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AUTHOR'S REPLY

Tridimensional virtual planning protocol for double-jaw orthognathic surgery with mandible first surgical sequence

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Introduction

Three-dimensional virtual treatment planning has greatly enhanced the efficiency and accuracy of dentofacial deformity correction through orthognathic surgery [1]. Moreover, the advent of rigid internal fixation has allowed a change in this classical sequence. Performing mandibular surgery first presents several advantages and surgeons must consider some indications in order to achieve better results, and the ability of the surgeon to reproduce the treatment plan in the operating room is essential [2]. Most of orthognathic surgery treatment plan has been performed by traditional sequence, but the surgery itself was performed using an inverted sequence. However, repositioning the lower jaw first during three-dimensional virtual planning, as well as in actual surgery, can be really advantageous. The purpose of this paper is to suggest a protocol for double-jaw orthognathic surgery repositioning the mandible first in both three-dimensional virtual planning and surgery itself.

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Tridimensional virtual planning protocol

Step 1: clinical and CT scan analyses of the patient in natural head position and centric relation

During this first step, facial and dental analysis are performed under a patient's natural head position (NHP), jaws in centric relation (CR), and lips relaxed. Such position is recorded photographically and repeated during CT scan afterward. A technique for establishing NHP should follow a logical sequence, in which the patient stands in front of the photographer looking straight towards the horizon. The photographer then first records the roll axis in a frontal view picture, followed by recording pitch axis in a profile view picture. It is very difficult to record yaw axis during facial pictures, hence the authors recommend to position yaw axis by the alignment of the ocular globe during CT-scan. One should be aware of enophthalmos, proptosis, and other conditions that may alter the position of ocular globe. All photographs are taken using a tripod and professional SLR cameras. (Figs. 1a, b and 2).

Step 2: treatment plan based on facial and dental analysis

Such analyses follow traditional parameters as described by many authors and dictate the treatment plan [3, 4].

Step 3: digital cephalometric prediction

Digital prediction trancing allows direct evaluation of both dental and skeletal bidimensional movements and provides predicted profile images [5]. A lateral cephalogram is generated by CT scan in NHP, with jaws in CR, and lips relaxed.

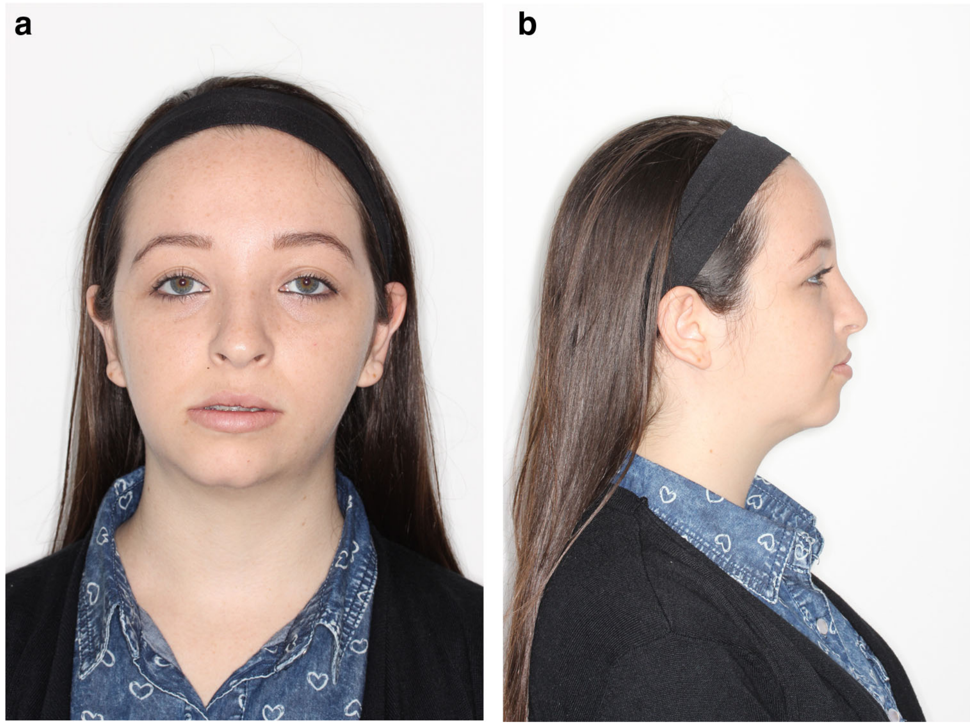


Fig. 1 This is a 20-year-old female patient with a development dentofacial deformity characterized by a mandibular asymmetry due to active condylar hyperplasia and maxillary deficiency. The patient underwent combined condylar hyperplasia resection and orthognathic surgery. The orthognathic procedures included BSSO and Le Fort I osteotomies for mandibular and maxillary advancement and correction of jaw asymmetries, as well as oblique osteotomy of the chin. Septoplasty and turbinectomy surgeries were performed as well. **a** Preoperative facial frontal view. **b** Preoperative facial profile view

From this point, there are two ways to predict the actual surgery. The first one is performed following the traditional method in which the maxilla is first positioned as planned, followed by placing the mandible in the desired final occlusion and then genioplasty if necessary. The second approach is initiated by first placing the mandible into the desired occlusion and next, moving both maxilla and mandible together until desired final skeletal position as desired. At last, genioplasty can also be predicted if necessary. Both methods allow good prediction if soft tissue responses configuration is adequate. Also, having dental casts available to observe dental relationships can make it easier to place the mandible into the best occlusion.

