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Research article

Reliabilities of three methods used to evaluate computer-assisted mandibular reconstructions using free fibula flaps

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A B S T R A C T

Objective: This study compared the reliabilities of three different methods used to calculate surgical deviations after mandibular reconstructions using free fibular flaps.
Study design: This retrospective study involved 35 patients who underwent computer-assisted mandibular reconstructions using free fibula flaps. The deviations between the virtual surgical plans and the postoperative results were independently analyzed by two researchers using three distinct methods. In Method A, the fibular axis, the center of gravity, and the osteotomy plane served as landmarks when measuring surgical deviations. In Methods B and C, manually designated points were used to measure errors in the fibular length and intersegmental angle. The primary outcome variables were the intraclass correlation coefficients (ICCs) that revealed the inter-rater agreements for all three methods.
Results: The use of Method A was associated with good agreement in terms of the fibular length deviation (ICC = 0.765) and intersegmental angle (ICC = 0.897); both were higher than those afforded by Methods B (ICC = 0.158 and 0.108) and C (ICC = 0.406 and 0.463). The measurements of the fibular transfer osteotomy deviation (ICC = 0.888), linear deviation (0.926), and angular deviation (0.958) were very reliable.
Conclusions: Method A afforded the highest reliability in clinical practice when evaluating surgical deviations after mandibular reconstruction using fibular flaps.

1. Introduction

In the time since the introduction of mandibular reconstruction using free fibular flaps (FFFs) [1], the fibula has been commonly selected as a donor site when treating mandibular defects. Given the progress in computer-aided design/computer-aided manufacturing (CAD/CAM) and rapid prototyping (RP) techniques over the past two decades, surgical accuracy has improved and the surgical time has been reduced [2–4].

Accurate quantitative analysis of a surgical outcome is not only essential, but also reveals the utility and effectiveness of the procedure. In the postoperative evaluation phase, pre- and post-operative computed tomography (CT) scans are usually compared to assess any surgical deviations [5]. With the aid of computer technology, quantitative evaluation can be very accurate. However, no widely accepted measurement parameters exist to date; different studies tend to take various measurements, severely limiting the ability to compare the results.

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Evaluation of the reliability of a technique is fundamental when it is sought to establish its utility [6]. Measurement error is almost always inevitable; this affects the reliability of data. Traditional mandibular measurements are mostly based on manual identification of landmarks such as the condylion and the gonion. The smooth and featureless surface of the fibular segment renders it difficult to identify reference points, thus increasing the likelihood of measurement errors. This encouraged the reliability analysis of the present study, which, to the best of our knowledge, has not yet been used to evaluate mandibular reconstruction using FFFs.

Of the available reliability indexes, including the Kappa statistics and Dahlberg's error, the intraclass correlation coefficient (ICC) seems to be useful. The ICC is the correlation between one measurement on a target and another measurement on that target [7]. The index is widely used in many fields to assess the quality of measurements; the conclusions of one study aided FDA product approval.

We developed a very reliable assessment method that quantitatively evaluates surgical deviations after computer-assisted mandibular reconstructions using FFFs. The measuring landmarks are automatically calculated from the fibular 3D contour, not manually identified. The inter-rater reliability was tested using the ICC and compared to those of two point-based measuring methods.

2. Materials and methods

This study enrolled 35 patients who underwent mandibular reconstruction with FFFs after segmental mandibulectomy at the First Affiliated Hospital, College of Medicine, Zhejiang University, Hangzhou, China, between April 2018 and November 2022. The quantitative assessment of surgical accuracy was performed using patient CT data. Ethical approval was obtained from the Clinical Research Ethics Committee of the First Affiliated Hospital, Zhejiang University School of Medicine. Written informed consent has been obtained from the patient or his or her legal representative. The study was performed in accordance with the ethical standards of the responsible committee on human experimentation and the Declaration of Helsinki.

The basic patient data are listed in Table 1. The patients were aged between 13 and 65 years (mean, 37.38 ± 15.58 years), and the male/female distribution was 16/19 (45.71 %/54.29 %). Among all cases, 29 (82.86 %) benign tumors and 6 (17.14 %) malignancies were diagnosed. According to the Brown classification [8], type I, type II, and type III mandibular defects were present in 12 (34.29 %), 18 (51.43 %), and 5 (14.28 %) cases, respectively. Mandibular reconstruction was performed using one segment in 9 patients, two segments in 15 patients, and three segments in 11 patients.

