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Accuracy of 3D virtual surgical planning for maxillary positioning and orientation in orthognathic surgery

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Abstract

Objective: This retrospective and observational study evaluated the accuracy of a 3D virtual surgical planning (VSP) for the maxillary positioning and orientation in patients undergoing bimaxillary orthognathic surgery, comparing the planned and postoperative outcomes.

Setting and Sample Population: Seventy consecutive patients of both sexes, who were submitted to bimaxillary orthognathic surgery between 2015 and 2019 were included in our study.

Material and Methods: The patients were evaluated by fusing preoperative planning and postoperative outcome using cone-beam computed tomography scan evaluation. Three-dimensional VSP and postoperative outcomes were compared by using three linear and three angular measurements. The main outcome interest was the difference between the VSP movement, and the surgical movement obtained. The success criterion adopted was a mean linear difference of <2 mm and a mean angular difference of <4°.

Results: Results were analysed using a linear mixed model with fixed and random effects, at α = .05. No significant statistical differences were found for linear and angular measurements between the planned and postsurgical outcomes (P > .05). All overlapping points presented values within the range considered clinically irrelevant (<2 mm; <1°).

Conclusions: Three-dimensional VSP was executed with a high degree of accuracy. When comparing the planned and postsurgical outcomes, all overlapping points presented values within the range considered clinically irrelevant.

KEYWORDS

computer-assisted surgery, cone-beam computed tomography, orthognathic surgery, virtual surgical planning

1 | INTRODUCTION

The main objective of the orthognathic surgery is to correct dentofacial deformities, functional and aesthetic problems. Its success depends not only on surgical techniques, but also on an accurate and detailed treatment plan.[1-4] Two-dimensional virtual surgical planning (VSP) has been used for more than 50 years, through patient's clinical data, imaging exams, lateral cephalograms, plaster dental models and semi-adjustable articulators.[2,3] With the advancement of imaging technology, 3D VSP has consolidated as an alternative that provides accurate surgical results, creating new possibilities for the treatment of dentofacial deformities,[5] predicting the repercussion of surgical movements in the skull bases and adjacent soft tissues,[4,6] and eliminating many of the laboratory steps.[4]

There are several three-dimensional (3D) VSP protocols, such as the computer-aided surgical simulation (CASS),[1,7] which represents a paradigm shift in surgical planning for patients with dentofacial deformities.[1,8] Using cone-beam computed tomography (CBCT) scans and software programs, a computerized composite skull model of the patient is generated to accurately represent the dentition, the skeleton and the soft tissues.[8] It allows high-quality surgical planning, with autonomy and safety to simulate different surgical movements, overcoming several limitations of 2D planning, in which small errors can accumulate during its various steps, leading to inaccuracies.[4] Moreover, it becomes an important communication tool among professionals.[6,9] An adaptation of the CASS protocol with fewer steps was proposed,[10] although it has not yet been widely disclosed.

The advent of 3D VSP protocols, CBCT equipment and software programs imposes the need to investigate the reliability of these methods to predict surgical outcomes. Thus, the aim of this study was to evaluate the accuracy of the 3D VSP for the maxillary positioning and orientation in patients undergoing bimaxillary orthognathic surgery. The null hypothesis was that no difference would be found between the 3D VSP accuracy and postoperative outcomes. The specific aims of the study were as follows: (a) compare the linear measurements of maxillary position (raw coordinates: *x*, *y*, *z*) between the 3D VSP and postsurgical outcomes; (b) compare the angular measurements of maxillary orientation (*pitch*, *roll* and *yaw*) between the 3D VSP and postsurgical outcomes.

2 | MATERIAL AND METHODS

After ethics approval (CAAE 66093317.6.0000.0104) by the Permanent Ethics Committee for Experiments Involving Humans at State University of Maringa (UEM), Brazil, this retrospective and observational study was developed according to STROBE initiative (Strengthening the Reporting of Observational Studies in Epidemiology).[11]

2.1 | Sample

Sample size calculation was performed on a pilot sample containing 27 subjects, with planned and postsurgical outcomes measurements. The effect size, test power and sample size were calculated using the R application. The calculated sample size was n = 53 at 5% significance with a test power of 95%.

