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Accuracy of virtual surgical planning in bimaxillary orthognathic surgery with mandible first sequence: A retrospective study

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ABSTRACT

The aim of this study was to verify treatment accuracy using virtual surgical planning (VSP) with a mandible-first sequence and strict surgical protocol to determine what surgical and methodological factors might influence outcomes.

VSP transfer accuracy was evaluated retrospectively through a modified method involving voxel-based superimposition in patients who had undergone bimaxillary surgery with a mandible-first sequence to correct dentoskeletal deformities. Data analysis showed that the movements planned and those executed were substantially equivalent ($p < 0.01$), with the exception of mandibular and maxillary sagittal movements that were 0.72 ± 0.90 mm and 1.41 ± 1.04 mm smaller, respectively, than planned.

This study showed that a mandible-first sequence is accurate for transferring virtual surgical planning intraoperatively. There are several factors involved in the proper transfer of virtual planning beyond the software, such as surgical technique and sequencing. Inaccurate sagittal movements and maxillary repositioning seem to depend mainly on surgical factors.

1. Introduction

The use of digital technology in orthognathic surgery can be considered the most important advancement in the field of maxillofacial surgery since the advent of rigid fixation, and interest in it is reflected in the numerous articles published on the subject. Use of digital technology has determined an improvement in diagnostic accuracy, planning and traditional treatment outcomes from both functional and aesthetic points of view (Lin, 2015).

Besides these advantages, a more in-depth review of the literature reveals that it is still not completely clear whether VSP is better than traditional surgical protocols as far as sagittal plane accuracy and patient satisfaction are concerned (Chen et al., 2021). The literature does not specify which surgical factors besides VSP may influence final outcomes. For instance, it is known that surgical sequencing could affect the outcomes accuracy-wise, although both sequences seem to produce similar outcomes when properly planned and executed (Borikanphanitphaisan et al., 2021; Perez and Ellis, 2016). For this reason, a mandible-first sequence has been a topic of interest in the literature in recent years, given its supposed advantages in large maxillary advancements and counter-clockwise rotation. Furthermore, various studies on VSP accuracy, with either surgical sequence, have reported limitations in interpreting their results due to weaknesses in the study design and/or to the methods used to evaluate results. Other weaknesses have involved limited information regarding planning and surgical stages (Alkhayer et al., 2020; Gaber et al., 2017).

The aim of this study was to verify the accuracy of sugery performed with digital planning using a mandible-first sequence and strict surgical protocol, and to determine which surgical and methodological factors may affect outcomes.

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2. Materials and methods

We designed a retrospective, observational study in patients who had undergone bimaxillary surgery with VSP to correct Class I, Class II, Class III, open bite and maxillo-mandibular asymmetry between September 2016 and March 2020. Due to the retrospective nature of this study, it was granted an exemption in writing by the University of Verona IRB. Evaluation was done by comparing the surgical movements executed, measured by comparing pre- and post-surgery cone-beam computed tomography), and those planned virtually in accordance with Gaber et al.'s recommendations (Gaber et al., 2017).

We included only subjects who had undergone bimaxillary surgery with a mandible-first sequence and virtual surgical planning, and only if pre-operative CBCT of the maxillofacial region in centric relation and post-operative CBCT of the same region performed in maximum intercuspation and without elastic bands 3 weeks after surgery were available.

Patients with idiopathic condylar resorption were excluded from the study.

2.1. Planning and surgery

Pre-operative CBCT (NewTom VGI EVO, Cefla, Verona, Italy) (FOV 24 × 19 cm) images were taken 15–20 days before surgery. The scans were carried out with the patient standing and with the head in its natural position. Patients were instructed not to swallow and to keep the lips in a relaxed position; occlusion was guided by a wax bite in a centric relation position. The need for maxillary segmental surgery was verified on stone models of dental arches. The models were then also scanned in occlusion with the same centric wax and in final occlusion.

Virtual planning was then carried out using a specifically developed software (Nemo FAB, Nemotec, Leganés, Madrid, Spain). Pre-operative volume was oriented according to the natural head position, as it had been established clinically at pre-surgical evaluation and registered in the planning software (Solow and Tallgren, 1971). Surgical movements were planned following Arnett et al.'s criteria, and then an intermediate splint was designed and printed (Arnett and Bergman, 1993a, 1993b). A final splint was not used in any of our cases (Fig. 1).

