Use of Three-Dimensional Medical Modeling Methods for Precise Planning of Orthognathic Surgery

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Stereolithographic (medical rapid prototyping) biomodeling allows three-dimensional computed tomography to be used to generate solid plastic replicas of anatomic structures. Reports in the literature suggest that such biomodels may have a use in maxillofacial surgery, craniofacial surgery, orthopedics, neurosurgery, otology, vascular, and nasal research. A prospective trial to assess the usefulness of biomodeling in orthognathic surgery has been performed. In 12 patients with mandibular prognathism and/or maxillary retrusion, in addition to routine preoperative cephalometric analysis, preoperative high-resolution (cutting slice thickness of 1 mm) three-dimensional computed tomography scan of the patients was obtained. Raw data obtained from computed tomography scanning was processed with a Mimics 9.22 Software (Materialise's Interactive Medical Image Control System, Belgium). Fabrication of three-dimensional medical models was obtained through a process called powder depositional modeling by use of a Spectrum Z 510 3D Color Printer (Z Corporation, Burlington, MA). Alveolar arches of the maxilla and mandibula of the models were replaced with orthodontic dental cast models. Temporomandibular joints of the models were fixed with Kirschner wire. Maxillary and mandibular bony segments were mobilized according to preoperative orthodontic planning done by analysis of cephalometric plain radiographs. The relation between proximal and distal mandibular segments after bilateral sagittal split osteotomies were evaluated on models preoperatively. The same surgeon had a role in both model cutting preoperatively and as an instructor preoperatively. The same bony relation was observed both in preoperative models and in the perioperative surgical field in all patients. Condylar malpositioning was not observed in any of the patients. Studying preoperative planned movements of osteotomized bone segments and observing relations of osteotomized segments of mandibula and maxilla in orthognathic surgery increased the intraoperative accuracy. Limitations of this technology were manufacturing time and cost.

Key Words: Orthognathic surgery, precise preoperative planning, three-dimensional medical modeling

The complexity of craniomaxillofacial anatomy combined with the variation encountered by the reconstructive surgeon makes surgery a conceptually difficult task in explanation, planning, and execution.[1] The need for clear images of cranial morphology played a large part in the development of three-dimensional (3D) imaging and more recently solid anatomic modeling. Improvements in computer hardware and software have not only made 3D images more realistic and detailed, but also allowed shape analysis and the measurement of distance and volume.[1] With the use of 3D medical modeling, it became possible to obtain an exact copy of the patient's skull and facial structures for preparation of implants to fit defective areas. Additionally, recent developments in software technology not only enabled simulation of osteotomies and movement of bony fragments, but also allowed soft tissues to be assessed after the underlying bony architecture has been manipulated.

Effectiveness and safety of using computer-generated alloplastic (hard tissue replacement) implants for the reconstruction of craniofacial region,

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use of medical modeling technology in craniofacial surgery and use of such biomodels compared with standard imaging modalities have already been evaluated.[1–4] However, effectiveness of preoperative use of life-sized, 3D models in orthodontic surgery has not been well evaluated yet.

An acrylic splint is used to transfer the preoperative treatment plan to the operating room, allowing for accurate intraoperative positioning of the maxilla relative to the mandible or of the mandibula relative to the maxilla depending on preoperative planning in single jaw surgery. When repositioning of both the maxilla and the mandible is planned, an intermediate splint in addition to the final splint is fabricated. This intermediate splint is used to align the osteotomized maxilla to the nonoperated mandible, and a final splint is used to position the mandible to the repositioned maxilla.

Although use of an acrylic splint may help adjust the anteroposterior positioning of the maxillary alveolar arch by stabilizing the dental casts of both maxillary and mandibular teeth in their final position in Le Fort I surgery, it is the surgeons' task to determine amount of impaction or downfracture of the maxillary alveolar arch to adjust the vertical length of the face. In the same way, although acrylic splints are useful in adjusting the anteroposterior positioning of the distal mandibular segment in bilateral mandibular osteotomies, they cannot help either adjusting the amount of rotational movement of distal mandibular segment on x-axis or stabilization of proximal mandibular segments in the glenoid fossae in bilateral sagittal split osteotomies.

