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Research Paper
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Navigation-assisted maxillofacial reconstruction: accuracy and predictability

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Abstract. The aim of this study was to evaluate the accuracy of navigation-assisted maxillofacial reconstruction and to identify the predictors of the clinical outcomes. A total of 112 patients who underwent navigation-assisted maxillofacial reconstruction with free flaps between 2014 and 2019, performed by a single surgical team, were assessed. Accuracy was evaluated by superimposing the postoperative computed tomography data with the preoperative virtual surgical plan. Predictors of the clinical outcomes affecting the accuracy were identified and analysed. The mean deviation and root mean square (RMS) estimate of the orbital, maxillary, and mandibular reconstructions were 0.88 ± 3.25 mm and 3.38 ± 0.73 mm, 0.77 ± 3.44 mm and 3.69 ± 0.82 mm, and 1.07 ± 4.16 mm and 4.67 ± 3.95 mm, respectively ($P < 0.05$). There was no significant difference in orbital volume or projection between the preoperative, postoperative, and healthy orbits ($P = 0.093$ and $P = 0.225$, respectively). Multivariate linear regression analysis confirmed significant associations between the accuracy of navigation-assisted mandibular reconstruction and preservation of the condyle, type of reconstruction, type of osteosynthesis plate, and number of bony segments. Navigation-assisted midface reconstruction yielded a higher level of accuracy in the final surgical outcome when compared to mandibular reconstruction. Computer-assisted techniques and intraoperative navigation can be an alternative or adjunct to current surgical techniques to improve the final surgical outcome, especially in more complex maxillofacial reconstructions.

Key words: oral cancer; reconstructive surgery; computer-assisted surgery; surgical navigation; head and neck neoplasm.

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Maxillofacial defects following tumour ablation in oncology patients often have significant physiological and psychological impacts due to the adverse effects on the form and function of the face. The complex anatomical structures of the maxillofacial region pose immense challenges to the surgeon, demanding exceptional surgical skill in head and neck reconstruction to achieve both aesthetic and functional goals.

Traditionally, the repair of maxillofacial defects following tumour resection has relied heavily on surgeon experience, which has often led to suboptimal reconstruction outcomes. Computer-assisted surgery (CAS) has been applied widely in the repair of head and neck defects in the past years. From adapting titanium

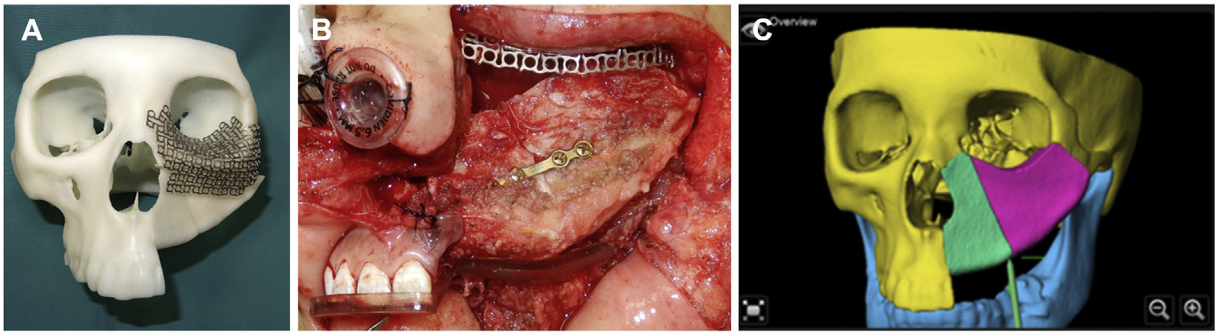

Fig. 1. (A) Titanium mesh was manually contoured and adjusted on the rapid prototype model. (B) Pre-contoured titanium mesh and DCIA flap in situ. (C) The position of the DCIA flap was verified using the intraoperative navigation system, in which the navigation probe corresponded with the green pointer on the screen.

plates to rapid prototyping models to patient-specific stereolithographic cutting jigs, CAS has markedly improved the surgical efficiency and outcomes. Numerous publications have also assessed the accuracy of three-dimensional (3D) virtual surgical planning (VSP) or CAS in maxillofacial reconstruction, with promising results, showing particular advantages in extensive defects[1]. Nevertheless, these procedures are susceptible to inaccuracies despite meticulous preoperative planning, due to limited access to the maxillofacial structures and above all the mandible being mobile.

