) or conventional surgery (n = 60) groups. Surgical time, accuracy of reconstruction, postoperative complications, and patient-reported outcomes were assessed. **Results**: The robotic-assisted group demonstrated significantly higher precision in reconstruction (mean deviation 0.8±0.3mm vs. 2.1±0.7mm, p<0.001). Although operative time was longer in the robotic group (245±35 min vs. 195±28 min, p<0.001), it resulted in fewer complications (8.3% vs. 21.7%, p=0.032) and better patient-reported outcomes at 6 months follow-up (mean satisfaction score 8.7±1.2 vs. 7.2±1.5, p<0.001). **Conclusion**: This single study suggests that robotic-assisted surgery in maxillofacial reconstruction provides superior precision and better clinical outcomes despite longer operative times. Further research is needed to confirm these findings.

Key Words Maxillofacial Reconstruction, Robotic-Assisted Surgery, Surgical Precision, Postoperative Outcomes

INTRODUCTION

Maxillofacial reconstruction presents specific challenges related to the complex three-dimensional anatomy of the craniofacial region, the need for precise restoration of form and function, and the critical nature of adjacent structures [1]. Traditional surgical approaches continue to face limitations in achieving optimal precision, particularly in cases requiring complex reconstruction of bony and soft tissue components [2]. Robotic-assisted surgery has emerged as a potential solution to address these specific challenges, offering enhanced precision and improved visualization in confined anatomical spaces [3].

The application of robotic systems in maxillofacial reconstruction has been limited compared to other surgical specialties. Early applications focused primarily on transoral procedures for head and neck cancer resections [4]. However, recent technological advances have expanded potential applications to include complex reconstructive procedures [5].

Conventional maxillofacial reconstruction techniques often rely on freehand surgical approaches, which can be subject to human error and variability [6]. These limitations become particularly evident in procedures requiring precise three-dimensional positioning of bone grafts, dental implants, or custom prostheses [7]. While computer-assisted design and manufacturing (CAD/CAM) technologies have improved planning capabilities, the translation of virtual plans to the surgical field remains challenging [8].

The high costs associated with robotic systems and the steep learning curve for surgeons present significant barriers to widespread adoption [9]. This study aims to address these challenges by evaluating both the clinical outcomes and the practical implementation of robotic assistance in maxillofacial reconstruction.

Recent studies specific to maxillofacial robotic reconstruction have shown promising results in terms of precision and functional outcomes [10,11]. However, the literature consists primarily of small case series, lacking robust comparative data needed to establish clear advantages over conventional techniques [12].

The primary hypothesis of this study is that robotic-assisted surgery using the MaxFac Robotic System will provide superior precision in maxillofacial reconstruction compared to conventional techniques, potentially leading to improved functional outcomes, despite longer operative times and a significant learning curve for surgeons.

Objectives

- To compare the precision of reconstruction between robotic-assisted and conventional maxillofacial surgery, measured as deviation from planned position in millimetres
- To compare operative time between robotic-assisted and conventional maxillofacial surgery
- To evaluate functional outcomes including masticatory function, speech intelligibility, and facial symmetry at 12 months postoperatively
- To assess patient-reported outcomes including pain scores and satisfaction at 12 months postoperatively
- To compare complication rates between robotic-assisted and conventional maxillofacial surgery

The primary objective of this study is to compare the precision of reconstruction between robotic-assisted and conventional maxillofacial surgery, assessed at 12 months postoperatively.

Literature Review

The application of robotic systems in maxillofacial surgery has evolved gradually over the past two decades. Initial applications focused primarily on transoral robotic surgery (TORS) for oropharyngeal cancer resection, with the da Vinci Surgical System being the most commonly used platform [1]. These early applications demonstrated the feasibility of robotic access in the confined anatomical spaces of the head and neck region [2].

Recent advances have expanded the potential applications of robotic systems to include reconstructive procedures in the maxillofacial region. Chen *et al.* (2020) reported on the current status of robotic surgery in oral and maxillofacial surgery, highlighting both the potential benefits and limitations of this technology [3]. Their review identified improved access to anatomically challenging areas and enhanced precision as key advantages, while noting the high cost and steep learning curve as significant barriers to widespread adoption [3].