Seventy consecutive patients of both sexes (23 male and 47 female), aged between 18 and 50 years (average 30.44 ± 8.9), who were submitted to bimaxillary orthognathic surgery between 2015 and 2019 were included in our study. All subjects presented Class II (ANB ≥ 4°; n = 24) or III (ANB ≤ 0°; n = 29)[12] dentofacial deformities and were submitted to CBCT imaging before and after surgery. Patients with craniofacial syndromes, history head and neck surgery or patients who did not perform 3D VSP were excluded.[13] All patients had basic initial photographic documentation and plaster models.

2.2 | CBCT acquisition

All CBCT scans were conducted by the same radiologist at the Clinical Research Imaging Laboratory at UEM (LIPC-UEM) using the i-Cat Next Generation® equipment (Imaging Sciences International), with a standardized scanning protocol, 120 Kvp, 3-8 mA, field of view 17 × 23 cm, 0.3 mm isometric voxel, 891.4 (mGy × cm^2).

The examinations were obtained at two intervals as part of the surgical protocol: 1-month preoperatively to assist diagnostics and 3D VSP, and 1-month postoperatively, to ascertain early surgery outcomes.[2,8,14] The patients were instructed to adopt a natural head position (NHP) by looking at their own eyes in a mirror on the opposite wall,[13,15-17] with their tongues and lips at rest,[16,18] breathing lightly and avoiding swallowing during image acquisition.[17,18] The support for the chin and head was used for the initial positioning but was removed during image acquisition as they could be confused with the soft tissues and negatively affect the VSP.[13] A wax bite registration was used during the preoperative CBCT acquisition, in order to promote a slight opening of the occlusion to facilitate the overlapping of the scanned plaster models and CBCT images.[19]

The images in DICOM (Digital Imaging and Communications in Medicine) extension were imported into Dolphin Imaging software version 11.95 (Dolphin Imaging & Management Solutions®).

2.3 | Creating the computerized composite skull model

Because CBCT does not render the teeth with the accuracy necessary for surgical simulation,[20] digital dental models are created by scanning the plaster dental models in order to replace the occlusal surfaces of the teeth in the CBCT images, resulting in a composite skull model. The computerized composite skull model simultaneously displays an accurate rendition of the bones and teeth.[20] It is created by incorporating and aligning the digital dental models into the 3D CBCT skull model.[8,20-22] For this, the upper and lower plaster models were scanned separately and in occlusion using a high-resolution laser scanner[8] (3Shape R700, A/S). The scanning of the models in occlusion works as a guide to obtain the final occlusion during the surgical treatment in the 3D virtual environment. The digital dental models were then recorded in Standard Triangulation Language (STL) extension.

The computerized composite skull model was oriented according to the patient's NHP, in which was confirmed with the data from the preoperative physical examination and photographic documentation. The cleaning of metallic artifacts, individualization of structures, such as the maxilla and the mandible were performed by a single surgeon, resulting in a high-quality image in 3D Dolphin software.

2.4 | Virtual surgical planning

Once the composite model was positioned in the *3D surgery module* of the software, the surgical simulation was performed.

All 3D VSP were performed by the same experienced surgeon, following an adaptation of the CASS protocol,[10] in which all landmarks are carried out directly in the software program. Osteotomies were marked, and virtual planning was initiated by moving the maxilla according to the treatment planning. All data concerning the movements were stored in the program. An intermediate splint was fabricated based on the virtual models that generated the computerized composite skull model.

2.5 | Orthognathic surgery

Pre-and postoperative orthodontic treatment was performed by different orthodontists, but all surgical procedures were performed by a same team of experienced surgeons (UEM). In our study, the sequence of bimaxillary surgeries is based on the studies of Perez and Ellis[23] and Borba et al.[24] Patients were submitted to mandibular setback or advancement through bilateral sagittal split osteotomy associated with Le Fort I osteotomy for maxillary advancement followed by functionally stable fixation. Only cases without maxillary segmentation (surgical cleavage) were included to avoid bias in the results. No differentiation was made between