In recent years, intraoperative navigation systems have been adopted to improve surgical accuracy and enhance treatment outcomes. Previous studies by the present authors' group have also shown computer-assisted techniques and surgical navigation to significantly improve the 3D position of osseous flaps in the maxilla in comparison with conventional surgery[2]. Furthermore, computer-assisted design/computer-assisted manufacturing (CAD/CAM) and intraoperative navigation were found to noticeably improve the final surgical accuracy while maintaining the position of the mandibular angle and condyles in the reconstruction of mandibular defects[3,4].

Nonetheless, a search for good evidence regarding whether navigation-assisted surgery improves the reconstructive outcomes revealed limited data, especially for maxillofacial oncology and reconstruction. It appears that research assessing the accuracy and determining the potential predictors affecting the clinical outcomes of navigation-assisted maxillofacial reconstruction is limited. The aim of this study was to evaluate the accuracy of navigation-assisted maxillofacial reconstruction and to identify the predictors of the clinical outcomes.

Patients and methods

This retrospective study included patients who underwent maxillofacial free flap reconstructive surgery in the Department of Oral and Maxillofacial Surgery of Peking University School and Hospital of Stomatology between April 2014 and September 2019. Further requirements for inclusion in the study were: (1) primary or secondary reconstruction of the maxilla and mandible with a vascularized free flap; (2) use of preoperative VSP and a surgical navigation system intraoperatively; (3) no residual tumour; and (4) complete flap survival. Baseline data including age, sex, diagnosis, and location of the defect were recorded. Overall, 140 cases were reviewed; 26 cases with incomplete postoperative computed tomography (CT) datasets and two failed flap cases were excluded. CT datasets obtained more than 6 months postoperatively were excluded from the study, as bony consolidation could have affected the results of the accuracy measurements. Patient-specific cutting guides were not incorporated in this study, as the aim was to explore the accuracy of navigation-assisted surgery in maxillofacial reconstruction with free microvascular flaps. The patients were divided into groups according to the defect site (maxilla or mandible) and the extent of the tumour, based on the Brown maxillary defect classification[5] and preservation versus resection of the condyle of the mandible, respectively.

Preoperative spiral CT scans of the maxillofacial region and lower extremities (fibula) or pelvis (ilium) were performed with the mandible in maximum intercuspation (field of view 20 cm, pitch 1.0, slice 0.75 mm, 120–280 mA). The CT data in Digital Imaging and Communications in Medicine (DICOM) format were uploaded to the image-guided surgery (IGS) software iPlan CMF 3.0 (BrainLAB, Munich, Germany) for tumour mapping. CT data of both the maxillofacial and donor sites (fibula or ilium) were uploaded to the VSP software ProPlan CMF 3.0 (DePuy Synthes, Solothurn, Switzerland and Materialise, Leuven, Belgium) for data conditioning, segmentation, and VSP. For Brown class II maxillary defects and mandibular defects, the existing dentition was segmented to serve as a reference for positioning of the fibula or ilium, in order to ensure an ideal prosthodontic rehabilitation while maintaining an optimal interdental distance.

In cases with orbital involvement, the orbital floor was reconstructed via a mirroring technique to achieve an ideal and symmetrical anatomical contour. The final reconstructed models were exported in standard tessellation language (STL) format for printing of rapid prototype models, to allow pre-contouring of the titanium mesh or UniLOCK Reconstruction Plate 2.4 preoperatively (Fig. 1A). In parallel, each component of the surgical plan, including the osteotomized mandible or maxilla and the fibula or iliac crest segments, were imported into the navigation software system and registered with the original CT dataset. The final surgical plan was exported and uploaded onto a Kick navigation workstation (BrainLAB) for intraoperative navigation and further handling during surgery. The length and angle of each fibula or iliac crest segment were measured in the VSP software and used as reference during flap harvesting, in which the osseous flap was shaped, facilitated by a protractor and ruler.