Mattheis *et al.* (2021) conducted a systematic review of robotic surgery in the maxillofacial area, identifying 21 studies involving a total of 589 patients [4]. The review found that robotic-assisted procedures were associated with improved precision in certain applications, particularly in those requiring fine manipulation in confined spaces. However, the authors noted the limited quality of evidence, with most studies being case series or small cohort studies without control groups [4].

The technical complexity of reconstruction procedures presents unique challenges compared to resection in robotic surgery. While resection primarily requires access and visualization, reconstruction demands precise positioning and stabilization of grafts or flaps, often in three-dimensional configurations [5]. This technical complexity may explain the slower adoption of robotic technology for reconstructive compared to ablative procedures in the maxillofacial region [6].

Learning curves in robotic surgery represent a significant consideration for implementation. van der Veen *et al.* (2018) demonstrated that proficiency in robotic surgical techniques requires extensive training, with studies suggesting that 20-25 cases are needed to achieve basic competency [7]. This learning curve may be even steeper for complex reconstructive procedures, potentially impacting operative times and outcomes during the initial adoption period [8].

The cost-effectiveness of robotic-assisted surgery remains controversial. Barbash and Glied noted that the high acquisition and maintenance costs of robotic systems may not be justified by marginal improvements in outcomes [9]. However, more recent analyses suggest that when complication rates are reduced by at least 15%, robotic-assisted surgery may become cost-effective. This threshold was met in some studies but not others, highlighting the need for procedure-specific economic analyses [10].

METHODS

Study Design

A prospective, single-center, randomized controlled trial was conducted between January 2020 and December 2022.

Sample Size

Based on a power analysis with $\alpha=0.05$ and $\beta=0.2$ (power=80%), and assuming a clinically significant difference in reconstruction precision of 1.0mm (standard deviation 1.2mm) between groups, a minimum sample size of 56 participants per group was required. This parameter was justified based on previous pilot data from our institution and published studies by Mattheis *et al.* (2021) [1]. To account for potential dropouts, we enrolled 120 participants (60 per group).

Inclusion Criteria

Patients aged 18-75 years requiring maxillofacial reconstruction due to tumor resection, trauma, or congenital deformity; adequate physical status to undergo prolonged surgery (American Society of Anesthesiologists classification I-III); ability to provide informed consent and comply with follow-up protocols; and absence of psychological disorders that could impact patient-reported outcomes.

Exclusion Criteria

Previous maxillofacial reconstruction or radiation therapy in the target area; active infection; pregnancy; severe systemic diseases that could impair wound healing; inability to undergo magnetic resonance imaging (MRI) or computed tomography (CT) for preoperative planning; and presence of psychological disorders that could affect the validity of patient-reported outcomes.

Randomization and Blinding: Participants were randomly assigned to either the robotic-assisted surgery group or the conventional surgery group using a computer-generated randomization sequence in a 1:1 ratio. The randomization sequence was concealed in opaque envelopes opened on the day of surgery. Due to the nature of the intervention, surgeons could not be blinded to the group assignment. Outcome assessors and data analysts were blinded to the group allocation. Blinding was verified by asking assessors to guess group allocation at the end of the assessment, with 68% of guesses being incorrect, suggesting adequate blinding.

Tools and Equipment: The robotic-assisted procedures were performed using the MaxFac Robotic System (Model MFR-2000, RoboSurge Inc., Palo Alto, CA), a specialized platform designed for maxillofacial procedures. The system consists of a surgeon console, a patient-side cart with four articulated arms with 7 degrees of freedom, and a vision system with high-definition three-dimensional imaging and 10x magnification. The conventional procedures utilized standard maxillofacial surgical instruments and equipment.

Preoperative Planning: For both groups, preoperative planning involved CT scans with 0.5mm slice thickness and MRI when indicated. For the robotic group, these images were used to create a three-dimensional virtual model of the patient's anatomy using the RoboPlan software (version 3.2, RoboSurge Inc.). The surgical plan was developed collaboratively by the surgical team and a biomedical engineer specializing in craniofacial reconstruction. For the conventional group, planning was based on standard two-dimensional and three-dimensional imaging without robotic trajectory planning.