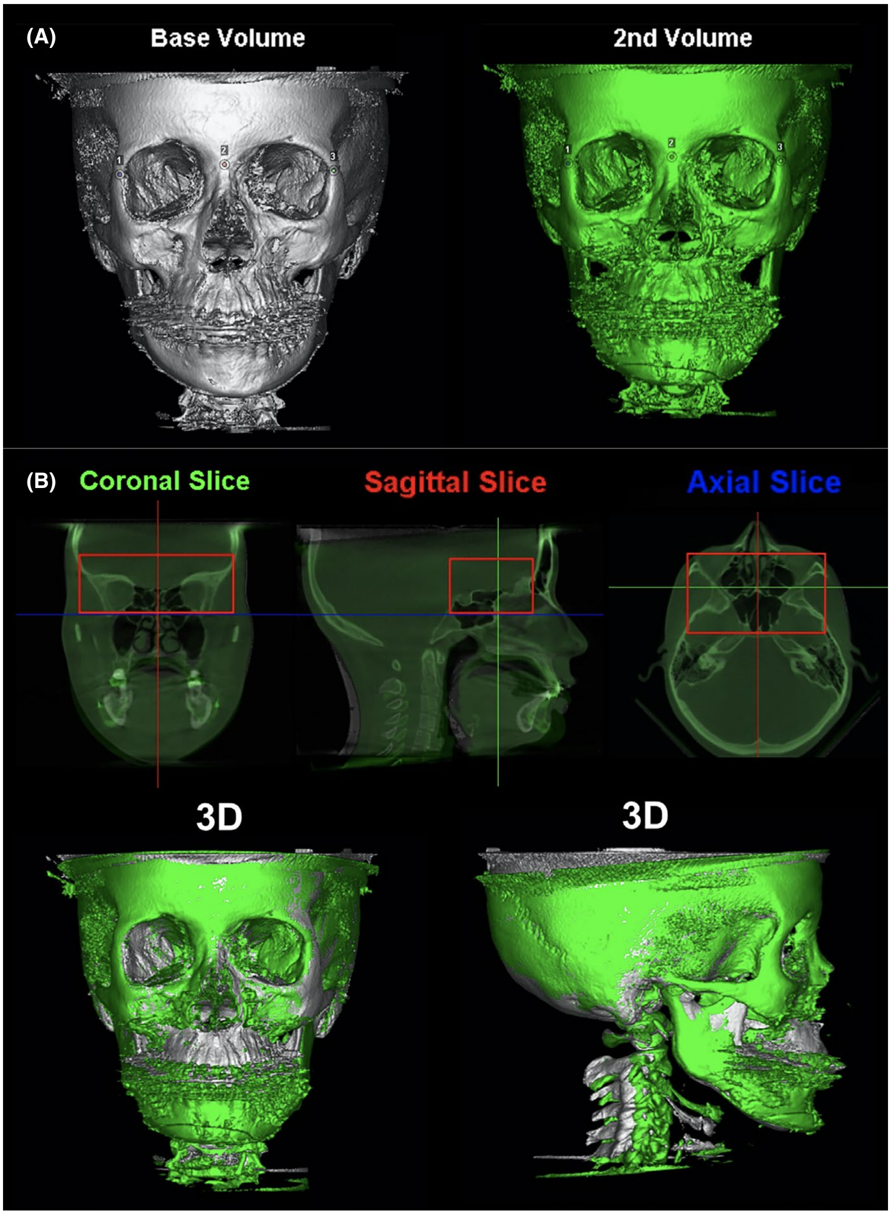

FIGURE 1 Dolphin 3D voxel-based superimposition on the cranial base. A, Selection of three anatomic references using the *side-by-side superimposition* tool; B, Voxel-based image superimposition on the cranial base. The red box is used to define the area of the cranial base to be used as a reference for superimposition in the three dimensions [Color figure can be viewed at wileyonlinelibrary.com]

the procedure sequence (if surgery was initiated by the maxilla or the mandible).

