

Article



Quantitative Asymmetry Assessment between Virtual and Mixed Reality Planning for Orthognathic Surgery—A Retrospective Study

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Abstract: Orthognathic surgical planning compromises three clinical needs: occlusal balancing, symmetry, and harmony, which may result in multiple outcomes. Facial symmetry is the ultimate goal for patients and practitioners. Pure virtual planning and mixed reality planning were two innovative technologies in clinical practices compared to conventional model surgery used for decades. We proposed quantitative asymmetry assessment methods in both mandibular contour (in 2D) and a midface and mandible relationship in 3D. A computerized optimal symmetry plane, being the median plane, was applied in both planning methods. In the 3D asymmetry assessment between two planning methods, the deviation angle and deviation distance between midface and mandible were within 2° and 1.5 mm, respectively. There was no significant difference, except the symmetry index of the anterior deviation angle between the virtual and mixed reality planning in the 3D asymmetry assessment. In the mandible contour assessment, there was no significant difference between the virtual and mixed reality planning in asymmetry assessment in the frontal and frontal downward inclined views. Quantitative outcomes in 3D asymmetry indices showed that mixed reality planning was slightly more symmetric than virtual planning, with the opposite in 2D contouring.

Keywords: asymmetry assessment; orthognathic surgery; virtual surgical planning; navigational planning system

1. Introduction

Orthognathic surgery is used to reposition the basal bone in the framework of maxillamandibular deformities [1], providing aesthetic and functional results [2]. Surgical planning prior to orthognathic surgery may include discussions on occlusal balancing, facial symmetry, and harmony [3]. Results may vary (depending on the surgeon). Choosing the best plan that is most suitable for a patient strongly dependents on the person who executing the planning. Facial symmetry is correlated with attractiveness in humans [4–7]. Contrarily, facial asymmetry is commonly observed in either mandible or maxilla deformities, resulting in mandibular skew. Mandibular contour is a useful way to evaluate facial symmetry before and after surgery [8]. Quantifying one's facial asymmetry status may not be comprehensive when only considering a two-dimensional (2D) analysis, since asymmetry expression can vary tremendously in a three-dimensional (3D) analysis. In fact, a complete evaluation of facial asymmetry requires three-dimensional involvement, and a more comprehensive method than comparing contours to quantitate an asymmetrical degree. In traditional two-dimensional "paper" planning for orthognathic surgery, based on landmarks, the surgeon evaluates the asymmetry status affecting the midface and mandible, with a midface line drawn on the anterior-posterior cephalogram [9]. Owing



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). to the progress of medical image processing techniques, we used the mid-plane formed by the landmarks on the 3D skeleton model reconstructed from computer tomography to assess the facial asymmetry [10–15]. However, for patients with serious facial deformities, the bilateral landmarks were congenially asymmetric; it was difficult to find the true and unique symmetry plane for both midface and mandible.

Compared to commonly used landmarks to manually define the median plane of the jawbone, the voxel-based method is stable and fully automatic, revealing the unique symmetry plane of the jawbone as well as soft tissue [16]. The voxel-based method was generated by computing the highest count of paired voxels on opposing sides of the computerized tomography image of the structure [17]. Any three-dimensional symmetrylike object, which includes, but is not limit to, soft or bony tissues, such as the maxilla, midface, mandible, the entire skull, or even soft tissues, can have its optimal symmetry plane automatically obtained without manual settings. The voxel-based method can be used to find the optimal symmetry plane (OSP) of the midface and mandible separately from computer tomography. The outcomes showed that the OSP worked best in bisecting the contour into two symmetrical halves. Proper mandibular alignment is the primary objective in facial asymmetry correction. Quantifying the mandible rotation in facial asymmetry by measuring the midfacial OSP could effectively help one evaluate the degree of mandibular misalignment [18]. OSP-based planning is clinically applicable as a reference in orthognathic surgical planning [19].