The same clinicians *(L.T.* and D.A.) who did the virtual planning performed the surgery. Surgical technique involved a mandible-first sequence with the execution of a BSSO according to Epker (1977) and subsequent positioning of the mandibular distal segment into its final position by means of an intermediate splint and rigid intermaxillary fixation with steel wires. The condyles were properly repositioned in the fossae with bivectoral seating (Arnett et al., 1992). Any premature bone contact that could interfere with correct proximal segments positioning during plating was eliminated to allow a better bone-to-bone fit while maintaining the condyle in the correct position with a bivectorial maneuver. The osteotomy was then passively stabilized with 2 titanium mini plates per side (Arnett et al., 1992, 2022a, 2022b). Once the osteosynthesis was complete, the intermaxillary fixation was removed, and the correct mandibular position was verified by checking correspondence to the intermediate splint when manipulated in centric relation. If the mandible did not fit precisely in the intermediate splint, the intermaxillary fixation was re-established with the splint in place and the mandible replated. The upper jaw was then mobilized, depending on the case, by one-piece or multisegment Le Fort I (Arnett et al., 2022a, 2022b; Kim et al., 2011) and repositioned using the lower arch as a guide to determine the final occlusion and position. The anterior facial height was the only value controlled intraoperatively through measurements involving an extraoral marker (self-tapping screw) positioned on the glabella. Finally, the osteotomized maxilla was stabilized using titanium mini-plates fixed to maxillary buttresses, and microplates, if necessary, at interdental osteotomy sites. Once again, the intermaxillary fixation was removed, and the correct maxillary position was verified by checking correspondence to the planned final occlusion when manipulated in centric relation. If the maxilla did not fit precisely, the intermaxillary fixation was restablished and the maxilla was replated. No rigid post-operative maxillo-mandibular fixation was used.

2.1.1. Surgical movement computation

Of the many methods described in the literature to compare planned surgical movements and final dentoskeletal outcomes (Marlière et al., 2019; Mazzoni et al., 2015; Tucker et al., 2010), we endeavoured to follow Gaber et al.'s recommendations to develop our own modified protocol involving voxel-based superimposition on the skull base of pre- and post-operative CBCT volumes to measure surgical movements and to compare them with those planned in an effort to obtain clear, reliable, repeatable, and, most of all, clinically interpretable results (Gaber et al., 2017). Following this protocol, we imported pre- and post-operative DICOM data into 3D Slicer 4.10.2 software (Fedorov et al., 2012).

Pre-operative orientation was transferred from the planning software to 3D Slicer via orientation matrixes. Voxel-based registration on the cranial base of the post-operative scan on the oriented pre-operative scan was then carried out. In each patient, dental landmarks were identified three-dimensionally on both volumes in order to measure the entity of surgical movements. The fiducials were positioned directly onto the radiographical slices at the mesiovestibular cusp tips of the upper and lower second molars, on the mesialincisal angle of the upper and lower right central incisors, and on the upper and lower canine cusps.

Although the repeatibility of three-dimensional landmark positioning has been previously verified in literature with a mean error of 0.2 mm (Titiz et al., 2012), for our study it was decided to identify only dental landmarks, as they are easier to place, and to limit their number in an effort to reduce intrinsic errors (de Oliveira et al., 2009; Lisboa et al., 2015; Stokbro et al., 2016) (Fig. 2).

In order to further evaluate the reproducibility of surgical movement computation, two separate doctors performed both the orientations and registrations of the volumes, then identified the fiducial points in the cases considered in order to evaluate the repeatibility of this identification/positioning. X-Y-Z coordinates for each landmark were exported onto a spreadsheet (Microsoft Excel, Microsoft Corp., Redmond, WA, USA), and the surgical movements with reference to positioned landmarks were measured by coordinate difference. The jaw movements considered were as follows.

- sagittal, vertical and lateral (midline) movements at the incisor level (Fig. 3)
- canine cant modifications
- vertical and lateral (yaw) movements at the molar level
- sagittal rotational (pitch) modifications of the occlusal plane computed with extrinsic Euler angles.

The same measurements were then calculated automatically and extrapolated from the virtual planning software for each case and compared with the data obtained by superimposing the scans.