In this particular study, we aimed to demonstrate the increase of accuracy in orthodontic surgery and prevention of condylar malpositioning and condylar sag by using life-sized, 3D models of our patients preoperatively.

PATIENTS AND METHODS

The study was designed as a prospective trial to assess the usefulness of biomodeling in orthognathic surgery. Six male and six female patients 18 to 29 years of age (mean, 29.4 years) were evaluated with 3D BT in addition to routine preoperative cephalometric analysis. Mean follow up was 12.66 months (range, 6–15 months).

Raw data obtained from computed tomography scanning was processed with a Mimics 9.22 Software (Interactive Medical Image Control System, Materialise, Inc., Leuven, Belgium). Fabrication of 3D medical models was obtained through a process called powder depositional modeling by use of a Spectrum Z 510 3D Color Printer (Z Corporation, Burlington, MA).

Preoperative bracket application on teeth made interference with computed tomography scanning and alveolar arches of the maxilla and mandibula of all models had artifacts, which reduced the accuracy of the models. Additionally, teeth are composed of enamel and dentin with different radiologic densities, which also contributes decreasing the accuracy of 3D medical modeling of the teeth.[5] Therefore, alveolar arches of all models were replaced with orthodontic dental cast models to increase the details of dental anatomy on the fabricated model, which is important in exact fitting of dental splints to the fabricated model. Mandibular condyles were attached to the glenoid fossae with Kirschner wire to make sure that the condyles were kept in exact position during preoperative model surgery. Maxillary and mandibular bony segments were osteotomized and mobilized according to preoperative orthodontic planning done by analysis of cephalometric plain radiographs. Both the relation between proximal and distal mandibular segments after bilateral sagittal split osteotomies and the relation between mandibular and maxillary alveolar segments were evaluated on models preoperatively. Dental splints, used in preoperative model surgery, were also used in operations of the same patients.

Acrylic dental splints of the patients were fabricated by using dental casts of patients adapted on semiadjustable articulators. To simulate the planned operative procedures, a model surgery is performed based on clinical assessment and cephalometric prediction tracings. The models are mounted on a semiadjustable articulator and the relative position of the dentition within the facial form of the patient is simulated. When the dental casts are in their final position, an acrylic splint is fabricated. This acrylic splint is used to transfer the treatment plan to the patient in the operating room, allowing for accurate intraoperative positioning of the maxilla relative to the mandible or of the mandibula relative to the maxilla. The acrylic splint ideally contains indentations of the incisal edges and cusps of the teeth, and it is trimmed on the buccal surfaces to allow good hygiene and permit visual verification of proper seating at the time of surgery.[6] When repositioning of both the maxilla and the mandible is planned, an intermediate splint in addition to the final splint is fabricated. This intermediate splint is used to align the osteotomized maxilla to a nonoperated mandible, and the final splint is used to position the mandible to the repositioned maxilla.

Technically, standard bilateral sagittal split osteotomies were performed on patients. The proximal segment of the mandibula was stabilized with an Allice clamp. Then the anterior aspects of the proximal segments of the patient's mandibula were shortened the same amount observed to juxtapose the margins of the proximal and distal fragments on the preoperative model in mandibular prognathism or distal segments were advanced until the same amount of gap as developed on the preoperative model developed between the margins of the proximal and distal fragments of the patient's mandibula in mandibular retrusion before fixation of the mandibular segments. First, the bicortical mandibular screw was always applied to the point where the proximal and distal mandibular segments came in contact with each other after planned movements of distal mandibular fragment unless this point targets the inferior alveolar nerve and highly increase the likelihood of nerve damage. Before application of the second screw for fixation, meticulous attention was paid to keep the gapping between mandibular fragments after planned movements to prevent applying load to the temporomandibular joints and bone grafts were used when necessary. The orientations of condylar positions of each patient in glenoid fossa were checked by both opening the maxillomandibular fixation intraoperatively to observe the occlusion patterns of the patients and obtaining the Panorex of the patients postoperatively.