Traditional orthognathic surgical planning was cephalogram-based, conducted by transferring individual dental casts to an articulator, in order to observe the in vitro status of the upper and lower jaw occlusions. Preliminary planning of the midface and mandibular movements included a lateral profile sketch, according to cephalometry analysis. Dental casts were cut from the base, which was fixed on an articulator, and then roughly moved to the preliminary position, by "paper" planning, accordingly. Finally, the associate positions of upper and lower dental casts were molded into one- or two-stage surgical wafers [20]. Pitfalls of the traditional planning—the two-dimensional "paper" planning was not sufficient to correct the complex situation of facial asymmetry three-dimensionally. Moreover, errors from mounting the dental casts onto the articulator could not be quantified. Furthermore, due to the transfer error caused by mimicking the 2D sketch by presenting on the 3D dental casts, it was impossible to truly quantify the rotation and movement. In addition, there was no corresponding change regarding the anteroposterior profile sketch when planning, using the lateral sketch, not to mention the asymmetry status. Nevertheless, the tedious maneuvering processes, such as face bow transferring and dental cast mounting on the articulator, as well as transfer errors, accumulated, affecting the planning outcomes [21,22].

A new technique by computer simulation, named virtual surgical planning (VSP), which appeared on the market, has reduced the accumulation errors and the labor-intensive processes planning [23–26]. The VSP technique is a pure computer simulation method, which simulates virtual midface and mandible osteotomy and repositions the segment parts to new positions according to the cephalometry meta-analysis and symmetry structure. There are several commercial VSPs on the market, such as SimPlant[®] Pro OMS in Materialise[®] Dental, Dolphin Imaging[™] in Dolphin Imaging, and VSP[®] in 3D systems. Via computer, the VSP performs digital operations that can simulate osteotomy, move, adjust, and observe the asymmetrical relationship of the digital models with cephalometry measurements simultaneously. The VSP method simplifies the complex operations and reduces most maneuver errors [27–29]. Based on the planning outcome, surgical splints can be fabricated and applied in operation rooms [30–32].

However, computer-simulated surgical planning lacks "haptic feedback" from the dental casts when adjusting the occlusal relationship. Orthodontists are unable to predict the bite points of occlusion or ensure the occlusal balance viewed from the screen. Hence, researchers integrated a bicameral tracking device with dental casts on the articulator to track corresponding movements of dental casts, in order to examine the spatial relationship between the upper and lower jawbones [33–35]. The combination of virtual and physical

means of planning was called a mixed reality simulation, which retains the learned practice of orthodontists and occlusal sensation compared to VPS. Relying on instant tracking, the technique can not only provide haptic feedback from the contact points of dental casts, but also simultaneously demonstrate midface and mandible alignments in 3D. We named it the navigational planning system (NPS). A well-planned outcome ensures the surgical outcome will be close to prediction. During surgical planning, the planner compromises the patient's occlusion, facial harmony, and symmetry at the same time, checking occlusal balance and bite points for further orthodontics treatment, determining a proper metaanalysis cephalometry for harmony, and checking for mandibular alignment, as much as possible, for facial symmetry. In this research, we compare the VPS and NPS planning outcomes in asymmetry assessments.

To compare the asymmetry status of virtual and mixed reality planning techniques, we invoked the mandibular contour evaluation method to quantify asymmetry. In both types of planning, the same functions in computer simulations were applied, such as osteotomy, 3D movements, occlusal detection, adjustment, alignment, and cephalometric measurements in real-time. Both types of planning invoked OSP as the respective median planes for the midface and mandible. We then investigated the asymmetry degree, from the mandible view to the midface, in both contours, in 2D, and the relationship in 3D. We used the mandibular contour to evaluate the planning outcomes of VPS and NPS, which was also suitable to be applied to one-jaw and two-jaw orthognathic surgery. Meta-analysis using the Wilcoxon signed-rank test was utilized to explore whether there was a significant difference in asymmetry outcomes between these two types of surgical planning.

