Journal of Dental Sciences

Volume 21 | Issue 2 Article 29

2026

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Le, Phuc Hoai; Hoang, Hung Trong; Lam, Phuong Hoai; Nguyen, Tuan Van; and Le, Chanh Trung (2026) "Enhanced accuracy of cutting planes and condylar positioning in mandibular reconstruction using three-dimensional-printed guides: An in vitro study," *Journal of Dental Sciences*: Vol. 21: Iss. 2, Article 29.
Available at: https://jds.ads.org.tw/journal/vol21/iss2/29

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Journal of Dental Sciences 21 (2026) 915—922

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Original Article

Enhanced accuracy of cutting planes and condylar positioning in mandibular reconstruction using three-dimensional-printed guides: An in vitro study

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Received 26 July 2025; Final revision received 12 August 2025
Available online 1 April 2026

KEYWORDS
3D printing;
Mandible;
Mandibular condyle;
Mandibular reconstruction;
Three-dimensional accuracy

Abstract *Background/purpose:* Accurate mandibular reconstruction, particularly condylar repositioning, is essential for restoring function and facial symmetry following segmental resection. This study aimed to evaluate the accuracy of cutting planes and three-dimensional (3D) condylar positioning using 3D-printed cutting guides combined with plate-guided positioning.
Materials and methods: This in vitro study included sixteen 3D-printed mandibular models simulating segmental defects. Virtual surgical planning was employed to fabricate 3D-printed cutting guides and plate-guided positioning. Postoperative models were compared with their corresponding virtual models using 3-Matic software to assess cutting plane and 3D condylar positioning deviations.
Results: The angular deviations of the proximal cutting plane averaged 13.27 ± 10.36 mm in pitch and 12.1 ± 8.67 mm in yaw, demonstrating acceptable alignment. The mean difference in defect distance was 0.51 ± 3.53 mm (*P* = 0.93). Intercondylar angulation deviation was 2.13 ± 2.53°, with no significant difference in intercondylar distance (100.75 ± 7.32 mm vs. 102.01 ± 6.99 mm, *P* = 0.51). On the operative side, deviations of the highest points of the condyle were 2.76 ± 3.39 mm (superior—inferior), 2.37 ± 2.76 mm (anterior—posterior), and 1.94 ± 2.93 mm (medial—lateral). Angular deviations of the condylar head axis were minimal

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https://doi.org/10.1016/j.jds.2025.08.023
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in the coronal (1.66 ± 1.38°) and transverse (1.52 ± 1.51°) planes, as opposed to the sagittal plane (5.61 ± 5.26°).
Conclusion: 3D-printed cutting guides and plate-guided positioning allowed for accurate replication of virtual surgical plans in mandibular reconstruction. All deviations remained within acceptable limits. Further research is recommended to validate these findings.
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Introduction

Mandibular segmental resection and reconstruction are widely used to treat mandibular tumors, which impact function and aesthetics.[1,2] Despite advances in surgical techniques, accurate condylar positioning after reconstruction remains a significant challenge. Improper condylar positioning can lead to facial asymmetry, temporomandibular disorders, and malocclusion, all of which negatively affect the patients' quality of life.[3]

Moreover, some reports suggest that the fibula is a gold standard for mandibular reconstruction.[4,5] Conversely, other research indicates that using a reconstruction plate without a bone graft is a viable option, particularly for patients with recurrent tumors or financial constraints. This approach can reconstruct the mandible's continuity and maintain a satisfactory quality of life, provided sufficient soft tissue support is available.[6] These reconstruction plates could help restore facial aesthetics.[6]

Three-dimensional (3D) printing and virtual surgical planning (VSP) have revolutionized mandibular reconstruction by enhancing accuracy, particularly in ensuring the correct positioning of the condyles post-reconstruction.[7] VSP improves bone cutting accuracy using 3D-printed cutting guides and ensures precise placement of the reconstruction plate through plate-guided positioning.[8–10] However, post-surgical condylar positioning remains a notable concern that necessitates comprehensive evaluation.

