

Preliminary assessment of maxillary positioning accuracy in orthognathic surgery using CAD-CAM-generated custom-made cutting guides and osteosynthesis plates. A short report

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Abstract

Background: Our study aims to verify the accuracy of maxillary positioning in orthognathic surgery using CAD-CAM cutting guides and custom-made osteosynthesis plates, comparing the preoperative 3D surgical plan with the final positioning determined from postoperative CT scans.

Methods: This prospective monocentric study included eight patients (aged 18–30) with dentofacial deformities (six Class III and two Class II malocclusions) who underwent bimaxillary orthognathic surgery. The digital workflow integrated CT scans and intraoral digital impressions. Customized cutting guides and selective laser-melted (SLM) titanium plates were designed to transfer the 3D-VSP to the operative field. Accuracy was assessed one month postoperatively by superimposing the surgical plan onto postoperative CT scans. Surface deviations were quantified and visualized using color maps.

Results: The transfer of the virtual plan was successful in all cases with no intraoperative complications. A 100% accuracy rate was achieved, defined as a three-dimensional deviation of less than 1.5 mm. The overall mean linear error was -0.24 mm (± 0.35 mm SD). Visual analysis via color maps confirmed a marked prevalence of discrepancies ≤ 1.0 mm (green zones) across all maxillary surfaces. Statistical analysis using a paired t-test showed no significant differences between the planned and achieved positions ($p > 0.05$), indicating an absence of systematic errors.

Conclusions: The reported findings suggest that CAD-CAM cutting guides and custom-made osteosynthesis plates tend to improve the accuracy in the maxillary positioning. Furthermore, custom-made osteotomy guides and plates increase the predictability and security of the surgical procedure.

Keywords: Orthognathic surgery; CAD-CAM; Virtual Surgical Planning; Maxillary accuracy.

Introduction

Orthognathic surgery is an established procedure for addressing moderate to severe dentofacial irregularities. This surgery primarily aims to restore proper occlusion and



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facial symmetry, enhance functionality, and achieve long-term skeletal stability (1).

Achieving optimal occlusion and facial aesthetics demands a high level of surgical precision and consistency in jaw repositioning. At present, the success of surgery still heavily depends on the individual surgeon's expertise in executing the planned procedure. Recent developments in computer-assisted orthognathic surgery, particularly advancements in virtual planning software, have significantly enhanced diagnostic accuracy, treatment planning, surgical precision, and postoperative outcome assessment in the correction of maxillofacial deformities (2, 3). Traditional methods and 2D planning techniques using cephalometry and model surgeries for hand-fabricated interocclusal surgical splint production are increasingly being replaced, as they have limitations such as inaccuracies in splint fabrication and difficulties with vertical control (4). To overcome such challenges, three-dimensional virtual surgical planning (3D-VSP) has emerged as a valuable tool. The primary objective of computer-assisted techniques in this context is to provide surgeons with tools to simulate surgical movements and predict surgical outcomes before intervention. Over the last decade, CAD-CAM technology, enabling the 3D printing of customized surgical guides, plates, and splints, has marked a paradigm shift in the field (5, 6). Although 3D-printed splints derived from virtual plans have shown improved accuracy compared to traditional methods, they are still prone to seating errors, and vertical control of the maxilla remains a challenge even with CAD-CAM-generated splints (7). In contrast, virtual planning enables the fabrication of patient-specific titanium fixation plates, which, when used alongside cutting guides, allow precise bone positioning, reduce surgical

duration, and eliminate reliance on occlusal splints or intermaxillary fixation (8).

This study aimed to verify the accuracy of maxillary positioning in orthognathic surgery using CAD-CAM patient-specific cutting guides and custom-made osteosynthesis plates, comparing the preoperative 3D surgical plan with the final positioning determined by postoperative CT scans.

Materials and Methods

Study Design and Selection Criteria

This prospective monocentric study was conducted at the Maxillofacial Surgery Unit of the San Salvatore Hospital in L'Aquila. The study sample consisted of 8 patients enrolled over 18 months, from October 2023 to April 2025. Inclusion was limited to subjects aged 18 to 30 years presenting with dentofacial deformities requiring surgical correction via LeFort I osteotomy. All patients underwent bimaxillary orthognathic surgery performed by the same surgeon following a "maxilla-first" protocol with the aid of CAD-CAM technologies. Exclusion criteria included patients with sequelae of cleft palate, syndromic craniofacial anomalies, previous trauma to the maxillomandibular complex, or the clinical necessity for segmental LeFort I osteotomy.

