Research Paper
Orthognathic Surgery

How accurate is digital-assisted Le Fort I maxillary osteotomy? A three-dimensional perspective

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Abstract. The aim of this study was to evaluate the surgical accuracy of Le Fort I surgery compared to the three-dimensional (3D) virtual planning. Fifty-five patients (29 males, 26 females; age range 15–58 years) with skeletal class III malocclusion, who underwent bimaxillary surgery were included. A validated 3D accuracy assessment tool was utilized to assess the surgical accuracy of the maxillary positioning. For translational movements, the least amount of error was associated with mediolateral translation, whereas the surgical accuracy for anteroposterior and superoinferior translation showed a tendency towards a more posterior and inferior positioning of the maxilla compared to the planning. For rotational movements, the highest discrepancy was observed for pitch. Linear regression showed increased inaccuracy with increasing advancement for anteroposterior, superoinferior and pitch movements. To conclude, 3D virtual planning of maxilla was generally accurate when compared to achieved outcome for skeletal class III patients undergoing bimaxillary surgery.

Key words: surgical accuracy; accuracy assessment; 3D virtual planning; Le Fort I surgery.

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Orthognathic surgery is an established procedure for correcting dentofacial deformities. Recent advances in technology have led to the development of three-dimensional (3D) tools in orthognathic surgery to overcome the limitations associated with inaccuracy of conventional two-dimensional (2D) methods^{1,2}.

Nowadays, 3D software packages are extensively being utilized for the purpose of diagnosis, surgical planning and postoperative follow-up evaluation³. The accuracy of treatment planning and surgical technique is an essential prerequisite for achieving optimal functional and/or aesthetic outcome⁴.

Several 3D methods have been proposed in the literature to compare the planned position of the maxilla and mandible with the final achieved result in orthognathic surgery. These accuracy assessment protocols have either been 3D cephalometry-based^{5,6} or registration-based^{7,8}. The registration-based accuracy

assessment is superior⁴ in comparison to cephalometry-based methods, which are more time-consuming and carry a higher risk of human error^{4,7,9}. Currently, three superimposition methods exist for the registration-based assessment, which include landmark-based¹⁰, surface-based¹¹ and voxel-based registration¹² (VBR). VBR is the most accurate and reliable method, as it automatically aligns the pre- and postoperative computed tomography (CT)/cone beam computed tomography (CBCT) scans based on the volumetric similarities^{12,13}.

A recent systematic review by Gaber et al.⁴ recommended a protocol to assess the accuracy of the postoperative outcome in relation to the 3D surgical planning. The first requirement was a voxel-based registration relying on the cranial base of the planned and postoperative images to overcome landmark identification error. The second requirement included application of an automated or semi-automated evaluation of translational and rotational outcome in three dimensions (x, y, z). Only Baan et al.⁸, Stokbro et al.⁷ and Shaheen et al.¹⁴ followed the recommended protocol with slight differences in implementation of the method. No evidence was found related to the application of an automated or semi-automated voxel-based tool for assessing surgical planning accuracy in a large group of orthognathic surgery patients. The only studies that recruited a large sample size either relied on 2D/3D cephalometry or surface-based registration^{2,6,15–17}. Therefore, the aim of this study was to assess the surgical accuracy with the application of a validated semi-automatic stepwise

tool in a large group of orthognathic surgery patients¹⁴.

Materials and Methods

This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research. Ethical approval was obtained from the Ethical Review Board of the University Hospitals Leuven (Reference number: S57587). The study was retrospective in design and patient-specific information was anonymized.

Patients and Radiographic Examination

A total of 55 patients (29 males, 26 females; age range 15–58 years) having skeletal class III malocclusion, who underwent bimaxillary surgery with Le Fort I and bilateral sagittal split osteotomy (BSSO) were recruited for the study. The inclusion criteria involved patients with preoperative and immediate postoperative (1–6 weeks) CT/CBCT scans and virtual surgical planning. Patients with craniofacial syndromes, cleft lip and/or palate, previous history of oral and maxillofacial surgery and multi-piece Le Fort I were excluded. Patients were scanned with the following devices: Somatom Definition Flash® CT (Siemens AG, Erlangen, Germany), Promax 3D Max® CBCT (Planmeca, Helsinki, Finland) and Newtom VGi-evo® CBCT (Newtom, Verona, Italy)¹⁸. All scans were acquired according to a standardized protocol, as described by Stratis et al.¹⁸, using a thin wax bite (2 mm) to seat the condyles in centric relation¹⁹.

