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Evaluation of virtual surgical plan applicability in 3D simulation-guided two-jaw surgery

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ABSTRACT

Background: Three-dimensional (3D) simulation-based orthognathic surgery is becoming a more popular technique. Therefore, standardized methods for evaluating the efficacy and reliability are required. The virtual surgical plan (VSP) applicability, which represents the degree of similarity between planned movements and actual surgical events, should be accurately measured as a separate entity. We present our method of calculating the VSP applicability and investigating the effect of some factors that are suspected to affect this applicability.

Methods: This retrospective study included 35 patients who underwent simulation-guided two-jaw surgery. The absolute differences between actual (Ta) and planned (Tp) travel distance of selected points were used as the absolute misapplication index (abMAI), whereas the ratio of this difference to the overall distance represented the relative form (rMAI).

Results: Mean abMAI was 1.11 mm [standard deviation (SD), 1.13] with significant differences ($p < 0.001$) between the maxilla (mean, 0.82; SD, 0.6 mm) and mandible (mean, 1.7; SD, 1.5). Using rMAI, calculated by $\left(\frac{(Ta-Tp)^2}{Ta}\right)$, we found no significant difference between the mandible and maxilla ($p = 0.186$). The correlation test of distance revealed no significant correlation with rMAI. Analysis of the factors affecting the applicability showed that the cleft-related deformities were associated with lower applicability than noncleft-related deformities ($p = 0.006$).

Conclusion: Thus, rMAI can be used to measure the VSP applicability regardless of the magnitude of the travel distance. Among all the factors studied, cleft-related deformities were found to be associated with lower applicability.

1. Introduction

Three-dimensional (3D) simulation-guided orthognathic surgery (SGOS) is a process of using 3D patient data to create a stepwise guide toward accurate diagnosis, 3D cephalometric measurements, virtual planning of the surgical steps, and finally predicting the consequences of these steps on the dentoskeletal complex and soft tissue envelope (Swennen, 2017; Efanov et al., 2018; Naran et al., 2018).

Several reports have recently aimed to establish the basics of this domain. The broad lines of the technique (starting from data acquisition and passing through segmentation, simulation of surgical steps, and design of the plan-transporting templates) are now widely accepted (Stokbro et al., 2014; Swennen, 2017; Lin et al., 2018). Furthermore, the development of simulation software not only allows for prediction of soft tissue response but also provides the aesthetic standards for different populations (aesthetic-centered virtual planning) (Marchetti et al., 2011; Liebregts et al., 2015; Van Hemelen et al., 2015). Studies on the efficacy of using virtual surgical planning (VSP) reported higher accuracy of the osteotomy and repositioning as well as more savings of time in planning and surgery stages compared to conventional methods (Iorio et al., 2011; Resnick et al., 2016; Dehghani et al., 2017; Steinhuber et al., 2018).

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As expected, the increased popularity of these techniques has drawn attention for measuring the outcome accuracy and comparing it to conventional methods as well as comparing different techniques (Bengtsson et al., 2017; De Riu et al., 2018; Ritto et al., 2018). However, measuring accuracy in SGOS has two considerations. The first is the VSP applicability to real surgery, which should be measured as a separate entity, as it has its own controlling factors regardless of the planning accuracy of techniques.The second is that the absolute difference between measurements mainly depends on large travel distances. Therefore, another method to detect the accuracy of small movement achievements can be used to accurately investigate factors affecting the VSP applicability.

Our study included patients who underwent 3D simulation-guided two-jaw surgery. We presented our protocol and described the methods of measuring the VSP applicability. We investigated the effects of patient-related factors suspected to affect the VSP applicability, such as the presence of facial asymmetry or cleft-related deformities, as well as orthodontic intervention timing.

2. Materials and methods

2.1. Study design

This retrospective study included patients with dentofacial deformities who underwent 3D simulation-guided two-jaw surgery from June 2015 to February 2017 in the Plastic Surgery Department, Asan Medical Center, Seoul, South Korea. The inclusion criteria were age ≥16 years, two-jaw orthognathic surgery under 3D VSP guidance, and digitally-designed plan-transporting templates. After excluding patients with previous orthognathic surgeries, there were 35 participants (Table 1).

