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Comparison of different 3D reconstruction software tools in preoperative modeling for cranio-maxillofacial surgery

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Abstract

Aim: This study evaluates the application of three-dimensional (3D) reconstruction technology in cranio-maxillofacial surgery, focusing on its ability to provide accurate anatomical data and essential support for preoperative planning.

Methods: A comparative analysis was conducted using three commonly utilized 3D reconstruction software programs: 3D Slicer, ProPlan CMF, and Mimics. Each was assessed based on modeling accuracy, operational efficiency, and functional specialization. Data were collected and analyzed to identify the strengths and weaknesses of each software in different surgical contexts.

Results: The findings demonstrate that all three software programs provide consistent modeling accuracy. However, significant differences were observed in terms of operational efficiency and functional specialization, which influence their applicability in various scenarios. Specifically, 3D Slicer excels in flexibility, ProPlan CMF in cranio-maxillofacial applications, and Mimics in precision and comprehensive functionality.

Conclusion: 3D reconstruction technology has significant potential for optimizing preoperative planning in plastic surgery, especially in cranio-maxillofacial surgery. This study offers critical insights into the selection and optimization of 3D reconstruction software, paving the way for more effective and tailored surgical planning. Future research may focus on integrating AI-driven tools to enhance operational efficiency and broaden the application scope of 3D reconstruction in cranio-maxillofacial surgery.

Keywords: Cranio-maxillofacial surgery, plastic surgery, digital modeling, 3D software, mandibular angle osteotomy, preoperative design

INTRODUCTION

Plastic surgery involves complex anatomical structures, carries high surgical risks, and demands strict postoperative aesthetic outcomes, emphasizing the importance of precise osteotomy location or surgical design. Such surgeries play a vital role in improving facial appearance, repairing functional defects, and enhancing patients' quality of life. With advancements in medical imaging technology, particularly the use of cranial CT, doctors can more accurately understand the cranial structure of patients, aiding better surgical planning and assessment.

Mandibular angle hypertrophy is a common facial disharmony issue that can lead to malocclusion and functional disorders, typically addressed through mandibular angle osteotomy. This procedure can also be indicated for facial feminization surgery, correction of asymmetries, and reconstruction after facial trauma. Computer-aided design (CAD) software, utilizing the three-dimensional (3D) reconstruction capabilities of CT images, is widely applied in surgical planning. Modeling software such as Mimics, ProPlan CMF, and 3D Slicer each have unique strengths, with Mimics being widely used in virtual surgical planning for its versatile segmentation tools and 3D modeling capabilities. ProPlan CMF features robust 3D visualization capabilities and is specifically designed for cranio-maxillofacial surgery. 3D Slicer, as an open-source software, is widely used for medical image visualization and 3D reconstruction[1].

Based on the above background, this study aims to compare the performance differences among 3D Slicer, ProPlan CMF, and Mimics in the preoperative planning of mandibular angle hypertrophy. By reconstructing 3D cranial models of patients, designing osteotomy lines for mandibular angle resection, and performing virtual preoperative surgeries, the effectiveness of each software is evaluated. The goal is to provide a basis for clinical surgical planning and to promote the optimization and advancement of personalized surgical design.

METHODS

Study subjects and data collection

This study randomly selected 10 patients with mandibular angle hypertrophy from the imaging system database of the First Affiliated Hospital of University of South China. The inclusion criteria were a diagnosis of mandibular angle hypertrophy by three senior cranio-maxillofacial surgeons based on clinical examination and imaging studies, with objective measurements such as a mandibular angle greater than 120° in cephalometric analysis. Patients had a normal occlusal relationship, with no history of cranio-maxillofacial deformities, tumors, or prior mandibular surgery. Additionally, there was no history of psychiatric disorders. Imaging data were acquired using a Siemens 64-slice spiral CT scanner (SIEMENS AG, Germany) with scanning parameters of 120 kV, 200-250 mAs, rotation time 0.5-1 s, matrix size 512 × 512, and slice thickness of 0.625 mm. Data were saved in DICOM format to ensure consistency and comparability of image quality. The 3D reconstruction process was carried out using three software programs: Mimics 21.0 (Belgium Materialise NV, Leuven, Belgium ©), 3D Slicer 5.6.1 (Harvard University, NIH), and ProPlan CMF 3.0 (Belgium Materialise NV, Leuven, Belgium ©). Statistical analysis was performed with SPSS 24.0 (open-source software, Brigham and Women's Hospital, Boston, MA, USA), and all operations were conducted on the same computer.