2.1. *Virtual planning and surgeries*

All patients underwent 64-slice CT of the mandible and maxilla (0.6 mm thick slices) and CT angiography (CTA) of the lower extremities (3 mm thick slices). The images were stored in Digital Imaging and Communications in Medicine (DICOM) format.

The DICOM data were preoperatively processed using Mimics software (ver. 17.0; Materialise, Leuven, Belgium) to create 3D virtual mandibular models. The resection range for each mandible was set and a cutting guide was designed (Fig. 1A). To restore facial symmetry, a mirrored model of the unaffected contralateral mandible was created using Magics software (ver. 14.0; Materialise, Leuven, Belgium) to be the ideal surgical target. The fibular cutting guide was designed to assist fibular osteotomy and subsequent recontouring (Fig. 1B). After the patient's fibular data were imported into the bony defect (Fig. 1C), fibular positioning proceeded with the assistance of the recontouring guide (Fig. 1D). All customized surgical guides were printed using a 3D printer (Objet Connex350™; Stratasys Ltd, Eden Prairie, MN, USA). The titanium reconstruction plates (Synthes, Zuchwil, Switzerland) were pre-bent preoperatively using a 3D-printed neomandible model.

All patients were operated upon under general anesthesia. With the assistance of the surgical guides, mandibular osteotomies were performed by reference to the cutting slots, and effectively replicated the virtual plans (Fig. 2A). During tumor resection, a fibular flap was harvested. The fibular cutting guides were placed using screws, and wedge osteotomies were performed following the guides (Fig. 2B). After the cutting guide was removed, the fibular segments were recontoured and fixed to the pre-bent titanium plate (Fig. 2C). All of these steps were completed before cutting the pedicles; this reduced the ischemia time. Thereafter, the pedicle was cut and the flap was transferred into the defect and fixed to the remnant mandible (Fig. 2D). The details of the surgical procedure are described in a previous study [9].

Table 1
Basic information of patients.

		Brown's classification		
		Brown I	Brown II	Brown III
Gender				
Male	16	5	9	2
Female	19	7	9	3
Age (yr)	37.38 ± 15.58	32.14 ± 12.08	39.81 ± 14.11	42.09 ± 21.27
Pathology				
Benign	29	11	16	2
Malignancy	6	1	2	3
Fibular segments				
One segment	9	8	1	0
Two segments	15	4	9	2
Three segments	11	0	8	3

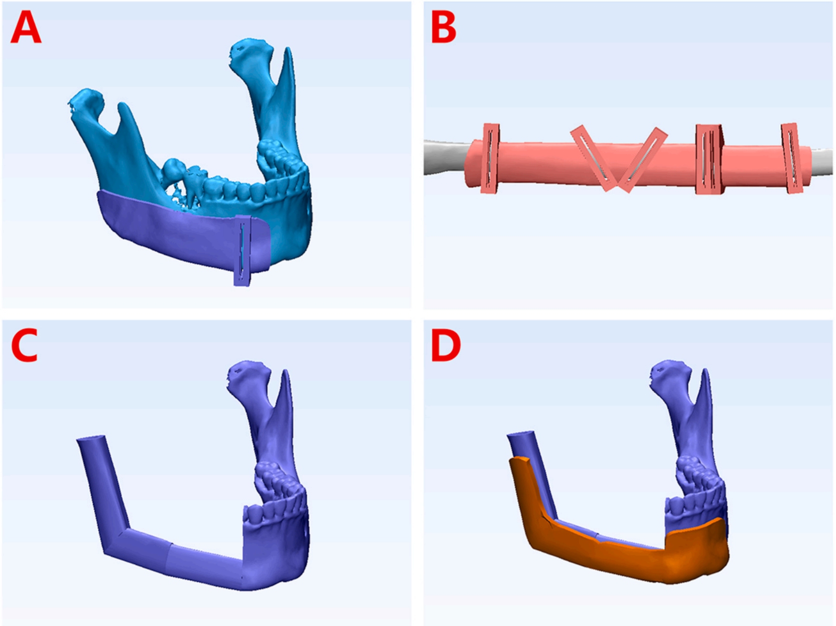

Fig. 1. Virtual design of the customized surgical guides. (A) The mandibular cutting guide. (B) The fibular osteotomy guide. (C) A virtual model of the fibula-reconstructed mandible. (D) The re-contouring guide.