2.2. Data acquisition

Two forms of data were acquired before the simulation process: (1) radiographic data from cone beam computed tomography (CT; 1 mm thick) in the form of a DICOM file and (2) the 3D file of the external facial appearance using a special 3D scanner (Morpheus 3D; Dental Solution MDS, Seoul, South Korea) designed to acquire a rich 3D file that can be used in the simulation process (soft tissue 3D file).

Subsequently, the two data forms were introduced to the simulation and aligned through a semiautomatic process. In some cases, where the dental landmarks were not clear, an additional file of scanned dental arches was merged to the skeletal 3D file. We used two types of software during the study: Mimics V.19 (Materialise-NV, Leuven, Belgium) was mainly used for bone segmentation and cephalometric analysis and Morpheus 3D (Dental Solution MDS, Seoul, South Korea) for soft tissue simulation. Moreover, both software programs were used in the VSP.

2.3. Virtual surgical planning

Using the simulation tools, the planned osteotomies were performed in both jaws, including Le Forte 1 osteotomy in the maxilla as well as bilateral sagittal split osteotomy (BSSO) and genioplasty

Table 1
Characteristics of the patients.

	Gender	Age (years)	Diagnosis	Type of surgical intervention
1	F	20	Cleft-related dentofacial deformity	LeFort I osteotomy, BSSO and Mandibuloplasty
2	M	22	Class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
3	F	17	Cleft-related dentofacial deformity	LeFort I osteotomy, BSSO and Mandibuloplasty
4	F	24	Class III malocclusion	LeFort I osteotomy and BSSO
5	M	33	Long face	LeFort I osteotomy, BSSO and Genioplasty
6	M	20	Class II malocclusion	LeFort I osteotomy and BSSO
7	M	26	Class III malocclusion	LeFort I osteotomy and BSSO
8	M	22	Facial asymmetry, class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
9	M	21	Class II malocclusion, obstructive sleep apnea	LeFort I osteotomy, BSSO and Genioplasty
10	F	27	Prominent mandible and maxilla	LeFort I osteotomy, BSSO and Genioplasty
11	F	24	Long face syndrome, class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
12	F	21	Class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
13	M	18	Midface hypoplasia	LeFort I osteotomy, BSSO and Genioplasty
14	F	18	Cleft-related dentofacial deformity	LeFort I osteotomy and BSSO
15	F	18	Facial asymmetry, class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
16	F	19	Cleft-related class III dentofacial deformity	LeFort I osteotomy and BSSO
17	M	20	Cleft-related class III dentofacial deformity	LeFort I osteotomy, BSSO and Genioplasty
18	F	18	Class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
19	M	22	Facial asymmetry with malocclusion	LeFort I osteotomy, BSSO and Genioplasty
20	F	40	Class III malocclusion	LeFort I osteotomy, BSSO and Mandibuloplasty
21	F	24	Class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
22	M	26	Class II malocclusion	LeFort I osteotomy, BSSO and Genioplasty
23	F	36	Facial asymmetry with malocclusion	LeFort I osteotomy, BSSO and Mandibuloplasty
24	F	17	Cleft-related dentofacial deformity	LeFort I osteotomy, BSSO and Genioplasty
25	M	19	Class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
26	F	18	Midface hypoplasia, class III malocclusion	LeFort I osteotomy and BSSO
27	F	18	Class III malocclusion	LeFort I osteotomy, BSSO and Genioplasty
28	M	28	Class III malocclusion	LeFort I osteotomy and BSSO
29	M	35	Class II malocclusion, obstructive sleep apnea	LeFort I osteotomy, BSSO and Genioplasty
30	M	17	Facial asymmetry	LeFort I osteotomy, BSSO and Genioplasty
31	M	19	Class III malocclusion	LeFort I osteotomy and BSSO
32	F	16	Class III malocclusion	LeFort I osteotomy, BSSO and Mandibuloplasty
33	M	20	Klippel-Feil syndrome	LeFort I osteotomy and BSSO
34	F	36	Class III malocclusion	LeFort I osteotomy and BSSO
35	F	24	Facial asymmetry with occlusal canting	LeFort I osteotomy, BSSO and Genioplasty
	Mean	22.94		

in the mandible. Afterwards, the bone segments were moved, in a scaled manner, in relation to the *XYZ* axes. This movement was under the guidance of two elements: (1) the orthodontic plan, which had been introduced into the software, and (2) the average aesthetic measurement of the Korean population, which are integrated in the program database in the form of reference anthropometric measurements.