The surgical procedures were completely guided by the intraoperative navigation system (Fig. 1B, C). Under general anaesthesia, the patient was intubated via nasotracheal intubation with the tube anchored cranially. Following fixation of the dy-

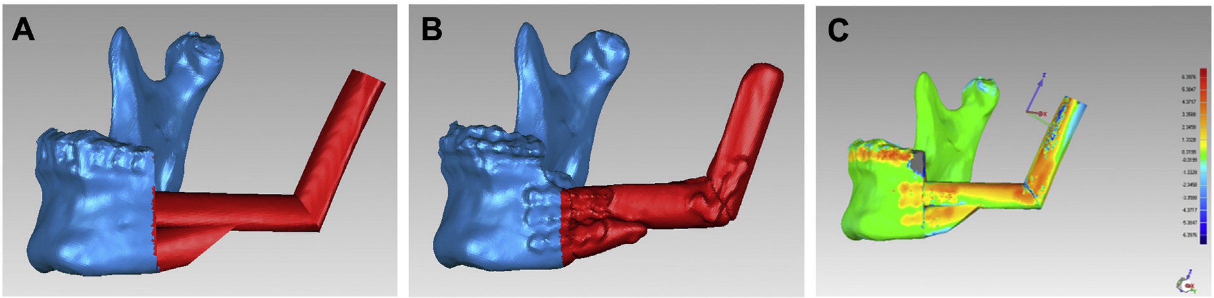

Fig. 2. The (A) preoperative VSP and (B) postoperative STL models were imported into Geomagic Studio software, where both models were registered using paired point registration; the selected area of interest is shown in red. (C) Colour map analysis of the preoperative and postoperative fibula segments, showing the deviation between the preoperative VSP and postoperative actual results. (VSP, virtual surgical plan; STL, standard tessellation language.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

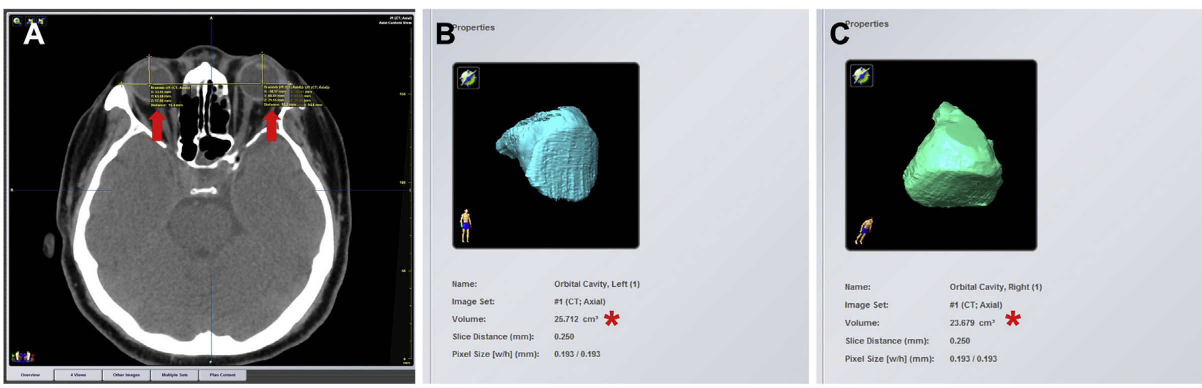

Fig. 3. (A) Measurements of the affected and unaffected globe projections, as shown by the red arrows. (B) (C) Measurements of orbital volume (red asterisks) were calculated via automatic segmentation of the orbital cavities (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

namic reference frame (DRF), laser surface scanning (z-touch) was used to allow skin surface registration of the patient's orientation on the navigation system. With the display of axial, sagittal, and coronal views and a 3D model reconstructed on the navigation workstation, each osteotomy line was marked and verified using the intraoperative navigation system.

The occlusion was stabilized with intermaxillary fixation and the position of the fibula or iliac crest flap was completely guided by the navigation system. In patients with a Brown class III maxillary defect, the position of the pre-contoured titanium mesh was confirmed with the navigation system to avert impingement of the orbital apex, while in patients undergoing mandibular reconstruction, the gonial and condylar positions of the mandible were also validated using the intraoperative navigation system prior to fixation of the flap.

All patients were subjected to the standard oncology follow-up protocol postoperatively. A facial CT scan was performed for all patients at 7 to 10 days postoperatively and the CT datasets were superimposed with the preoperative virtual plan using Geomagic Studio 2012 (3D Systems, Rock Hill, SC, USA). Upon receiving the postoperative scan, a 3D model was generated and exported in STL data format. Both the preoperative VSP and postoperative models were imported into Geomagic Studio software. In the manual registration dialogue, the preoperative and postoperative 3D models were defined as fixed and floating models. Using paired point registration, three to nine corresponding points of the overlapping section from both objects were selected to allow initial registration of both the preoperative and postoperative models. Subsequently, the reconstructed area was marked and excluded, while the unaffected area was selected for global registration, to fine-tune the spatial position of both models. Congruity analysis was then performed based on the osseous surfaces of the selected areas of interest. The unaffected area served as the reference for registration and was excluded in the accuracy analysis. The mean, standard deviation (SD), and root mean square (RMS) estimates of the surface deviations were computed automatically. The number of bony flap segments was also recorded.