This study was approved by the Medical Ethics Review Committee of the First Affiliated Hospital of University of South China (2024110604001). Written informed consent for participation was obtained from all subjects.

3D modeling and deviation analysis

The 3D reconstruction process for mandibular angle models was simplified as follows: Using 3D Slicer, DICOM (Digital Imaging and Communications in Medicine) data were imported, threshold values (137-1,458) were set in the Segment Editor module, and extraneous parts were trimmed before exporting the model in STL format. In Mimics, a threshold range (230-3,060 HU) was set in the Mask module to complete segmentation, generate a 3D model, and export it. In ProPlan CMF, bone tissue thresholds were set using the Segmentation function, and unnecessary parts were removed to complete the modeling and export. The final 3D cranial reconstruction data for patients were obtained for subsequent analysis [Figure 1]. The 3D reconstructed models were then subjected to deviation analysis using Materialise's 3-matic software to evaluate image overlap and model congruence [Figure 2A]. During the statistical analysis stage, voxel counts, surface area, and volume of the models generated by each software were calculated using the Segment Statistics module.

Feature size measurement

Ten facial feature dimensions were defined from the cranial data of 10 patients, with each dimension formed by a pair of anatomical landmarks: Dimension 1 is from the glabella to the pogonion; Dimension 2 from the nasal bone to the nasal crest; Dimension 3 measures the distance between the left and right zygomatic bones; Dimension 4 measures the distance between the left and right mental foramina; Dimension 5 is the distance between the left and right canine fossae; Dimension 6 measures from the left infraorbital foramen to the right infraorbital foramen; Dimension 7 is the distance between the left and right mandibular condyles; Dimension 8 measures from the left mandibular angle to the right mandibular angle. Dimension 9 measures the distance from the left to the right lacrimal bone; Dimension 10 measures the distance from the nasal bone to the pogonion. These measurements are used for precise evaluation of facial features and support anatomical structure and symmetry analysis. All feature size measurements were performed by the same operator using the three software programs, and the average values were calculated.

Virtual osteotomy surgery

This study conducted a preoperative virtual osteotomy design for patients with mandibular angle hypertrophy using oblique osteotomy. The osteotomy line was defined by Go' (new mandibular angle region), E (projection of the second molar, empirical value), and A2 (intersection of the occlusal plane and mandibular ramus), forming the osteotomy plane by connecting these points [Figure 3A], and determining the bone volume to be removed [Figure 3B]. After completing the virtual osteotomy, the postoperative mandibular angle and ramus height were measured [Figure 3C], with each parameter measured three times to calculate the average.

Operational efficiency evaluation

To compare the efficiency of model creation among the three software programs, 30 medical students were invited to participate in an experiment. They used a 3D reconstruction model of the same mandibular angle hypertrophy patient, and the number of mouse clicks for modeling and virtual osteotomy was recorded to assess software usability.