2.4. Template design and Manufacture

The surgical templates were designed in the form of intermediate and final wafers along with reposition guides. The designs were performed using (3matic V.11, Materialise-NV leuven-Belgium) based on the simulation results. Subsequently, these templates underwent 3D printing, using liquid-based techniques (stereolithography), to be ready for intraoperative use.

2.5. Surgical intervention

These templates preoperatively underwent low temperature plasma sterilization to avoid deformation. After the Le Forte 1 osteotomy was performed, the intermediate wafer and maxillary reposition template were used to guide maxilla movement in 3D patterns. Similarly, after mandibular osteotomies, the final wafer and mandibular reposition template were used for mandible repositioning.

2.6. Postoperative analysis

CT was performed within three weeks postoperatively. The DICOM file was similarly uploaded to the simulation software to create the early postoperative 3D model (see Fig. 1).

2.7. Measurements protocol

The preoperative, post-simulation, and postoperative 3D models underwent the same measurement methods by recording certain point positions: for the maxilla (Upper canine Rt-Upper canine Lt-Upper molar 1 Rt-Upper molarl1Lt-Upper incisor-Anterior nasal spine ANS-Posterior nasal spine PNS) and for the mandible (Lower molar1Rt-Lower molar1Lt-B point-Pogonion) in relation to three fixed planes (Frankfort horizontal, coronal, and sagittal planes), which are perpendicular to each other at the Sella point (Fig. 2). Subsequently, the travel distances were calculated as the positional difference for each point in relation to the *XYZ* axes as follows: the planned travel distance (Tp) represented the movement from preoperative to post-simulation, while the actual travel distance (Ta) represented that from preoperative to early postoperative. Each point was measured twice, and the mean of two measurements was approximated to 0.01 mm values.

To calculate the applicability, we measured the absolute difference between Ta and Tp, which represented the absolute misapplication index (abMAI) and two other equations for relative MAI (rMAI):

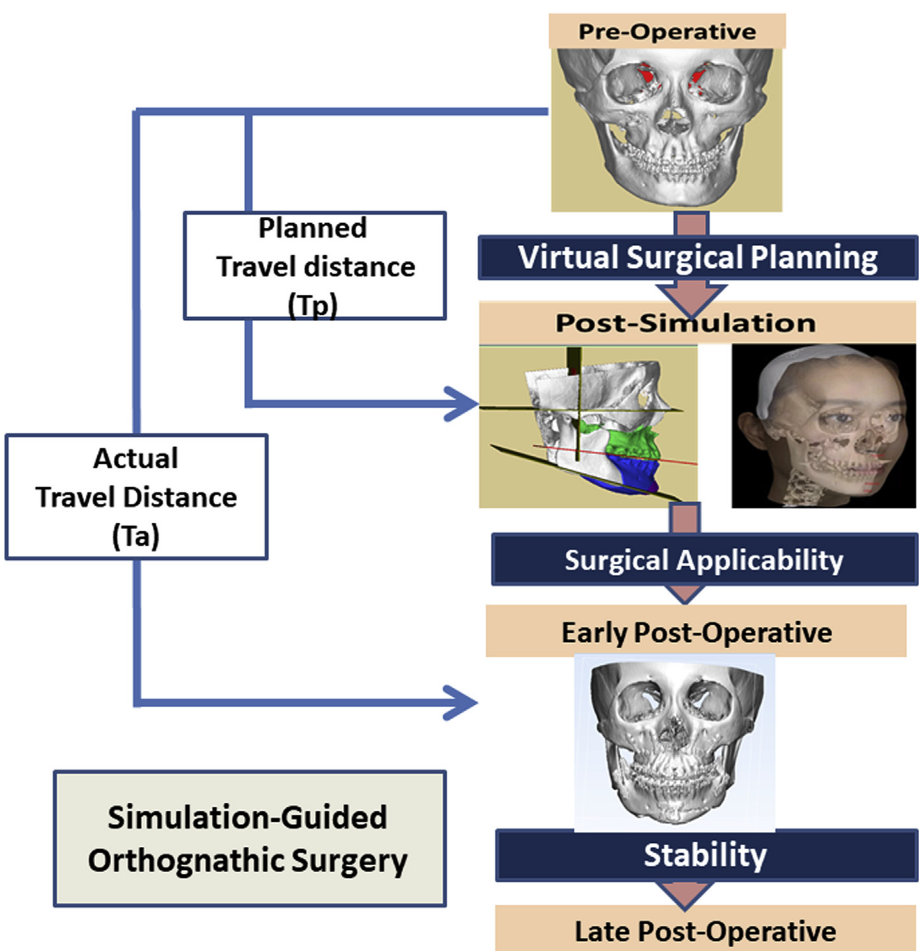

Fig. 1. The sequence of events in 3D SGOS.