Step 4: identification of first dental contact between operated mandible and unoperated maxilla

Determination of the center of mandibular autorotation (CAR) should be performed as the very first action. Many CAR's have been described, but the most common method is to place CAR outside the center of condyles [6]. In an attempt to locate the center of mandible autorotation during maxillary surgical impaction and identify discrepancies between the resultant mandibular position following maxillary surgical impaction, Wang et al. [7] demonstrated that the center of mandibular autorotation

Fig. 2 Yaw axis positioning by the alignment of the ocular globe on CT scan

is located 2.5 mm behind and 19.6 mm below the radiographic condylar center of the mandible on average, with large individual variations. Moreover, the authors reported that by using the radiographic condylar center of the mandible to predict the mandibular autorotation would overestimate the horizontal position of the chin by 2 mm and underestimate the vertical position of the chin by 1.3 mm following an average of 5 mm surgical maxillary impaction. In a similar study, Lou et al. [8] reported that the mandibular rotation center is located outside the condylar head in all patients of the study, in average 15.64 mm below and 0.82 mm behind the center of the condylar head. Another technique is to individualize the CAR as described by Nasser Nadjmi et al. [9] Both methods are available and present accurate results. Next, the mandible is rotated until first tooth contact between the operated mandible and unoperated maxilla occurs.

Step 5: record of surgical movements obtained in steps 3 and 4

Surgical movements of both maxilla and mandible obtained in step 3 are initially recorded. Mandibular position obtained in step 4 is then recorded as well. Main landmarks registered are upper and lower incisors tips, upper and lower first molar cusps, anterior nasal spine, and pogonium. Such landmarks must be individually documented horizontally and vertically. Moreover, both tooth contacts and distances between upper and lower jaws should also be recorded to allow the best accuracy of mandibular position during virtual surgery.

Step 6: virtual patient generation in NHP and CR

CT scan clean-up is important to remove unnecessary data from scans. Dental casts superposition and generation of hard and soft tissue surface of the patient's face are very important actions as well. All software provide different tools to edit such images and the surgeon must be able to handle and coordinate skills to create the best image of the virtual patient in NHP and CR. Although the authors recommend generating virtual patient in CR considering it a diagnostic and reproducible position, it is important emphasize that the actual surgery is also performed using an inverted sequence, hence patient generation in perfect CR is not mandatory and errors in such position will not affect treatment results. Virtual dental models superimposition on the virtual patient's teeth is perhaps the most challenging procedure during virtual patient generation. Using a high-resolution laser scanner, digital dental models are generated by scanning patients' teeth or stone models and incorporated into the 3D CT reconstruction (Fig. 3a–d).

Such superimposition could be performed automatically (auto superposition) or manually. If manually performed by the surgeon, it should also follow an established sequence, as described below:

- 6.1) The very first action involves placing upper digital dental models in front of 3D CT model and rapidly presetting roll, pitch, and yaw axis of such digital models in frontal, profile, and axial views respectively. These steps should necessarily follow the mentioned adjustment order.
- 6.2) In a profile view, superimpose the upper incisors of digital casts onto 3D CT reconstruction in vertical and horizontal position. A CT scan sagittal section can assist to enhance such superimposition.
- 6.3) In a tridimensional frontal view, adjust the upper dental midlines. Different opacities patterns of dental casts and 3D CT reconstruction can be very helpful to assist such superposition.

The next steps encompass refinement of digital dental models superimposition.

- 6.4) In CT scan coronal section, adjust roll axis of superimposed teeth.
- 6.5) In CT scan sagittal section, adjust pitch axis of superimposed teeth.
- 6.6) In CT scan axial section, adjust yaw axis of superimposed teeth.
- 6.7) Repeat steps 6.4, 6.5, and 6.6 until reaching a perfect superimposition.
- 6.8) Review and check perfect superimposition of upper dental cast in the 3D CT reconstruction with different opacity patterns, as well as in CT scan coronal, sagittal, and axial sections.
- 6.9) Repeat the same steps for lower cast superimposition.

Step 7: virtual osteotomies generation

Virtual osteotomies design and length must be identical to the surgery itself in order to gather important information about the bone segments contact area, bone interferences that may need adjustments, and gaps that may need to be grafted [10]. Each software contains specific tools to generate preset classic midface and mandible osteotomies, including segmented osteotomies. Besides, it is possible to trace customized osteotomies which allow elaboration of a variety of treatment planning. The authors suggest customizing BSSO for each specific case according to patient's anatomy (i.e., inferior alveolar neurovascular bundle position, inferior teeth roots position, and mandibular bone architecture), bony movement direction, and magnitude.