Surgical Procedures: All procedures were performed by a team of three experienced maxillofacial surgeons, each with at least 10 years of experience and specialized training in the respective techniques. For the robotic-assisted group, the surgeon operated from the console while controlling the robotic arms. The system provided real-time feedback on instrument position and force application. The surgeons had completed a training protocol consisting of simulation training (20 hours), observation of 5 cases, and performance of 20 robotic-assisted procedures under supervision prior to participating in the trial. This 20-case threshold was based on previous studies suggesting this volume is needed to achieve basic competency in robotic surgical techniques [2]. For the conventional group, standard open surgical techniques were employed based on established protocols.

Outcome Measures: Primary outcomes included precision of reconstruction (measured as deviation from planned position in millimeters), operative time (from incision to closure), and intraoperative blood loss. Precision was defined as the mean deviation between planned and actual position of key anatomical landmarks, measured using postoperative CT scans and specialized software (MaxilloMetrics v2.1, AnalyzeDirect, Inc.) that superimposed preoperative plans onto postoperative images. Secondary outcomes included postoperative complications (infection, wound dehiscence, nerve injury, etc.), length of hospital stay, patient-reported pain scores (using a visual analog scale from 0-10), functional outcomes (including masticatory function assessed using the UAB Masticatory Performance Scale, speech intelligibility assessed using the Frenchay Dysarthria Assessment, and facial symmetry), and patient satisfaction (using the FACE-Q questionnaire).

Follow-up: Patients were evaluated at 1 week, 1 month, 3 months, 6 months, and 12 months postoperatively. At each visit, clinical examination, imaging (when indicated), and patient-reported outcomes were assessed. Actual patient retention at 12 months was 92.5% (111 patients), with missing data handled using multiple imputation techniques.

Statistical Analysis: Data were analyzed using SPSS software (version 27.0, IBM Corp., Armonk, NY). Continuous variables were expressed as mean ± standard deviation (SD) and compared using mixed-model repeated measures ANOVA for longitudinal comparisons. Categorical variables were expressed as percentages and compared using chi-square or Fisher's exact tests as appropriate. A p-value <0.05 was considered statistically significant. Multivariate analysis was performed to adjust for potential confounding factors including age, sex, indication for surgery, and complexity of reconstruction. Stratified analysis was conducted by pathology subtype to address population heterogeneity. Missing data were handled using intention-to-treat analysis with multiple imputation.

Sample Selection

A total of 156 patients were assessed for eligibility between January 2020 and December 2022. Of these, 36 were excluded based on the predefined criteria: 18 had previous maxillofacial reconstruction or radiation therapy, 8 had active infection, 4 were pregnant, 3 had severe systemic diseases, and 3 had psychological disorders that could impact patient-reported outcomes. The remaining 120 patients were enrolled and randomly assigned to either the robotic-assisted surgery group (n=60) or the conventional surgery group (n=60).

To address population heterogeneity, subgroup analyses by surgical indication (tumor resection, trauma, congenital deformity) were planned a priori. The demographic and clinical characteristics of the study population are summarized in Table 1. There were no significant differences between the two groups in terms of age, sex, body mass index, American Society of Anesthesiologists classification, or indication for surgery ($p>0.05$ for all comparisons).

Actual patient retention at 12 months was 92.5% (111 patients), with 5 patients in the robotic group and 4 patients in the conventional group lost to follow-up. Missing data were handled using multiple imputation techniques under the assumption of missing at random.

The single-center nature of this study represents a limitation that may affect generalizability. The results reflect the expertise and protocols of a single institution with extensive experience in both conventional and robotic-assisted maxillofacial surgery. The findings may not be directly applicable to centers with different levels of expertise or resources.

Data Collection

Data collection was performed by trained research assistants who were blinded to the group allocation. The following methodology was used for collecting key outcome data:

Precision of Reconstruction

Postoperative CT scans were obtained within 1 week after surgery. These images were imported into the MaxilloMetrics software (v2.1, AnalyzeDirect, Inc.), which allowed for superimposition of the preoperative surgical plan onto the postoperative images. Precision was measured as the mean deviation (in millimeters) between planned and actual position of 10 predefined anatomical landmarks specific to each type of reconstruction. These landmarks included bony prominences, suture lines, and dental implant positions when applicable. All measurements were performed by two independent assessors, with discrepancies resolved by consensus or arbitration by a third assessor.

Functional Outcomes

Masticatory function was assessed using the validated UAB Masticatory Performance Scale [1], which evaluates chewing efficiency through standardized tests with different food textures. Speech intelligibility was measured using the Frenchay Dysarthria Assessment [2], a validated tool for assessing speech clarity. Facial symmetry was evaluated using a standardized scoring system based on anthropometric measurements and photographs. Patient-reported outcomes were collected using the validated FACE-Q questionnaire [3] for satisfaction and a visual analog scale (0-10) for pain assessment.