2.6 | Analysis of maxillary positioning accuracy

The accuracy of 3D VSP was evaluated by comparing the VSP with the actual postoperative outcomes. Firstly, the superimposition of planning and postoperative tomographic images were performed with the voxel-based method in Dolphin 3D software.[25] Using the *side-by-side superimposition* tool, VSP and postoperative 3D images were approximated using three neurocranial reference points located on the glabella and right and left frontal zygomatic sutures. The *voxel-based superimposition* tool was used so that the anterior cranial base area was selected in both CBCT scans, using the subregion red box, in axial, sagittal and coronal reconstructions.[26] (Figure 1). Using this technique, Dolphin 3D software combines the voxels in the defined area and automatically superimposed both images.[27] The teeth in the postoperative CBCT were replaced by digital dental models obtained before surgery. Then, these superimposed images were imported into a computer graphics software (3DS Max®, Autodesk Inc) in STL format. In this program, the landmark-based method was used to quantify the linear and angular differences between the VSP and the postoperative outcomes.[6,8] Three maxillary reference points were analysed[8]: (a) in the midline between the central incisors; (b) in the mesiobuccal cusp tip of the left first molar; (c) in the mesiobuccal cusp tip of the right first molar. To avoid the observer bias, the marking of these landmarks was performed on the VSP maxilla (Figure 2A,B). Then, the postoperative