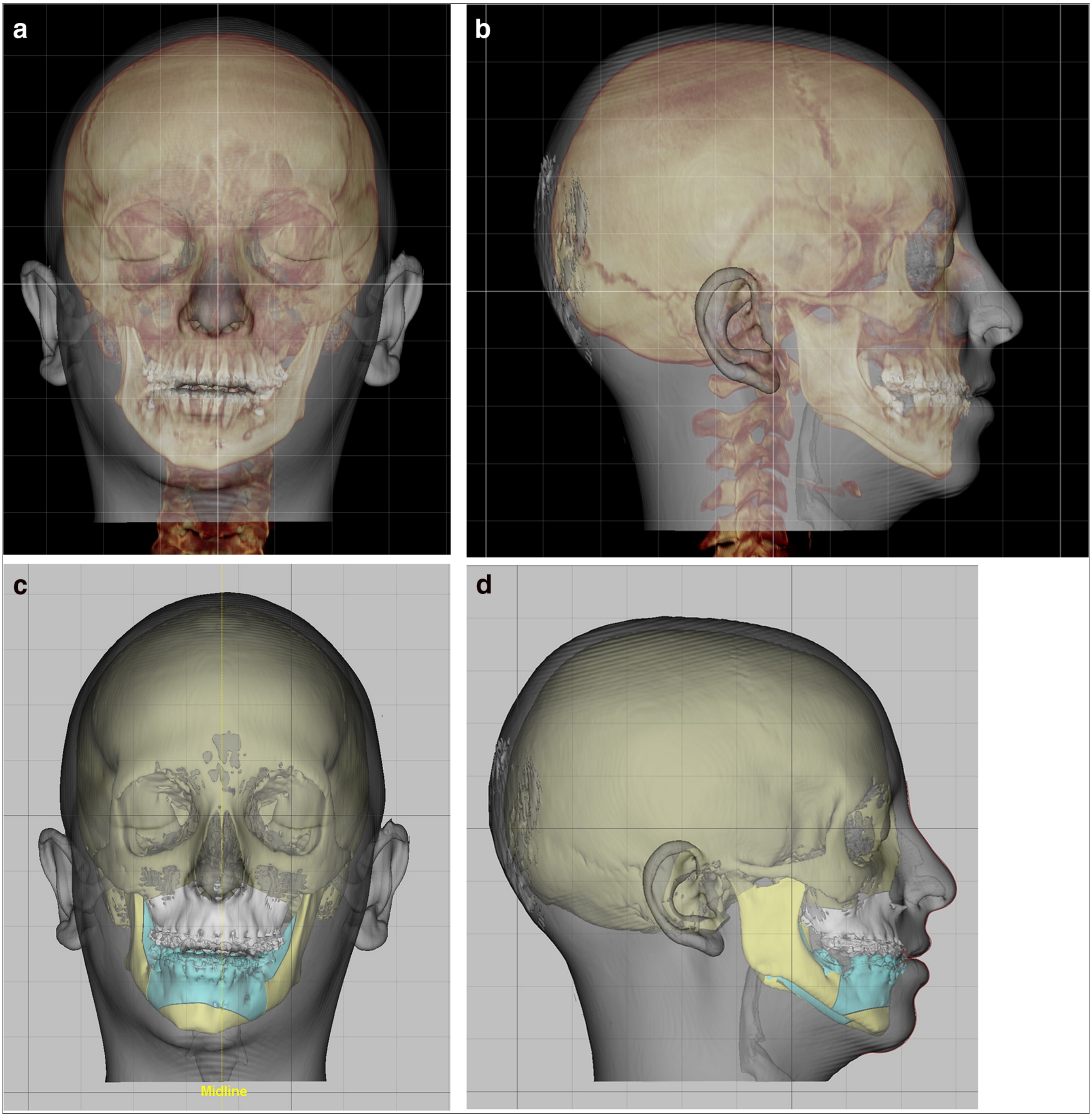


Fig. 3 Establishing NHP (**a** frontal view; **b** lateral view) and virtual patient generation in NHP and CR after digital dental models superposition onto 3D CT reconstruction (**c** frontal view; **d** lateral view)

Step 8: setting the landmark points

Some tridimensional landmarks should be registered on the maxilla, mandible, and soft tissue to allow understanding all tridimensional movements planned to reach the desired goals. Each software also contains a preset list of hard and soft tissue reference landmarks, as well as specific tools to assist in setting such landmarks. Special care should be taken to the CAR and reference landmarks registered, which should be coincident to the parameter used on digital cephalometric prediction in steps 4 and 5 respectively.

Step 9: virtual 3D surgery

9.1 Mandibular roll correction

Always start by leveling the mandibular cant. The rotation center should be positioned at the uppermost point of inferior dental midline and roll the mandible until the desired position. Any change in roll position will interfere in pitch and yaw position, as well as midlines alignment. Hence, misalignment in roll axis will jeopardize the desired occlusal contact between repositioned mandible and unoperated maxilla need in step 9.4.

9.2 Inferior midline correction

Inferior midline should be corrected in order to centralize the lower jaw. It also allows the next step to obtain the same occlusal contact between operated mandible and unoperated maxilla as reached in step 4.

9.3 Mandibular yaw correction

Yaw axis is aligned by rotating the mandible until the desired position. The rotation center for such procedure should be inferior dental midline. Yaw axis correction is best accomplished in a superior axial view in which gridlines will assist aligning the mandible in a suitable position. Any misalignment in yaw axis will also jeopardize the desired occlusal contact between repositioned mandible and unoperated maxilla needed in step 9.4.

9.4 Find the first occlusal contact between operated mandible and unoperated maxilla

The mandible should be moved both horizontally and vertically until it coincides with occlusal contact obtained in step 4. The occlusion dental collision map is very helpful in reaching the desired occlusal contact.