2. Materials and Methods

A retrospective review was conducted on 20 patients with facial asymmetry, in whom both planning methods were applied separately by an orthognathic surgeon (NPS) before surgery, and an orthodontist (VSP) after surgery, for planning comparisons. Diagnosis of facial asymmetry cases were examined for the deviation distance between the upper and lower incisors midpoints, and the deviation angle between the midface and mandible OSPs. Deviations that were greater than 4 mm and 4° , respectively, were classified as severe asymmetry [18]. Twenty severe facial asymmetry patients, aged from 20 to 23 years, 10 males and 10 females, who had undergone orthognathic surgery without mandibular contouring were included in this study. The inclusion criteria were adults who had been diagnosed with craniofacial dysplasia, and who had undergone orthognathic surgery at National Cheng Kung University Hospital. Patients who had one of the physical conditions, such as a facial fracture, orthognathic revision surgery, or temporomandibular joint correction, were excluded. All patients underwent a spiral CT with 1.0-mm slice (STOMATOM Sensation 16; Siemens, Erlangen, Germany), and had pre-surgical splint in their presetting CR position for CT scanning. The trial was approved by the Institutional Review Board (IRB) of NCKUH, number A-ER-105-495. The asymmetry assessments were measured in both 2D and 3D to compare the VSP and NPS planning outcomes.

2.1. Optimal Symmetry Plane

The optimal symmetry planes of the mandible and midface were calculated and obtained using a voxel-based method. We previously described a CT-based method to find the OSPs of the midface and mandible that requires no landmark identification. The OSP is the unique median plane that results in the highest count of paired voxels on opposite sides of the CT image [19]. Assuming plane E passes through the center of a structure,

$$E: (\sin\varphi\cos\theta)x + (\sin\varphi\sin\theta)y + (\cos\varphi)z + d = 0, \begin{cases} 0 \le \varphi \le \pi, 0 \le \theta \le \pi \\ -80 \le d \le 80 \end{cases},$$
(1)

The symmetry ratio (SR) of the structure is

$$SR = \frac{\iiint [v(x, y, z) \times \overline{v}(x, y, z)] dx dy dz}{\iiint dx dy dz}, 0 \le SR \le 1$$
(2)

$$\min_{\varphi,\theta,d} f = 1 - SR, \begin{cases} 0 \le \varphi \le \pi, \ 0 \le \theta \le \pi \\ -80 \le d \le 80 \end{cases},$$
(3)

2.2. Canonical Coordinates and the Projection Planes

For setting up the same evaluation baseline for VSP and NPS planning methods, the canonical coordinate of the skull and its associated projection planes were first determined. The midface OSP was generated from computer tomography. Normal vector of the midface OSP was defined as the *x*-axis, which pointed to the left side of the skull. Bilateral orbitals and porion points were identified and projected onto the midface OSP. Point y1 was the midpoint between the projected orbitals and point y2 was the midpoint between the projected porion points. The y-axis was oriented as y1y2 (pointed backward). The z-axis was orthogonal to both the y- and the x-axes and pointed upward. Point y2 (mid-porion point) was defined as the origin. Figure 1 illustrates the canonical coordinate system of the skull. The y-z, x-y, and y-z planes were the midface OSP shown in red, yellow, and green, respectively. Based on the predefined coordinate, the frontal and the frontal downward inclined planes were set up for mandible projection on the planes. The frontal plane was parallel to the x-z plane. The frontal downward inclined plane was obtained by rotating the x-y plane 45° along the x-axis. Canonical coordinate defined by midface OSP and landmarks provided a reference coordinate for both VSP and NPS planning. The CT calibration was not required to setup a neutral head position during the scanning.



Figure 1. The frontal and the frontal downward inclined planes defined in the canonical coordinate system.

2.3. Asymmetry Assessment in Three Dimensions

The midface and the mandible OSPs were first established. To assess the mandibular misalignment, the midface OSP served as the reference plane for the facial skeleton. To quantify the misalignment degree between midface OSP and mandible OSP in 3D (Figure 2), we defined:

- 1. Three-dimensional (3D) deviation angle (DA): the angle formed by the midface OSP and mandible OSP in 3D.
- 2. Frontal deviation angle (FDA): the angle formed by the 3D deviation angle projected onto the frontal (x-z) plane.
- 3. Horizontal deviation angle (HDA): the angle formed by the 3D deviation angle projected onto the horizontal (*y*-*z*) plane.
- 4. Anterior deviation distance (ADD): the distance between the chin point to the midface OSP; a positive value indicates the point on the left side of midface OSP, and negative otherwise. The chin point is where the mandibular OSP meets the lower border of the chin.
- 5. Posterior deviation distance (PDD): the distance between midface and mandible OSPs at the point where the intergonial line meets the mandibular OSP; a positive value indicates the point at the left of the midface OSP, and negative otherwise.