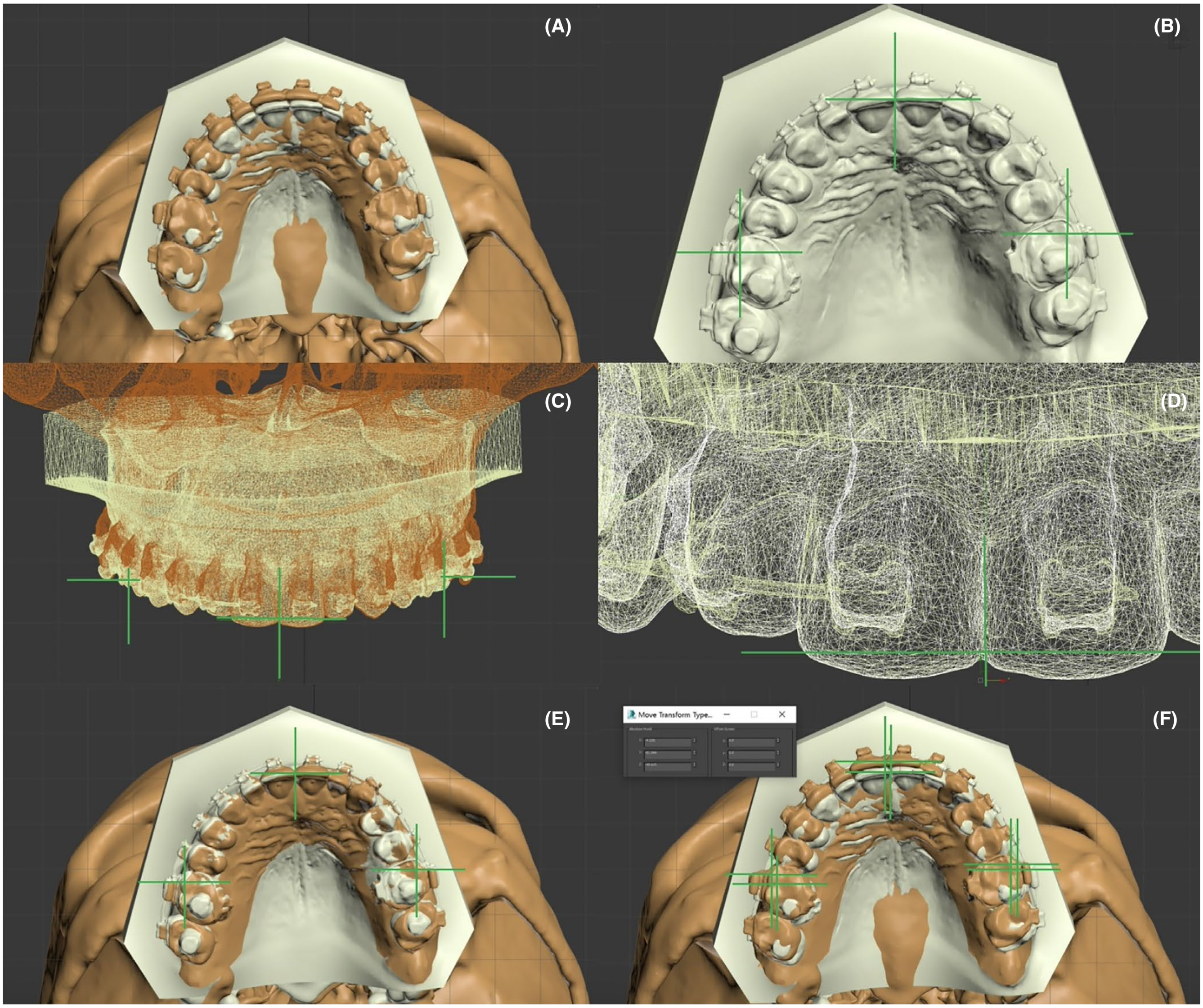

FIGURE 2 A, Superimposition of VSP (beige) and postoperative maxilla (brown) in the original position; B, Marking of the three maxillary reference landmarks (green) on the VSP surface; C, Postoperative maxilla moves towards VSP using the triangle mesh overlay tool; D, Zoom of triangle mesh overlay to verify the accuracy of the superimposition; E, Cloning of the three reference landmarks of the VSP maxilla and subsequent linking with the postoperative maxilla; F, Postoperative maxilla with the landmarks linked returns to its original position (3DS Max software) [Color figure can be viewed at wileyonlinelibrary.com]

maxilla was moved towards the VSP maxilla using the triangle mesh overlay tool (Figure 2C,D). The three landmarks were cloned and linked to the postoperative maxilla (Figure 2E), so that it returned to its original position with the linked landmarks (Figure 2F). Thus, the reference points are in exactly the same position on both surfaces, allowing us to quantify the linear and angular difference between them.

To measure the linear differences between the planned and postoperative positions, the differences between the coordinates (x - mediolateral, y - anteroposterior and z - superoinferior) were calculated. (Figures 3A-C). Angular differences were computed in pitch, roll and yaw discrepancies between VSP and postoperative results.[8] (Figure 4).

All measurements were assessed by two independent observers (experienced radiologists), in duplicate with a 1-week interval. Both were calibrated based on the criteria and variants established prior to their evaluation, using 20 randomized scans.

2.7 | Outcome and predictor variables

Our outcome variables were the differences in the linear measurements of maxillary position (raw coordinates: *x*, *y*, *z*) and angular measurements of maxillary orientation (*pitch*, *roll* and *yaw*) between the 3D VSP and postsurgical outcomes (predictor variables).

2.8 | Statistical analysis

The reliability of the method was determined according to the Weir's criteria.[28] Thus, a linear mixed model was used for each linear and angular outcome variable to analyse the accuracy of 3D VSP. For this, the following covariates were used as predictors: linear (*x*, *y*, *z*) or angular (*pitch*, *roll* and *yaw*) measurements; time (VSP and postoperative outcomes) and examiner (1 and 2). This model has a latent variable, that is the effect of inherent variability on the individual was accommodated by the random effect of the model. Therefore, the model accommodates the correlation of repeated measurements performed in 3D VSP and postoperative CBCT and estimates a covariance of each individual. The likelihood ratio (LR) test was used to assess the heteroskedasticity. Intra and inter-examiner agreement were tested using the linear mixed model. All data were tested on the R 3.2 software for Windows (R-project for statistical computing) with a significance level of 5% ($P < .05$).

3 | RESULTS

The intra and inter-examiner agreements were good ($P = .870$) and excellent ($P = .988$) for linear and angular variables, respectively, where <0.50 = poor reliability; 0.50-0.75 = moderate reliability; 0.75-0.90 = good reliability; >0.90 = excellent reliability.[29] The variability for both linear and angular data was homoscedastic between planned and postsurgical measurements.

No significant statistical differences were found for the linear measurements (maxillary position) between the planned and postsurgical models (Table 1). The mean linear differences obtained were 0.262, 0.801 and 1.310 mm for *x*, *y* and *z*, respectively. Regarding the maxillary orientation, the *pitch*, *roll* and *yaw* rotations did not show statistically significant differences between the planned and postsurgical models (Table 1). The mean angular differences obtained were 0.549°, 0.125° and 0.575° for *pitch*, *roll* and *yaw*, respectively.