Because of routine use of semirigid fixation of the mobilized alveolar segments with anteriorly applied two plates to only nasomaxillary buttress of maxilla after Le Fort I osteotomy (instead of use of four plates to nasomaxillary and pterygomaxillary buttresses) and with only two bicortical screws to each side of the mandibula after bilateral sagittal split osteotomy (instead of three screws to each side), maxillomandibular fixation with elastics was applied to all patients for 15 days in the postoperative period. Maxillomandibular fixation was done 48 hours after surgery.

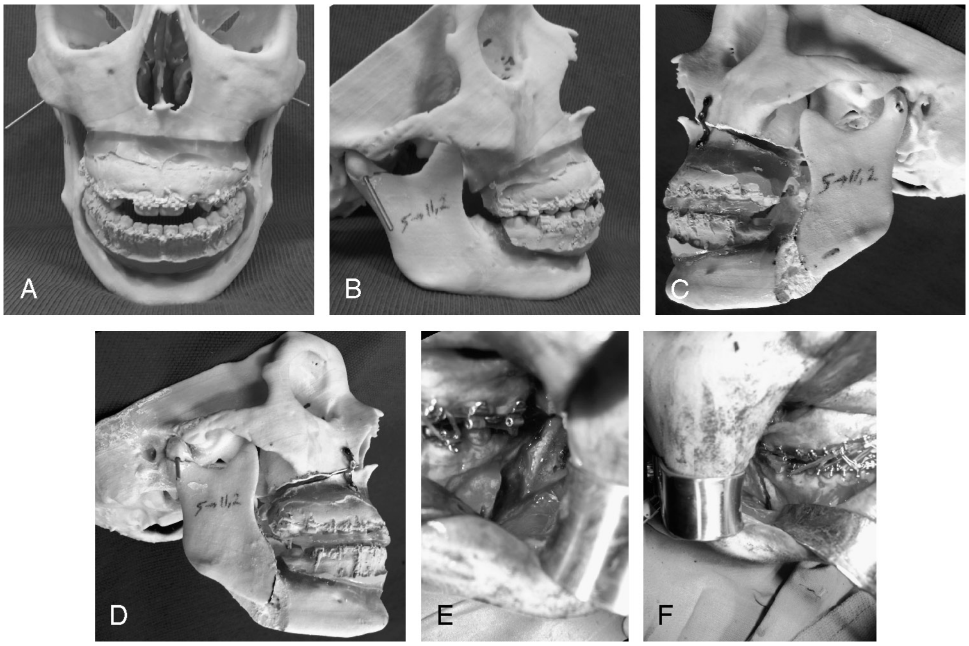

Fig 1 Preoperative appearance of the maxillomandibular discrepancy of the patient on model (A) from the anterior view, and (B) from the right lateral view. (C) Appearance of the left side of the mandibula after 4-mm mandibular setback (linear backward movement) in z axis and for 3-mm rotational movement to the right side in the y axis to correct both the mandibular prognathism and midline shift of mandibular incisive teeth. It seems as if the mandibula was advanced forward on that side because of the simultaneous rotational movement of the mandibular segment to the opposite side. (D) Appearance of the right side of the mandibula after the same movements. Mandibular segments seem to be in much closer contact with each other when compared with the opposite side. (E) Intraoperative view of the left side of the mandibula of the same patient. Almost the same relationship between the proximal and distal mandibular segments can be observed that has been seen on the model before. (F) Intraoperative view of the right side of the mandibula of the same patient. Almost the same relationship between proximal and distal mandibular segments can be observed that has been seen on the model before.

Patient No. 1

A 26-year-old female patient was scheduled to have bilateral sagittal split osteotomies for 4-mm mandibular setback (linear backward movement) in the z axis and for 3-mm rotational movement to the right side in y axis to correct both the mandibular prognathism and midline shift of mandibular incisive teeth (Fig 1A, B).

There was asymmetric posterior movement on the right and left side of the distal mandibular segment because of the rotational movement of the distal segment in addition to the linear set back movement. Since the rotation was done to the right side, it was reflected as if the right side was moved more posteriorly when compared with the left side (Fig 1C, D). Additionally, there was a gap between proximal and distal mandibular segments on the left side (on the opposite side of rotation) and the proximal and distal segments of the mandibula were in close contact with each other on the right side (on the same side of the rotation). The same relations between the right and left sides of the patient were observed intraoperatively (Fig 1E, F).