9.5 Mandibular pitch correction

After finding the first occlusal contact between operated mandible and unoperated maxilla, pitch axis is adjusted. To best adjust the pitch axis, the surgeon must place the rotation center on occlusal contact found on the previous step and rotate the mandible up until the desired occlusal plane angulation and anteroposterior chin projection. After this manipulation, all horizontal and vertical movements in the lower incisors, lower molars, and pogonium, as well as eventual distances between upper and lower dental arches (i.e., distances between molars for counterclockwise rotations and between incisors for clockwise rotations) recorded on step 5 should coincide. Such maneuver carried previously to proximal segment orientation is imperative for appropriate segment alignment.

9.6 Proximal segment alignment

After all mandibular corrections, the proximal segments can finally be appropriately aligned. The surgeon should take special care during this step in order to avoid temporomandibular disorders or condylar resorption caused by incorrect proximal segment alignment. According to Liu et al. [11], maximum angulation in proximal segment positioning should not be more than 4° in pitch axis, 3° in roll axis, and zero in yaw axis. At this moment, all information is saved into a new slot in the software before continuing the virtual planning. It allows access to all information of intermediate occlusal relationships during the actual surgery.

Figures 4 a–d show mandibular repositioning previous to any maxillary movement.

9.7 Maxillary reposition

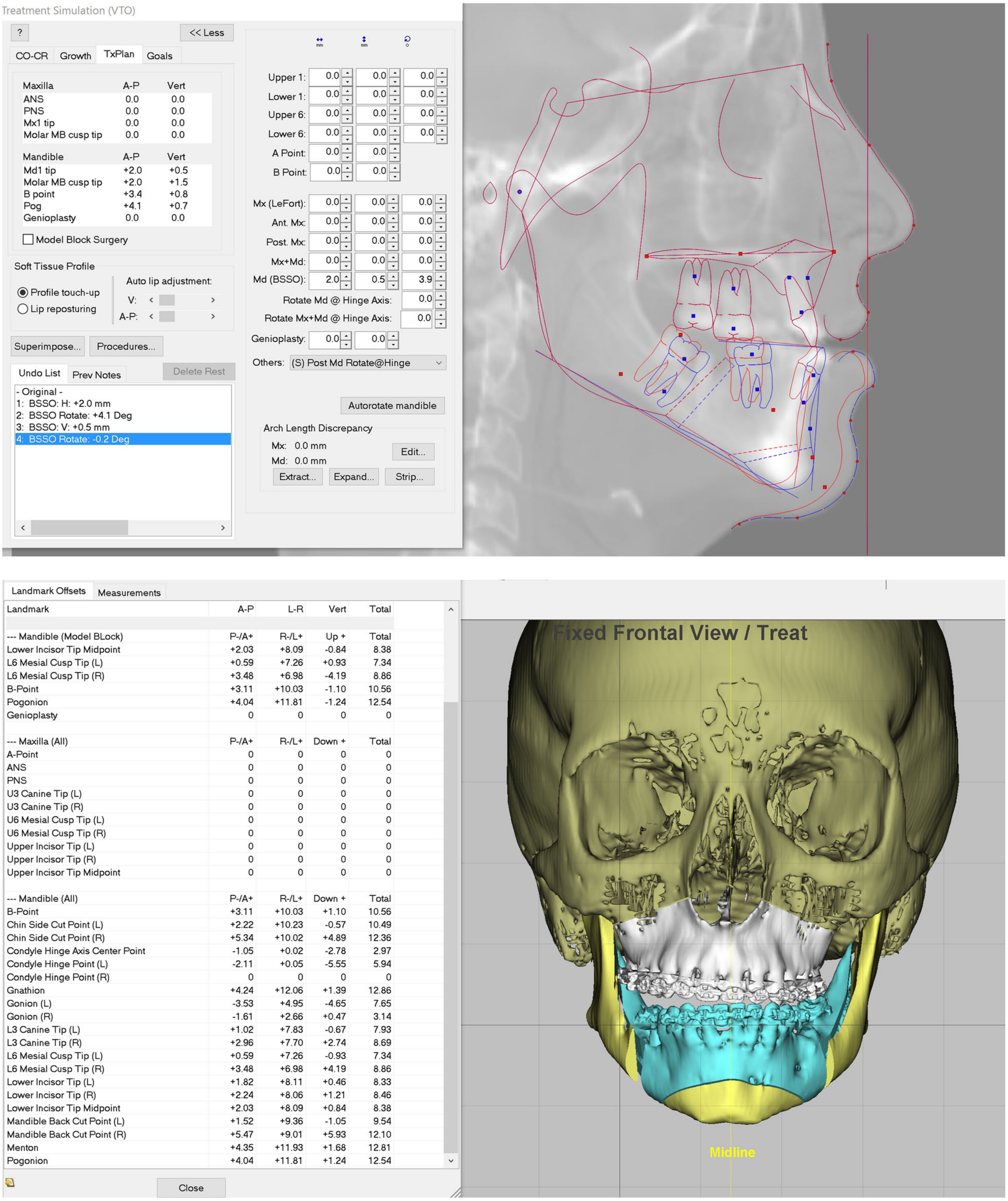
The maxilla is repositioned on operated mandible according to the desired final occlusion. Software provides different tools for this purpose and such reposition could be performed either automatically or manually, according to the surgeon's preference. Manual positioning is performed by fitting virtual tridimensional teeth in a desired final occlusion. This maneuver is oriented and reviewed by direct view of 3D model in several perspectives (frontal, oblique, lateral, superior, inferior, and posterior) as well as axial, coronal, and sagittal tomographic sections. Furthermore, it is assisted by an occlusion dental collision map that displays upper and lower teeth relationships and hence, indicates possible area and magnitude of dental superposition. Having dental casts available to observe dental relationships will help find the best final occlusion. Automatic position is driven by dental casts scanning mounted in the desired final occlusion. Digital superior and inferior dental casts are first superimposed in the desired occlusion and based on this superposition the maxilla will move until fitting into the desired occlusion.