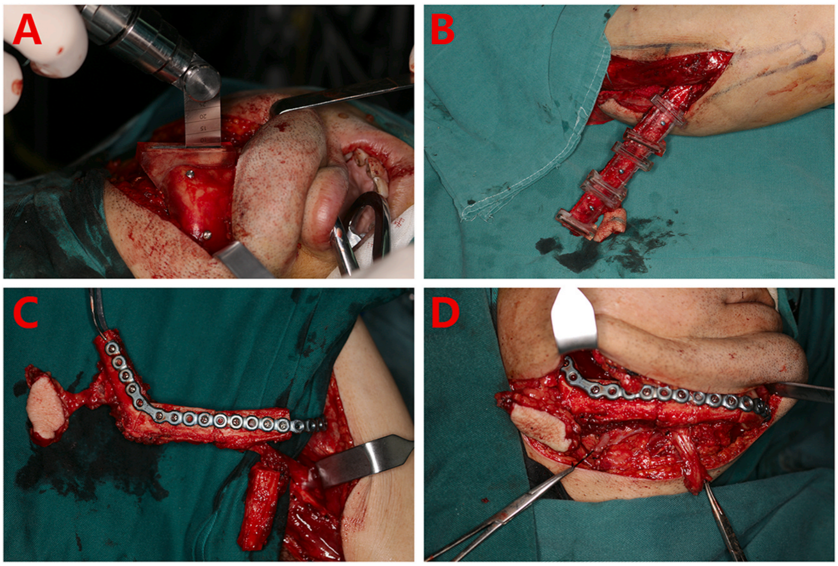

Fig. 2. Surgical procedure. (A) Mandibular osteotomy performed by reference to the planned margin using a cutting guide. (B) Harvesting of a fibular flap using the osteotomy guide. (C) Recontouring of the fibular flap prior to pedicle cutting (to reduce ischemia time). (D) Insertion of the fibular flap into the defect and fixation of the titanium plate.

2.2. Preparation for postoperative evaluation

A postoperative CT scan was taken for each patient 1 week after surgery; the purpose was to evaluate surgical accuracy. We sought to ensure that there would be no long-term changes in the volume or position of the bone segments. When creating the 3D models, the titanium plates and screws were removed from the images; only the bony structures were used. The virtual 3D mandibular models were output as stereolithographic (STL) files for further evaluation.

Finally, each case featured two STL mandibular models: the model of the virtual planning and that of the postoperative outcome. These were imported into 3-matics software (ver. 9.0; Materialise, Leuven, Belgium) and discrepancies between the two models were measured. The two models were superimposed by reference to the nonsurgical parts of the mandible. Then, to check the reliability of alignment, any surface discrepancy in the reference area was calculated using an iterative closest-point algorithm. The subsequent procedures commenced when the mean surface discrepancy was <1 mm [10].

In what follows, measurements of surgical accuracy were obtained using a newly designed method (Method A); the measuring landmarks were not manually designated. Two different point-based measuring methods (Methods B and C) were used for comparison [11,12]. The measurements were performed independently by two researchers. The interrater agreements of the three methods were compared.

2.3. Method A

Before measurement, landmarks were identified after marking the surface of each fibular segment, including the osteotomy plane (OP) (Fig. 3A), the inertial axis, and the center of gravity (Fig. 3B).

A flowchart of method A is shown in Fig. 4. Errors occurred principally during three surgical steps: osteotomy, recontouring of the fibular segments, and implantation of the fibular flap into the defect. Therefore, deviations corresponding to these steps were sought. A deviation in the fibular length (DFL) and an angular deviation of the osteotomy plane (ADOP) arose during osteotomy. During the recontouring procedure, a deviation of the intersegmental fibular angle (DIFA) occurred. When the fibular flap was implanted into the mandibular defect, a positional deviation of the fibula developed, including a linear deviation of the fibula (LDF) and an angular deviation of the fibula (ADF).

1. The DFL was defined as the deviation between the planned and actual fibular length (FL). The fibular length was determined by measuring the length of the fibular axis (Fig. 5A and B).
2. The DIFA was defined as the deviation between the planned and actual intersegmental fibular angles (IFAs). Each IFA was established by measuring the angle between the two axes of adjacent fibular segments (Fig. 5A and B).
3. The ADOP was determined by measuring the angle between the virtual and the actual OP on each end of each segment (Fig. 5C).
4. The LDF was determined by measuring the distance between the planned and actual center of gravity of each fibular segment, and the ADF was determined by measuring the angle of the planned and actual axis of each fibular segment (Fig. 5D).