While clinical studies offer crucial insights into long-term outcomes, in vitro studies provide a reproducible, controlled environment for testing new techniques without the variability introduced by biological factors. By utilizing 3D-printed cutting guides and plate-guided positioning, this study seeks to assess the accuracy of condylar positioning in mandibular reconstruction. The ability to replicate virtual planning with high precision in a physical model offers the potential to reduce human error during surgery, improving both functional and aesthetic outcomes.[11,12]

Thus, this study aimed to demonstrate the efficacy of using 3D-printed cutting guides and plate-guided positioning in an in vitro environment to improve the precision of mandibular reconstruction.

Materials and methods

Study design

This study utilized sixteen 3D-printed mandibular models to assess the precision of condylar positioning and cutting planes during mandibular reconstruction. These models were digitally constructed using patient-specific imaging data sourced from DICOM (Digital Imaging and Communications in Medicine) files. The DICOM data were obtained from preoperative computed tomography (CT) scans of patients diagnosed with mandibular tumors. The sample included 16 patients (9 men, 7 women), comprising 15 cases of ameloblastoma and 1 case of odontogenic myxoma. The inclusion criterion was a clear indication for segmental mandibular resection and reconstruction, whereas the exclusion criterion was the presence of tumors involving the condylar region to minimize potential confounding. The study was conducted using 3D-printed cutting guides and plate-guided positioning from November 2023 to June 2025 at the Department of Maxillofacial Surgery, National Hospital of Odonto-Stomatology in Ho Chi Minh City, Viet Nam.

Ethics statement

This study did not involve direct participation of human subjects. Patient-specific DICOM data were obtained from anonymized preoperative CT scans of patients diagnosed with mandibular tumors at the National Hospital of Odonto-Stomatology in Ho Chi Minh City, Viet Nam. Ethical approval for the use of the anonymized patient data was obtained from the Ethics Committee of Biomedicine Study at the University of Medicine and Pharmacy at Ho Chi Minh City (approval number: 1089/HDDD-DHYD, dated 02/11/2023). Written informed consent for the use of the anonymized data was obtained from all patients whose imaging data were used in this study.

Procedures

The study followed a structured workflow to evaluate the accuracy of cutting planes and condylar positioning in mandibular reconstruction using 3D-printed guides.

Image acquisition

Preoperative CT scans obtained from anonymized patients diagnosed with mandibular tumors were processed into DICOM files. CT scans were performed using a spiral CT scanner (Somatom Spirit, Siemens, Berlin, Germany) at the National Hospital of Odonto-Stomatology in Ho Chi Minh City. Imaging parameters were adjusted based on the patients' conditions, with a slice thickness of 1 mm, field of view of 20–25 cm, and exposure time of 35–55 s.

Virtual surgical planning

The DICOM files were imported into 3D Slicer (version 5.6.2; http://www.slicer.org) to create virtual 3D models of the mandible. Virtual resection of the tumor defects was performed to replicate common clinical scenarios, with the tumor's size, location, and geometry carefully simulated. Based on these virtual models, 3D-printed cutting guides and plate-guided positions were designed to facilitate precise cutting and accurate condylar positioning during the surgical procedure using OrtogOnBlender version 2.91 (Blender Foundation) (Fig. 1).

Fabrication of 3D-printed cutting guides and plate-guided positions

The 3D mandibular models generated through VSP were then used to fabricate the 3D-printed cutting guides and plate-guided positions. These were produced using stereolithography 3D printing technology with the Elegoo Saturn 4 Ultra Resin 3D Printer, ensuring high precision in their design and production.

Simulated surgery

The in vitro surgeries were performed using 3D mandibular models with simulated tumor. The models, along with the 3D-printed cutting guides, were used to make precise cuts as planned during the virtual planning phase. The plate-guided positioning was employed to ensure accurate placement of the reconstruction plates, aligning the screw holes for optimal fit and function. The pre-bent plates were manufactured using commercial surgical plates from Jeil Medical Co., Korea (Fig. 2). The in vitro surgeries were conducted by a board-certified oral and maxillofacial surgeon with extensive clinical experience in mandibular reconstruction.