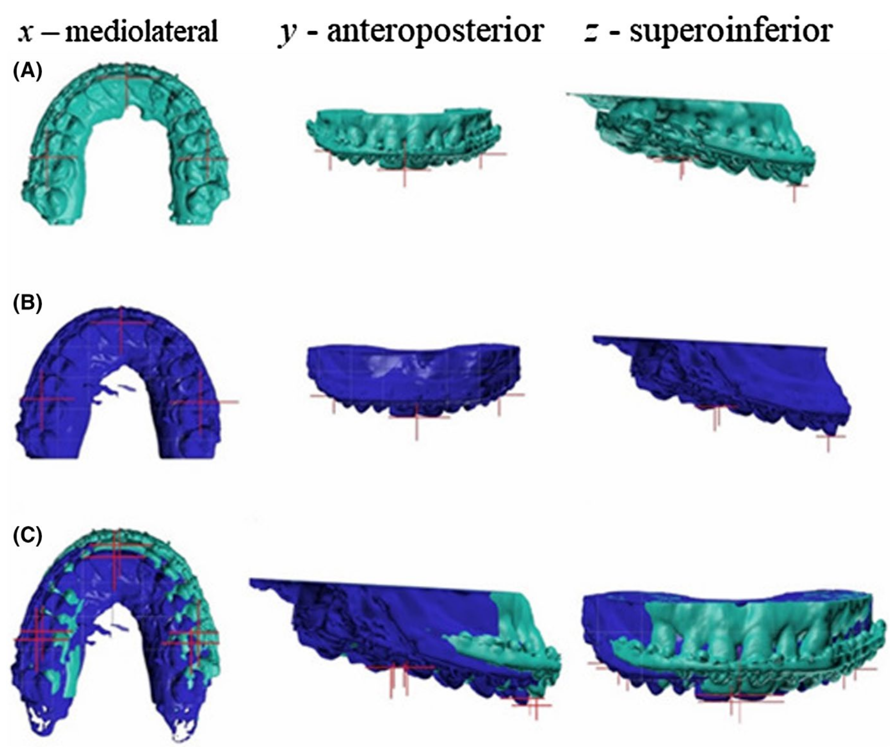

FIGURE 3 Landmarks digitized on the occlusal surface: in the midline between the central incisors and in the mesiobuccal cusp tip of the left and right first molars. A, 3D VSP; B, Postoperative CBCT; C, Superimposition (3DS Max software) [Color figure can be viewed at wileyonlinelibrary.com]