9.8 Maxillomandibular complex rotation

After repositioning the maxilla, the entire maxillomandibular complex is rotated for final vertical and horizontal correction. The upper incisors edges are the most useful vertical reference. Special care should again be taken to the CAR, which should be coincident to the parameter used before. After this rotation, all horizontal and vertical movements in the upper and lower incisors, upper and lower molars, anterior nasal spine, and pogonium should coincide the prediction tracing.

9.9 Genioplasty

At last, genioplasty can also be simulated if necessary, according to treatment plan and surgery prediction.



Landmark	A-P	L-R	Vert	Total
--- Mandible (Model BLock)	P-/A+	R-/L+	Up +	Total
Lower Incisor Tip Midpoint	+2.03	+8.09	-0.84	8.38
L6 Mesial Cusp Tip (L)	+0.59	+7.26	+0.93	7.34
L6 Mesial Cusp Tip (R)	+3.48	+6.98	-4.19	8.86
B-Point	+3.11	+10.03	-1.10	10.56
Pogonion	+4.04	+11.81	-1.24	12.54
Genioplasty	0	0	0	0
--- Maxilla (All)	P-/A+	R-/L+	Down +	Total
A-Point	0	0	0	0
ANS	0	0	0	0
PNS	0	0	0	0
U3 Canine Tip (L)	0	0	0	0
U3 Canine Tip (R)	0	0	0	0
U6 Mesial Cusp Tip (L)	0	0	0	0
U6 Mesial Cusp Tip (R)	0	0	0	0
Upper Incisor Tip (L)	0	0	0	0
Upper Incisor Tip (R)	0	0	0	0
Upper Incisor Tip Midpoint	0	0	0	0
--- Mandible (All)	P-/A+	R-/L+	Down +	Total
B-Point	+3.11	+10.03	+1.10	10.56
Chin Side Cut Point (L)	+2.22	+10.23	-0.57	10.49
Chin Side Cut Point (R)	+5.34	+10.02	+4.89	12.36
Condyle Hinge Axis Center Point	-1.05	+0.02	-2.78	2.97
Condyle Hinge Point (L)	-2.11	+0.05	-5.55	5.94
Condyle Hinge Point (R)	0	0	0	0
Gnathion	+4.24	+12.06	+1.39	12.86
Gonion (L)	-3.53	+4.95	-4.65	7.65
Gonion (R)	-1.61	+2.66	+0.47	3.14
L3 Canine Tip (L)	+1.02	+7.83	-0.67	7.93
L3 Canine Tip (R)	+2.96	+7.70	+2.74	8.69
L6 Mesial Cusp Tip (L)	+0.59	+7.26	-0.93	7.34
L6 Mesial Cusp Tip (R)	+3.48	+6.98	+4.19	8.86
Lower Incisor Tip (L)	+1.82	+8.11	+0.46	8.33
Lower Incisor Tip (R)	+2.24	+8.06	+1.21	8.46
Lower Incisor Tip Midpoint	+2.03	+8.09	+0.84	8.38
Mandible Back Cut Point (L)	+1.52	+9.36	-1.05	9.54
Mandible Back Cut Point (R)	+5.47	+9.01	+5.93	12.10
Menton	+4.35	+11.93	+1.68	12.81
Pogonion	+4.04	+11.81	+1.24	12.54

Fig. 4 **a** Prediction tracing of mandibular movement identifying first dental contact between operated mandible and unoperated maxilla. Note that in the case presented, there was no contact between the upper and lower teeth. Such relationship between the upper and lower dental arches are common in asymmetries correction since bidimensional prediction trancing does not consider roll adjustment. Hence, it must be adjusted during 3D virtual planning in order to reach the desirable outcome. **b** Frontal view of complete mandible first reposition on 3D virtual planning. **c** Right lateral view of complete mandible first reposition on 3D virtual planning. **d** Left lateral view of complete mandible first reposition on 3D virtual planning. In this specific patient, there are very similar movements measured on lower incisors, B-point, and pogonium while considerable difference could be measured between lower molars due to roll adjustment and correction during such 3D virtual planning