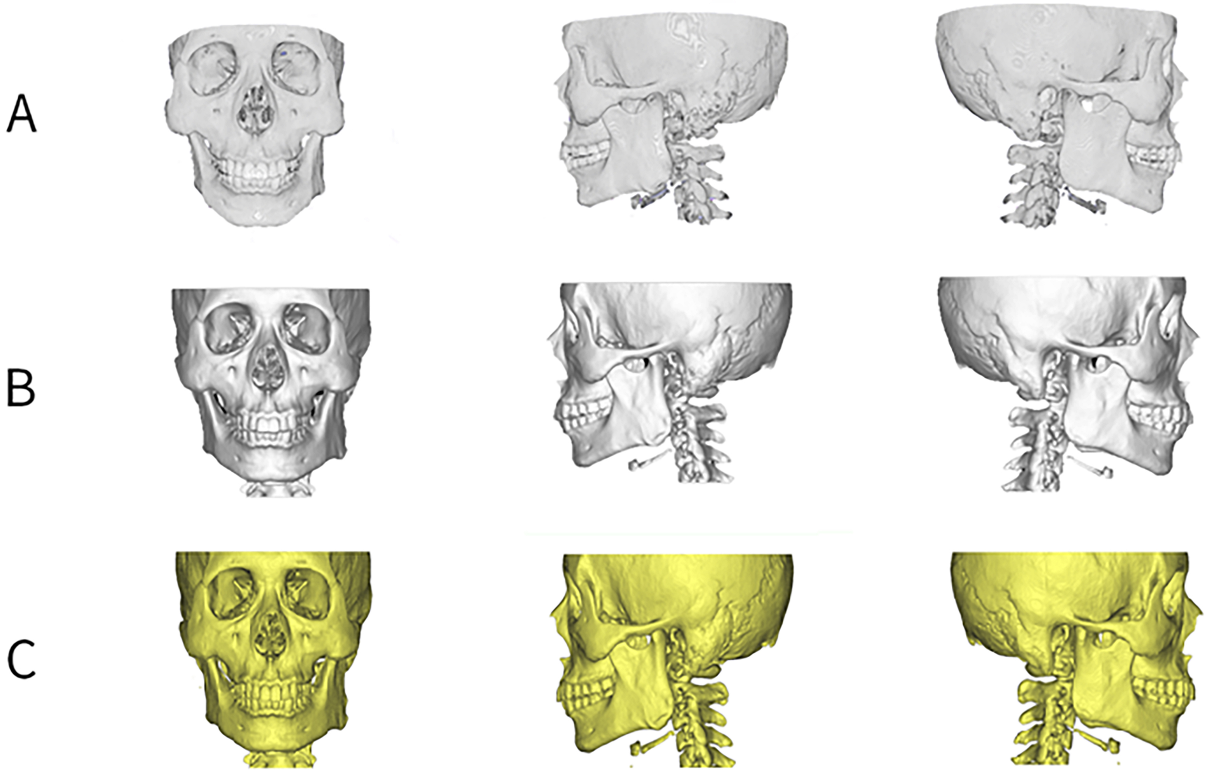

Figure 1. Frontal, left lateral, and right lateral views of cranial 3D reconstruction models. (A) represents the 3D reconstruction by 3D Slicer, (B) by ProPlan CMF, and (C) by Mimics.

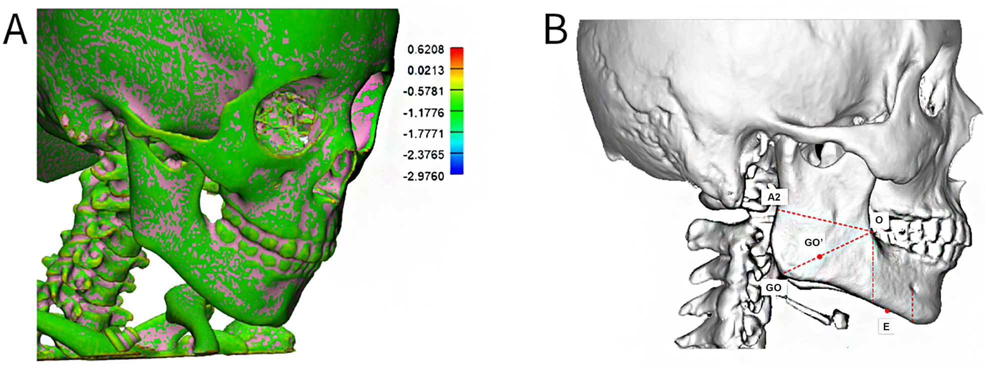

Figure 2. (A) Deviation analysis of 3D reconstruction models generated by the three software programs; (B) Schematic diagram of the long straight-line osteotomy plane design.