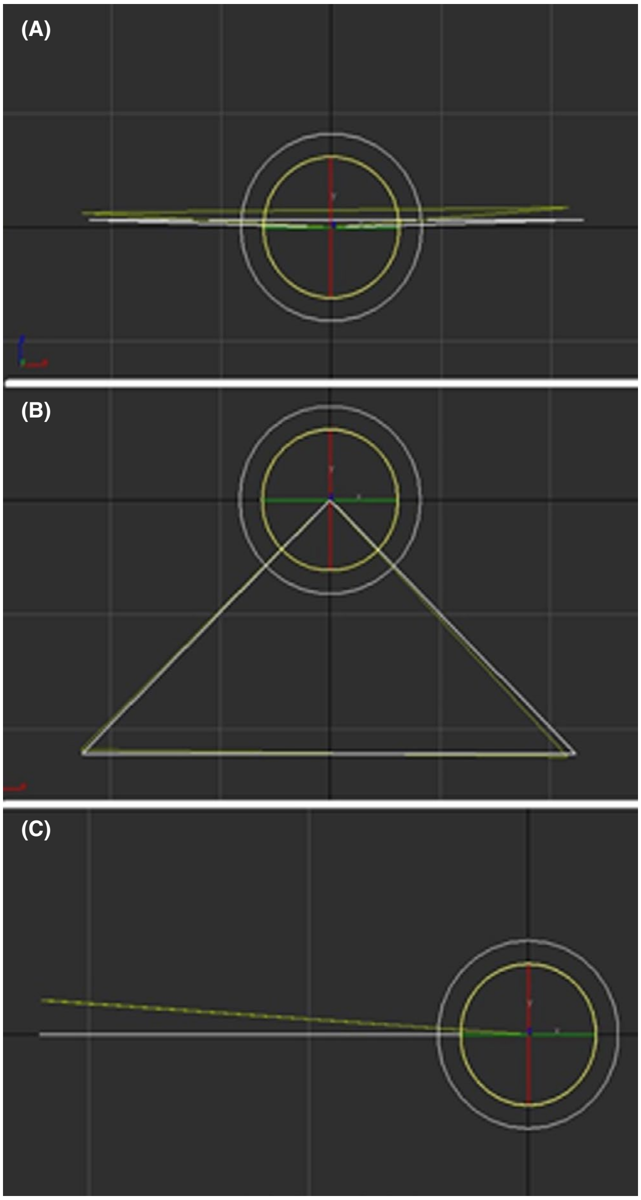

FIGURE 4 Angular differences between the planned and actual outcomes. A, *Roll*; B, *Yaw*; C, *Pitch* (3DS Max software) [Color figure can be viewed at wileyonlinelibrary.com]

Statistically significant differences ($P < .05$) were found only when covariates were interacted (Table 2), with standard deviation values varying substantially between coordinates and between rotations, indicating a heteroskedasticity of these data.

4 | DISCUSSION

The aim of this study was to evaluate the accuracy of the 3D VSP for the maxillary positioning and orientation in patients undergoing bimaxillary orthognathic surgery comparing the planned and postsurgical outcomes. Based on previous studies,[4,8,21] we assumed a positional difference between the planned and postsurgical outcomes of <2 mm as clinically insignificant, as well as orientation differences of <4°.[4,6,8,21]

TABLE 1 Mean linear and angular differences for planned (3D VSP) and postoperative outcomes

	3D VSP		Postoperative		
	Mean	SD	Mean	SD	*P*-value
Coordinates (mm)					
x	111.641	3.90	111.379	3.88	.999
y	52.537	4.68	53.338	4.74	.965
z	−107.219	8.32	−108.530	8.50	.767
Rotations (°)					
Pitch	5.933	3.63	6.482	4.35	.546
Roll	1.525	1.30	1.650	1.44	.546
Yaw	2.075	1.93	2.65	2.57	.546

Abbreviation: SD, standard deviation.

TABLE 2 Differences in measurements between *x*, *y* and *z* coordinates and between *pitch*, *roll* and *yaw* rotations

Coordinates	Difference (mm)	*P*-value
x/y	58.57	<.05*
x/z	219.44	<.05*
y/z	160.86	<.05*
Rotations	**Difference (°)**	***P*-value**
Pitch/Roll	4.601	<.05*
Pitch/Yaw	3.844	<.05*
Roll/Yaw	0.757	.0433*

*$P < .05$.

Although a cut-off value of 2 mm for clinical significance may seem high, we believe it is important to consider a literature well-established value to interpret our results. Despite some outliers were found (deviation larger than two standard deviations from the overall mean), the differences did not exceed these values. We observed that all overlapping points presented values of <2 mm and <1°, and there were no statistically significant differences between the planned and the postsurgical measurements. Thus, the null hypothesis was not rejected.

Using varied protocols, previous studies showed that the 3D VSP is accurate to predict maxillary positioning, with mean linear differences within the 2 mm.[4,6,8,20,30,31] As in the present study, in most studies,[4,6,8,21,30] accuracy was assessed by measuring the mean linear difference between reference points. Tucker et al[31] evaluated accuracy through the linear difference between the superimposed surfaces. The mean accuracies varied: 0.39 mm,[30] <0.5 mm,[6,29] <0.9 mm,[21] and <1 mm.[8] Ritto et al[4] found a mean linear difference between planned and obtained movements of 1.20 ± 1.08 mm, with more accuracy for the anteroposterior position of the maxilla, and, conversely, found the highest discrepancies in the anteroposterior movement (0.72 mm) and speculated that it may represent a tendency for overcorrection in the anteroposterior position of the maxilla.[30] In this context, we found a tendency for a slight overcorrection in the superoinferior movement, since the greater mean discrepancy was found in the *z*-axis (1.310 mm), although it is still a small inaccuracy.