Post-operative measurement and assessment

After the simulated surgery, post-operative CT scans were acquired to assess the accuracy of the procedure. The actual surgical outcomes were compared with the virtual models by superimposing the post-surgical models onto the preoperative, virtual ones to assess the accuracy of cutting planes and 3D condylar positions with 3-Matic software (version 13.0; Materialise, Leuven, Belgium). All measurements and data analyses were performed by a team of oral and maxillofacial surgeons. Prior to data collection, these specialists underwent standardized training in digital measurement protocols and conducted repeated assessments to ensure intra-observer reliability. The evaluation procedures followed the established methodologies described by Yang et al.[8]

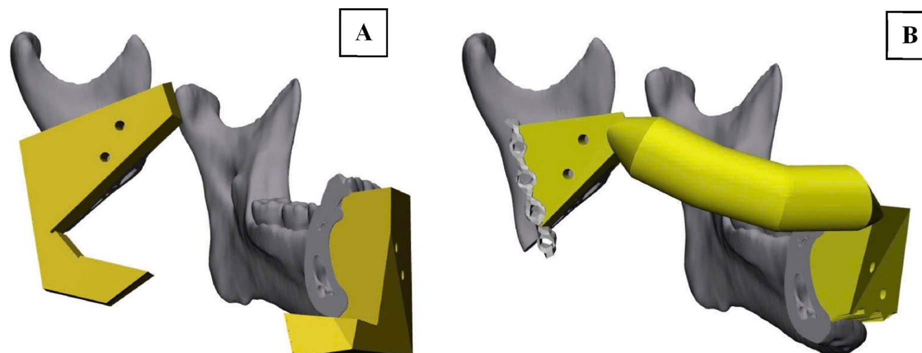

Figure 1 VSP in mandibular reconstruction with prebent plates. (A) three-dimensional (3D)-printed cutting guides. (B) Plate-guided positioning based on corresponding screw holes, including a reconstruction plate position guide. VSP, virtual surgical planning.

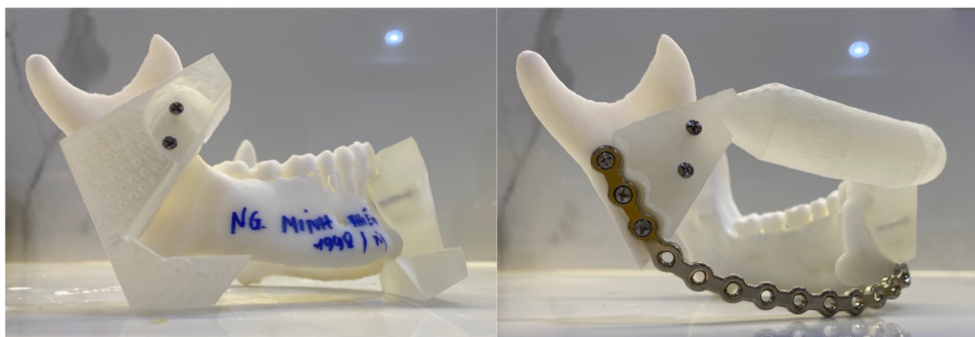

Figure 2 In vitro mandibular surgery using a three-dimensional (3D) stereolithographic model. (A) 3D-printed cutting guides for mandible resection. (B) Prebent plate supported by plate-guided positioning.

Outcomes and measurement

The primary outcomes were the deviations in cutting planes and condylar positioning post-surgery. These outcomes were selected based on their clinical relevance in achieving accurate mandibular reconstruction.

Deviations in cutting planes. Cutting planes are defined by the resection margins of the mandible during surgery. Deviations in cutting planes measure the discrepancy between the virtual planned and actual resection planes. Yaw and pitch are the angular parameters for assessing deviations in the cutting planes: Yaw is the craniocaudal axis rotation, which measures any side-to-side discrepancies in the cutting plane. In contrast, pitch is the buccolingual axis rotation, indicating any forward or backward deviations in the cutting plane.

First, a cutting plane accuracy analysis was conducted as outlined by El-Mahallawy et al.[13] The actual and virtual mandibular models were aligned using the distal plane as the reference, and the absolute deviations were evaluated based on the proximal plane (Fig. 3A and B). Three points were defined by placing two points at the buccal and lingual superior borders of the cutting plane, with the third point positioned at the lower border of the remaining plane (Fig. 3B). Angular deviations of the proximal cutting planes between the actual and virtual planes were measured in yaw (craniocaudal axis) and pitch (buccolingual axis) rotations (Fig. 3C and D).