Patient No. 2

A 21-year-old male patient was scheduled to have Le Fort I osteotomy for 4-mm advancement and 2-mm impaction of the maxillary alveolar process and bilateral sagittal split osteotomies for 4-mm mandibular setback (linear backward movement in z axis) and for 4-mm rotational movement to the left side in the y axis to correct both the mandibular prognathism and midline shift of mandibular incisive teeth (Fig 2A, B).

There was asymmetric posterior movement on the right and left sides of the distal mandibular segment because of the rotational movement of the distal segment in addition to the linear setback movement. Since the rotation was done to the left side, it was reflected as if the left side was moved more posteriorly when compared with the right side. Additionally, there was a gap between proximal and

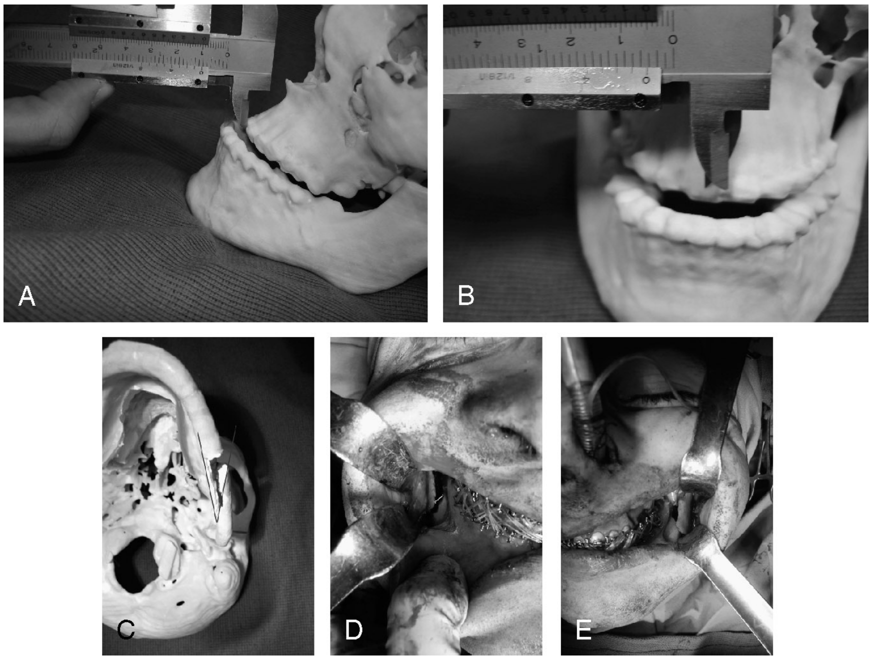

Fig 2 (A) Preoperative maxillomandibular discrepancy in the anteroposterior direction. (B) Preoperative midline shift in the frontal plane. (C) Angulation between proximal and distal segments of the mandibula on the opposite side of the rotation. Note the bones are in touch with each other posteriorly and a gap develops in between them anteriorly so that angulation faces anteriorly. (D) Intraoperative view of the right side of the mandibula of the same patient. Note that the overlapping segments of the bones resulting from mandibular setback are compensated by the rotational movement to the left side and it is only the anterior gapping (marked with white line) apparent after planned movements on the left side. (E) Intraoperative view of the left side of the mandibula of the same patient. Note that the overlapping segments of the bones seems to be more that one expects because of the additive effect of mandibular setback and rotational movements on the same side of rotational movement.

distal mandibular segments on the right side (on the opposite side of rotation) and the proximal and distal segments of the mandibula were in close contact with each other on the left side (on the same side of the rotation) (Fig 2C). Same relations between right and left sides of the patient were observed intraoperatively (Fig 2D, E).