The RMS is the absolute mean deviation of the planned (Fig. 2A) and postoperative models (Fig. 2B), generated automatically and expressed on a colour map (Fig. 2C), in which the standard deviation between the two surfaces in the reference model and test model with the closest Euclidean distance was measured. A lower value of RMS denotes higher accuracy, while a higher value indicates otherwise.

The orbital projection of the preoperative, postoperative, and healthy sides was measured using iPlan CMF in orbital reconstruction cases (Fig. 3A). The orbital volume was calculated via automatic segmentation, and manual adjustments were

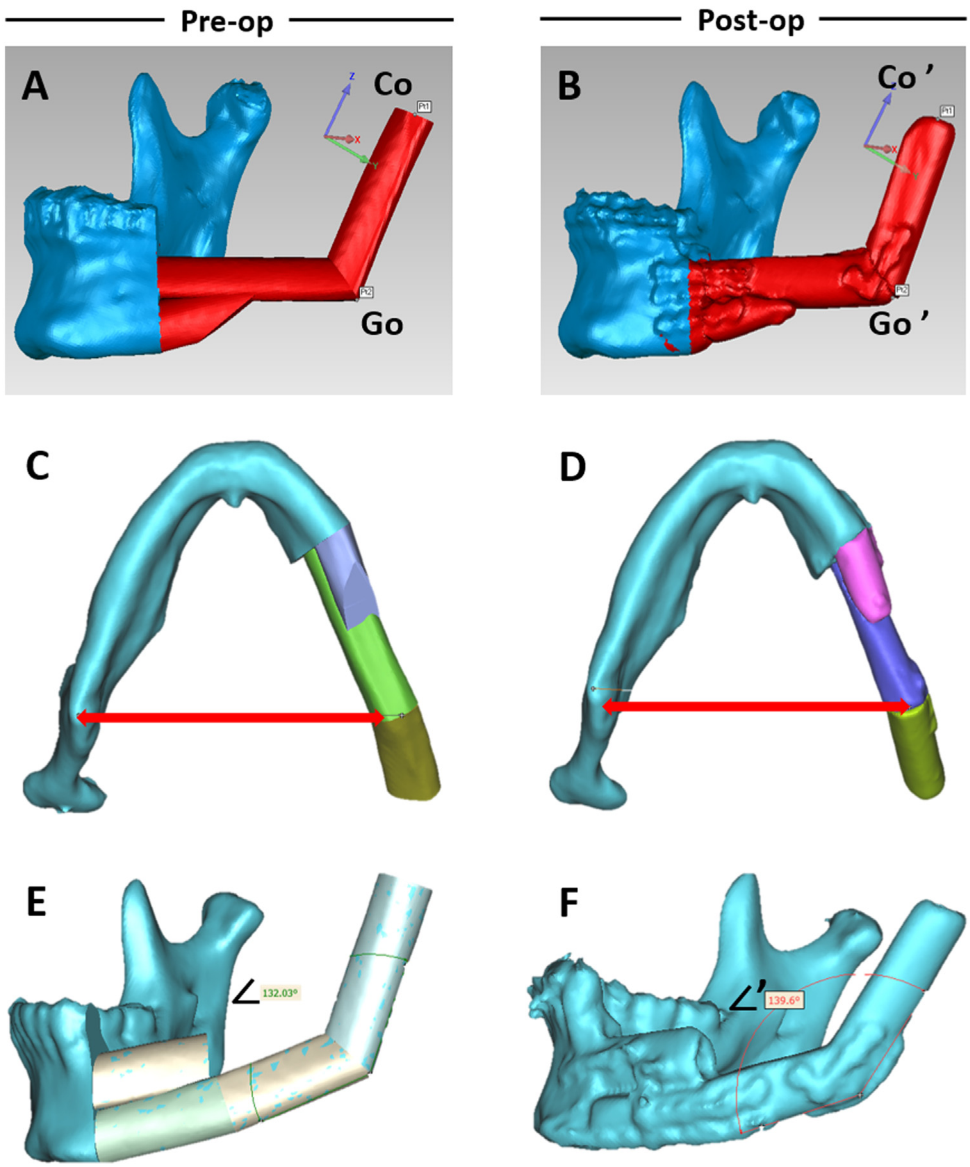

Fig. 4. Measurements of (A) preoperative and (B) postoperative condylar positions (marked as Co and Co′, respectively) and gonial positions (Go and Go′, respectively). (C) (D) The intergonial distance was measured in worm's eye view from the unaffected angle of the mandible to the affected side (shown by the red arrows). The gonial angle was measured directly by indicating ascending ramus–angle of mandible–body of mandible on the (E) preoperative (∠) and (F) postoperative (∠′) models (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