Figure 2. Asymmetry indices in three dimensions.

Units of the above angular and linear deviations are in degrees and millimeters, respectively.

2.4. Asymmetry Assessment in Two Dimensions

The mandibular was projected on the frontal plane and the frontal downward inclined plane to form the frontal and the inclined mandibular contours, respectively. A leveling plane of the mandible was given as the plane pass through the lower gonion and parallels the *x-y* plane. Regions below the leveling plane of the mandible were used for asymmetry evaluation in the mandible contour and area. The three-dimensional midface and mandible in the frontal view (Figure 3a) and the mandible in the rear view (Figure 3b) illustrate the intersecting segment in the leveling line on the leveling plane. The landmarks were previously obtained in the VSP and NPS planning; therefore, the leveling line on the leveling plane was defined as the segment between the right and the left gonion, shown in Figure 3b. Pixel is the unit of the projection image; we needed to transfer the unit from pixels into a computable length. By measuring the length of the intercepting segment in 3D in true millimeters, and dividing it by the number of pixels, the ratio was obtained. Neither

the length nor the ratio of the intercepting segment for each patient was the same. The ratio was automatically calculated by image processing before further evaluation on the asymmetry of the mandible contour.





The region of interest in the mandible region is below the leveling plane. The mandible contours on the frontal view and the frontal downward inclined view were obtained by the computational theory of the Canny edge detection method [36]. The midface OSP divides the prescribed mandibular contour into left and right contours. Left and right contour areas were enclosed by the boundaries of the leveling line, the symmetry line, and left or right contour, respectively (Figure 4). Asymmetry assessments of mandibular contour were carried out in both frontal and frontal downward inclined views, by means of the frontal mandibular contour.



Figure 4. Mandible contour areas and its contours in frontal view.

Suppose pixels $p_a(x_a, y_a)$ and $p_b(x_b, y_b)$ were located on a projection plane, then the length between these two pixels is

$$d(p_a, p_b) = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}$$
(4)

The symmetry line is the intersecting line between the midface OSP and the projection plane, which separates the mandibular contour into left and right. Below the leveling line,

there are *m* pixels in the left, and *n* pixels in the right. Hence, the floating pixel lengths of left and right contours become

Left contour length =
$$\sum_{i=1}^{m} d(l_i, l_{i+1}), i = 1, ..., m.$$
 (5)

Right contour length =
$$\sum_{i=1}^{n} d(r_i, r_{i+1}), i = 1, \dots, n.$$
 (6)

The enlarged details of the mandible contour and mandible contour and their enclosed areas on the projection plane are depicted in Figure 5. We defined the contour length deviation and the contour area deviation as the absolute value of the difference of length and area, respectively, between the left and right mandible contours on the projection plane. The enclosed area is the region between the right contour and the mirror from the left contour as shown in Figure 6. Those overlapped pixels of the left mirroring contour and right contours shown in purple in Figure 6a were removed from the calculated region. The remaining pieces shown in Figure 6b depicted the pixels of the enclosed area deviation. Therefore, the number of pixels in the left and right contour area is

Enclosed area =
$$\sum_{i=1}^{p} ea_i, i = 1, \dots, p.$$
 (7)

where ea_i denotes the *i*-th piece of the enclosed area. Moreover, the contour deviation and contour area indices were also used to compare the mandibular contour discrepancy in both NSP and VSP planning.

$$Contour deviation = \frac{enclosed area}{left contour area + right contour area}$$
(8)

$$Contour area index = \frac{contour area deviation}{left contour area + right contour area} \times 100\%$$
(9)

The larger the contour deviation and the contour area indices are, the more the mandible contour asymmetry is.