Second, the gap between the proximal and distal planes was calculated in the actual planes and compared with the measurement acquired in the virtual plane[13] (Fig. 3E and F).

Condylar position changes. Based on the study by Le et al.,[14] researchers superimposed actual and virtual models using the non-operative side of the condyle as a reference to measure deviations on the operated side. Initially, deviations in intercondylar angulation and distance were evaluated based on the highest points of the condylar heads (Fig. 4A). Subsequently, deviations of the highest points of the condyles were assessed in three dimensions: medial-lateral (side-to-side) and anterior-posterior (front-to-back) in the horizontal axis and superior-inferior (up-and-down) in the vertical axis (Fig. 4B).

Finally, angulation deviations of the condylar axis in the coronal, transverse, and sagittal planes were calculated by

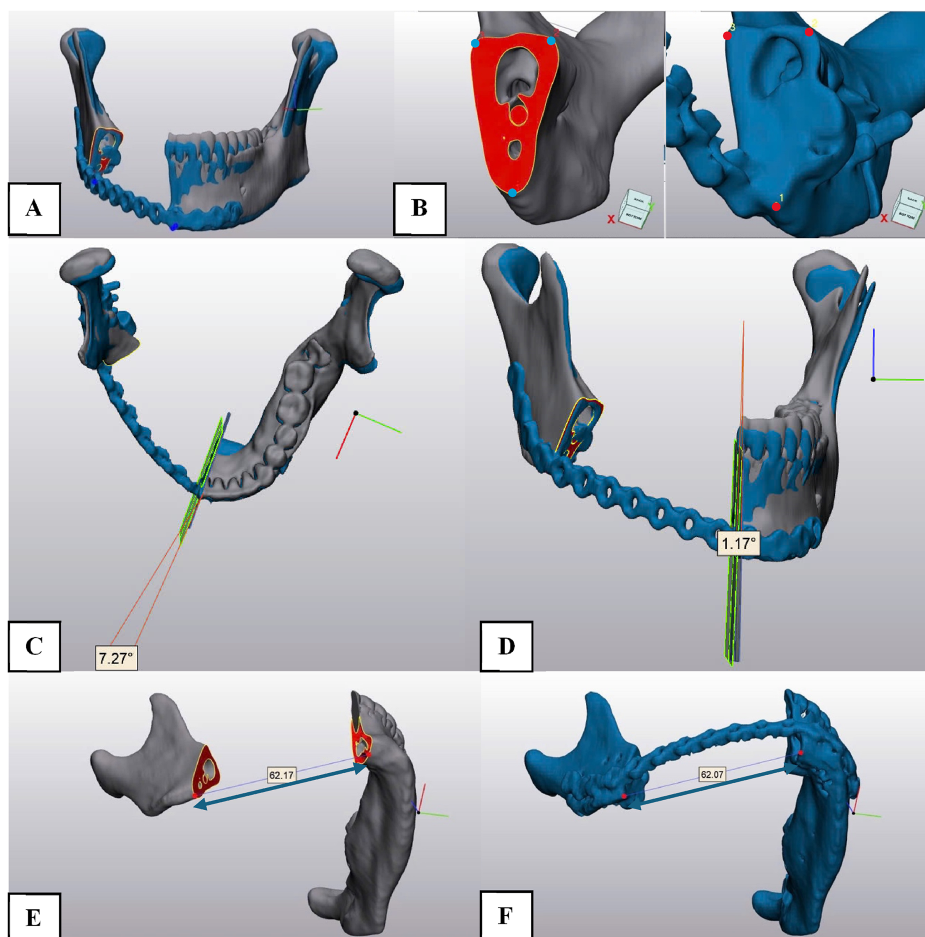

Figure 3 Absolute deviations of cutting planes at the proximal plane. The virtual model (silver) and actual model (Blue) were superimposed using the distal plane as a reference. (A, B) Superimposed distal planes of virtual and actual models. (C, D) Absolute deviations at the proximal planes during yaw and pitch rotations. (E, F) Accuracy of defect distance measurements between virtual and actual Models. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