Virtual 3D Planning Protocol

Three-dimensional surgical planning was carried out virtually utilizing Proplan software (Materialise, Leuven, Belgium). First, dental plaster cast models were scanned with an optical scanner (Activity 885; Smartoptics, Bochum, Germany) and exported in stereolithography (STL) format. Thereafter, preoperative CT or CBCT in Digital Imaging and Communications in Medicine (DICOM) format and the maxillary/mandibular STL models were imported into Proplan software for creation of maxillary and mandibular composite models. Virtual Le Fort I and BSSO osteotomies were performed and operated segments were repositioned as defined by the surgical team. Based on the virtual planning, intermediate and final wafers were designed and fabricated with a bio-compatible material, utilizing an Objet Connex 350 3D printer (Stratasys, Eden Prairie, Minnesota, USA), for transferring the virtual planning to the patient in the operating theatre^{19,20}. The original and final positions of maxilla (Le Fort I segments) were then exported in an accuracy assessment tool for assessing surgical accuracy.

Surgical Technique

All surgeries were performed by the same surgical team with a maxilla-first approach. Maxillary Le Fort I osteotomy was performed, as described by Bell²¹ and Politis²², where the intermediate 3D-printed wafer was used to reposition maxilla and two L-shaped miniplates (2.0, KLS Martin; Mühlheim, Germany) and

Fig. 1. The translational displacements (A–C) included: medial/lateral (M/L), anterior/posterior (A/P) and superior/inferior (S/I). (A) Anterior/posterior: positive = anterior, negative = posterior. (B) Superior/inferior: positive = superior, negative = inferior. (C) Medial/lateral: positive = right, negative = left. The rotational movements (D–F) were categorized into pitch, roll and yaw. (D) Roll: positive = anti-clockwise rotation around horizontal axis, negative = clockwise rotation. (E) Pitch: positive = anticlockwise rotation, negative = clockwise rotation. (F) Yaw: positive = anti-clockwise rotation around vertical axis, negative = clockwise rotation.

Table 1. Overall difference between preoperative planning and postoperative outcome for the 55 patients.

	Translational movements (mm)			Rotational movements (°)		
	M/L	A/P	S/I	Pitch	Roll	Yaw
MD ($\pm$ SD)	0.1 ± 0.7	-0.5 ± 1.3	-0.6 ± 1.3	-1.2 ± 2.5	0.0 ± 1.2	0.0 ± 1.3
MAD ($\pm$ SD)	0.5 ± 0.5	1.0 ± 0.9	1.1 ± 0.9	1.8 ± 2.0	0.9 ± 0.8	0.9 ± 0.9
% Patients with AD 2–4 mm or $>4^\circ$	0.0%	16.4%	20.0%	12.7%	0.0%	0.0%

AD, absolute difference; MAD, mean absolute difference; MD, mean difference; SD, standard deviation.

monocortical screws were utilized to fixate the maxilla in final position on each side. Following mandibular surgery based on Hunsuck/Epker modification of BSSO^{23,24}, the final 3D-printed wafer was used to reposition mandible into optimized occlusion. The mandible was fixated with two miniplates and monocortical screws transorally for each split.