Digital Workflow and CAD-CAM Design

The preoperative diagnostic phase involved integrating clinical, radiographic, and cephalometric data through the acquisition of computed tomography (CT) scans and intraoral digital impressions. Virtual surgical planning (VSP) was performed using DOLPHIN software (<https://dolphinsimaging.it/it/>), enabling three-dimensional simulation of skeletal movements and prediction of soft-tissue profile (Figures 1 and 2).

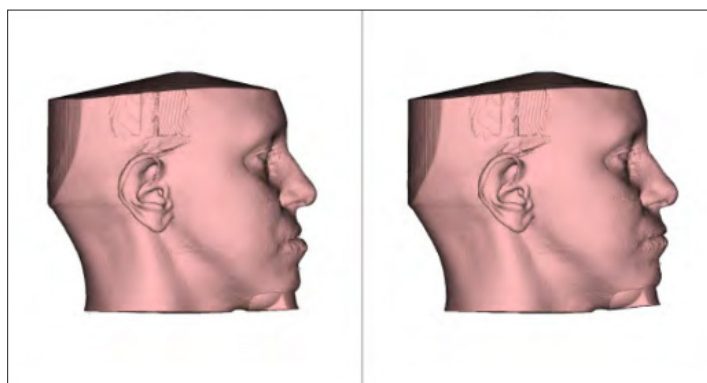


Figure 1. 3D soft tissue simulation after LeFort I osteotomy + BSSO

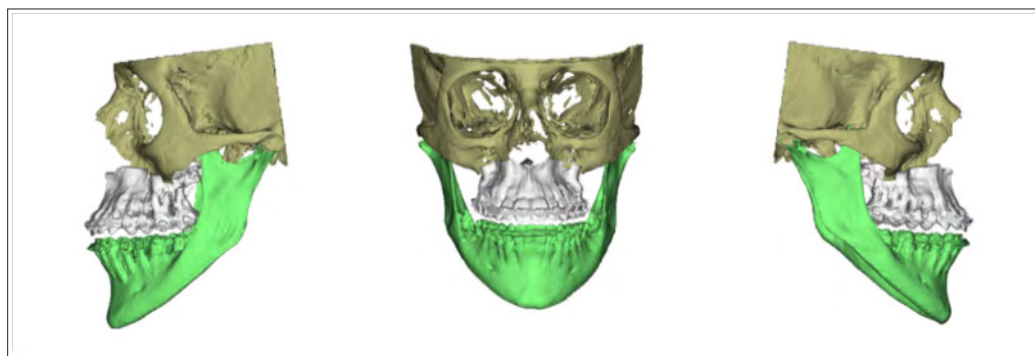


Figure 2. Virtual surgical planning of osteotomy after 3D reconstruction of maxillofacial CT scan

Customized cutting guides, titanium fixation plates, and 3D-printed surgical splints were designed using the software's advanced computer-aided design (CAD) tools based on the individualized virtual surgical plans. The planned movements were exported as numerical data and sent to the laboratory responsible for CAD-CAM device production, together with the DICOM data from the CT scan (Figure 3). Three-dimensional surgical one-piece cutting guides and bone fixation plates made of titanium alloy were processed by selective laser melting for each patient. Finally, the cutting guides were applied during surgery to direct the preoperatively planned osteotomy line, while the custom-made fixation plates enabled the planned repositioning of the maxilla. To assess the maxillary deviation between the planned and postoperative positions, the preoperative planning image was superimposed on the post-treatment CT scan, and the mean positional differences were measured three-dimensionally.

Surgical technique and preparation

The surgical procedures were performed under hypotensive general anesthesia to minimize intraoperative bleeding and improve surgical field visibility. All patients underwent Le Fort I osteotomy in combination with bilateral sagittal split osteotomy (BSSO) with maxilla-first approach. Upper maxillary repositioning was performed waferless.