2.5. Statistical Analysis

The Wilcoxon signed rank test was used to compare the asymmetry status in 2D and 3D between the VPS and the NSP methods for orthognathic planning. The statistical power of this analysis was 0.6. The type I error indicated as $\alpha = 0.05$, which assumed that the null hypothesis H₀ of the asymmetry assessments between these two planning methods were not different. It was considered a significant difference if *p* < 0.05; otherwise, there was no significant difference between these two planning methods. Asymmetry assessment for the planning outcomes were taken into account, including both mandibular contour in 2D by means of contour area deviation, contour length deviation, enclosed area, contour deviation, and contour area index; and spatial relationship between midface and mandible OSPs by means of DA, ADD, PDD, FDA, and HDA.



Figure 5. Mandible contour and contour area on the projection plane.



Figure 6. (a) Mirroring the left contour to the right along the symmetry line; (b) the enclosed area of the left and the right contours.

3. Results

Table 1 shows the asymmetry assessment comparisons in both NPS and VSP planning in 3D, the deviation measurements between midface and mandible OSPs. In terms of the planning outcomes of asymmetry evaluation in general, the NPS was slightly better than the VSP. The differences in average between the two planning methods at DA, ADD, PDD, FDA, and HDA were 0.44°, 0.18 mm, 0.12 mm, 0.39°, and 0.27°, respectively. There was a significant difference between the two planning methods at FDA, and no significant differences on the other symmetric assessments at DA, ADD, PDD, and HDA.

Index –	NPS		VSP		u Value
	$\mathbf{Mean} \pm \mathbf{SD}$	Median	$\mathbf{Mean} \pm \mathbf{SD}$	Median	<i>p</i> -value
DA: deviation angle ($^{\circ}$)	0.91 ± 1.01	0.5	1.35 ± 1.25	1.2	0.0701
ADD: anterior deviation distance (mm)	0.89 ± 0.76	0.7	1.07 ± 0.95	0.9	0.4202
PDD: posterior deviation distance (mm)	0.44 ± 0.37	0.4	0.56 ± 0.56	0.4	0.4203
FDA: frontal deviation angle (°)	0.55 ± 0.72	0.3	0.94 ± 1.20	0.5	0.0439 *
HAD: horizontal deviation angle (°)	0.53 ± 0.87	0.3	0.80 ± 0.62	0.5	0 0797

Table 1. Comparisons of the NPS and VSP planning in three-dimensional asymmetry assessment.

NPS, navigational planning system; VSP, virtual surgical planning. * p < 0.05.

Tables 2 and 3 show the quantitative outcomes in asymmetry assessment of the mandibular contour from the two planning procedures. The transformation ratio from pixel to mm for each case was automatically computed by our developed software. The asymmetry indices of the NPS and the VSP planning were listed in millimeters or millimeters squared. The mandibular contour analysis showed that there was no significant difference in symmetry in either the frontal or the frontal downward inclined views. The larger the asymmetrical index was, the less the symmetrical mandibular contour was. Most of the indices demonstrate that the outcomes of the VSP planning were slightly symmetric compared to the NPS planning.

Index	NPS		VSP		n Value *
	$\mathbf{Mean} \pm \mathbf{SD}$	Median	$\mathbf{Mean} \pm \mathbf{SD}$	Median	- <i>p</i> -value
Contour area deviation ^a	53.26 ± 43.00	46.99	32.84 ± 26.33	26.42	0.0973
Contour length deviation ^b	1.31 ± 1.18	0.84	0.91 ± 0.78	0.94	0.1650
Enclosed area ^c	78.64 ± 40.18	73.55	62.86 ± 23.28	63.21	0.1054
Contour deviation ^d	0.54 ± 0.26	0.52	0.44 ± 0.17	0.43	0.1140
Contour area index ^e	1.80 ± 1.40	1.64	1.21 ± 0.96	0.88	0.1429

Table 2. Comparisons of NPS and VSP planning in asymmetry assessment of mandibular contour in fontal view.

NPS, navigational planning system; VSP, virtual surgical planning. ^a Contour area deviation (mm^2) = deviation in absolute value between left and right contour. ^c Enclosed area (mm^2) = sum of the crossing area between the mirrored right and left contours. ^d Contour deviation (mm) = enclosed area/sum of the left and right contour lengths. ^e Contour area index (%) = difference between the left and right contour areas/sum of the left and right contour areas ×100. * p < 0.05.

Table 3. Comparisons of NPS and VSP planning in asymmetry assessment of mandibular contour in frontal downward inclined view.