made using eraser and smart brush tools in the presence of conspicuous errors, such as inclusion of the ethmoidal sinuses (Fig. 3B, C). In mandibular reconstruction cases, the preoperative and postoperative differences in the position of the condyle, angle of the mandible, and intergonial distance were also calculated (Fig. 4A–D). On the 3D model, the gonial angle was measured directly by indicating three points (ascending ramus–angle of mandible–body of mandible) in the gonial region using the 3D angle measurement tool, while the intergonial distance was measured in worm's eye view using the 3D distance measurement tool (Fig. 4E, F).

All analyses were conducted using IBM SPSS Statistics version 24.0 (IBM Corp., Armonk, NY, USA). An exploratory data analysis was performed on each possible clinical predictor using linear regression analysis; predictors with a *P*-value less than 0.05 were included in the multivariate linear regression analysis to further identify the clinical predictors affecting the accuracy of navigation-assisted maxillofacial reconstruction. The independent *t*-test was used to compare the means of the predictors identified in the multivariate linear regression analysis. The paired *t*-test was used for the comparison of orbital projection and orbital volume between the preoperative, postoperative, and unaffected orbits. A *P*-value below 0.05 was considered to be statistically significant.

Results

One hundred and twelve vascularized free flap transfers were performed under the guidance of the intraoperative navigation system between April 2014 and September 2019. Of these, 35 were midface reconstructions and 77 were mandibular

Table 1. Linear regression analysis of potential predictors affecting the accuracy of maxillofacial reconstructive outcomes.

Factors	*n*	Standardized beta coefficients	*P*-value
Age (years)		0.090	0.374
≤50	81		
>50	31		
Site		0.406	0.018*
Brown class II maxillary defect	23		
Brown class III maxillary defect	12		
Mandible	77		
Diagnosis		−0.051	0.013*
Benign	73		
Malignant	28		
Others[a]	11		
Type of reconstruction		0.135	0.084
FFF	98		
DCIA	14		
Type of osteosynthesis plate		−0.296	0.001*
Miniplates	99		
Reconstruction plate 2.4	13		
Number of bony segments		0.028	0.870
1	8		
2	53		
3	46		
>3	5		

DCIA, deep circumflex iliac artery flap; FFF, free fibula flap. *$P < 0.05$.
[a] Osteoradionecrosis, congenital defects, secondary defects.

Table 2. Comparison between the preoperative and postoperative orbital projection and orbital volume of the healthy and affected orbits.

	Unaffected orbit	Preoperative orbit	Reconstructed orbit	Difference	*P*-value
Postoperative orbital projection (mm)	15.77 ± 1.62	16.48 ± 1.91	16.98 ± 1.99	1.01 ± 1.69	0.225
Postoperative orbital volume (ml)	27.78 ± 3.61	27.73 ± 1.95	26.72 ± 2.99	0.50 ± 1.21	0.093

reconstructions. Postoperative facial CT scans were performed at 7–10 days post-surgery in all patients. Out of the 73 benign tumours, ameloblastoma was the most common (45 cases, 57.7%), while 14 of the 28 malignant tumours (48.3%) were squamous cell carcinoma. Other diagnoses included ossifying fibroma, adenoid cystic carcinoma, odontogenic myxoma, osteoradionecrosis, congenital defects, and secondary defects, etc. Ninety-eight free fibula flaps (FFF) and 14 deep circumflex iliac artery flaps (DCIA) were recorded. Twelve (34.3%) of the midface reconstruction cases were categorized as Brown class III maxillary defects (with orbital involvement), while 23 (65.7%) were classified as Brown class II. The native condyles were preserved in 47 cases (61.0%), while the condyles were sacrificed in 30 (39.0%), however with preservation of the temporomandibular disc.