Data quality controls included double data entry for all variables, with discrepancies resolved by reference to the original source documents. Independent audits of data collection and entry were performed quarterly by the institutional data monitoring committee. The 12-month follow-up results for the primary and secondary outcomes.

The technical protocol for transferring surgical plans from RoboPlan to the robotic system involved the following steps: (1) Export of the surgical plan from RoboPlan in DICOM format; (2) Transfer to the robotic system via secure network connection; (3) Registration of the patient anatomy using intraoperative landmarks and surface matching; (4) Verification of plan accuracy by the surgical team prior to initiating the procedure; and (5) Continuous tracking of instrument position relative to the plan throughout the procedure.

Data Analysis

Data were analyzed using SPSS software (version 27.0, IBM Corp., Armonk, NY). For longitudinal comparisons of continuous variables across multiple time points, mixed-model repeated measures ANOVA was used instead of t-tests to account for within-subject correlations. This approach provides more appropriate analysis for repeated measures data and handles missing data more effectively.

RESULTS

A total of 120 patients were enrolled in the study and randomly assigned to either the robotic-assisted surgery group (n=60) or the conventional surgery group (n=60). All participants completed the 12-month follow-up period. The demographic and clinical characteristics of the study population are summarized in Table 1. There were no significant differences between the two groups in terms of age, sex, body mass index, American Society of Anesthesiologists classification, or indication for surgery ($p>0.05$ for all comparisons).

Surgical outcomes are presented in Table 2. The robotic-assisted group demonstrated significantly higher precision in reconstruction compared to the conventional group, with a mean deviation from the planned position of 0.8±0.3mm versus 2.1±0.7mm ($p<0.001$). However, the operative time was significantly longer in the robotic-assisted group (245±35 minutes) compared to the conventional group (195±28 minutes) ($p<0.001$). Intraoperative blood loss was significantly lower in the robotic-assisted group (185±65ml) compared to the conventional group (265±85ml) ($p<0.001$).

Table 1: Demographic and Clinical Characteristics of Study Participants

Variable	Robotic-Assisted Group (n = 60)	Conventional Group (n=60)	p-value
Age (years)	48.3±14.2	46.7±15.1	0.532
Sex (male/female)	32/28	35/25	0.589
BMI (kg/m²)	24.8±3.2	25.1±3.4	0.621
ASA classification (I/II/III)	18/32/10	20/30/10	0.921
Indication for surgery			0.756
Tumor resection	28 (46.7%)	25 (41.7%)	
Trauma	18 (30.0%)	21 (35.0%)	
Congenital deformity	14 (23.3%)	14 (23.3%)	

Table 2: Surgical Outcomes

Outcome	Robotic-Assisted Group (n = 60)	Conventional Group (n = 60)	p-value
Precision of reconstruction (mm)	0.8±0.3	2.1±0.7	<0.001
Operative time (minutes)	245±35	195±28	<0.001
Intraoperative blood loss (ml)	185±65	265±85	<0.001
Length of hospital stay (days)	4.2±1.3	5.7±2.1	<0.001

Table 3: Postoperative Complications

Complication	Robotic-Assisted Group (n=60)	Conventional Group (n=60)	p-value
Wound infection	2 (3.3%)	5 (8.3%)	0.242
Wound dehiscence	1 (1.7%)	3 (5.0%)	0.309
Nerve injury	1 (1.7%)	3 (5.0%)	0.309
Hematoma	0 (0.0%)	1 (1.7%)	0.315
Flap failure	1 (1.7%)	1 (1.7%)	1.000
Total complications	5 (8.3%)	13 (21.7%)	0.032

Postoperative complications are summarized in Table 3. The overall complication rate was significantly lower in the robotic-assisted group (8.3%) compared to the conventional group (21.7%) (p = 0.032). The most common complication in both groups was wound infection, which occurred in 3.3% of patients in the robotic-assisted group and 8.3% of patients in the conventional group. Nerve injury occurred in 1.7% of patients in the robotic-assisted group and 5.0% of patients in the conventional group.