Statistical analysis

All data were analyzed using SPSS software. Continuous variables were expressed as mean ± standard deviation, and intergroup differences were assessed using one-way ANOVA or paired *T*-tests. The significance level was set at $P < 0.05$.

RESULTS

Modeling accuracy

This study performed 3D reconstruction and deviation analysis on data from 10 patients with mandibular

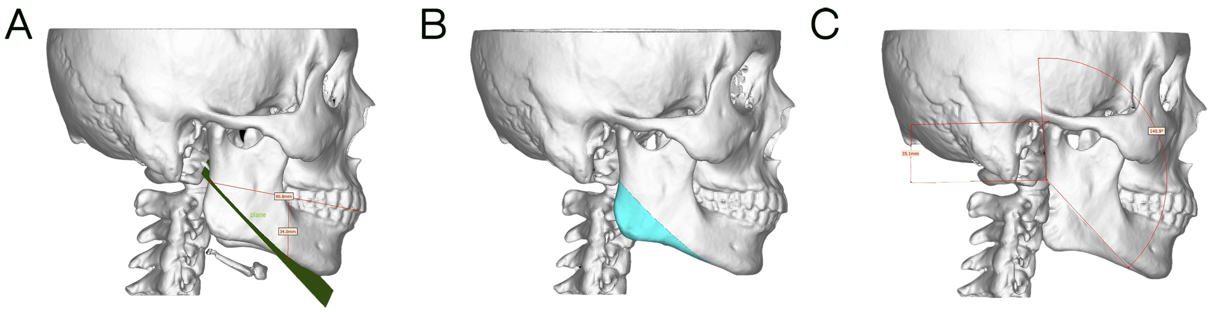

Figure 3. (A) Design method for oblique osteotomy line, determining osteotomy location and plane, setting line angle and length; (B) Schematic of osteotomy; (C) Measurement of mandibular ramus height (mm) and mandibular angle (°) after removal of hypertrophic mandibular angle.

angle hypertrophy [Figures 1 and 4]. Models A, B, and C constructed using 3D Slicer, ProPlan CMF, and Mimics software, respectively, showed the following results: Model A showed a deviation range of -5.08 to 0.52 mm, a mean deviation of 2.26 ± 1.69 mm, a maximum dimension of 231.55 mm, a deviation percentage of 0.98%, and a model overlap rate of 99.02%. Model B had a deviation range of -2.97 to 0.62 mm, a mean deviation of 2.21 ± 1.04 mm, a maximum dimension of 230.10 mm, a deviation percentage of 0.96%, and a model overlap rate of 99.04%. Model C exhibited a deviation range of -5.13 to 0.62 mm, a mean deviation of 2.26 ± 1.71 mm, a maximum dimension of 233.55 mm, a deviation percentage of 0.97%, and a model overlap rate of 99.03%. The deviation percentages of all three software programs were within 1%, and the model overlap rates were close to 99%, with no differences. ($P > 0.05$)

Voxel count, surface area, and volume data with feature size measurements

The voxel count, surface area, and volume comparison data after cranial modeling are shown in Table 1. The performance of the three software tools varies: Mimics exhibits a significant advantage in voxel count, with the highest voxel count among the three. In terms of surface area, the model generated by 3D Slicer has the largest surface area, while ProPlan CMF produces the smallest. Regarding volume, ProPlan CMF generates the largest model volume, while Mimics produces the smallest. Thus, it can be concluded that each of the three software programs has its own advantages. From the feature size measurements of cranial models [Table 2], no differences were observed among the three software programs ($P > 0.05$), indicating consistency in anatomical structure measurements across all three software programs.