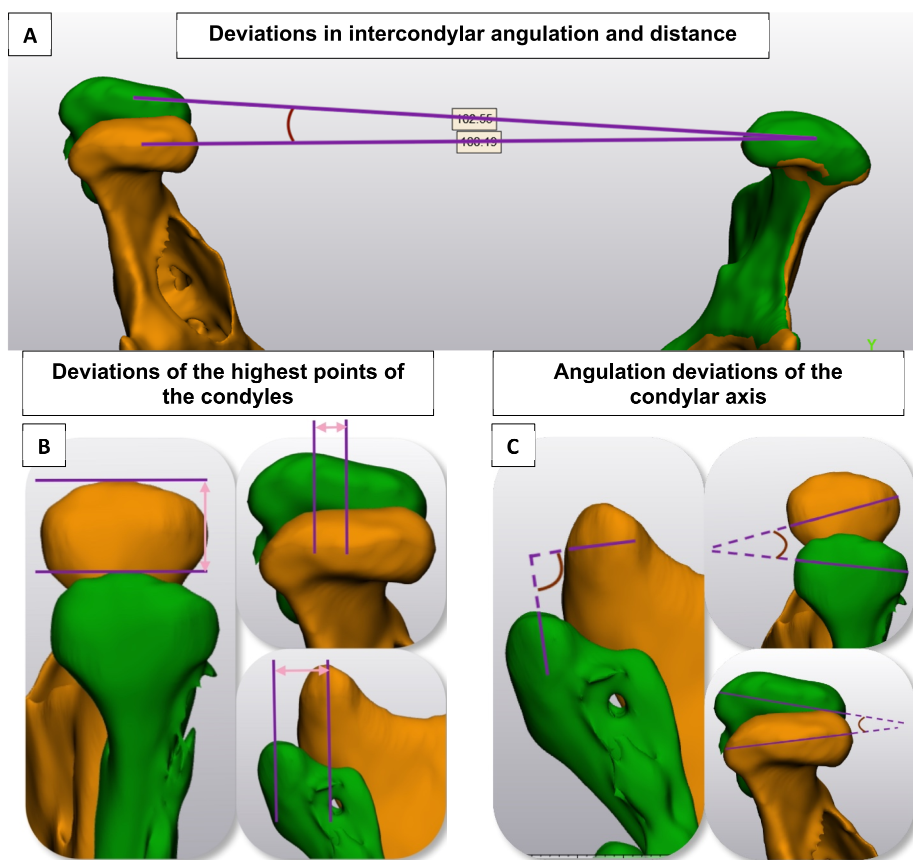

Figure 4 Outcome parameters for spatial deviations of condylar position. (A) Deviations in the intercondylar angulation and distance. (B) Deviation of the highest points of the condyles. (C) Angulation deviation of the condylar axis.

connecting the most lateral and mesial points of the condyle[6] to evaluate its rotational positioning (Fig. 4C).

Statistical analysis

We used the Shapiro—Wilk test to evaluate the normality of data distribution. An independent sample t-test was used to compare data exhibiting a normal distribution and the Wilcoxon signed-rank test for non-normally distributed data. Continuous variables are presented as mean ± standard deviation. All statistical analyses were performed as two-sided tests, with significance set at a *P* value of <0.05. R Statistical Software (version 4.3.2; R Foundation for Statistical Computing, Vienna, Austria) was utilized for all statistical analyses.

Table 1 Absolute angular deviations of the proximal plane and accuracy of defect distance measurements between actual and virtual models.

Absolute angular deviations of the proximal plane	Mean ± SD
Pitch rotation (°)	13.27 ± 10.36
Yaw rotation (°)	12.1 ± 8.67
Accuracy of defect distance measurement	
Defect distance virtual models (mm)	73.32 ± 13.02
Defect distance actual models (mm)	72.75 ± 12.58

mm: millimeter; °: degree; SD: standard deviation.

Results

A total of sixteen 3D stereolithographic mandibular models were utilized in this study.

Deviations in cutting planes

During pitch rotation, the angular deviation between the actual and virtual planes at the proximal plane was 13.27 ± 10.36 mm (Table 1). This indicates a modest angular deviation within the measurement range. Similarly, the angular disparity between the actual and virtual planes during yaw rotation was 12.1 ± 8.67 mm (Table 1), showing a comparable deviation.