Landmark Offsets | Measurements

Landmark	A-P	L-R	Vert	Total
--- Mandible (Model BLock)	P-/A+	R-/L+	Up +	Total
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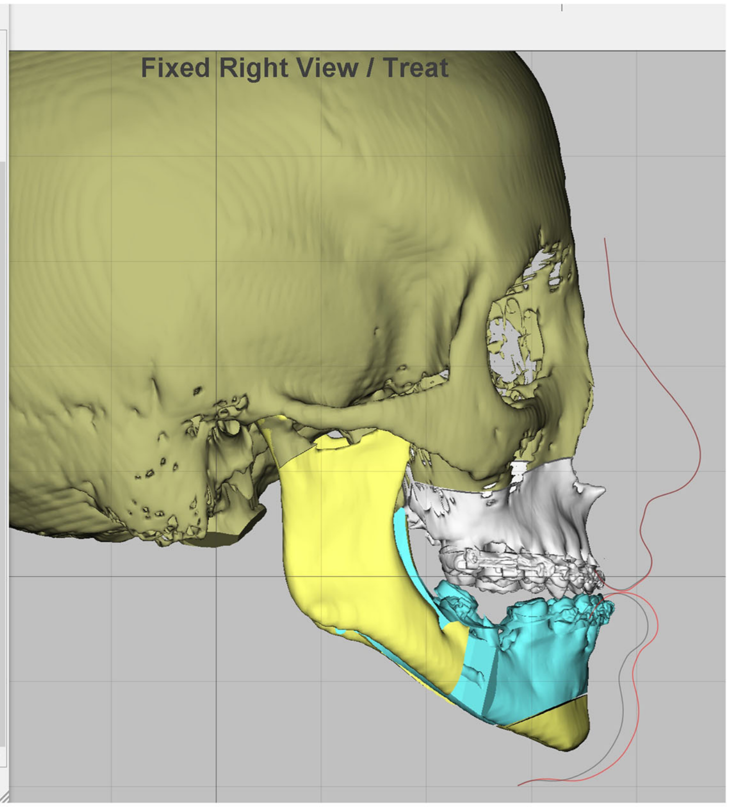

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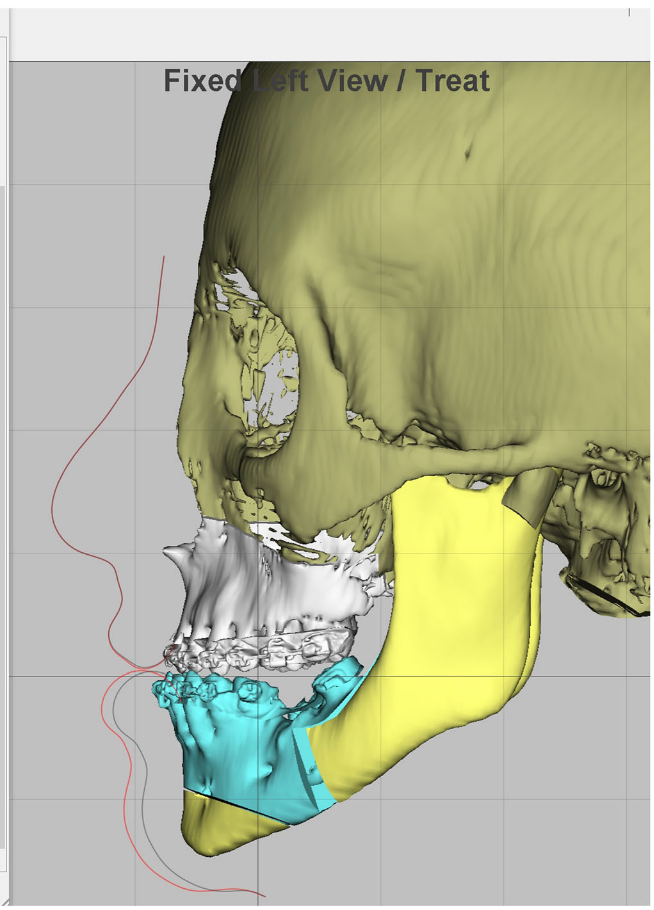

Fig. 4 continued.

Checklist

Review all tridimensional movements and compare the data obtained in steps 2 and 3. All horizontal and vertical movements and pitch axis correction are reviewed considering the prediction tracing as a guideline while roll and yaw axis, as well as dental midlines, are reviewed according to clinical analysis (Figs. 5a–d and 6a, b).

Construct surgical splint

Each software contains specific tools to generate the surgical splint, which should be designed on the computer and fabricated using a rapid prototyping machine. It is important that the surgical splint has suitable thickness to provide resistance to deformation and fracture during its use, a highly detailed and precise surface, and be free of interference with the orthodontic appliance. In addition, the surgical splint should be fabricated in a fast and economical way to improve logistics in clinical practice.

Discussion

Accurate treatment planning and execution are essential for success in orthognathic surgery, regardless of the method used to achieve its goals [12]. In order to accurately reproduce treatment plan and achieve the most reliable and predictable result, the protocol reported in this manuscript presents several advantages over a traditional tridimensional virtual treatment planning for inverted sequence in double-jaw orthognathic surgery in which treatment plan is based primarily on maxillary position.

Facial symmetry is essential for a desirable outcome after orthognathic surgery and such harmony is mainly attained by