The mean deviation and RMS estimate of the orbital, maxillary, and mandibular reconstructions were 0.88 ± 3.25 mm and 3.38 ± 0.73 mm, 0.77 ± 3.44 mm and 3.69 ± 0.82 mm, and 1.07 ± 4.16 mm and 4.67 ± 3.95 mm, respectively. One-way analysis of variance (ANOVA) was performed and showed statistically significant differences among the three groups ($P < 0.05$). Using linear regression analysis, the site of reconstruction ($P = 0.018$), diagnosis ($P = 0.013$), and type of osteosynthesis plate ($P = 0.001$) were identified to be potential factors affecting the accuracy of reconstruction (Table 1). By contrast, the accuracy of the navigation-assisted maxillofacial reconstruction was not associated with the age of the patient, type of reconstruction, or number of bony segment(s). No statistically significant difference between the preoperative and postoperative orbital projection ($P = 0.225$) or volume ($P = 0.093$) was observed in navigation-assisted orbital reconstruction (paired *t*-test) (Table 2).

Multivariate linear regression analysis revealed significant independent predictors affecting the accuracy of navigation-assisted mandibular reconstruction, which included preservation of the condyle, type of reconstruction, type of osteosynthesis plate, and the number of bony segments (Table 3). The independent *t*-test was performed to compare the means of predictors identified between the groups in mandibular reconstruction (Table 4). A slight reduction in accuracy was observed in cases with tumour extension into the condylar region, which necessitated condylar resection (mean 1.41 ± 5.74 mm) as compared to those with preservation of the condyles (mean 0.85 ± 3.16 mm). There was no significant association between the potential predictors and the accuracy of the maxillary and orbital reconstruction detected in the multivariate linear regression model.

Discussion

The results of this study revealed that the average deviation in navigation-assisted maxillary reconstruction was less than that of mandibular reconstruction: 0.77 ± 3.44 mm and 1.07 ± 4.16 mm, respectively. This result is similar to that reported in the systematic reviews conducted by van Baar et al., in which the accuracy deviation of maxillary reconstruction was less than that of mandibular reconstruction, ranging between 0.44 mm and 7.8 mm, and between 0 mm and 12.5 mm, respectively[6]. The

Table 3. Multivariate linear regression analysis of the potential predictors in mandibular reconstruction.

Factors	Interdental distance		Condylar position		Gonial position		Intergonial distance	
	β (95% CI)	*P*-value	β (95% CI)	*P*-value	β (95% CI)	*P*-value	β (95% CI)	*P*-value
Preservation of condyle	4.36 (1.66 to 7.07)	0.0016*	−8.24 (−12.3 to −4.19)	<0.0001*	−4.88 (−7.86 to −1.90)	0.0013*	3.37 (0.20 to 6.53)	0.0369*
Type of reconstruction	−1.70 (−9.84 to 6.45)	0.6831	0.13 (−11.9 to 12.16)	0.9825	11.02 (2.16 to 19.88)	0.0147*	0.18 (−9.29 to 9.65)	0.9710
Type of osteosynthesis plate	−0.65 (−8.97 to 7.68)	0.8787	2.07 (−10.3 to 14.40)	0.7418	−8.30 (−15.4 to −1.24)	0.0212*	−6.87 (−14.4 to 0.64)	0.0729
Number of bony segments	0.29 (−1.91 to 2.49)	0.7982	3.32 (0.09 to 6.54)	0.0437*	5.01 (2.64 to 7.39)	<0.0001*	−2.14 (−4.68 to 0.39)	0.0976

β, beta coefficient; CI, confidence interval. *$P < 0.05$.

Table 4. Independent *t*-test of the predictors in mandibular reconstruction.