Accuracy of defect distance measurements

In terms of defect distance accuracy, our study revealed a mean difference of 0.51 ± 3.53 mm between the actual and virtual models. There was no significant disparity in the

defect distance between the two models (72.75 ± 12.58 mm vs. 73.32 ± 13.02 mm, $P = 0.93$) (Table 1).

Condylar position changes

Deviations in the intercondylar angulation and distance. The intercondylar angulation between the actual and virtual models was 2.13 ± 2.53°. The average intercondylar distance showed no significant difference between the actual and virtual models (100.75 ± 7.32 mm vs. 102.01 ± 6.99 mm, $P = 0.51$) (Table 2).

Deviations in the highest points of the condyle. Deviations were observed in the superior—inferior (2.76 ± 3.39 mm), anterior—posterior (2.37 ± 2.76 mm), and medial-lateral dimensions (1.94 ± 2.93 mm) (Table 2). These results suggest that deviations in the treated side are relatively small, with the medial-lateral dimension showing the least variation.

Angulation deviations of the head condylar axis. Deviations were observed in the coronal (1.66 ± 1.38°) and transverse planes (1.52 ± 1.51°), both showing minimal variation. In contrast, significant deviations were noted in the sagittal plane (5.61 ± 5.26°), indicating a larger deviation in this plane (Table 2).

Discussion

This in vitro study assessed the precision of cutting planes and postoperative 3D condylar positioning by utilizing 3D-printed cutting guides and plate-guided positioning. The findings revealed a reliable alignment between real outcomes and virtual planning, showing no significant deviations in most measurements. In cases where significant differences were observed, the discrepancies were less than those in prior literature, highlighting enhanced spatial accuracy and hinting at the potential superiority of the suggested workflow.

Table 2 Accuracy of three-dimensional condylar position based on deviations in the intercondylar angulation and distance, deviation of the highest points of the condyle, and angulation deviation of the condylar axis between actual and virtual models.

The deviation in the intercondyles	Mean ± SD
Intercondylar angulation (°)	2.13 ± 2.53
Intercondylar distance (mm)	1.91 ± 2.82
The deviation of the highest points of the condyle	
Superior-inferior (mm)	2.76 ± 3.39
Anterior-posterior (mm)	2.37 ± 2.76
Medial-lateral (mm)	1.94 ± 2.93
The angulation deviation of the condylar axis	
Coronal (°)	1.66 ± 1.38
Sagittal (°)	5.61 ± 5.26
Transverse (°)	1.52 ± 1.51

mm: millimeter; °: degree; SD: standard deviation.

Our study demonstrated a significant improvement in the positional accuracy of the cutting planes when utilizing 3D-printed cutting guides. Two possible reasons account for the decreased deviation in cutting plane accuracy. First, 3D-printed cutting guides facilitate precise and continuous movement of the saw blade, aligning it with the guide and enhancing control during the cutting process. Second, 3D-printed cutting guides boost accuracy by significantly diminishing the risk of errors stemming from factors such as surgeon fatigue or external influences. Given the mandible's dense bone structure and relatively long osteotomy distances, traditional methods often depend on the surgeon's judgment, leading to potential variability.

Based on the research by El-Mahallawy et al.,[13] our study evaluated the absolute deviation of the cutting planes by comparing the distal and proximal planes in a physiological position. The results showed mean deviations of 13.27 ± 10.36° in pitch rotation and 12.1 ± 8.67° in yaw rotation between the actual and virtual planes. However, El-Mahallawy et al.[13] observed pitch rotation deviations of 4.7 ± 4° versus 2.2 ± 0.55° and yaw rotation deviations of 5.1 ± 3.1° versus 9.1 ± 9°, with measurements taken in the physiological position relative to the maxillary bone. In a study by Shu et al.,[15] 3D-printed cutting guides showed less deviation, with a mean distance of 2.06 ± 0.86 mm, compared with the virtual osteotomy distance. Similarly, Roser et al.[16] noted a deviation of 2.00 ± 1.12 mm between the actual and virtual planes. Furthermore, Brouwer de Koning et al.[17] reported mean deviations of 2.2 ± 0.9 mm and 1.2 ± 1.0 mm for posterior and anterior osteotomies, respectively, when utilizing 3D-printed cutting guides for mandibular osteotomy. These previous studies have confirmed the benefits of 3D-printed cutting guides in improving the accuracy of cutting planes; however, they lacked a detailed superimposition method for comparing actual and virtual planes.