Patient No. 3

A 24-year-old male patient was scheduled to have bilateral sagittal split osteotomies for 6-mm mandibular setback (linear forward movement in the z axis) to correct the class III malocclusion for 3-mm rotational movement to the right side (rotational movement in the y axis) to correct the midline shift of mandibular incisive teeth and for 2-mm rotational movement in clockwise direction (rotational movement in z axis) to correct the asymmetric closure pattern of molar teeth (Fig 3A, B). There was asymmetric posterior movement on the right and left side of the distal mandibular segment because of the rotational movement of the distal segment in addition to the linear setback movement (Fig 3C, D). Since the rotation was done to the right side, it was reflected as if the right side was moved more posteriorly when compared with the left side. Additionally, there was a gap between proximal and distal mandibular segments on the left side (on the opposite side of rotation) and the proximal and distal segments of the mandibula were in close contact with each other on the right side (on the same side of the rotation) (Fig 3E). Moreover, because of rotational movement around the z axis, there was also coronal triangular gapping between distal and proximal segments of osteotomized mandibula in such a way that the angulation between bone segments develops at the superior part of the osteotomized bones (leading to gapping inferiorly) on the left side (ie, the side of downward rotation) and at the inferior part of the osteotomized bones (leading to gapping superiorly) on the side of upward rotation (ie, the side of upward rotation). The same relations between the right and left sides of the patient were observed intraoperatively (Fig 3F, G).

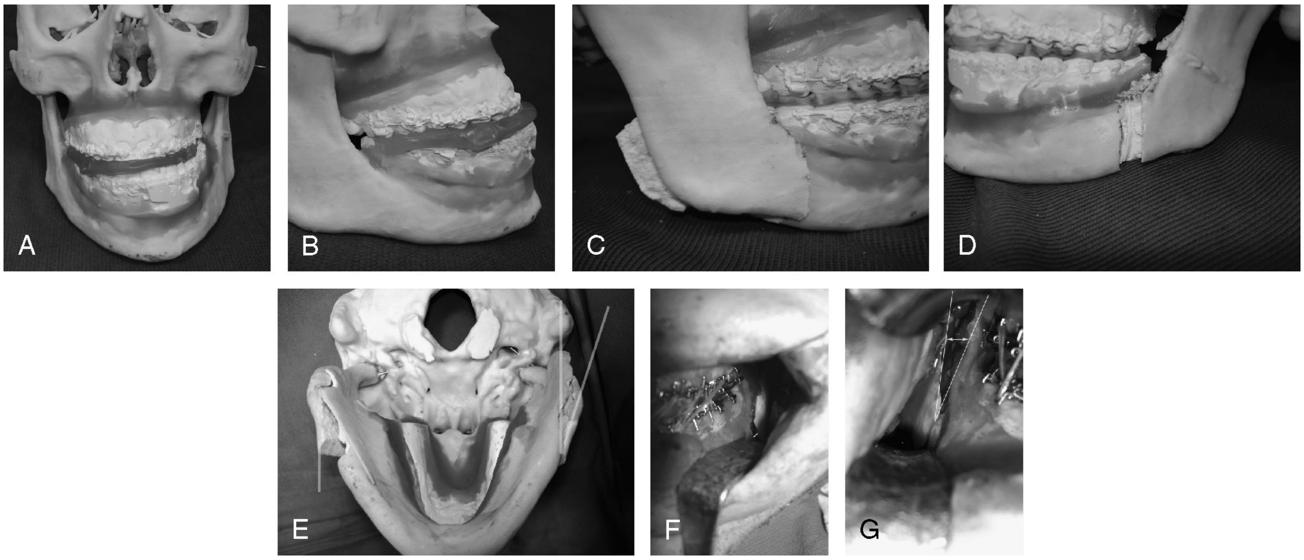

Fig 3 Preoperative appearance of maxillomandibular discrepancy of the patient on model (A) from the anterior view and (B) from the right lateral view. (C) View of the right side of the mandibula after preoperative movements of distal mandibular segment done on the model. Note that the mandibular setback and rotational movements increase the amount of overlapping bone segments. (D) View of the left side of the mandibula after preoperative movements of distal mandibular segment done on the model. Although the mandibula was setback, instead of bony overlap, one observes bones are split over each other on left side as if it was seen in mandibular advancement. (E) Appearance on mandibula from bottom after rotation to right. On the side of rotation (right side), the bones are in touch with each other anteriorly and a gap develops in between them posteriorly, so that angulation faces posteriorly; whereas on the opposite side (left) of rotation, the bones are in touch with each other posteriorly and a gap develops in between them anteriorly so that angulation faces anteriorly. (F) Intraoperative view of the left side of the mandibula, showing the anteriorly located gapping. (G) Intraoperative view of the right side of the mandibula showing posteriorly located gapping (line between two arrowheads) and angulation (white solid lines).