Index	NPS		VSP		u Value *
	$\mathbf{Mean} \pm \mathbf{SD}$	Median	$\mathbf{Mean} \pm \mathbf{SD}$	Median	- <i>p</i> -value
Contour area deviation ^a	91.27 ± 73.04	72.71	76.83 ± 60.58	71.50	0.6215
Contour length deviation ^b	1.90 ± 1.28	1.65	1.38 ± 0.88	1.40	0.4304
Enclosed area ^c	124.40 ± 71.25	109.79	120.94 ± 55.04	112.34	0.8404
Contour deviation ^d	0.61 ± 0.35	0.55	0.60 ± 0.30	0.56	0.9273
Contour area index ^e	1.65 ± 1.30	1.37	1.46 ± 1.28	1.36	0.7562

NPS, navigational planning system; VSP, virtual surgical planning. ^a Contour area deviation (mm^2) = deviation in absolute value between left and right contour area. ^b Contour length deviation (mm) = deviation in absolute value between left and right contour. ^c Enclosed area (mm^2) = sum of the crossing area between the mirrored right and left contours. ^d Contour deviation (mm) = enclosed area/sum of the left and right contour lengths. ^e Contour area index (%) = difference between the left and right contour areas/sum of the left and right contour areas × 100. * p < 0.05.

4. Discussion

Traditional paper planning for orthognathic surgery was based on cephalometric analysis and the transfer of the midface–mandible relationship to the articulator via dental casts [20]. The entire procedure contained plenty of manual maneuvering, and errors were derived from it; for instances, the face bow transfer and the rough transfer from "paper" planning to physical dental casts [21,22]. These errors were difficult to assess. The latest computerized techniques, VSP and NPS, simulate most of the maneuvering on the computer by digital models reconstructed from CT, and provide comprehensive knowledge to overcome pitfalls of previous practices. VSP is a pure computer simulation method, whereas NSP is a hybrid simulation that tracks the movements of physical dental casts and displays them on computer screens. Both clinical considerations are risks due to radiation exposure caused by computer tomography.

In this retrospective study, we have included the cases in which the deviation distance between midpoints of the upper and lower incisors, and the deviation angle between the midface and mandible OSPs were greater than 4 mm and 4°, considered severe asymmetry. The method is also applicable to patients who have slight and moderate asymmetry. The advantage is that it retains symmetrical planning in patients with slight or moderate asymmetry. The unique canonical coordinate for each individual skull was defined initially, which could overcome confounding factors, such as head position, CT calibration. Therefore, for further analysis, the process of setting the neutral head position of each subject was not necessary. However, the canonical coordinate may vary slightly, because the landmarks in bilateral orbitals and porion points were manually selected to form the FH plane as a horizontal plane in the coordinates. Moreover, quantification values in 2D contouring and 3D asymmetry assessments could contain minor changes as well. The automatic method of landmark identification can be developed in the future to improve the manual selection of forming the FH plane.

The NPS planning method retains a conventional model surgery procedure in which the dental casts act as 3D mice for both functions of testing occlusal bite points and balancing between upper and lower dental casts, while synchronizing the viewing of the asymmetry indices in real time when moving the dental casts. Surgeon or orthodontist planners follow their customary practices of sensing haptic balance from the contacts of the upper and lower dental casts during planning, and in such circumstances, post-operative bite points can be easily predicted. The VSP technique is a pure computer simulation operated with a mouse on a computer screen.

Compared to the VSP method, from the planner's point of view, the NPS operation delivered a shorter learning curve. However, the NPS required a long preparation by technicians, such as presetting markers for tracking, registration of images, and casts. In our experience, the preparation took 14 vs. 6 h for NPS and VSP methods, respectively. Both planning methods adopted the same OSP, being the target reference of symmetry. Comparing the two planning methods, the 3D asymmetry index in each deviation angle were less than merely 0.5° on average, and the significant difference only appeared at FDA. For asymmetry assessment in the mandibular contour, there was no significant difference in any 2D indices, regardless of frontal or frontal downward inclined view.