2.2. Statistical analysis

STATA 13 (College Station, TX, USA) was used for statistical analysis. Repeatability of surgical movement measurements was verified by determining the inter-operator inter-observer

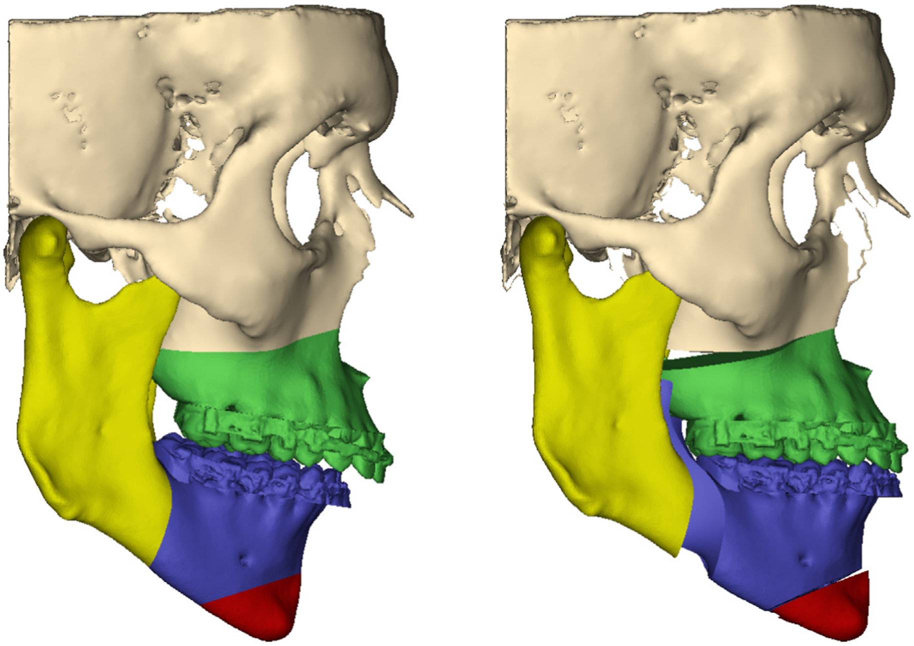

Fig. 1. Virtual surgical simulation.

variations and interclass correlations (ICC) coefficient. Because repeatability of landmark positioning has been verified in the literature (de Oliveira et al., 2009; Lisboa et al., 2015; Stokbro et al., 2016; Titiz et al., 2012), the value was instead calculated for each surgical movement (since more than one landmark is needed to compute them), as well as for the total of 900 movements evaluated by each operator according to a mean-rating, absolute-agreement, 2-way, mixed-effects model ICC (Koo and Li, 2016; Sabour, 2020).

A comparison between planned and surgical movements was done using the two one-sided test (TOST) equivalence test for paired values to compare measurements in the two groups with intervals set at ±2 mm.

Statistical significance was set at 0.05; a lower p-value indicates significant equivalence between planned and measured surgical movements. The Pearson correlation was used to measure the degree of association between specific variables.

3. Results

A cohort of 83 patients were evaluated. Of these, 33 had incomplete records or poor CBCT scans; 50 were eligible (aged 26 ± 7 years); 14 patients had undergone single-piece Le Fort I, whereas 36 had undergone three-piece Le Fort I (Table 1). Only 2 patients were Angle Class 1 pre-operatively, 18 were Class 2 and 30 Class 3. Of the population considered, only two patients had undergone a slight clockwise rotation of the maxillomandibular complex with maxillary vertical lengthening; the remaining patients had all undergone counter-clockwise rotation with maxillary impactation of different magnitude. The planned mean mandibular and maxillary advancements were of 5.75 ± 4.95 mm and 5.62 ± 1.64 mm, respectively, whereas occlusal plane rotations in the sagittal projection were of $-7.80 \pm 3.96^\circ$ and $-4.06 \pm 3.90^\circ$, respectively (Table 2 and 3).

Repeatability of hard-tissue displacement measurement, verified with ICC, was confirmed by very similar results in the measurements taken by two separate clinicians on manually positioned dental landmarks. The average inter-operator discrepancy, confidence interval, and inter-operator interclass coefficient for each surgical movement measured are presented in Table 4. None of the measured movements showed mean inter-operator discrepancies above 0.2 mm or 0.3°; this was observed by the high total ICC (0.994).

Most of the surgical mandibular and maxillary movements were substiantially similar to those planned (Tables 2 and 3). The discrepancies measured were all statistically negligible with the exception of mandibular and maxillary advancements, which were 0.72 ± 0.90 mm ($p = 0.10$) and 1.41 ± 1.04 mm ($p = 0.06$) smaller, respectively, compared with those planned (Fig. 4). No correlation was found between surgical discrepancies and the amplitude and direction of the movements ($p = 0.53$, $p = 0.17$, $p = 0.87$, and $p = 0.41$ for the sagittal, vertical, and lateral movements and occlusal plane rotation, respectively.