The upper maxilla was accessed through an intraoral vestibular incision that was made between the first molars, at least 7 mm above the mucogingival junction. The full-thickness mucoperiosteal flap was elevated, and the anterior wall of the maxilla was exposed. A one-piece, customized cutting guide was introduced into the surgical field and stabilized in the correct position, taking advantage of the good anatomic engagement afforded by the natural curvature of the maxillozygomatic buttress and the anterior maxillary walls. The cutting guide was fixed in place with 2.0 mm titanium screws to

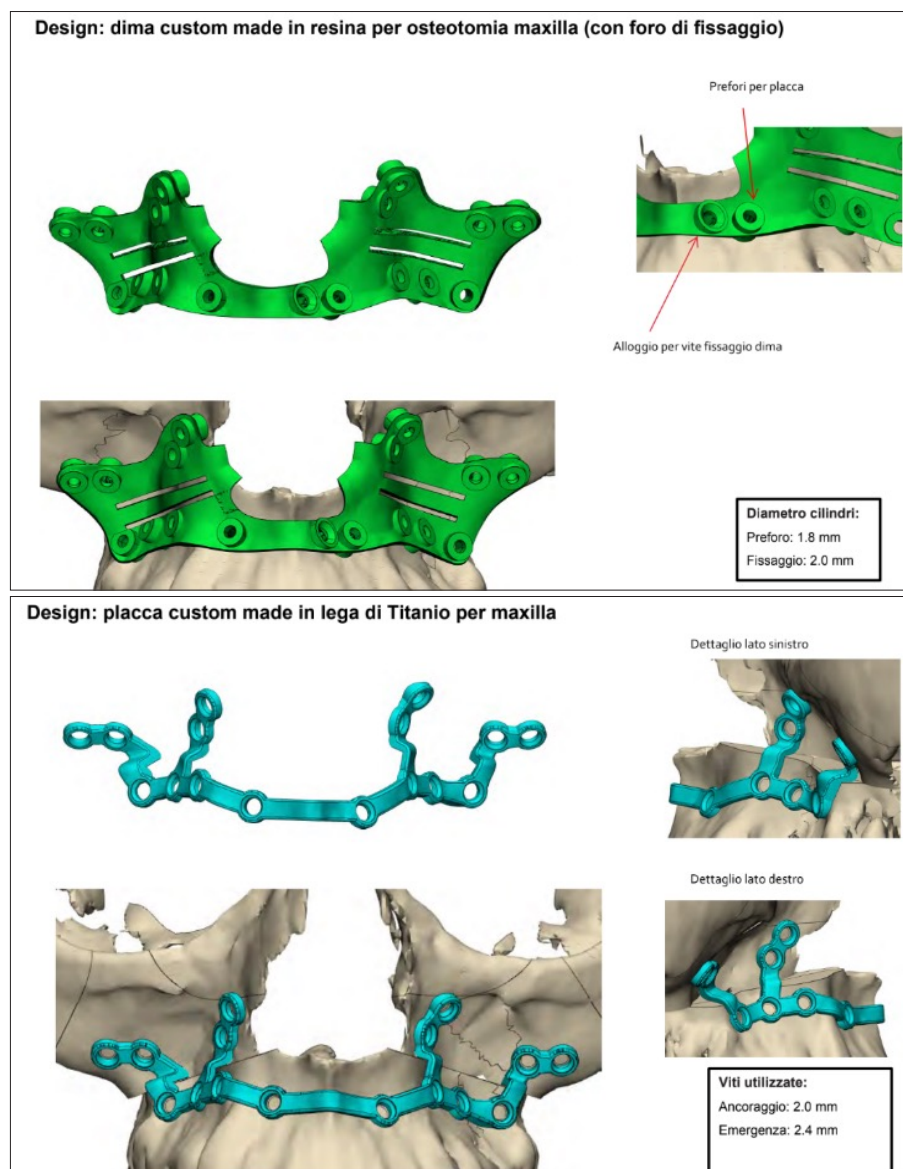


Figure 3. Virtual surgical planning design of bone cutting guide (in green) and customized bone fixation titanium plate (in blue)