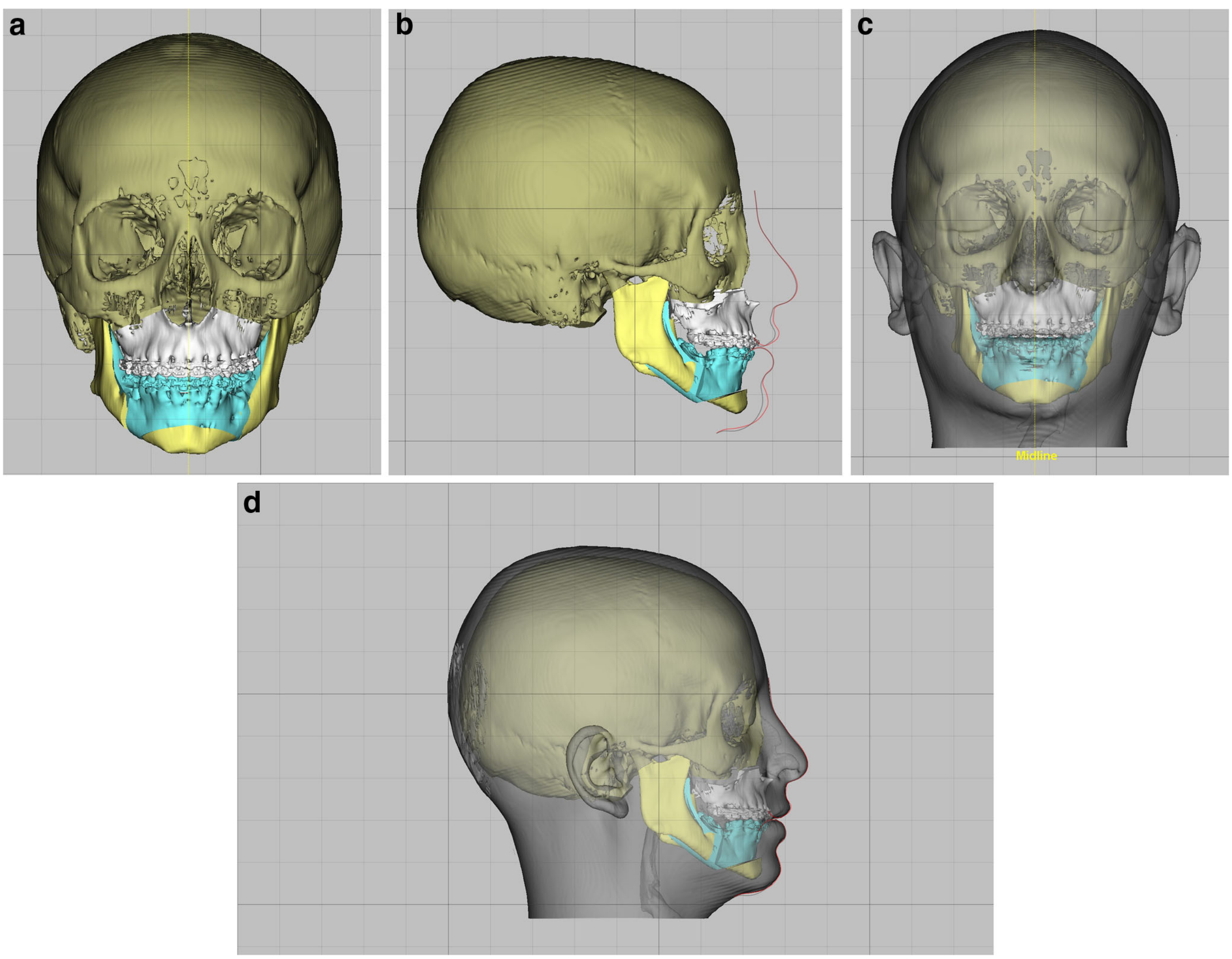

Fig. 5 Final tridimensional treatment simulation (**a** hard tissue frontal view; **b** hard tissue profile view; **c** hard and soft tissue frontal view; **d** hard and soft tissue profile view)

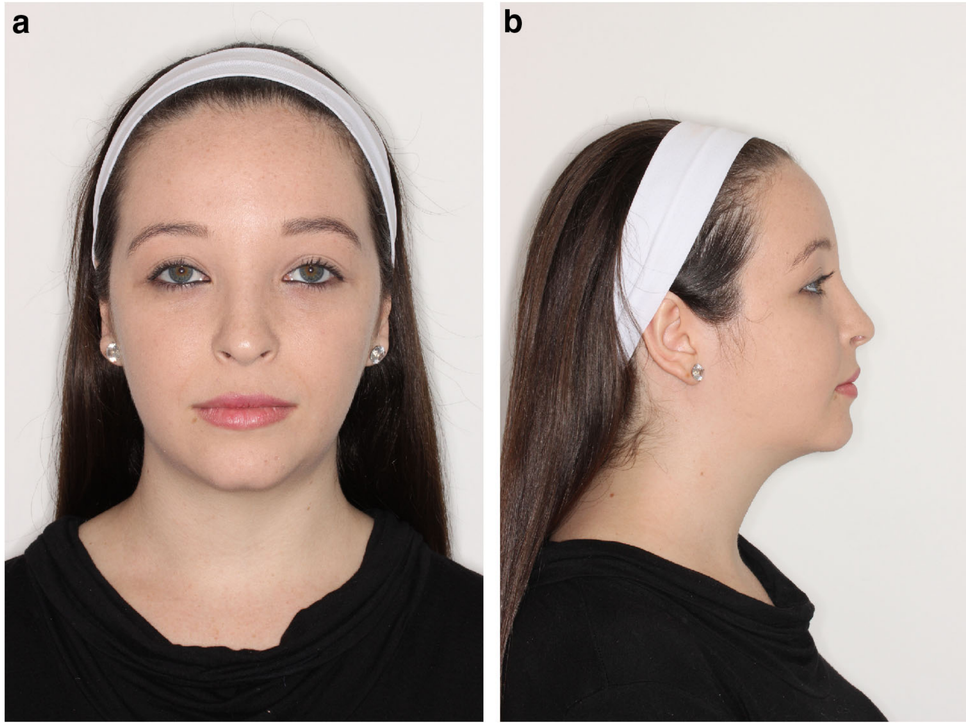

Fig. 6 **a** Postoperative facial frontal view; **b** postoperative facial profile view