2.4. Method B

A point-based assessment was employed to measure the FL, IFA, DFL, and DIFA [11] of preoperative plannings (Fig. 6A) and postoperative results (Fig. 6B).

1. The FL was established by measuring the length between two points that were manually identified on the surface of each fibular segment. The DFL was the deviation between the planned and actual FLs.
2. The IFAs were determined by measuring the angles among three points identified on the ends of the fibular segments. The DIFA was calculated as the deviation between the planned and actual IFAs.

2.5. Method C

1. The FL was the mean value of the lengths along the outer upper margin, outer lower margin, and inner median margin [19], which were measured between two points on the ends of each fibular segment (Fig. 7A and C). The DFL was calculated as the deviation between the planned and actual FLs.
2. The IFA was calculated as the mean value of the angles that were determined by the deviations of three points along the outer upper margin, outer lower margin, and inner median margin (Fig. 7B and D). The DIFA was calculated as the deviation between the planned and actual IFAs.

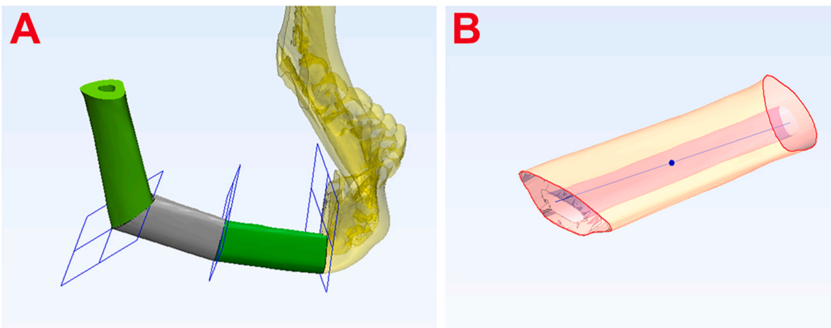

Fig. 3. The landmarks of Method A. (A) The osteotomy planes were determined for each section of the fibular segment. (B) The inertial axis and the center of gravity of each fibular segment were automatically calculated after marking the surface of the segment.

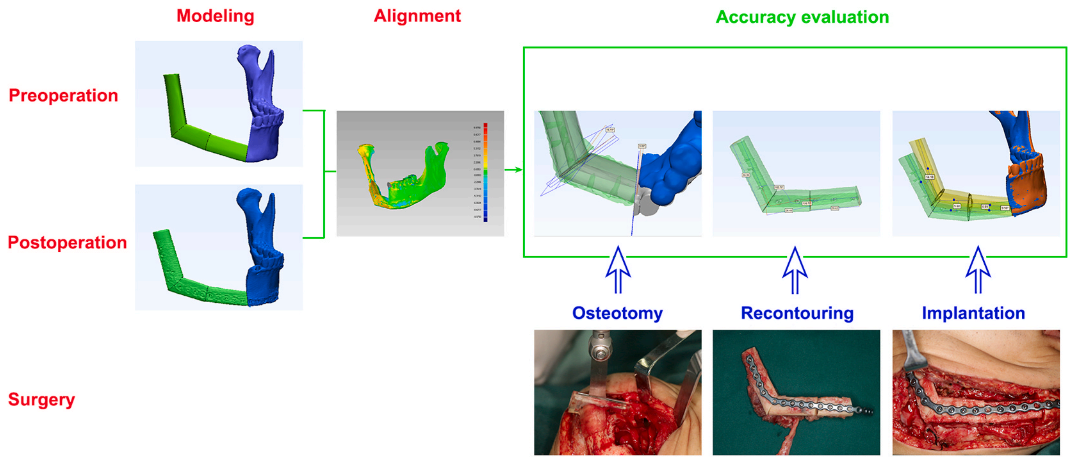

Fig. 4. The flowchart of Method A that shows the evaluations performed at various surgical steps. The 3D virtual models derived via preoperative planning, and postoperatively, were aligned. An iterative closest-point algorithm was used to check the reliability of alignment. The accuracy of osteotomy, recontouring, and implantation were evaluated using the angular deviation of the osteotomy plane, the length and angular deviation of the axis, and the positional deviation of the center of gravity, respectively.