Virtual osteotomy results

This study utilized 3D mathematical models of the crania of 10 patients with mandibular angle hypertrophy to measure mandibular angle, ramus height, and design the osteotomy line position and angle [Figure 2B], performing virtual osteotomy surgery [Figure 5]. Paired T-test results for mandibular angle and ramus height before and after simulated osteotomy are shown in Table 3. There were differences ($P < 0.05$) between pre- and postoperative measurements for all three software programs, demonstrating high accuracy in their simulation effects.

Operational efficiency

Thirty medical students performed modeling and virtual osteotomy on the same dataset. Results showed 3D Slicer required 11.7 ± 1.19 clicks for modeling, 34.4 ± 2.06 clicks for virtual osteotomy, totaling 46.1 ± 1.87 clicks; ProPlan CMF required 13.3 ± 1.27 clicks for modeling, 36.4 ± 1.8 clicks for osteotomy, totaling 49.7 ± 2.65 clicks; Mimics required 7.8 ± 0.75 clicks for modeling, 36 ± 2.32 clicks for osteotomy, totaling 43.8 ± 2.64 clicks. The results indicate minimal differences in operational efficiency among the three software

Table 1. Voxel count, surface area, and volume of models generated by the three software tools

Software	Voxel count	Surface area (mm^2)	Volume (mm^3)
3D Slicer	1360662	283953	518968
ProPlan CMF	1818603	220697	573629
Mimics	4768177	326299	550223

Table 2. Comparison of feature sizes (mm) in cranial models reconstructed using 3D slicer, ProPlan CMF, and mimics software ($\bar{x} \pm s, n = 10$)

Size (mm)	3D slicer	ProPlan CMF	Mimics	*F*-value	*P*-value
Size1	125.54 ± 2.59	127.27 ± 1.62	130.51 ± 1.12	3.606	0.094
Size2	30.33 ± 1.25	33.24 ± 0.82	31.00 ± 0.82	4.811	0.057
Size3	101.33 ± 2.62	103.77 ± 2.55	106.07 ± 0.90	2.368	0.175
Size4	52.00 ± 1.63	51.00 ± 0.82	51.27 ± 0.52	0.446	0.660
Size5	42.90 ± 1.76	44.00 ± 2.16	43.00 ± 2.45	0.161	0.855
Size6	54.67 ± 2.05	55.27 ± 0.52	55.50 ± 4.30	0.048	0.953
Size7	131.00 ± 2.16	131.00 ± 2.94	137.30 ± 15.72	0.305	0.748
Size8	111.17 ± 1.03	110.33 ± 1.25	116.77 ± 3.62	4.671	0.060
Size9	21.00 ± 2.94	21.67 ± 0.82	22.00 ± 1.72	0.307	0.755
Size10	92.67 ± 2.52	90.67 ± 1.53	90.00 ± 2.00	1.368	0.324

Table 3. Preoperative and postoperative measurements of mandibular angle virtual osteotomy and their comparison ($\bar{x} \pm s, n = 10$)

Software	Parameter	Preoperative	Simulated postoperative	*P*-value
3D slicer	Mandibular ramus height (mm)	66.35 ± 4.43	40.06 ± 5.10	< 0.05
	Mandibular angle (°)	114.5 ± 5.25	138.0 ± 3.45	< 0.05
Proplan CMF	Mandibular ramus height (mm)	66.4 ± 4.23	35.1 ± 5.40	< 0.05
	Mandibular angle (°)	115.4 ± 5.77	140.9 ± 5.12	< 0.05
Mimics	Mandibular ramus height (mm)	66.36 ± 4.80	38.8 ± 5.01	< 0.05
	Mandibular angle (°)	111.15 ± 4.8	137.02 ± 5.25	< 0.05