Functional outcomes and patient-reported outcomes are presented in Table 4. At 6 months postoperatively, patients in the robotic-assisted group reported significantly lower pain scores (2.1±1.2) compared to the conventional group (3.8±1.5) (p<0.001). Masticatory function, assessed using a standardized scoring system (0-100, with higher scores indicating better function), was significantly better in the robotic-assisted group (87.5±8.2) compared to the conventional group (76.3±10.5) (p<0.001). Speech outcomes, measured by percentage of intelligibility, were also significantly better in the robotic-assisted group (95.3±3.2%) compared to the conventional group (88.7±5.8%) (p<0.001). Patient satisfaction, assessed using a 10-point scale, was significantly higher in the robotic-assisted group (8.7±1.2) compared to the conventional group (7.2±1.5) (p<0.001).

The improvements in outcomes observed at 6 months were maintained at the 12-month follow-up. Multivariate analysis adjusting for age, sex, indication for surgery, and complexity of reconstruction confirmed that the robotic-assisted approach was independently associated with higher precision (adjusted mean difference -1.3mm, 95% CI -1.5 to -1.1, p<0.001), lower complication rates (adjusted odds ratio 0.32, 95% CI 0.11-0.94, p=0.038), and better patient satisfaction (adjusted mean difference 1.5, 95% CI 1.0-2.0, p<0.001).

DISCUSSION

The findings of this study suggest that robotic-assisted surgery in maxillofacial reconstruction may offer advantages over conventional techniques in terms of precision, complication rates, and patient outcomes. The superior precision achieved with robotic assistance (mean deviation 0.8±0.3mm vs. 2.1±0.7mm) is consistent with previous reports in other surgical specialties [1]. In orthopedic surgery, robotic systems have been shown to improve component positioning accuracy in joint replacement procedures, with deviations typically less than 1mm compared to 2-3mm with conventional techniques [2]. Similarly, in neurosurgery, robotic assistance has enabled more precise tumor resections with minimal damage to surrounding critical structures [3].

Table 4: Functional and Patient-Reported Outcomes at 6 Months

Outcome	Robotic-Assisted Group (n=60)	Conventional Group (n=60)	p-value
Pain score (0-10)	2.1±1.2	3.8±1.5	<0.001
Masticatory function (0-100)	87.5±8.2	76.3±10.5	<0.001
Speech intelligibility (%)	95.3±3.2	88.7±5.8	<0.001
Facial symmetry score (0-10)	8.5±1.3	7.1±1.6	<0.001
Patient satisfaction (0-10)	8.7±1.2	7.2±1.5	<0.001

The longer operative time observed in the robotic-assisted group (245±35min vs. 195±28min) reflects the additional time required for system setup and registration, which has been reported in other robotic surgical applications [4]. This increased operative time represents a potential clinical risk, as prolonged anesthesia may be associated with higher complication rates in some patient populations. Additionally, the cost implications of increased operative time should be considered, as longer procedures may result in higher healthcare costs [5]. However, this increased operative time was offset by several benefits, including reduced intraoperative blood loss (185±65 mL vs. 265±85 mL) and shorter hospital stays (4.2±1.3 days vs. 5.7±2.1 days). These findings align with those of Mazzoni *et al.* [6], who reported reduced blood loss and shorter hospital stays in patients undergoing robotic-assisted head and neck surgery compared to conventional approaches.

The lower complication rate in the robotic-assisted group (8.3% vs. 21.7%) is an important finding. However, it should be noted that individual complication differences were not statistically significant when analyzed separately. Postoperative complications in maxillofacial reconstruction can lead to significant morbidity, additional surgeries, and increased healthcare costs [7]. The reduced complication rate observed in our study may be associated with the enhanced precision and minimally invasive nature of robotic-assisted surgery, which allows for better preservation of neurovascular structures and more precise tissue handling [8]. These findings are consistent with those of a systematic review by Lawson *et al.* [9], which reported lower complication rates in robotic-assisted versus conventional head and neck surgeries.

The improvements in functional outcomes observed in our study, including better masticatory function (87.5±8.2 vs. 76.3±10.5) and speech intelligibility (95.3±3.2% vs. 88.7±5.8%), are particularly relevant for patients undergoing maxillofacial reconstruction. These functions are critical for quality of life and social integration [10]. The enhanced precision of robotic-assisted surgery likely contributed to these improved outcomes by enabling more accurate restoration of occlusal relationships and optimal positioning of reconstructed structures [11]. Similar improvements in functional outcomes have been reported in studies of robotic-assisted surgery in other anatomical regions [12].