	RMS estimates	Relative mean	Relative SD	Interdental distance		Condylar position		Gonial position		Intergonial distance	
				Mean ± SD	*P*-value	Mean ± SD	*P*-value	Mean ± SD	*P*-value	Mean ± SD	*P*-value
Preservation of condyle					0.034*		0.003*		0.003*		0.620
Yes	4.22 ± 5.13	0.79 ± 0.77	3.18 ± 1.08	0.92 ± 4.30		6.00 ± 3.73		7.13 ± 3.74		1.78 ± 4.87	
No	6.13 ± 3.55	1.45 ± 1.32	5.91 ± 3.38	3.78 ± 5.98		13.36 ± 11.57		12.83 ± 9.06		0.85 ± 8.96	
Type of reconstruction					0.757		0.001*		0.001*		0.432
FFF	5.22 ± 4.60	1.12 ± 1.13	4.56 ± 2.89	2.00 ± 5.45		9.66 ± 9.03		10.04 ± 7.25		1.55 ± 7.24	
DCIA	4.07 ± 1.22	1.04 ± 1.14	3.87 ± 0.95	2.41 ± 3.43		4.64 ± 2.71		5.64 ± 2.73		0.58 ± 2.48	
Type of osteosynthesis plate					0.473		0.104		<0.001*		0.114
Miniplates	5.29 ± 4.63	1.14 ± 1.14	4.63 ± 2.90	1.92 ± 5.46		9.42 ± 9.10		10.21 ± 7.26		1.73 ± 7.25	
Reconstruction plate	3.25 ± 0.35	0.78 ± 0.67	3.09 ± 0.46	2.85 ± 3.54		6.38 ± 4.53		5.11 ± 1.96		0.28 ± 2.70	
Number of bony segments					0.592		0.451		0.031*		0.799
1	4.22 ± 0.98	0.75 ± 0.89	4.08 ± 0.95	2.43 ± 3.69		8.10 ± 4.97		7.49 ± 3.51		1.18 ± 4.73	
2	3.59 ± 1.64	0.84 ± 0.57	3.49 ± 1.63								
3	4.89 ± 4.59	1.12 ± 1.08	4.04 ± 2.42	1.81 ± 6.02		9.51 ± 10.36		10.68 ± 8.31		1.57 ± 7.89	
>3	7.35 ± 4.28	1.85 ± 1.94	7.03 ± 3.99								

DCIA, deep circumflex iliac artery flap; FFF, free fibula flap; SD, standard deviation; RMS, root mean square. *$P < 0.05$.

accuracy of navigation-assisted maxillary reconstruction was notably superior to that of mandibular reconstruction, as the maxilla is fixed to the cranium, which allows accurate dataset synchronization with the navigation system as compared to the mandible.

The average deviation of orbital reconstruction in this study was 0.88 ± 3.25 mm, which is comparable to the results published by Tarsitano et al.[7] from a prospective study that utilized CAD/CAM printed titanium mesh, in which an average error of 2.9 mm with highest difference of 3.4 mm was demonstrated. The outcomes of orbital reconstruction were satisfactory as there was no titanium mesh exposure or diplopia reported upon ophthalmic assessment. There was no statistically significant difference noted when comparing the orbital projection and volume between the healthy and affected globes. The use of preoperative VSP and stereolithographic models is invaluable in reproducing an accurate contour and length of the titanium mesh, as intraoperative freehand adaptation of titanium mesh can be technically challenging and time-consuming. Additionally, navigation-assisted surgery can ensure precise and safe positioning of the titanium mesh without encroaching on the orbital apex.

The application of navigation-assisted surgery in the mandible is controversial and has been widely discussed. van Baar et al.[6] conducted a systematic review on planning and evaluation methods in studies that evaluated the accuracy of mandibular reconstruction aided by CAS. However, the authors were unable to compare the postoperative outcomes and perform a meta-analysis due to inconsistent planning and evaluation methods. Out of the 42 studies reviewed, only 10 incorporated surgical navigation and the largest sample size was 26 cases[2,4,6,8–15]. The present study included 77 navigation-assisted mandibular reconstruction cases, which is a large sample size for assessing the accuracy of reconstructive outcomes.

Although the mandible is attached to the cranium via the temporomandibular joint (TMJ), there is constant mandibular movement and such mobility may compromise accurate synchronization of the dataset with the navigation system in mandibular reconstruction. The discontinuity of the mandible following tumour resection further aggravates the difficulties in maintaining a stable and reproducible mandibular position. Yu et al.[16] summarized several methods of using navigation-assisted surgery and guiding plates in different mandibular defects to stabilize the mobile mandibular segments, including occlusal wafers, reconstruction plates, a mandibular fixation device, and stereolithographic models. Other alternatives including the fabrication of dental splints with radiopaque markers or attaching the DRF directly onto the mandible or lower dentition have also been advocated to improve the accuracy of navigation[17–21]. In this study, a mandibular fixation device was applied in these cases to maintain the intergonial distance while reducing the rotation of the condyles[12]. A previous study by the present authors also demonstrated larger condylar shift and reduced reconstruction accuracy in the conventional surgery group as compared to the surgical navigation and surgical navigation with CAD groups[14].