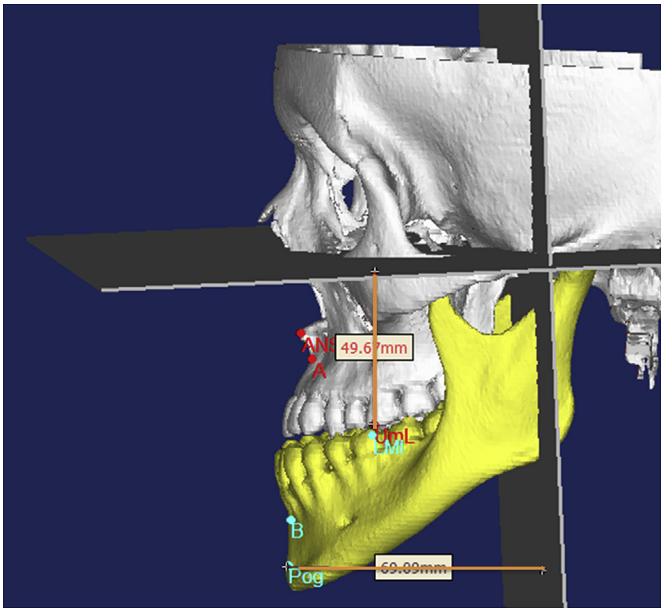

Fig. 2. Measurement of point position in relation to fixed perpendicular planes.

$$\left(\mathrm{r1MAI} = \frac{\mathrm{ab(Ta - Tp)}}{\mathrm{Tp}} \;\&\; \mathrm{rMAI} = \frac{(\mathrm{Ta - Tp})^2}{\mathrm{Tp}}\right).$$

2.8. Statistical analysis

After calculating the previously described indices for each point, we used Kolmogorov–Smirnov and Shapiro–Wilk tests to determine distribution normality. Subsequently, the MAI values for the mandibular and maxillary points were compared using the Mann–Whitney *U* test. Moreover, the Pearson correlation coefficient test was used to analyze the correlation between different formulas of MAI and the Tp.

3. Results

All patients had satisfactory functional and aesthetic outcomes with no major complications. The age of patients ranged from 16 to 40 (mean, 22.9) years, and 54% were females. After excluding travel distances of <0.5 mm, the total number of planned movements was 330 [range, 0.5–18; mean, 4.96; standard deviation (SD), 3.7] mm. The corresponding actual movements ranged from 0 to 19.3 (mean, 4.6; SD, 3.5) mm. Regarding the variation of travel distance between the maxilla and mandible, mean Tps were 3.3 (SD, 2.1) and 8.4 (SD, 4.1) mm, respectively. The Pogonion and B points had the longest movements (mean, 10; SD, 4.5 and mean 9.7; SD, 3.7 mm, respectively), whereas the shortest mean travel distances were 1.6 (SD 1.1) mm for Ucan point and 2.2 (SD, 0.7) mm for ANS.

Analysis of the absolute difference between post-simulation Tp and Ta, which represented the abMAI, revealed that mean abMAI was 1.11 (SD, 1.13) mm (Table 2). The Mann–Whitney *U* test showed a significant difference ($p < 0.001$) between maxilla (mean, 0.82; SD, 0.69 mm) and mandible (mean, 1.7; SD, 1.5 mm). Furthermore, there were variations among points with highest abMAI in the B point (mean, 2.4; SD, 1.8 mm) and lowest for Ucan and Umol (mean abMAI, approximately 0.7 mm for each; Fig. 3a) (see Table 3).