A slightly greater mean correspondence with planned sagittal movements was found for mandibular repositioning compared with maxillary movements.

4. Discussion

Virtual surgical planning is currently widely used in orthognathic surgery, as it allows surgeons to overcome certain intrinsic limitations of traditional methods thanks to the greater amount of information available. However, its ability to achieve better clinical outcomes compared with traditional planning is still unclear (Chen et al., 2021). Although several variables may affect VSP study results, some of them may not have been taken into appropriate consideration: for instance, surgical variables and clearly the method used to evaluate VSP accuracy and reproducibility. Based on these considerations, our study an entailed strict surgical protocol and analyzed various methods of accuracy evaluation outlined in the literature.

Ideally, in terms of surgical movement measurements, voxel-based registration of the osteotomized segments performed on pre- and post-operative images is able to measure, with almost absolute accuracy, surgical movements produced in the absence of operator dependency (Bazina et al., 2018; Ghoneima et al., 2017; Haas Junior et al., 2019; Luebbers et al., 2008). However, the

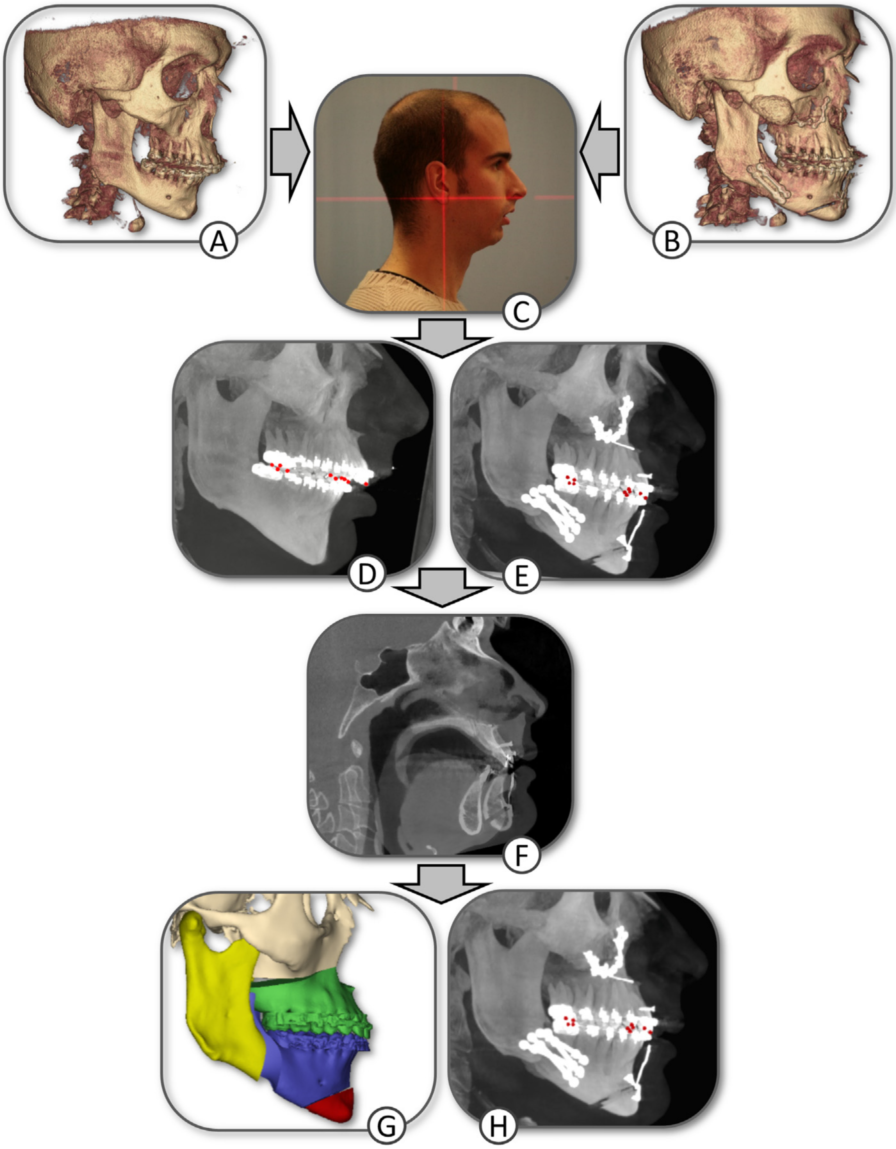

Fig. 2. Visualization of the surgical movements evaluation method. A: Pre-operative cone-beam computed tomography (CBCT) acquisition. B: Post-operative CBCT acquisition. C: Pre-operative CBCT orientation following clinical orientation parameters. D–E: Fiducial points localization on the pre-operative (D) and post-operative volume (E). F: Voxel-based registration of the post-operative cranial base on the pre-operative cranial base. G–E: Comparison between virtual surgical planning movements and actual surgical movements calculated on fiducial points.