The present study results are novel as they demonstrate that 3D-printed cutting guides enhance the spatial accuracy of cutting planes. The accuracy of reconstructive surgery relies heavily on the precision of these guides in transferring the 3D position during surgery.[18,19] Our study focuses on assessing the absolute deviation of the planes, introducing a new method where pre- and actual models are superimposed using the distal plane.

Regarding condylar position changes, the present findings align with prior reports that have also emphasized the benefits of VSP and plate-guided positioning in enhancing the precision of mandibular reconstruction.[3,20] Specifically, Metzler et al.[21] reported discrepancies of 1.7 mm in condylar distance and 4.6° in angulation with VSP utilization for mandibular reconstruction. In the present study, we observed even smaller deviations. Notably, in accordance with Bao et al., the mean condylar deviation in the VSP and plate-guided positioning group using prebent plates was significantly lower than that in the control group ($P < 0.01$).[3] Furthermore, the absolute disparity between preoperative and actual measurements on the ipsilateral side was lesser in the VSP group than in the conventional group. This indicates that the VSP application results in a diminished alteration in the actual condylar position.[22,23]

This study uniquely demonstrates that plate-guided positioning enhances the accuracy of 3D deviations of the

condylar alignment in 3D stereolithographic mandibular models. Following Schulz et al.,[24] Wilde et al.[22] reported that mandibular reconstruction with VSP and 3D-printed guides helps maintain a stable condylar position. In the present study, no statistically significant differences were observed in the deviation of the highest points of the condyles or in the angular deviations of the condylar head axis. These findings are consistent with those of a previous study that used the same evaluation method involving titanium customized plates and VSP for mandibular reconstruction. On the sagittal and transverse planes, our study demonstrated lower deviation values compared with those reported by Le et al. (2025),[14] who utilized titanium customized plates. Taken together, these findings suggest that plate-guided positioning may assist surgeons in accurately positioning the reconstruction plate in the absence of anatomical landmarks.[22]

Considering the roles of the condyles in the condyle-fossa relationship, we also assessed the displacement of the condylar heads, as these landmarks are commonly evaluated in the literature.[8,14] The actual and virtual models were superimposed using the non-operated side for accuracy. Some prior studies have determined condylar deviations through alternative methods but lacked a comprehensive view of these deviations. These studies computed deviations by analyzing the condyles' relationship with the cranial base in the horizontal, vertical, and mid—sagittal planes.[25—27]

Some key limitations should be acknowledged. First, measurement variability, including potential inter-operator inconsistencies during the simulated surgeries and software precision issues, could affect the accuracy of the cutting planes and condylar positioning. Future studies should consider assessing inter-operator reliability and software reproducibility to ensure consistency across different operators and software versions. Second, reproducibility of the 3D planning and surgical workflow in clinical practice remains an open question. Reproducibility studies should be conducted in clinical environments with different 3D printers and materials to verify the robustness of the methodology. Third, the sample size of 16 models may limit the statistical power of the study. Future research should involve larger sample sizes to increase the statistical power and provide more reliable and generalizable results. Finally, the lack of a control group using conventional freehand reconstruction techniques limits the ability to directly compare the accuracy and efficacy of the proposed 3D-printed guides approach with standard methods. Future studies should consider including such control groups for a more comprehensive assessment of the clinical value and advantages of 3D-printed cutting guides and plate-guided positioning.

In conclusion, this study demonstrates the potential of 3D-printed cutting guides and plate-guided positioning for accurate replication of virtual plans in mandibular reconstruction. The results showed acceptable accuracy in the positioning of cutting planes and condyles. However, as this study was conducted in an in vitro setting and lacks a control group using conventional techniques, the conclusions cannot definitively claim improvements over existing methods. Further research comparing these methods with traditional approaches in clinical settings is necessary to evaluate their effectiveness and clinical feasibility.

Declaration of competing interest

None.

Acknowledgments

We thank the staff members of the Department of Maxillofacial Surgery and The Department of Anesthesia, National Hospital of Odonto-Stomatology in Ho Chi Minh City, Viet Nam, for their assistance during the study. This study did not receive financial support from any public, commercial, or non-profit funding agencies.

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