The Pearson correlation coefficient revealed a significant positive correlation between the abMAI and the length of travel distance (Fig. 4). Analysis of the two formulas for relative MAI revealed a negative correlation for r1MAI and no significant correlation with rMAI. Mean rMAI was 0.51 (SD, 0.83, Table 2). Repeating the Mann–Whitney *U* test using rMAI values showed no significant difference between the maxilla (mean, 0.46; SD, 0.75) and mandible (mean, 0.63; SD = 0.97; $p = 0.186$).

Repeating the comparison between the maxilla and mandible regarding rMAI showed insignificant differences (mean, 0.46; SD, 0.75 for maxilla and mean, 0.63; SD = 0.97 for mandible). Furthermore, the rMAI values for the maxillary and mandibular points had different arrangements from that of abMAI (Fig. 3b).

Analyzing the effects of certain factors on applicability using mean rMAI for each patient revealed the following: Regarding asymmetry, the results showed insignificant differences between asymmetric and symmetric cases ($p = 0.677$; Fig. 5). Similarly, we detected insignificant differences between the surgery-first and orthodontic-first groups ($p = 0.224$). On the other hand, the cleft group showed lower applicability (mean rMAI, 0.51; SD = 0.22) compared to the noncleft group (mean, 0.28; SD = 0.1; $p = 0.006$).

4. Discussion

Two-jaw surgery, which depends on interactive repositioning of multiple segments, is an important application of 3D SGOS. VSP better predicted the effect of moving each segment, not only on the skeletal cephalometric measurements and occlusion pattern, but also on the overlying soft tissue envelope, and therefore, the final aesthetic outcome (Marchetti et al., 2011; Liebregts et al., 2015; Olate et al., 2016; Heufelder et al., 2017).

Several studies have focused on measuring the accuracy of SGOS, aiming for evaluation of this rapid development in the technology and establishment of the ideal strategy for application. Some investigators used the difference in 3D cephalometric measurements (Bengtsson et al., 2017; De Riu et al., 2018), whereas others measured the angular values for each segment (Stokbro et al., 2016). However, most studies used the method of tracing points movements in the XYZ (Zhang et al., 2016; Cousley et al., 2017; Dreiseidler et al., 2017; Heufelder et al., 2017).

In this study, calculating the absolute difference between Ta and Tp (abMAI) revealed significant differences between the maxilla (mean, 0.82; SD, 0.6 mm) and mandible (mean, 1.7; SD, 1.5) ($p < 0.001$). We reviewed other studies of CAD/CAM guided two jaw surgery that utilized the method of point tracing for accuracy estimation.

In a multicentric study (Hsu et al., 2013) that used 3d printed wafers and reposition guides, the maxilla had higher accuracy in VSP achievement (1.5 mm) than the mandible (1.8 mm). The same finding was reported in (Zhang et al., 2016) who also used 3D printed occlusal and reposition guides. They reported error means of 0.71 and 0.91 mm for the maxilla and mandible, respectively. Similarly, Tran et al. (2018) reported means of 0.79 and 1 mm, respectively. Furthermore, other studies highlighted the good VSP achievements in maxillary reposition in two jaw surgery. For instance, a study that depended on using 3D printed reposition guides and patient specific plates (Heufelder et al., 2017) reported accuracy of 0.39 mm in maxilla. Another study that utilized 3d printed wafer reported mean accuracy of 0.58 mm and 1.18 mm in maxillary central incisors and first molar, respectively.

This previously mentioned difference in VSP application between the maxilla and mandible can be attributed to the variation in mean travel distances between the maxilla and mandible (in our study 3.3 and 8.4 mm, respectively). Thus, we tried different equations for relative MAI. Subsequently, the correlation test of distance revealed that the equation $\left(\frac{(\mathrm{Ta-Tp})^2}{\mathrm{Ta}}\right)$ can be used to

Table 2
Difference in virtual plan applicability between the maxilla and mandible.

		Maxilla (n = 220)	Mandible (n = 108)	Total (n = 330)	*U*	*p*
abMAI	Mean	0.8283	1.7330	1.1244	8277.500	0.000
	SD	0.69781	1.55119	1.13595		
rMAI	Mean	0.4610	0.6395	0.5197	10813.500	0.186
	SD	0.75126	0.97120	0.83287		

U and *p* values for Mann–Whitney *U* test. abMAI, absolute misapplication index; rMAI, relative misapplication index.
*Statistically significant at $p \leq 0.05$.