For maxillary orientation, the higher deviations were found in the *pitch* (0.549°) and *yaw* (0.575°) values. These results partially agree with previous studies.[6,8] According to Hsu et al[8], the largest orientation difference was 1.5° for *pitch*. Stokbro et al[6] showed that differences in *pitch* were also greater (and statistically significant), with a slightly greater decrease in the maxillary occlusal plane than planned. The authors explain that, since *pitch* rotates around the mediolateral axis, these discrepancies may be due to intraoperative complications, such as surgical splints that had a poor fit.[6] Additionally, they found that segmentation had no significant influence on maxillary placement.[6] In the present study, only cases with no maxillary segmentation were included to avoid bias.

When each covariate was evaluated separately within the planned or the postsurgical outcomes, the differences were negligible, but greater discrepancies ($P < .05$) were observed when the covariates were interacted (*x/y*, *x/z*, *y/z*, *pitch/roll*, *pitch/yaw*, *roll/yaw*), corroborating a previous investigation.[30] The higher deviations in the *z*-axis in comparison with *x*-axis and *y*-axis resulted in significant difference between *x/z* and *y/z*, for example. Similarly, greater deviations in *pitch* resulted in significant difference between *pitch/roll* and *pitch/yaw*. However, these differences do not appear to have any impact from a clinical point of view.

Previous studies[6,8] also assessed both maxillary positioning and orientation. Both used the CASS protocol and found reliable results. Hsu et al[8] found differences in linear measurements of 0.8, 1 and 0.6 mm for *x*, *y* and *z*; and 1.5°, 0.9° and 1.3° for *pitch*, *roll* and *yaw*, respectively. Although this was a multicentric study, in which different surgeons with different degrees of familiarity with the CASS protocol performed the VSP, similar results were obtained, and the method was considered as reproducible and reliable.[8]

There are many 3D VSP protocols and several VSP software programs available on the market. However, there is currently no gold standard or generally accepted method for overlapping 3D CBCT scans. Three superimposition methods based on image registration type are commonly used: landmark-based, surface-based and voxel-based.[27,32] We used the voxel-based superimposition on Dolphin 3D software to superimpose the planning and the postoperative CBCT images. It combines voxel greyscale values for CBCT image information and is considered accurate, reliable and fast.[25] Although this method is algorithm-based, proper management of images by the surgeon is still crucial for efficient and accurate results,[4] that is proper operator management is required, which makes it difficult to reproduce the method. It requires some sort of marking for the initial approximation to be performed. This initial approximation of images is of great importance to reduce the working time in the software and the accuracy of the superimposition.[25] However, Dolphin 3D software does not yet allow quantifying the accuracy of 3D VSP. For this reason, these superimposed images (STL format) were imported into 3DS Max® computer graphics software. At this time, the landmark-based method was used in order to quantify the linear and angular differences between the VSP and the postoperative outcomes, as reported in previous studies.[6,8] Some commercial third-party and open-source programs have been developed using more advanced algorithms. They may represent new alternatives for VSP. Nevertheless, studies that evaluate their accuracy and reliability are still needed.

The uniqueness of this study lies in the fact that the sample is very standardized, since all CBCT scans were conducted by the same radiologist with a standardized scanning protocol. In addition, all 3D VSP were cautiously performed by a single surgeon in 3D Dolphin software and the surgical procedures were executed by a same team of experienced surgeons. Although no differentiation was made between the procedure sequence (if surgery was initiated by the maxilla or the mandible) in our study, it was prioritized start with the mandible in the following situations: clinical difficulty in establishing the initial bite record; condylar alterations; segmentation of maxilla; large mandibular advancement with counterclockwise rotation and possibility of dislocation or extrusion of condyle of glenoid fossa. This topic remains controversial, with some authors advocating the mandible-first sequence,[33] and others the maxilla-first sequence.[34] Some authors state that each case should be evaluated individually.[23,24] According to a recent systematic review,[24] this decision has relied on accurate preoperative planning based on the surgeon's experience and preference. As there are not enough scientific evidences that the procedure sequence influences the accuracy of VSP, further studies are needed.[24]

5 | CONCLUSIONS

Three-dimensional VSP was executed with a high degree of accuracy. When comparing the planned and postsurgical outcomes, all overlapping points presented values within the range considered clinically irrelevant.

ACKNOWLEDGEMENT

None.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICAL APPROVAL

This study was approved by the Permanent Ethics Committee for Experiments Involving Humans at the State University of Maringa (UEM), Brazil (CAAE protocol: 66093317.6.0000.0104).

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