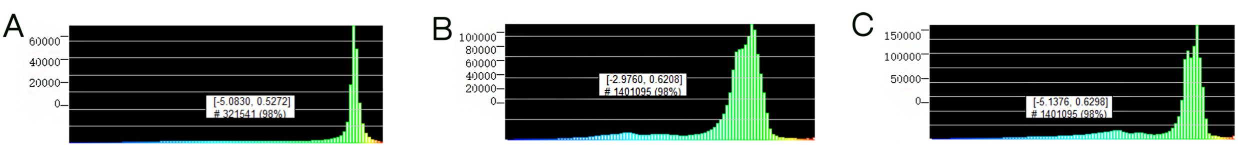

Figure 4. (A) Deviation analysis of 3D reconstruction models: Mimics *vs.* ProPlan CMF; (B) 3D Slicer *vs.* Mimics; (C) 3D Slicer *vs.* ProPlan CMF.

programs. Mimics required fewer clicks for initial modeling, suggesting a potentially more intuitive interface for novice users. However, further studies incorporating user experience assessments and learning curve evaluations are needed to validate these findings.

DISCUSSION

Main findings

In the 3D reconstruction of cranial CT data from patients with mandibular angle hypertrophy, each software demonstrated unique features. For example, 3D Slicer provided clearer images at certain angles, while ProPlan CMF excelled in detail processing[2]. We used the Curvature Analysis tool in 3-matic software

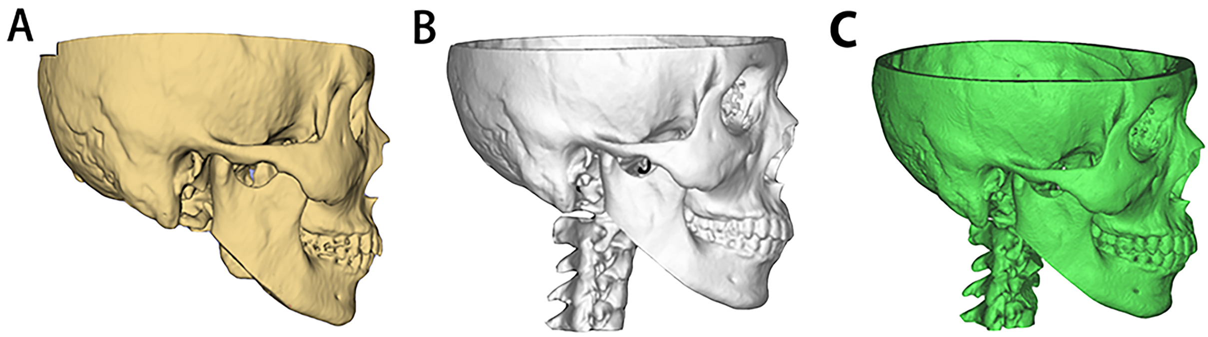

Figure 5. Post-Virtual Osteotomy Diagram: (A) for 3D Slicer Software; (B) for ProPlan CMF Software; (C) for Mimics Software.

to analyze deviations, revealing differences in reconstruction accuracy among the software programs. The mean reconstruction deviation for Mimics compared to ProPlan CMF was 2.26 ± 1.69; for 3D Slicer compared to Mimics, it was 2.21 ± 1.04; and for 3D Slicer compared to ProPlan CMF, it was 2.26 ± 1.71. Regarding model overlap rates, Mimics and ProPlan CMF achieved 99.02%, 3D Slicer and Mimics achieved 99.04%, and 3D Slicer and ProPlan CMF achieved 99.03%. The overall differences were not statistically significant. In terms of voxel count, Mimics generated the highest voxel count, indicating superior performance in image reconstruction and segmentation accuracy. For surface area, 3D Slicer produced the largest surface area, while ProPlan CMF had the smallest, highlighting differences in surface reconstruction capabilities. In volume measurement, ProPlan CMF produced the largest model volume, while Mimics generated the smallest, suggesting different software suitability for handling volume and surface area.

Measurements of feature dimensions using the three software programs showed no differences ($P > 0.05$), indicating consistency in model reconstruction and feature dimension measurement across all three. Overall, 3D Slicer, ProPlan CMF, and Mimics all demonstrated stable performance in mandibular angle reconstruction, making them reliable tools for surgical planning in plastic surgery.