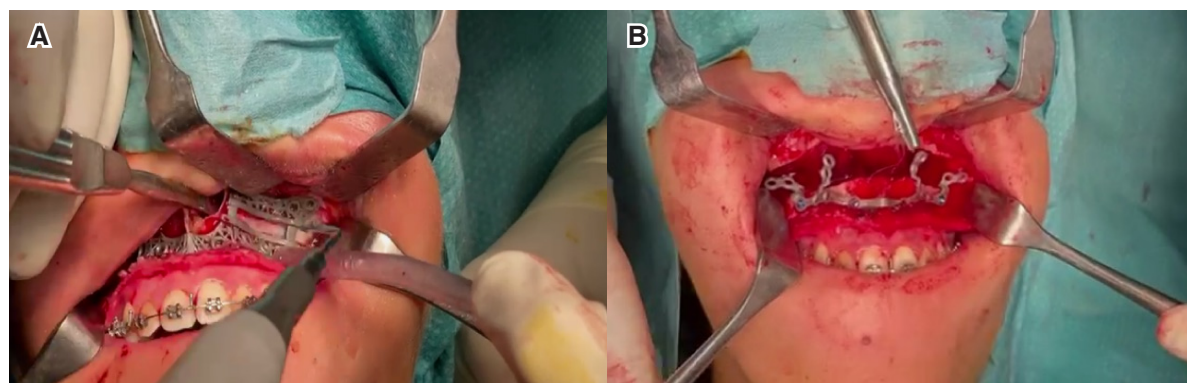


Figure 4. (A) Fixation of custom-made cutting guide to enable correct osteotomy as per virtual surgical planning; (B) Positioning and fixation of custom-made titanium plate

ensure stability, and a piezoelectric saw (tip diameter, 0.55 mm; Mectron, Sestri Levante, Genova, Italy) was used to perform the osteotomy as per the cutting guide design (Figure 4A). The cutting guide was then removed, and the Le Fort I osteotomy was completed. The lateral nasal walls were sectioned using nasal chisels, and the nasal septum was separated with a septum osteotome. The pterygomaxillary junction was carefully separated using curved osteotomes. Upon completion of the osteotomies, the maxilla was down-fractured. Next, with the aid of the customized titanium plate, the maxilla was repositioned according to the preoperative surgical plan, and the plate was secured with 2.0 mm titanium screws (Figure 4B). The fixation plate was designed to allow attachment to the maxilla via the holes through which the cutting guide had previously been fixed. A BSSO was performed for mandibular correction, and the proper occlusion was finally verified. The vestibular incisions of the maxilla and mandible were closed using 3-0 Vicryl in continuous running suture.

Accuracy Analysis and Statistical Evaluation

The primary outcome of the study was the precision with which the virtual plan was transferred to the actual surgical procedure. In contrast, secondary outcomes included operative times, the accuracy of the customized devices, the incidence of postoperative infections, and plate stability. One month after surgery,

a postoperative CT scan was acquired for dataset comparison. The superimposition between the planned and achieved maxillary positions was quantified using MeshLab software (<https://www.meshlab.net/>) by a single experienced examiner. Surface deviations were represented on a color map, where green indicates an error ≤ 1.0 mm, yellow between 1.1 and 2.0 mm, and orange between 2.1 and 3.0 mm (Figure 5).

Data analysis was performed by calculating the mean and standard deviation (SD). A paired t-test was used to assess the significance of differences between virtual and actual values, with a significance level of $p < 0.05$.

Results

Clinical Outcomes and Postoperative Course

The study cohort comprised 8 patients (6 females, 2 males) with a mean age of 18–30 years. The clinical cases included six subjects diagnosed with Class III malocclusion (two of whom presented with associated asymmetry) and two subjects with Class II malocclusion. The VSP transfer was completed in all cases using the integrated CAD-CAM system of customized guides and plates. No intraoperative complications were recorded, and no replacement of the osteosynthetic devices was required. The postoperative course was uneventful for the entire sample, with no infections, soft-tissue dehiscence, or hardware instability during follow-up.

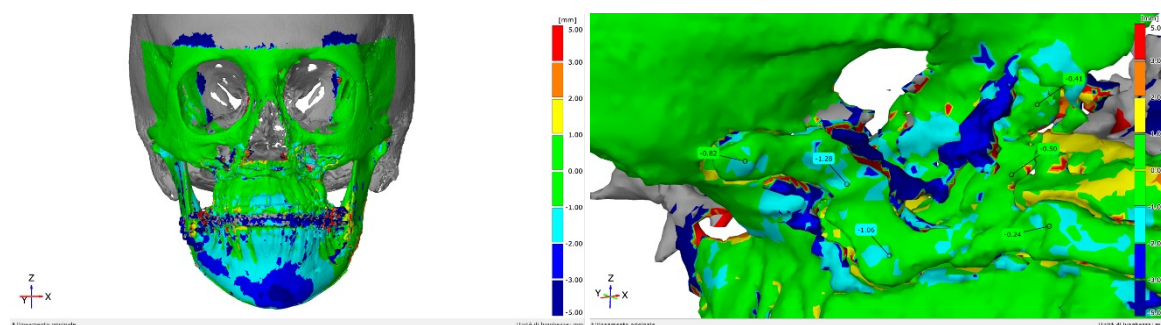


Figure 5. Evaluation of accuracy using preoperative planning and postoperative computed tomography data. Superimposition of the 2 models visualizes the matching error with different colors (color error scale at right)