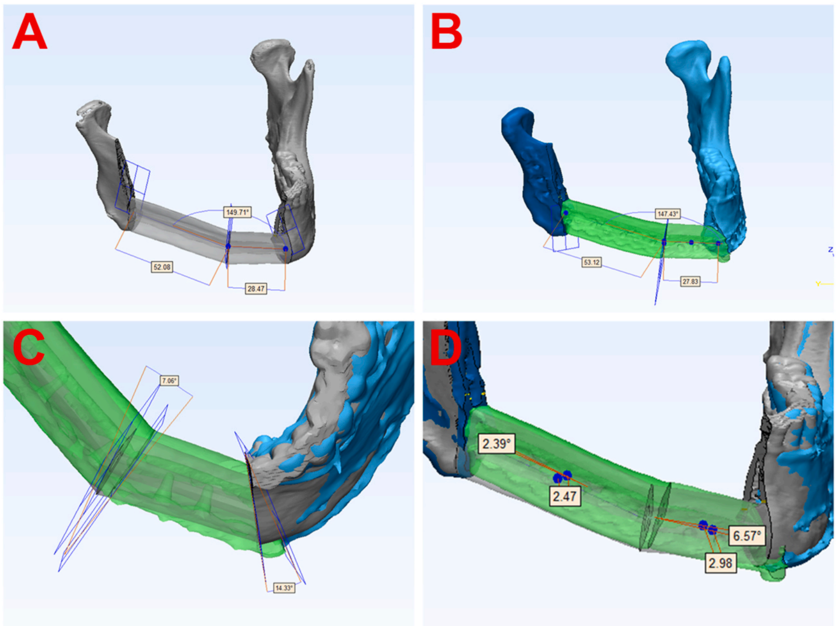

Fig. 5. Using Method A, measurements were obtained using both preoperative and postoperative mandible models, the latter derived from postoperative CT scans. (A) Preoperative measurements of segmental lengths and intersegmental angles by reference to the fibular axis. (B) Postoperative measurements of segmental lengths and intersegmental angles by reference to the fibular axis. (C) The angular deviations of osteotomy planes were obtained by measuring the angles between the pre- and the corresponding postoperative osteotomy planes. (D) There were two positional deviations of each single fibular segment: the linear deviation between the pre- and postoperative fibular centers of gravity, and the angular deviation between the pre- and postoperative fibular axes.

Two examiners independently performed all landmark identifications and measurements on all cases following the same protocol. Both examiners had been well-trained in terms of software use before the study.

2.6. Statistical analysis

Descriptive data are presented as means ± standard deviations (SDs). The data were analyzed using IBM SPSS ver. 19.0 (SPSS Inc., Chicago, IL, USA). The interrater agreements among measurements were assessed using the ICCs. Based on the 95 % confidence intervals of the ICC estimates, the following intervals were defined for all evaluations: 0.00–0.49 = poor agreement, 0.50–0.74 =

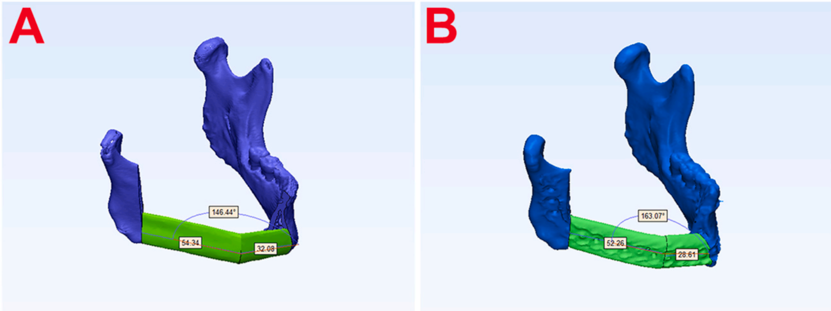

Fig. 6. Measurements of fibular lengths and intersegmental angles derived using Method B. (A) Preoperative measurements of the fibular lengths and intersegmental angles of the outer surfaces of fibular segments. (B) Postoperative measurements of the fibular lengths and intersegmental angles of the outer surfaces of fibular segments.