correct tridimensional lower jaw position. Correction of a facial asymmetry and, most important, avoid creating new asymmetries after orthognathic surgery becomes a challenge due to the geometric complexity of the jaws and other facial structures. These situations are best managed by first repositioning the mandible during tridimensional virtual surgical planning. This sequence simplifies the asymmetry correction and avoids establishing new asymmetries as the surgeon possesses much more control of tridimensional mandibular position during the virtual planning. In contrast, once the maxilla is first repositioned and this position guides mandibular replacement, facial symmetries may be under-corrected or even new asymmetries may be created since mandibular dentition has more skeletal bulk than the maxilla and any asymmetric repositioning is much more evident (i.e., contour of the inferior borders or asymmetry in mandibular angles).

Some of tridimensional virtual surgical planning software does not allow to reset the position of the maxilla if it is repositioned first. Therefore, if one chooses to first operate the mandible on actual surgery, the software will not accurately show intermediate occlusal relationships after mandible surgery. Other software allows to reset the position of the maxilla, but it is still a limited view. Therefore, if one chooses to first reposition the mandible during tridimensional virtual surgical planning, all information of intermediate occlusal relationships for inverted sequence double-jaw orthognathic surgery are available. The surgeon can use all the tools to check and measure the intermediate position and save these information into a new slot in the software before continuing the virtual planning. Thus, during the actual surgery, the surgeon will have full access to all measurements and references, as well as ascertain the intermediate occlusion predicted in treatment plan.

Concomitantly, performing double-jaw orthognathic surgery with mandible first sequence presents several advantages over traditional “maxilla first” technique, as discussed by Ellis and Perez [2]. Unlike the traditional maxilla first method, the mandible first protocol is not affected by interocclusal relationship discrepancies or vulnerable CR position. Although the authors seek CR position during surgical planning to gather as much information as possible, an accurate CR registration is not mandatory to achieve surgical accuracy [2]. Such protocol renders an increasing attention in patients without a reliable centric relation in which the maxilla first method may be devastating for the final outcome, as presented by Posnick, Ricalde, and Ng [13].

Mandible first alternative to virtual planning and surgical sequence leads to improved results with good facial esthetics and more accurate occlusal outcomes. Both mandibular and maxillary surgical reposition show very accurate precision after a detailed and meticulous treatment plan, but mandibular surgical reposition is subject to many variables (i.e., temporomandibular joint individual position) and occasionally can lead to occlusal interferences. Aware that occlusal outcomes are more susceptible to these minimal “errors” than facial esthetics, a traditional surgical sequence may cause unstable occlusal relationship while the mandible first protocol leads to a more stable perfect occlusion without compromising facial esthetics, mainly when maxilla segmentation is required to achieve satisfactory esthetic and occlusal outcomes. Furthermore, in specific situation in which the mandible has to rotate a significant amount to allow intermediate splint to position the maxilla (i.e., large occlusal plane counterclockwise rotation), the maxilla might be positioned with the condyles out of its centric relation position. Such limitation might lead to distinct intermediate occlusion virtually planned and therefore, lead to misplacement of the maxilla and consequently jeopardize mandible position as well. In order to achieve the same final occlusion, as planned, condylar correct position is sometimes neglected or condylar torque is eminent, causing occlusal instabilities in short or long-term outcomes.

Potential disadvantages exist and should also be mentioned. The most important drawback of the protocol presented above is the fact that it is only suitable for bimaxillary orthognathic surgery in which the surgeon elects the mandible first sequence. In such sequence, complications such as unfavorable split of sagittal ramus osteotomy should be properly managed and rigidly stabilized prior to maxilla reposition, otherwise, maxilla reposition might need to be delayed. As with all new approaches and techniques, such protocol also requires previous training and a steep learning curve might be addressed as well. Although the sequence may seem complex at first, the entire process is actually simplified once the surgeon recognizes its advantages.

xAlthough the suggested protocol has been used by two authors of the study in two different centers in a fair number of patients and has been promoting suitable and satisfying outcomes, limitations of this paper and suggested protocol include lack of validation tests and, most importantly, lack of clinical trials or prospective studies confirming its accuracy and reliability. The authors also acknowledge the inherent bias of reporting a protocol when the data are based on the clinician's surgical practice. Even so, the description of such protocol must instigate pilot studies and clinical trials in order to certify its accuracy, endorse its reliability, and establish itself as an alternative to uncertain traditional virtual surgical plan sequence. Moreover, different software provides the same or similar mechanisms to the tools described in this protocol, and it should be suitable independently on the software surgeons decide to adopt.

Conclusion

In summary, the decision regarding the jaw to be operated on first in tridimensional virtual surgical planning and in the surgery itself depends on vantages and disadvantages of such protocol, as well as surgeon's preference and experience. Although success depends on a host of factors, the authors firmly believe on the accuracy and reliability of the protocol presented to virtually plan double-jaw orthognathic surgery when the mandible first sequence is indicated and suggests to consider such planning sequence to reach outstanding short and long-term outcomes.

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Compliance with ethical standards

Competing interests The authors declare that they have no competing interest.

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