Quantitative Accuracy Analysis and Color Map Correlation

Three-dimensional evaluation, performed by superimposing postoperative CT scans onto preoperative virtual models, confirmed the protocol's high precision. Assuming a clinical tolerance threshold of 1.5 mm or less, 100% accuracy was achieved across all analyzed patients. The overall mean linear error was -0.24 mm (± 0.35 mm SD).

Visual analysis using color maps revealed a marked prevalence of green across all maxillary surfaces, indicating discrepancies of ≤ 1.0 mm in nearly all repositioned regions. Yellow areas (1.1–2.0 mm) were limited and primarily localized at the osteotomy margins, while no significant deviations in orange (> 2.1 mm) areas were detected. The widest error range was documented in patient no. 6, ranging from -1.45 mm to +1.36 mm, thus remaining within the pre-established tolerance limits.

Statistical validation via paired t-test

the system's reliability was corroborated by inferential statistical analysis of the spatial coordinates of predefined anatomical landmarks. The paired t-test, used to compare virtual planning values with actual postoperative data formally, showed no statistically significant differences ($p > 0.05$). This evidence demonstrates the absence of systematic errors in the digital transfer process. It validates the efficacy of the waferless protocol in ensuring predictable and accurate surgical reproducibility, independent of the manual variability associated with traditional occlusal splints.

Discussion

Achieving both functional and aesthetic outcomes in orthognathic surgery depends largely on the accurate repositioning of the upper maxilla in line with the

preoperative surgical plan. As the central structural component of the facial skeleton, the maxilla plays a pivotal role in determining the alignment and movement of adjacent bones, especially the mandible. Therefore, maintaining precise three-dimensional (3D) control of the maxilla during surgery is essential. However, the optimal technique for achieving this level of control remains a subject of ongoing discussion in the field (9, 10). The results of the present study confirm the efficacy of CAD/CAM technologies in overcoming the inherent limitations of traditional surgery using occlusal splints.

Traditionally, maxillary repositioning has been performed using surgical splints fabricated from dental impressions and plaster models obtained during preoperative planning. Measurements, often subject to human error and typically transferred manually onto physical models, may introduce several inaccuracies. These include errors during splint fabrication and measurement deviations, which may lead to positioning errors of up to 5 mm (10, 11). Despite these shortcomings, this conventional method remains widely used by maxillofacial surgeons. A splintless approach, as adopted in the current study, demonstrated significantly superior accuracy. All eight patients in our sample presented a three-dimensional deviation of less than 1.5 mm, with a mean error of -0.24 mm (± 0.35 mm SD). This data not only falls well within the conventionally accepted clinical tolerance range of 2.0 mm for postoperative orthodontic correction (12) but also establishes an extremely high standard of precision.

In recent years, advances in computer-aided design and manufacturing (CAD/CAM) have led to the development of customized cutting guides and patient-specific fixation plates to improve the accuracy of maxillary repositioning and eliminate the need for surgical splints. These tools facilitate the translation

Table 1. Quantitative analysis of linear discrepancies between virtual surgical planning (VSP) and the postoperative outcome. Values are expressed in millimeters (mm). Accuracy was defined as a deviation of less than 1.5 mm. SD: Standard Deviation.