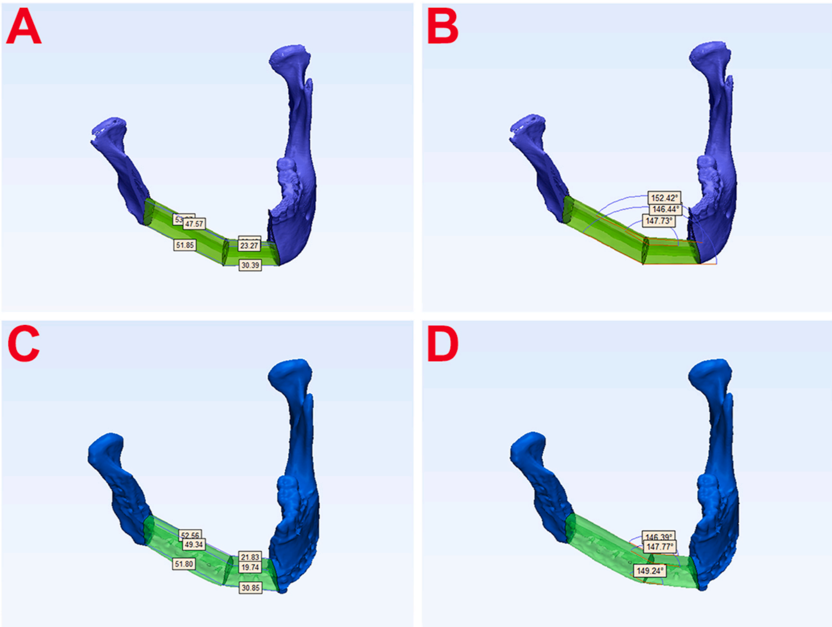

Fig. 7. Measurements of fibular lengths and intersegmental angles derived using Method C. (A) Preoperative measurements of the fibular lengths along three different ridges: the outer superior, outer inferior, and inner median segment lengths. (B) Preoperative measurements of the fibular intersegmental angles of the outer superior, outer inferior, and inner median fibular ridges. (C) Postoperative measurements of the outer superior, outer inferior, and inner median fibular lengths. (D) Postoperative measurements of the fibular intersegmental angles of the outer superior, outer inferior, and inner median fibular ridges.

moderate agreement, 0.75–0.89 = good agreement, and 0.90–1.00 = excellent agreement [13]. The ICCs of the FL, DFL, IFA, and DIFA were compared among Methods A, B, and C.

3. Results

In all, 72 fibular segments used for the reconstruction of 35 mandibular defects were evaluated. The results of Method A are presented in Table 2. The ICCs indicated perfect agreement between the two examiners in terms of the PFL (1), AFL (0.998), PIFA (0.998), AIFA (0.995), LDF (0.926), and ADF (0.958). Those for DFL (0.765), ADOP (0.888), and DIFA (0.897) were in good agreement. The results of Method B are presented in Table 3. The ICCs of PFL, AFL, PIFA, and AIFA were 0.993, 0.994, 0.996, and 0.976, respectively, indicating perfect agreement. Those for DFL and DFA were 0.158 and 0.108, respectively, indicating poor agreement. The results for Method C are presented in Table 3. The ICCs of PFL, AFL, PIFA, and AIFA were 0.994, 0.993, 0.979 and 0.979, respectively, indicating perfect agreement. Those of DFL and DFA were 0.406 and 0.463, respectively, indicating poor agreement.

Table 2
The results of method A.

Measured variables	Examiner 1	Examiner 2	ICC
	Mean value	Mean value	
PFL (mm)	39.12 ± 13.76	39.11 ± 13.74	1
AFL (mm)	40.27 ± 13.75	40.17 ± 13.4	0.998
DFL (mm)	1.54 ± 1.6	1.75 ± 1.59	0.765
PIFA (°)	126.09 ± 17.28	125.89 ± 17.39	0.998
AIFA (°)	129.91 ± 15.98	127.91 ± 16.87	0.995
DIFA (°)	3.15 ± 2.76	3.12 ± 2.79	0.897
ADOP (°)	6.81 ± 3.86	7.56 ± 3.86	0.888
LDF (mm)	3.38 ± 3.02	3.33 ± 2.91	0.926
ADF (°)	5.14 ± 3.34	5.74 ± 3.63	0.958

Abbreviations: PFL=Planned fibular length; AFL = Actual fibular length; DFL = deviation of the fibular length; PIFA=Planned intersegmental fibular angle; AIFA = Actual intersegmental fibular angle; DIFA = Deviation of intersegmental fibular angle; ADOP = angular deviation of the osteotomy plane; LDF = linear deviation of figula; ADF = angular deviation of fibula.