Reconstruction of the TMJ is technically challenging as the TMJ is a unique and complex ginglymoarthrodial joint. The choice of graft versus TMJ prosthesis in reconstruction is debatable and beyond the scope of discussion in this paper. In the present study, preservation of the condyles was significantly associated with the accuracy of the mandibular reconstruction (P = 0.0111). Multivariate linear regression analysis demonstrated a statistically significant association between preservation of the condyle and interdental distance ($P = 0.0016$), condylar position ($P < 0.0001$), gonial position ($P = 0.0013$), and intergonial distance (P = 0.0369). There was no case of displacement, dislocation, ankylosis, or disturbance of TMJ function reported in any of the cases of condylar resection. Using the independent t-test, the difference in mean gonial position appeared to be statistically significant for all predictors identified in the multivariate linear regression analysis. The type of reconstruction was noted to be significantly associated with condylar position; this could be due to all of the disarticulation resection cases being reconstructed with a FFF, while the use of the DCIA was relatively limited to condyle-preserving cases in this study.

The deviation of interdental distance was observed to be higher in cases with condylar resection as compared to those preserved. This deviation might have been derived from incorrect positioning of the neocondyle in the glenoid fossa as a result of sagging of the neocondyle inferiorly. In this study, a slight decrease in accuracy was observed in cases requiring condylar resection (mean 1.41 ± 5.74 mm) as compared to those with preservation of the condyles (mean 0.85 ± 3.16 mm). Metzler et al.[1] reported a larger deviation in their 10 condyle-preserving mandibular reconstruction cases in which higher osteotomies were required within the condylar neck. It was highlighted that the 3D movements of the mandibular segments and reconstruction plates could have contributed to the sensitive changes in condylar position. Hidalgo[22] described the effectiveness of preservation of the resected condylar segment and insetting into the free flap mandibular reconstruction in enhancing the aesthetic outcomes. Nonetheless, the emphasis should be put on achieving safe surgical margins and reducing the risk of local recurrence, as the average deviation of the reconstruction following condylar resection was acceptable in this study[23].

The choice of osteosynthesis plate was also observed to have a significant association with the gonial position. The mean deviation measured in cases in which the UniLOCK Reconstruction Plate 2.4 was used was significantly lower than that of the cases in which miniplates were used: 5.11 mm and 10.21 mm, respectively. The large difference in mean deviation noted between the different osteosynthesis plates can be explained by the integrated CAD/CAM technology in which the reconstruction plates were adapted on the rapid prototype models preoperatively. The pre-bent reconstruction plate served as a guiding template, which aided the surgeon in assembling and fixing the bony flaps to the plate prior to dissection of the vascular pedicle. This result is comparable to the findings of a study conducted by Yu et al.[4], who observed that enhanced surgical outcomes can be achieved using CAD and intraoperative navigation technologies. Tarsitano et al.[24] demonstrated better reconstructive outcomes by incorporating a CAD/CAM reconstruction plate in the mandibular reconstruction following disarticulation resection, in which the average condylar shift was 3.8 mm.

There are several inherent limitations in this study. The retrospective nature of the study may have contributed to the heterogeneity of the patients. Substandard image dataset resolution, discrepancies during image fusion, and distance from the patient tracking device to the working field may further have contributed to inaccuracies[25,26]. The registration method used in this software was point-landmark-based followed by global registration of unaffected areas to refine the registration. The corresponding anatomical landmarks, such as mental foramina of the unaffected or stable areas, were indicated manually in both modalities in mandibular cases, while the cranial base was used as the reference in maxillary cases. The main drawback of this method is that the accuracy is largely dependent on the accurate indication of the corresponding anatomical landmarks with both modalities. Koerich et al.[27] presented an ideal and fast registration method using regional voxel-based superimposition; however, we were not able to utilize such a registration method as this is unavailable in the current software used in this study.

In summary, the application of computer-assisted surgery and intraoperative navigation has immense potential in improving accuracy and reconstructive outcomes by reducing guesswork and human error, particularly in advanced and complex oncological cases. The use of intraoperative navigation offers significant advantages in maxillofacial reconstruction, including the maxilla, orbital floor, and particularly the mandible. The accuracy of navigation-assisted mandibular reconstruction was significantly associated with preservation of the condyle, the type of reconstruction, type of osteosynthesis plate, and the number of bony segments. Condylar and gonial positions were observed to be more sensitive to three-dimensional changes in the mandibular segments and type of osteosynthesis plate. A standard protocol to enumerate and evaluate the accuracy should be developed to allow further validation and assessment of the technologies.

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Competing interests

None of the authors has a financial interest in any of the products, devices, or drugs mentioned in this manuscript.

Ethical approval

The study was approved by the Institutional Review Board of Peking University School of Stomatology and was conducted according to the tenets of the Declaration of Helsinki with approval number PKUSSIRB-201949126.

Patient consent

Due to the retrospective nature of this study, patient consent was not required.

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