Patient	Gender	Angle Classification	Min Error (mm)	Max Error (mm)	Mean Error ($\pm$ SD)
1	F	Class III	-1.33	+1.40	0.03 $\pm$ 0.68
2	F	Class III + asymmetry	-1.50	-0.16	-0.83 $\pm$ 0.45
3	F	Class III	-1.49	+1.13	-0.18 $\pm$ 0.72
4	M	Class III + asymmetry	-0.98	+1.11	0.06 $\pm$ 0.52
5	F	Class III	-1.36	-0.23	-0.79 $\pm$ 0.38
6	F	Class III	-1.45	+1.36	-0.04 $\pm$ 0.81
7	F	Class II	-1.44	+1.20	-0.12 $\pm$ 0.76
8	M	Class II	-1.10	+0.95	-0.07 $\pm$ 0.55
Patient			-1.33	+0.84	-0.24 $\pm$ 0.35

of virtual surgical plans into the operative setting with improved precision. In 2014, Mazzoni et al. and Gander et al. were among the earliest to introduce a fully personalized system that integrates surgical custom-made guides and fixation plates (13, 14). In the following years, more studies have highlighted the accuracy of custom-made surgical guides and titanium plates in orthognathic surgery, assessing additional benefits, such as reduced operative time and reduced postoperative complications associated with ill-fitting titanium plates (15-17). Suojanen et al. reported that the use of PSO does not result in differences in required plate removal, infections, or other soft-tissue problems. Regarding the necessity of surgical splints, several studies have compared traditional splint-guided surgery with splintless, customized surgery. In our series, the absence of complications suggests that the superior anatomical fit of SLM (Selective Laser Melting) plates reduces residual tension on soft tissues, which is often caused by the manual contouring of conventional plates.

Statistical validation via a paired t-test ($p > 0.05$) further corroborates the thesis that the personalized method can eliminate systematic errors.

In 2020, Kraeima et al. conducted a randomized controlled trial comparing patient-specific osteosynthesis in one group of patients to a control group that received conventional model surgery supported by 3D VSP splints for maxillary repositioning, concluding that PSO improves the accuracy of maxillary translation compared to model surgery with surgical splints (18). With the use of custom-made cutting guides and titanium osteosynthesis plates, there is no further need for an occlusal splint for the achievement of the desired maxillary movements. The cutting guides are designed for straightforward placement and help ensure the Le Fort I osteotomy is performed along the planned trajectory. They enable precise bone cutting, even in cases requiring vertical maxillary movement or changes in the occlusal plane. Additionally, the predrilled holes in these guides allow for precise placement of CAD/CAM plates, providing reliable control over the maxillary sagittal, transverse, and vertical positioning as per the preoperative plan. This approach has also been associated with reduced operative time, as it minimizes the need for intraoperative plate adjustment and final bone positioning verification. Traditionally, deviations of less than 2.0 mm in the maxilla have been deemed acceptable, as they may be corrected through orthodontic treatment (12). In our study, all patients presented with a deviation of less than 1.5 mm and thus achieved satisfactory results.

The present study suggests that, while conventional surgery remains widely practiced, the transition to an entirely digital workflow represents a necessary evolution to ensure reproducible results, particularly in cases of complex asymmetries or Class III deformities, which constituted the majority of our cohort. The millimetric accuracy achieved (100% of cases < 1.5 mm) demonstrates that the synergy between customized cutting guides and patient-specific plates not only eliminates the dependence on occlusal splints but also elevates orthognathic surgery to a level of digital

precision that ensures long-term stability and aesthetic harmony.

Study Limitations and Future Perspectives

Despite the promising results in terms of accuracy and reproducibility, the present study has several limitations that must be considered when interpreting the data. First, the sample size is relatively small, and the research was conducted at a single center of excellence. These factors may limit the generalizability (external validity) of the findings to larger patient populations or to surgical teams with varying levels of experience in digital technologies. Second, the absence of a control group precluded a direct statistical comparison between the CAD-CAM protocol and alternative therapeutic options, such as traditional occlusal splint-guided surgery. Finally, the follow-up period was limited to 1 month postoperatively, focusing exclusively on immediate surgical accuracy; consequently, it was not possible to evaluate long-term functional outcomes or the incidence of potential late complications.

To address these limitations, future studies involving larger patient cohorts and extended follow-up periods are already being planned. Such research will be fundamental to evaluating long-term skeletal stability, patient satisfaction, and definitive functional outcomes resulting from the systematic use of patient-specific technology.

Conclusions

In conclusion, the present results suggest that the use of CAD-CAM cutting guides and customized titanium plates for upper maxilla repositioning is a promising method for accurately reproducing preoperative virtual planning in the operative field. Customized titanium plates demonstrate high accuracy in maxillary positioning, respecting the pre-operative virtual surgical plan, while offering technical advantages such as ease of use, procedural efficiency, and reduced surgical time.

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