Postoperative Assessment Protocol

For the postoperative assessment protocol, a validated semi-automatic stepwise accuracy assessment module in Amira software (Version 6.3.0, Thermo Fischer Scientific Merignac, France) was applied¹⁴. After importing CT/CBCT DICOM images, the postoperative images were superimposed on preoperative anterior cranial base, using rigid VBR with mutual information. Thereafter, the preoperative maxillary segment was registered to the achieved postoperative maxillary segment applying VBR, hence, eliminating human error associated with cephalometric landmarking. The STL files of preoperative planning and final surgical position of Le Fort I maxillary segments were imported into the module. Following the placement of three landmarks on the occlusal surface of planned maxillary segment STL file (midpoint of the incisal edge and mesiobuccal cusps of the maxillary left and right first molar), it was superimposed on to the postoperative achieved maxillary segment utilizing SBR to reposition the three landmarks from the planned position to the achieved position. A singular value decomposition (SVD) algorithm was implemented within the module for calculating the translational and rotational difference between planned and achieved outcome objectively. The translational displacements included: medial/lateral (M/L), anterior/posterior (A/P) and superior/inferior (S/I) (Fig. 1A–C). The rotational movements were categorized into pitch, roll and yaw (Fig. 1D–F).

Statistical Analysis

All data analysis was performed with the statistical software MedCalc (Version

12.0, Ostend, Belgium). The difference between the virtual planning and the postoperative outcome was calculated as the mean difference (MD), mean absolute difference (MAD) and standard deviation (SD). The direction of the error was presented by MD, whereas MAD corresponded to the magnitude of error. A difference of less than 2 mm and 4° between the virtual surgical planning and surgical outcome was considered clinically insignificant²⁵. The mean difference between the planned and actual surgical outcome is presented as box-and-whisker plots for the three translational and three rotational movements. Scatter plots show the linear regression between the amount of planned horizontal advancement and the mean difference for the total group

of patients. The Spearman correlation coefficient was calculated to determine correlations between the six movements and between the surgical accuracy and the amount of planned horizontal advancement. Statistical analysis was performed under the supervision of a certified statistician.

Results

Table 1 demonstrates the overall MD and MAD between the preoperative planning and postoperative outcome. The MAD for the translational and rotational movements showed highest difference for S/I translation ($1.1 \text{ mm} \pm 0.9 \text{ mm}$) and pitch ($1.8^\circ \pm 2.0^\circ$). The MD of A/P and S/I translation was $-0.5 \text{ mm} \pm 1.3 \text{ mm}$ and

Fig. 2. Box-and-whisker plots of the mean difference for the three translational and three rotational movements.

Fig. 3. Mean difference of translational movements between planned and achieved surgical position. The dashed lines represent the linear regression fit. Number of patients with absolute error between 2 and 4 mm: 0 for L/R, nine for A/P and 11 for S/I translation.

$-0.6 \text{ mm} \pm 1.3 \text{ mm}$, respectively, corresponding to a more posterior and inferior position of the maxilla. The MD for pitch was $-1.2^\circ \pm 2.5^\circ$, correlating to a more inferior position of the maxilla.

The box-and-whisker plots in Fig. 2 show the distribution of the mean differences between the planned and obtained surgical maxillary position. For A/P and S/I translation, an error of between 2 and 4 mm was seen in, respectively, nine (16.4%) and 11 (20.0%) of the 55 patients, whereas for pitch seven (12.7%) of the patients showed an error $>4^\circ$ (Table 1). Pitch and A/P translation showed a relevant correlation as the Spearman correlation coefficient (r) was 0.44. No other correlation was found between the surgical accuracy of the six types of movements ($|r| < 0.3$).

Figures 3 and 4 depict the scatter plot of mean error (y-axis) in relation to the amount of planned horizontal advancement (x-axis) for the translational and rotational movements. A linear regression line was created, illustrating the

underlying relation of the MD of each individual patient in relation to horizontal advancement. The M/L error was independent to the amount of advancement (Fig. 3A). For the A/P (Fig. 3B) and S/I (Fig. 3C) translation, a tendency towards an increased planning error was seen with increasing maxillary advancement. Furthermore, an increasing advancement resulted in a higher error for pitch (Fig. 4A). Table 2 demonstrates the Spearman correlation coefficient (r) between the amount of planned horizontal advancement and the MD (direction) and MAD (magnitude) for the six movements. Values of r were between -0.38 and 0.12 indicating no relevant correlation to large advancements.