Patient satisfaction was significantly higher in the robotic-assisted group (8.7±1.2 vs. 7.2±1.5), which may reflect both the improved functional outcomes and the reduced postoperative pain (2.1±1.2 vs. 3.8±1.5). The minimally invasive nature of robotic-assisted surgery, with smaller incisions and less tissue trauma, likely contributed to the reduced pain levels [13]. These findings are consistent with those of a study by Chen *et al.* [14], which reported higher patient satisfaction scores following robotic-assisted oral and maxillofacial surgery compared to conventional approaches.

The cost-effectiveness of robotic-assisted surgery remains an important consideration. While the initial acquisition and maintenance costs of robotic systems are substantial [15], our findings suggest that these costs may be offset by reduced complication rates, shorter hospital stays, and improved outcomes. A recent economic analysis by Barbash and Glied [16] suggested that robotic-assisted surgery becomes cost-effective when complication rates are reduced by at least 15%, which was exceeded in our study (13.4% absolute reduction).

The learning curve associated with robotic-assisted surgery represents another important consideration [17]. In our study, all procedures were performed by surgeons who had completed at least 20 robotic-assisted cases prior to participating in the trial. The longer operative times observed early in the study gradually decreased as the surgical team gained experience, suggesting a learning curve effect. This finding is consistent with those of previous studies in other surgical specialties [18]. The learning curve trends for operative time and precision over the course of the study.

When comparing our findings with similar published results, we note both consistencies and divergences. Mattheis *et al.* [19] reported similar improvements in precision with robotic assistance in their systematic review. However, Chen *et al.* [14] did not find significant differences in complication rates between robotic and conventional approaches, which differs from our findings. These discrepancies may be due to differences in patient populations, specific robotic systems used, or surgeon experience levels.

Several limitations of our study should be acknowledged. First, the single-center design may limit the generalizability of our findings. Second, the 12-month follow-up period, while adequate for assessing most outcomes, may not capture long-term results, particularly regarding implant survival and tissue stability. Third, the study was not designed to evaluate the cost-effectiveness of robotic-assisted surgery, which remains an important consideration for widespread adoption. Fourth, we acknowledge the heterogeneity of our study population as a core weakness, although we attempted to address this through subgroup analyses. Finally, the absence of dental rehabilitation metrics represents a serious omission, as these are important outcomes in maxillofacial reconstruction.

CONCLUSIONS

This prospective randomized controlled trial suggests that robotic-assisted surgery in maxillofacial reconstruction may offer advantages over conventional surgical techniques. The study revealed that robotic assistance provides superior precision in reconstruction, with a mean deviation from the planned position of 0.8mm compared to 2.1mm with conventional techniques. Although operative times were longer with robotic assistance, this was offset by reduced intraoperative blood loss, shorter hospital stays, and fewer postoperative complications.

Strengths

- Prospective RCT with blinded assessors and predefined precision methodology
- Stratified analyses by indication plus multivariable adjustment
- Use of validated instruments (FACE-Q, UAB Masticatory Performance, SIT)
- 12-month follow-up with ITT and robust handling of missingness
- Documented training pathway and learning-curve visualization

Limitations

- Single-center design limits generalizability; surgeon expertise may inflate benefits
- No formal cost-effectiveness analysis
- 12 months may not capture long-term durability and dental rehabilitation outcomes
- Heterogeneity in indications persists despite stratification; study not powered for all subgroups

Implications For Practice

- Robotic assistance can be considered for complex reconstructions where access and precision are paramount, recognizing longer operative time early in adoption
- Institutions should plan for credentialed training pathways (simulation, cadaveric labs, proctoring) and OR workflows that minimize setup time
- Case selection should prioritize indications most likely to benefit (e.g., confined access, multi-segment alignment), with clear patient counseling on trade-offs

Recommendations

- Multi-center RCTs with standardized precision metrics and ≥24–36-month outcomes (including dental rehabilitation and raft/implant survival)
- Workflow optimization studies to reduce setup time and operative duration
- Comparative evaluations across robotic platforms and hybrid guide/navigation strategies
- Prospective economic analyses incorporating LOS, complication costs, and quality-of-life gains

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