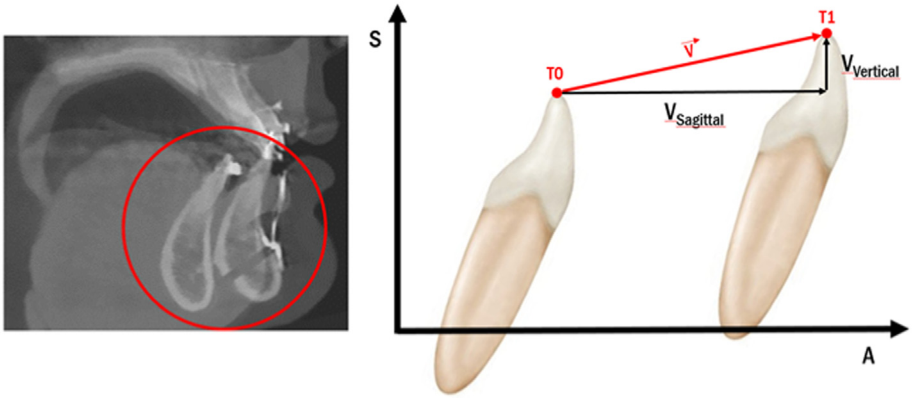

Fig. 3. Example of sagittal and vertical movement computation at the lower incisor.

Table 1
Study population details.

Age (y)	Mean = 26 (18–46)
Sex	F = 37 (74%) M = 13 (26%)
Pre-operative class	Class I = 2 (4%) Class II = 18 (36%) Class III = 30 (60%)
Le Fort I	Single piece = 14 (28%) Three pieces = 36 (72%)

literature reports limitations in the evaluation of collected data and clinical interpretation. Evaluation of rotation matrices applied to points such as centroids (Otranto de Britto Teixeira et al., 2020; Stokbro et al., 2016), single incisor landmarks (Sun et al., 2013), or pure translational and rotational matrices (Baan et al., 2016; Liebregts et al., 2017) is not open to easy clinical interpretation. Furthermore, the components of a linear traslation of a moving point with 6 degrees of freedom differ depending on the location considered (Fig. 5).

Another common assessment method compares pre-operative surfaces generated by CBCT/CT volumes with those generated post-operatively. (Marlière et al., 2019; Mazzoni et al., 2015; Tucker et al., 2010). Besides radiolucency scatterings, iterative closest point (ICP) algorithms can be used to calculate mean deviations in three spatial dimensions; they cannot, however, be applied to any point of the mesh.

Another possible reason for inaccuracy is the use of landmarks identified on 3-dimensional radiographic volumes with positioning errors ranging from 0.02 mm to 2.47 mm in all directions, depending on the method used to identify the landmark (Titiz et al., 2012). For this reason, in the current study a landmark-based evaluation with multiple albeit a limited number of easily identifiable dental fiducial points was used. This method allowed us to reduce systematic error during landmark identification on CBCT volumes (Gaber et al., 2017; Lisboa et al., 2015) and to overcome

Table 2
Mandibular maxillary post-operative versus planning discrepancies and TOST p-values.

	Mandibular mean movements (mm)		Mandibular discrepancies (mm)		
	Planned	Outcome	Mean discrepancy	St. deviation	TOST p-value
Sagittal movements					
Advancement of R. incisor	5.75	5.04	−0.72	0.90	**0.10**
Lateral movements					
Midline correction	0.12	0.54	0.42	1.11	<0.0001
Lateral correction of R. 7°	0.19	0.49	0.30	1.08	<0.0001
Lateral correction of L. 7°	0.14	0.41	0.27	1.04	<0.0001
Vertical movements					
Vertical correction of R. incisor	−5.57	−4.71	0.86	1.19	<0.01
Canine CANT	0.20	0.01	−0.18	0.77	<0.0001
Vertical correction of R. 7°	−1.16	−0.76	0.40	1.20	0.00
Vertical correction of L. 7°	−0.86	−0.63	0.22	1.16	0.00
Rotational movements					
Occlusal plane rotation	−7.80	−6.86	−0.93	1.69	<0.0001

"R. 7°" and "L. 7°" indicate the right second molar and left second molar, respectively. A negative sagittal discrepancy means that the mandible is positioned posteriorly when compared to the planning. A positive lateral discrepancy means that the mandible is positioned to the right when compared to the planning. A negative vertical discrepancy value means that the mandible is positioned cranially when compared to the planning. A negative occlusal plane rotation discrepancy means that the mandible is rotated clockwise when compared to the planning.