Discussion

The surgical accuracy of orthognathic surgery has been investigated with the application of 2D lateral cephalometry^{16,17}, however, recent evidence suggests 3D assessment to be more accurate compared

to 2D analysis^{1,2}. A few studies applied a validated 3D semiautomatic accuracy assessment method^{7,8,14}, therefore, this study was conducted to observe the surgical accuracy in relation to 3D planning with the application of a validated tool in a large group of patients. According to our findings, the mean absolute difference between planned and actual outcome for translational and rotational maxillary movements was within clinically accepted values of $<2 \text{ mm}$ and $<4^\circ$ ²⁵. However, for A/P translation, S/I translation and the pitch, this difference was clinically relevant (error between 2 and 4 mm and $>4^\circ$) in, respectively, nine (16.4%), 11 (20.0%) and seven (12.7%) of the 55 patients. No relevant correlation was found for the surgical accuracy (MAD) between the six movements.

For translational movements, the M/L translation was associated with the least amount of error, which was in line with previous studies^{8,15,26}. Regarding the A/P movements, a tendency towards more posterior positioning of maxilla was observed, which was in accordance with studies of Baan et al.⁸ and Stokbro et al.²⁷ who found MD of -0.46 mm and -0.39 mm , respectively. These inaccuracies might have been associated with intraoperative changes in condylar position, resulting from imperfect condylar seating⁸.

For rotational movements, the highest discrepancy was associated with pitch, having a higher tendency towards a more inferior positioning of the maxilla compared to the planned outcome^{8,15,27–29}. Further investigations are necessary to determine the origin of these inaccuracies.

For the vertical direction, we found an MAD of $1.1 \text{ mm} \pm 0.9 \text{ mm}$ with a tendency towards a more inferior positioning of the maxilla compared with the planning. These findings were similar to previous studies^{8,26}. As the wafer only controls surgical movements in the sagittal and transverse plane, the vertical maxillary repositioning is more challenging³⁰. Therefore, application of techniques such as intraoperative computer navigation, 3D-printed surgical guides and patient-specific osteosynthesis plates could improve the limitations encountered with the wafer technique. In a systematic review by Van den Bempt et al.³¹, an accurate transfer of the virtual surgical plan was observed with the application of aforementioned techniques, however, a significant variability was detected amongst various studies using either same or different accuracy-assessment methodology. To overcome methodological

Fig. 4. Mean difference of rotational movements between planned and achieved surgical position for 55 patients. The dashed lines represent the linear regression fit. Number of patients with absolute error $>4^\circ$: seven for pitch, one for roll, 0 for yaw.

Table 2. Spearman correlation coefficient between amount of planned advancement and the surgical accuracy (MD and MAD) of the translational and rotational movements.

	Translational movements (mm)			Rotational movements ($^\circ$)		
	M/L	A/P	S/I	Pitch	Roll	Yaw
Planned advancement & MD ($\pm$ SD)	0.02	-0.16	-0.07	-0.25	0.00	-0.38
Planned advancement & MAD ($\pm$ SD)	-0.07	0.10	0.08	0.12	-0.07	0.04

MAD, mean absolute difference; MD, mean difference; SD, standard deviation.

inaccuracies, it is recommended that future studies should be conducted following the accuracy assessment criteria as suggested by Gaber et al.⁴

The scatter plots bring more detailed understanding of the relation between the planned amount of advancement and the accuracy of the surgical movements. Fig. 3 shows a tendency towards an increased inaccuracy with increasing advancement for the A/P and S/I translation, with a more posterior and inferior position of the

maxilla. For the rotational movements, the mean error for the pitch had a tendency towards more negative values when larger horizontal movements were performed. This corresponds with a more inferior position of the maxilla, in comparison with the planned pitch movement. No relevant correlation was found between the planned amount of advancement and the MD and MAD for the six movements (Spearman correlation coefficient between -0.38 and 0.12).

In conclusion, 3D virtual planning of maxilla was generally accurate when compared to the achieved outcome for skeletal class III patients undergoing bimaxillary surgery.

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Ethical approval

Ethical approval was obtained from the Ethics Review Board of the University Hospitals Leuven (S57587). Informed consent was not required for this retrospective study, as no identifiable patient data were disclosed.

Competing interests

The authors report no conflicts of interest related to this study.

Patient consent

Not required.

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