Table 3
The results of methods B and C.

Measured variables	Method B		ICC	Method C		ICC
	Rater 1	Rater 2		Rater 1	Rater 2	
PFL (mm)	41.51 ± 13.37	41.85 ± 13.04	0.993	37.49 ± 14.59	37.51 ± 14.65	0.994
AFL (mm)	41.33 ± 13.46	42.51 ± 13.49	0.994	37.78 ± 14.23	37.74 ± 14.39	0.993
DFL (mm)	1.25 ± 0.98	1.52 ± 1.23	0.158	1.98 ± 1.75	1.66 ± 1.71	0.406
PIFA (°)	129.55 ± 15.19	130.13 ± 15.58	0.996	130.48 ± 15.11	130.84 ± 15.42	0.979
AIFA (°)	133.54 ± 15.74	130.76 ± 13.94	0.976	132.21 ± 14.55	132.24 ± 14.61	0.979
DIFA (°)	4.78 ± 3.76	2.22 ± 2.45	0.108	3.85 ± 3.19	3.47 ± 2.87	0.463

Abbreviations: PFL=Planned fibular length; AFL = Actual fibular length; DFL = deviation of the fibular length; PIFA=Planned intersegmental fibular angle; AIFA = Actual intersegmental fibular angle; DIFA = Deviation of intersegmental fibular angle.

4. Discussion

Surgical accuracy was defined as the similarity between the postoperative outcome and the preoperative plan. Using computer technology, quantitative evaluation of the accuracy of mandibular reconstruction can be achieved in detail. However, no widely accepted measuring techniques that assess surgical accuracy have been established to date; different studies use various measurements; comparisons are difficult. We developed a new assessment method that reliably measured surgical deviations after mandibular reconstructions.

The FFF-reconstructed mandible contains two types of bony tissue: the remnant mandible and the fibular segments. In our experience, most bone deviations occur during three surgical steps: osteotomy, recontouring of the fibular segments, and transfer of fibular segments into the defect. Accordingly, we evaluated the surgical deviations using four measures: the deviation of OP, the length deviation of the fibular segments, the intersegmental angle shift, and the positional deviation of the fibular segments (Fig. 4).

It is very important to prepare CT models before analysis. Cone-beam computed tomography (CBCT) is increasingly being used by maxillofacial surgeons given the low cost and low radiation dose. However, this technology is heavily affected by the "cone-beam" geometry of the X-ray beam [14,15]; this causes image noise. Moreover, the relatively large area irradiated during CBCT increases scatter and reduces contrast. These disadvantages affect the precision of the CT model. In Eijnatten et al. [16], CBCT did not deliver reproducible STL models; multi-detector row CT (MDCT)-derived STL models were characterized by lower geometric variation and a higher accuracy than those of CBCT. Therefore, MDCT data were used when creating the 3D STL models of the present study. In this approach, the metal plates and the screws are segmented from the postoperative CT data, and only the bony structures are used for postoperative measurements. In this approach, metal scattering caused by the fixation plate(s), which introduce inaccuracies in terms of alignment of and measurements on STL models [17,18], was avoided.

Tarsitano et al. [19] presented a method for evaluating mandibular reconstruction in 34 cases; the surgical deviations were evaluated by superimposing the preoperative plans on the postoperative outcomes. The average linear discrepancy was automatically calculated using an iterative closest-point algorithm. Compared to a point-based analysis, this technique eliminates any human error that might influence manual measurements [19]. Moreover, the accuracies could be three-dimensionally visualized using a colored quality mapper function, facilitating visual rendition of discrepancies [11,20]. In our opinion, the utility of this method is limited because the deviation was a surface linear assessment of the entire mandible and thus the origins of deviations were not traceable [10], and the deviations were measured in mm, while other measurements such as angular deviations were absent. Nonetheless, alignment of pre- and post-operative mandibular STL files can serve as the basis for subsequent assessments, particularly positional deviations. The differences between two models can be directly compared once the files are aligned. In the current study, the healthy side of the mandible was not influenced by surgery; hence, this served as a suitable reference after superimposition. Meanwhile, a 'best fit' analysis of the entire mandibular reconstruction was avoided, preventing underestimation of deviations.