Table 3
Summary of Mann Whitney U test for comparing the means of rMAI in 3 variables (symmetry, cleft related deformities and orthodontic timing).

Groups	N	Mean Ranks	Sum of Ranks	Mann–Whitney U	Z	Asymp. Sig. (2-tailed)
Symmetrical	27	15.87*	365.00	72.00	−.417	0.677
asymmetrical	8	14.29	100.00			
Cleft	9	25.40	127.00	13.00	−2.75	0 .006
Non-Cleft	26	13.52	338.00			
Surgery first	23	14.41	317.00	64.00	−1.12	0.260
Orthodontic first	12	18.50	148.00			

p values for ManneWhitney U test. *Statistically significant at *p* less than 0.05.

calculate rMAI, which is not affected by the overall travel distance and does not indicate a significant difference between the maxilla and mandible. Therefore, this suggested index (rMAI) can be used to accurately measure applicability even in small movements.

As expected, several factors can affect the VSP applicability in real surgery. The first is the accuracy of the plan-transporting templates, which are responsible for controlling the movement of maxillary and mandibular segments according to preplanned values. Although there are multiple forms of these templates, the occlusal wafers are still considered the most important component, especially for guiding the occlusion-related movements. Furthermore, the surgeon may decide to modify some movements intraoperatively according to clinical judgment, especially those related to the aesthetic outcome, such as chin repositioning. Long-term cooperation between the same surgical, orthodontic, and simulation teams is essential to narrow this gap between VSP and the surgeon's goals.

As all of our cases were performed by the same team using the same simulation techniques, we studied the effect of the deformity pattern on the VSP applicability. First studied was facial asymmetry, which represented a challenge for the presurgical planning using 2D methods (De Riu et al., 2014; Chen et al., 2018; Thiesen et al., 2018). Some aspects in planning, such as rotational movement of the maxilla–mandibular complex around the *Y* axis (Yaw movement), have been more predictable using the 3D virtual planning. Statistical analysis revealed no significant difference in rMAI between the asymmetric and symmetric groups ($p = 0.677$). This

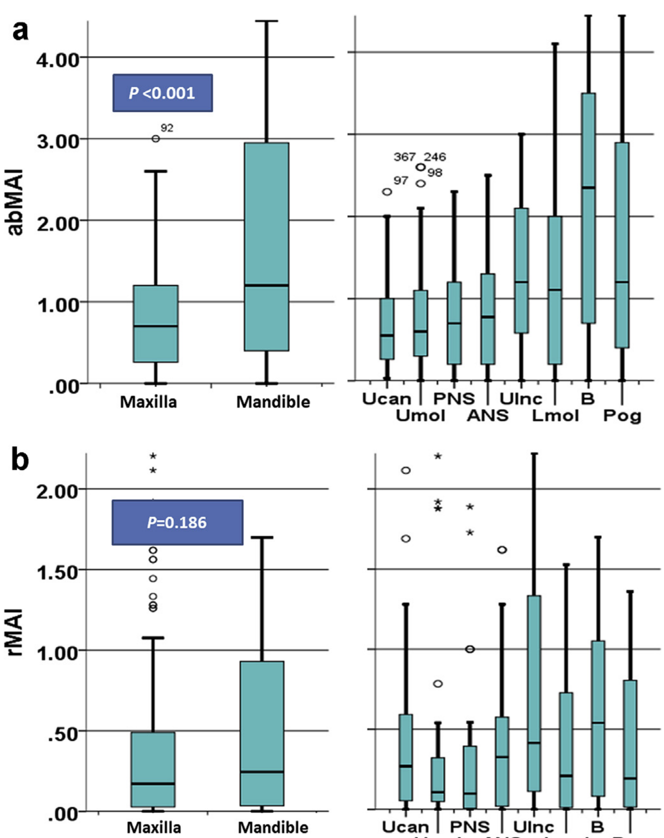

Fig. 3. Comparison of the virtual plan applicability between the maxillary and mandibular movements using: (**a**) abMAI and (**b**) rMAI. *p* value represents the significance interpretation of the Mann–Whitney *U* test (significance at $p \leq 0.05$).