Table 3
Maxillary post-op versus planning discrepancies and TOST p-values.

	Maxillary mean movements (mm)		Maxillary discrepancies (mm)		
	Planned	Outcome	Mean discrepancy	SD	TOST p-value
Sagittal movements					
Advancement of R. incisor	5.62	4.21	−1.41	1.04	**0.06**
Lateral movements					
Midline correction	−0.18	0.41	0.60	1.22	<0.0001
Lateral correction of R. 7°	1.29	0.87	−0.42	1.71	<0.0001
Lateral correction of L. 7°	−1.42	−0.32	1.10	1.67	<0.01
Vertical movements					
Vertical correction of R. incisor	−2.10	−1.75	0.35	1.19	<0.0001
Canine CANT	0.09	−0.14	−0.23	0.94	<0.0001
Vertical correction of R. 7°	0.56	−0.18	−0.74	1.47	<0.001
Vertical correction of L. 7°	0.64	−0.04	−0.68	1.54	<0.01
Rotational movements					
Occlusal plane rotation	−4.06	−2.68	−1.38	2.79	0.00

"R. 7°" and "L. 7°" indicate the right second molar and left second molar, respectively. A negative sagittal discrepancy means the maxilla is positioned posteriorly when compared to the planning. A positive lateral discrepancy means the maxilla is positioned to the right when compared to the planning. A negative vertical discrepancy value means the maxilla is positioned cranially when compared to the planning. A negative occlusal plane rotation discrepancy means the maxilla is rotated clockwise when compared to the planning.

Table 4
Method reliability verification: Inter-observer variations and interclass correlations (ICC) for the evaluated movements.

	Mandibular inter-operator ICCs			Maxillary inter-operator ICCs		
	Mean discrepancy	95% Confidence interval	ICC	Mean discrepancy	95% Confidence interval	ICC
Sagittal discrepancies						
Anteroposterior correction of R. incisor	0.155	(-0.6584 - 0.9679)	**0.998**	−0.139	(-1.0025 - 0.7253)	**0.989**
Lateral discrepancies						
Midline correction	−0.041	(-0.8109 - 0.7324)	**0.991**	0.014	(-0.7271 - 0.7553)	**0.958**
Lateral correction of R. 7°	−0.092	(-1.3229 - 1.1395)	**0.948**	−0.063	(-0.9482 - 0.8216)	**0.978**
Lateral correction of L. 7°	−0.090	(-1.3208 - 1.1399)	**0.948**	−0.014	(-1.1389 - 1.1119)	**0.971**
Vertical discrepancies						
Vertical correction of R. incisor	−0.195	(-1.3655 - 0.9747)	**0.983**	0.060	(-0.8555 - 0.9762)	**0.980**
Canine CANT	−0.084	(-1.1262 - 0.9577)	**0.915**	0.013	(-0.7711 - 0.7970)	**0.969**
Vertical correction of R. 7°	−0.092	(-0.9206 - 0.7364)	**0.989**	−0.059	(-0.5154 - 0.3969)	**0.993**
Vertical correction of L. 7°	−0.091	(-1.1929 - 1.0119)	**0.983**	−0.044	(-0.5502 - 0.4622)	**0.995**
Rotational discrepancies						
Occlusal plane rotation	−0.279	(-2.0852 - 1.5280)	**0.983**	0.228	(-1.3775 - 1.8335)	**0.985**
Total	−0.090	(-1.2510 - 1.0712)	**0.995**	0.000	(-0.9456 - 0.9449)	**0.992**
Md + Mx grand total	−0.045	(-1.1070 - 1.0168)	**0.994** (0.993–0.995)			

"R. 7°" and "L. 7°" indicate the right second molar and left second molar, respectively.