Precise osteotomy is core in terms of accurate mandibular recontouring. The angles and the lengths of bones are directly affected by the accuracy of osteotomy. Even with a slight deviation of a single OP, the multiple small errors are additive and thus result in a large final error. Ciocca et al. [21] published an evaluation method for mandibular osteotomy. After alignment, the accuracy of fibular sectioning was measured from the lateral perspective. The OP served as the landmark during measurements of osteotomy deviation by Goormans et al. [12]. This assessment was three-dimensional in nature, and thus close to reality. In our study, the cutting guides with screw holes were used to control the exact position and direction of osteotomy [9]. The ICC of ADOP was 0.888, indicating good reliability. The linear deviation of the OP was not measured for two reasons: there is no simple mathematical method that measures the distance between two non-parallel planes and the linear deviation of the OP principally affects the accuracy of bone length measurements, which were evaluated independently.

The fibular length and the intersegmental angle are two of the most common parameters used to evaluate surgical reconstruction. However, we considered that the fibular axis would serve as a more stable landmark for angle and length measurements. Schepers et al. introduced a method that created the fibular axis [14]; this was determined by placing virtual cylinders around the fibular segments. In Method A of the current study, each fibular axis was directly calculated by reference to the 3D contour of the fibular segment. The procedure thus became simple; reduced manual manipulation is usually associated with smaller measurement errors. Methods B and C are both point-based measurement methods, both of which have often been used in previous studies [11,12,22]. The ICCs of FL and IFA for all three methods were extremely high and similar. Both the point-based and the axis-based measurements were sufficiently reliable for clinical application. However, the situation differed when measuring the surgical deviations. The measurement errors, calculated as interrater differences, were around 1 mm for DFL and several degrees for DIFA. The ICC results indicated that measurement errors clearly affected the reliabilities of deviation evaluations performed during surgery. Both point-based measurements (Methods B and C) exhibited poor mutual agreement ($ICC < 0.5$) in terms of measurements of both DFL and DIFA. The axis-based measurements (method A) were associated with higher ICCs and better agreement ($0.75 < ICC < 0.9$). The key findings are that the measurement errors were very small for both point-based and axis-based measurements, these miniscule errors suggest that the focus should shift to the reliability of surgical deviations, and the reliability of axis-based measurements.

The positional relationships between the fibular segments and the mandibular remnants greatly affect the final contour of mandibular reconstruction. Positional analyses of bone grafts must consider both angle and distance. After alignment, the angle and distance deviations were calculated by comparing the preoperatively planned and the postoperative outcomes. The angle deviations between the pre- and postoperative axes of the fibular segments were measured. To evaluate the distances between bone segments, we used the centers of gravity of all bone grafts as the relevant landmarks. The distance deviation was defined as the linear difference between the pre- and postoperative centers of gravity that were identified by software that explored the contours of fibular segments. Similar landmarks were used by Yang et al. [23] to assess both angle and distance deviations. Our work shows that the reliability of the new technique is excellent.

The excellent reliability aside, the proposed evaluations afford further advantages: (1) High universality. In many prior works, mandibular defect classifications required prior knowledge of the complexity of mandibular reconstructions to predict their accuracy, but our evaluations are applicable to all mandibular defects, reducing the need to explore the complexity of the chosen clinical application. (2) Strong traceability. Each parameter is tightly linked to a specific surgical step to which a result can be attributed. For example, DFL and ADOP issues are associated with osteotomy but DIFA problems are associated with recontouring. Consequently, the cause of any deviation can be traced, and the effectiveness of a modification of any surgical procedure can thus be evaluated, greatly enhancing the clinical utility of our proposed approach.

However, our work had certain limitations. First, Method A requires more advanced computing skills and more time than point-based measurements. All researchers required more than 1 h to complete assessments of all procedures, including landmark identifications and measurements. Second, Method A is less flexible than point-based measurements and thus cannot replace point-based measurements.

In the present work, we compared the reliabilities of three methods used to evaluate the accuracies of computer-assisted mandibular reconstructions. The highest reliability was that of the newest method, the landmarks of which were based on the target 3D contours. This contour-based method afforded very reliable evaluation of clinical results.

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Data availability statement

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Tingwei Bao: Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Di Yu:** Writing – review & editing, Validation, Methodology, Conceptualization. **Wenyuan Zhu:** Validation, Software. **Jianfeng He:** Investigation, Formal analysis. **Jiaqi Zheng:** Software. **Huiming Wang:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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