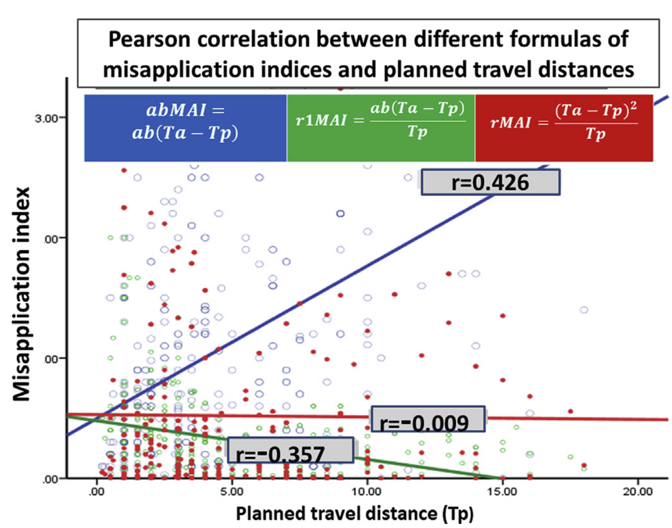

Fig. 4. Scatter plot and Pearson correlation test between different formulas of MAI and planned travel distance (Tp).

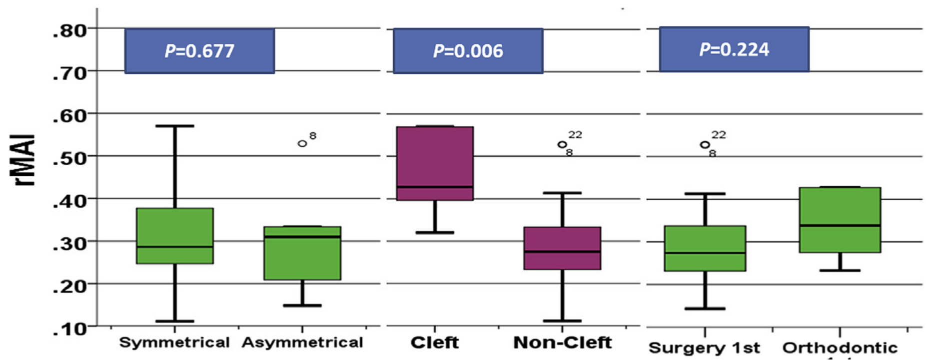

Fig. 5. The impact of some factors on the applicability of the virtual plan. rMAI, relative misapplication index. *P* value represents the significance interpretation of the Mann–Whitney *U* test (significance at $p \le 0.05$).

finding indicated that the difficulty gap in preoperative planning between the asymmetric and symmetric groups was diminished using the 3D simulation.

On the other hand, the study revealed less VSP applicability in cleft-related dentofacial deformities compared to the noncleft group ($p = 0.006$). This can be attributed to restricted movement of the maxillary segment because of scar tissue resulting from the primary cleft repair. In addition, the characteristic deformity pattern, which entails horizontal and vertical maxillary hypoplasia, can also account for this decreased applicability (Yun et al., 2015; Yamaguchi et al., 2016; Jeong et al., 2018). This finding requires further VSP analysis and the corresponding surgical application in cleft-related orthognathic surgery.

The third factor was the orthodontic timing, which was an important topic of research in the last decade. Several studies presented the surgery-first approach as an alternative for the classic sequence (Choi et al., 2015; Huang and Chen, 2015; Uribe et al., 2015). Data analysis revealed no significant difference in the VSP applicability between surgery-first and orthodontic-first groups ($p = 0.224$). These findings correlate with previous studies indicating no difference in reliability and the final outcome between the two protocols.

Analyzing factors affecting the VSP applicability should be an important target for future studies to establish the clinical basics for developing these simulation techniques. Furthermore, establishing standardized methods for reporting these results will permit more accurate comparison among different studies.

5. Conclusion

The use of bone and soft tissue simulation in two jaw surgery allowed accurate planning of the maxillary and mandibular segments in a 3D pattern. The applicability of this plan into real surgery is an essential component of measuring the overall accuracy of SGOS. Therefore, we presented our method of calculating the MAI, which numerically describes how much the VSP was applied into real surgery, even in the smaller movements. By studying the effects of some factors on applicability, the cleft-related dentofacial deformities were associated with lower VSP applicability, whereas asymmetry and orthodontic timing had no effect on the VSP applicability.

Financial Disclosure Statement

The authors have no financial interest to declare in relation to the content of this article.

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