Clinical significance

Mandibular angle osteotomy is a common plastic surgery procedure. A new method proposed by Hwang *et al.* in 2004, involving simultaneous removal of the mandibular outer plate and angle, has advantages such as minimal trauma, no facial scars, and high patient satisfaction[3]. Excessive osteotomy volume can lead to neurovascular injury, intraoperative bleeding, and postoperative complications such as facial numbness or secondary fractures, while insufficient osteotomy volume may result in suboptimal outcomes and increased surgical difficulty[4]. The application of 3D digital models provides more precise tools for preoperative planning and doctor-patient communication, significantly enhancing surgical accuracy. CT-based craniofacial plastic surgery simulation systems have been developed internationally, enabling mandibular angle osteotomy simulations and personalized treatment planning[5,6]. However, diagnostic criteria for mandibular angle hypertrophy remain inconsistent and require further study. Various surgical techniques and adjunctive technologies, such as 3D digital design, guided surgery, navigation, and robotic-assisted surgery, offer more treatment options for mandibular angle hypertrophy patients[7,8]. ProPlan CMF enhances surgical planning accuracy and success rates through its intelligent virtual surgical tools[9-13].

Digital technology has advanced the refinement and personalization of mandibular angle osteotomy, paving the way for more precise treatment solutions in the future[14-19]. Although virtual surgery can predict bony changes, it struggles to accurately simulate soft tissue changes. Patients with masseter hypertrophy or poor skin elasticity should be informed preoperatively about potential additional fat or muscle procedures[9,20-24].

Research limitations

Although this study conducted an in-depth comparison of three 3D reconstruction software applications in preoperative planning for plastic surgery, several limitations exist. First, the sample size of only 10 cases may not fully represent the applicability of the three software tools to a larger patient population, limiting the robustness and generalizability of the statistical results. Secondly, the study used a single-center retrospective design, leading to relatively homogeneous data sources and an increased risk of selection bias. Reliance on existing imaging data may not encompass all potential application scenarios. Additionally, the study primarily focused on bony structure changes, without fully accounting for the impact of soft tissue morphology on postoperative aesthetic outcomes. Predictions of soft tissue adaptability in cases of masseter hypertrophy or skin laxity remain unexplored. Although virtual osteotomy design was precise, the study did not directly compare its consistency with actual surgical outcomes, limiting its clinical translational significance. Finally, there is a lack of data to support the long-term tracking of postoperative outcomes, such as surgical stability and potential complications. Future research should expand the sample size, incorporate multicenter collaboration, and integrate soft tissue simulation modules. Evaluating the consistency between virtual surgery and actual surgical outcomes could comprehensively improve the scientific and clinical utility of 3D modeling in surgical planning.

In conclusion, a comprehensive comparison of 3D Slicer, ProPlan CMF, and Mimics in cranial 3D modeling and virtual osteotomy demonstrates that each software has distinct advantages depending on the application. Mimics is well-suited for complex cases due to its advanced segmentation capabilities and high voxel resolution, making it ideal for detailed surgical planning. ProPlan CMF excels in cranio-maxillofacial applications, offering specialized visualization tools tailored for clinical use. 3D Slicer, as an open-source platform, provides a flexible and cost-effective solution, making it particularly valuable for research, educational purposes, and institutions with limited resources.

The choice of software should be based on specific clinical and technical requirements to optimize preoperative planning and surgical outcomes. Future studies incorporating usability assessments and a larger sample size could further refine the understanding of each software's practical applications in surgical workflows.

DECLARATIONS

Authors' contributions

Wrote and edited the manuscript: Huang C, Xiong T
Software, resources: Chen Y
Methodology: Wei Y
Data curation: Li W, Li Z
Wrote and edited the manuscript, supervision, funding acquisition: Liao J

Availability of data and materials

All the data and materials used in the study are available from the corresponding author upon reasonable request.

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
This study was approved by the Medical Ethics Review Committee of the First Affiliated Hospital of University of South China (2024110604001). Written informed consent for participation was obtained from all subjects.

Consent for publication
Not applicable.

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