Since there is no haptic feedback from the mouse or keyboard operation in the VSP planning, separate movements of the upper and lower dental models may easily penetrate each other during position adjustment. Therefore, preset occlusion and the upper and lower dental casts moving in tandem were required before planning, so that both dental models could be positioned together. If the bite points in occlusion needed to be adjusted in VSP, it was necessary to reload a new occlusion of dentitions, and restart the process from the beginning. In such circumstance, midface and mandible alignment would be compromised. During NPS planning, it was capable of independently tracking the position of the single dental cast associated to the midface or mandible, and the planner was able to fine-tune the occlusion during planning; moreover, predicting and balancing the post-operative bite points of the upper and lower dentitions.

On both frontal and inclined views for mandibular contour asymmetry assessment, the VSP was slightly better than the NPS method. It is because the contact regions between the upper and lower dental casts limited the alignment movements, whereas the dental model bundle allowed it to move freely in VSP. Moreover, functions in VSP provided jawbone mirroring along the OSP, which was easier to approach symmetry outcomes.

Regarding the 3D asymmetry assessment of the two planning procedures, every asymmetry index in NPS was better than that in VSP, which meant that the planning outcome in NPS was a bit more symmetric than VSP (three-dimensionally), because the NPS method allowed the surgeon to move individual dental casts separately, free-hand, to observe the synchronized data of deviation distance and deviation angle between the midface and mandible when planning. Although most of the quantitative 3D asymmetry indices in NPS were a bit more symmetric than VSP, the differences in asymmetry indices were within the 0.2 mm or 0.5° range, so the outcome differences between the two planning were ignorable. The transformation ratio from the units of pixel (image) to mm (model) was individual-dependent, and automatically calculated in our developed evaluation software.

Outcomes of asymmetry assessment in mandibular contour in VSP were better than NPS in both frontal and frontal downward inclined views. Commercially available VSP software, such as SimPlant[®], Dolphin Imaging[™], and VSP[®], provide a landmark-based or user-defined median plane as the target plane for viewing asymmetry status, which is planner-dependent and would usually cause minor asymmetry after the surgery because of the skewed median plane. In this research, we introduced the computerized and unique OSP for individuals to be the referencing median plane used in VSP planning. The asymmetry assessment results showed that the application of OSP to these two planning methods were able to obtain similar symmetrical outcomes. In the future, asymmetry

evaluation cases can be conducted by mandible contouring or 3D asymmetry assessments after applying both NPS and VSP planning. Therefore, the associated surgical splints, developed from more symmetrical planning outcomes, can be chosen for further operation.

In this study, we proposed a 2D contouring and a 3D deviation/angulation method for asymmetry assessment. These assessments involved both structures of the maxilla and mandible that were strictly defined in the canonical coordinate of each participant. Indeed, the contouring analysis provided two-dimensional assessments only on the mandible since this is where most of the visible asymmetry occurred. The frontal and frontal downward inclined views usually appeared on the mandible, and were two of the most assessments in the eye of the beholder in facial asymmetry.

In this study, we proposed 2D and 3D quantitative methods for facial asymmetry assessment in both virtual (VSP) and mixed reality (NPS) techniques for orthognathic surgical planning. Unique OSPs of the midface and mandible were introduced to both NPS and VSP planning in the same case as a reference median plane.

5. Conclusions

Quantitative outcomes of 3D asymmetry indices showed that NPS was slightly more symmetric than VSP. Differences in 3D asymmetry indices were within 0.2 mm and 0.5°. Except for the frontal deviation angle between the midface and mandible OSPs, there was no significant difference between VSP and NPS planning in the 3D asymmetry assessment. Quantitative outcomes of 2D asymmetry indices showed that the VSP was slightly more symmetric than NPS. There was no significant difference between VSP and NPS planning in 2D asymmetry assessment. Based on the same median plane, the NPS and VSP for orthognathic surgical planning yielded similar facial symmetry status. The selection of the median plane was crucial, and could provide an apt prediction of the degree of facial asymmetry after surgery. In our previous study [19], we presented a unique OSP, which was applied again, so that the median reference plane would not be different from each another. Since there was no significant difference in asymmetry for VSP and NPS planning, compared to VSP, NPS involves a long planning preparation time; thus, the VSP method could be a more suitable choice for orthognathic planning.

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