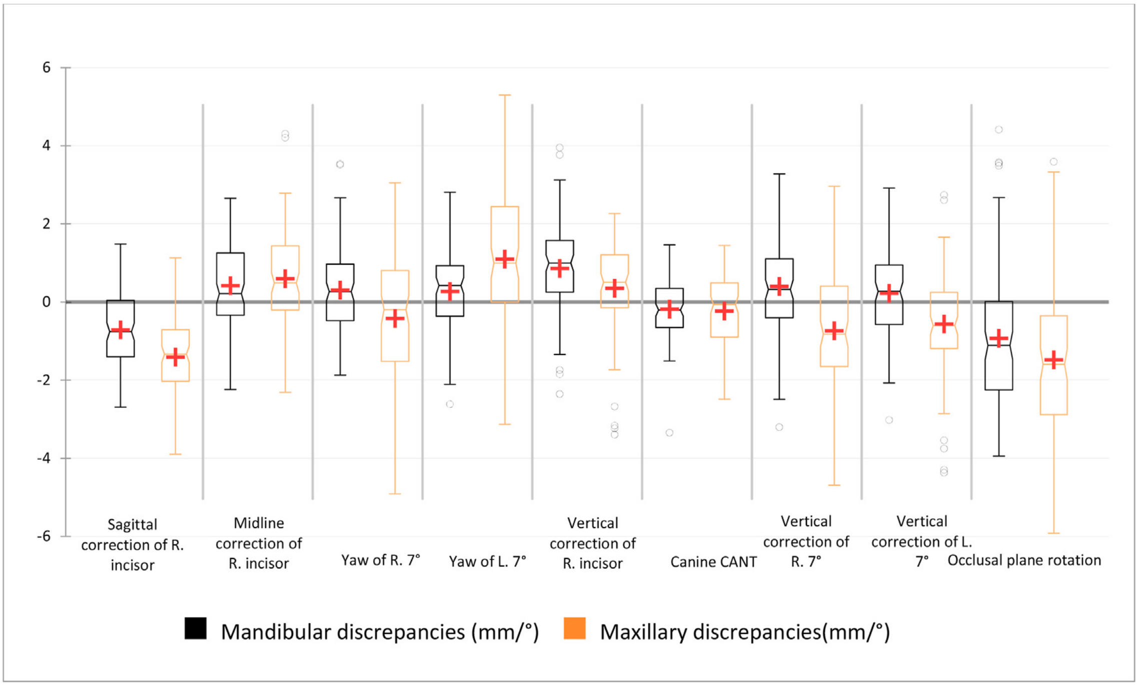

Fig. 4. Discrepancy distributions between virtual surgical planning and surgical results.

other method limitations such as difficult clinical interpretation of results.

Another critical point concerns the protocol used to acquire CBCT images. Many studies did not clearly specify this step in their method descriptions (Antonini et al., 2020; Chin et al., 2017; Falter et al., 2013; Hsu et al., 2013; Marlière et al., 2019). Our study's post-surgical CBCT images were taken in maximum intercuspation without elastics approximately 3 weeks after surgery to permit intra-articular edema reabsorption. Pre- and post-operative volumes were voxel-based superimposed and oriented according to natural head position values determined clinically at the time at which presurgical data were collected. Volume orientation, that is, establishing a coordinate system, is essential to avoid linear measurement errors (Ruellas et al., 2016).

These measures, together with a blind assessment of movements carried out and the number of subjects, helped to reduce potential sources of bias in data collection, and allowed us to obtain a data sample referring to surgical movements that were as objective, reliable and accurate as possible. This was confirmed by the high ICC for all measurements (0.994) (95% CI = 0.993–0.995).

Regarding the comparison between planned and actually performed movements, our results show that the intraoperative transfer of VSP with a mandible-first sequence is highly accurate and reproducible in all space dimensions. No discrepancies between planned movements and those executed were statistically

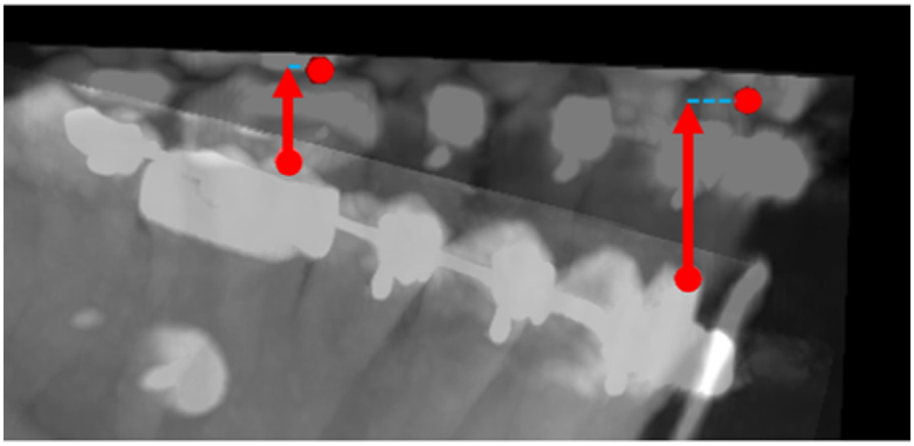

Fig. 5. Note how, in the case of large counterclockwise mandibular rotation (CCWr), it is evident how the incisor translates with pure vertical movement more than the molar.

significant with the exception of sagittal movements at the incisor level. In any case, the mean discrepancy appeared to be lower than 2 mm, the threshold considered to be clinically relevant in other studies (Chin et al., 2017; Donatsky et al., 1997; Hsu et al., 2013; Tng et al., 1994; Zhang et al., 2016). It is important to emphasize that the accuracy of VSP does not actually depend on the planning procedure alone. There are a number of other factors that may have a bearing on results: the method used to collect pre-operative data (as stated above), surgical sequence (Liebregts et al., 2017), fixation methods (Van Sickels and Richardson, 1996), operator expertise (Antonini et al., 2020), and the intraoperative management of the condylar position (Ellis, 1994). For example, incorrect repositioning of the condyle within the fossa during osteosynthesis, hypothetically due to factors such as improper technique, poor bone segment passivation, or plates and screws, can also lead to a final position of the mandible that is different from that planned, regardless of the quality of the VSP process (Antonini et al., 2020; Baan et al., 2016; McMillen, 1972; Ritto et al., 2018; Sharifi et al., 2008). Maxillary impaction by osteotomy different from that planned could also lead to discrepancies (Antonini et al., 2020; Otranto de Britto Teixeira et al., 2020; Sun et al., 2013). The roles that these variables play seem to be underestimated or at least inadequately evaluated in most studies on this topic.

Recurrence of one of the problems listed above, which can occur in patients regardless of the type and amount of movement carried out, could determine a systematic difference between the planned and the final outcome.

The current study seems to confirm this hypothesis only where sagittal movements were concerned, which were approximately 1 mm less than those planned. These differences were not significantly correlated with movement amplitude and direction. They seem to be due mainly to surgical factors rather than sequencing; no relationship was found even in cases with movements considered unfavourable for mandible-first sequencing (CW rotation of the occlusal planes, vertical impaction of the maxilla). Furthermore, these results are in accordance with mandible-first literature (Bobek et al., 2015; De Riu et al., 2018; Liebregts et al., 2017). Greater accuracy in mandible repositioning compared with the maxilla can be explained by the fact that only an intermediate bite with no final one and a mandible-first sequence were used during the procedures outlined in this study. This means that only mandibular repositioning is controlled intraoperatively by VSP. Subsequently, any discrepancy in a mandible's distal segment positioning would be amplified in the maxilla (Stokbro et al., 2016). In addition, the upper arch's final position is determined not by a final splint but by using the lower arch as a template. A further reason for inaccuracy could be incorrect identification of the virtual axis of the condylar rotation upon which planning depends (Antonini et al., 2020; Chin et al., 2017). This could cause increasing inaccuracy of sagittal movements as occlusal plane rotation increases. Correlations found in the current study validate the accuracy of virtual condylar hinge axis for a mandible-first sequence, because the entity of the mandibular distal segment's rotation and the sagittal and vertical discrepancy at the lower incisor are not correlated significantly, showing values of $p = 0.27$ and $p = 0.15$, respectively.

To better investigate causes of errors, a larger cohort should be analyzed and different study designs tried. This could help to identify which of the numerous variables considered might be the cause of error.

5. Conclusions

The results of this study confirm the possibility of high-accuracy intraoperative VSP transfers with a mandible-first sequence regardless of preoperative malocclusion and potential maxillary segmentation. The assessment method guarantees reliability of results and reduces the risk of inaccuracies linked to the analysis itself.

The only statistically significant discrepancy was in the sagittal direction, and this seems to be mainly due to surgical factors rather than virtual planning.

In conclusion, VSP accuracy is not solely dependent on the software used or the digital planning approach itself; sequencing and surgical techinique can have a significant influence as well.

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Declaration of competing interest

The authors declare that they have no conflicts of interest in regard to this work.

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