RESULTS

Same bony relation was observed both in preoperative models and in the perioperative surgical field in all patients. None of the patients had infection at the maxillary osteotomy side. Unilateral local infection at the osteotomy side was seen in only one patient after double jaw surgery. It was treated with oral antibiotics and follow up of that patient was uneventful otherwise.

Condylar malpositioning was not observed in any of the patients. Although postoperative maxillomandibular fixation with elastics was applied routinely to all patients for 15 days, none of the patients had complaint related with temporomandibular joint discomfort such as pain, restricted joint motion, and so on.

DISCUSSION

The critical point in performing mandibular osteotomies in orthognathic surgery is the stabilization of the condyles in glenoid fossae, whereas the distal segment of the mandibula is repositioned over proximal segments according to preoperative orthodontic planning before fixation of these segments. One of the most common technical complications of mandibular surgery is inability to orient and maintain condylar position with precision in the glenoid fossa, namely condylar malpositioning. There is evidence that condylar positioning after bilateral sagittal split osteotomy of the mandible influences postoperative skeletal stability.[7–11]

Several different types of rigid condylar fixation techniques have been reported. The primary intent of each of these techniques is to determine a proper condylar position before surgery and obtain a bite registration in this position. At the time of surgery, before creating the osteotomy cuts, the ramus is oriented in its proper position with the presurgical bite, and a rigid fixation appliance is attached to some stable landmark. This procedure fixates the ramus in a predetermined position. Next the rigid fixation appliance is removed, the osteotomy is completed, and the appliance is reapplied, placing the condyle in the proper position. The proximal segment is then fixated to the repositioned distal segment of the mandible. Long-term effectiveness of these techniques, however, is somewhat limited. Additionally, another drawback of all of these techniques is the increased operation time. Moreover, surgical fixation techniques that necessitate an intervention to the temporomandibular joint may lead to temporomandibular joint dysfunction in the postoperative period.

Sagittal split osteotomy is the most frequently used osteotomy for correction of skeletal problems in the mandible, because it provides better bone contact for bone healing and bicortical screwing for better fixation, therefore, reduces the risks of nonunion.[12,13] Sliding the mandibular segments over each other enables to keep the bone contact between the osteotomized mandibular segments.

In a simple anteroposterior linear displacement operation, one may easily guess the amount of bone that should be removed from the anterior aspect of the proximal segment juxtaposing the margins of the proximal and distal fragments in mandibular prognathism or the gap developing between the proximal and distal fragments in mandibular retrusion. Additionally, simple anteroposterior linear displacement operation does not lead to any angulation between the osteotomized mandibular segments. The clinical situations, however, are not that simple in most of the cases. In addition to simple linear anterior posterior movements, rotational movements for correction of deviations from midline and/or the occlusion pattern are necessary.

Deviations of mandibular incisive teeth from midline can be corrected by a linear movement of distal mandibular segment on the x axis or a rotational movement of distal mandibular segment around the y axis.[14] Because the osteotomized distal segment of the mandibula stays between two lateral mandibular segments (ie, ramus and the condyles), any linear movement on the x axis will lead to lateral angulation of the condyle on the same side of movement and either medial angulation of the contralateral condyle or gapping between the proximal and distal segments of the mandibula. In other words, it is not possible to move the median osteotomized segment of the mandibula on the x axis without applying load to the temporomandibular joints. Therefore, skeletal deformities of the mandibula, leading to deviation of mandibular incisive teeth from midline are preferred to be corrected by rotational movement of distal mandibular segment around the y axis. Isolated rotational movement of the distal mandibular segment around the y axis leads to development of axial triangular gapping between distal and proximal segments of osteotomized mandibula in such a way that the angulation between bone segments develops at the distal part of the osteotomized bones (leading to gapping posteriorly) on the same side of rotation (Fig 4A) and at the proximal part of the osteotomized bones (leading to gapping anteriorly) on the opposite side of rotation (Fig 4B). Additionally, proximal segment juxtapose over the distal segment on the

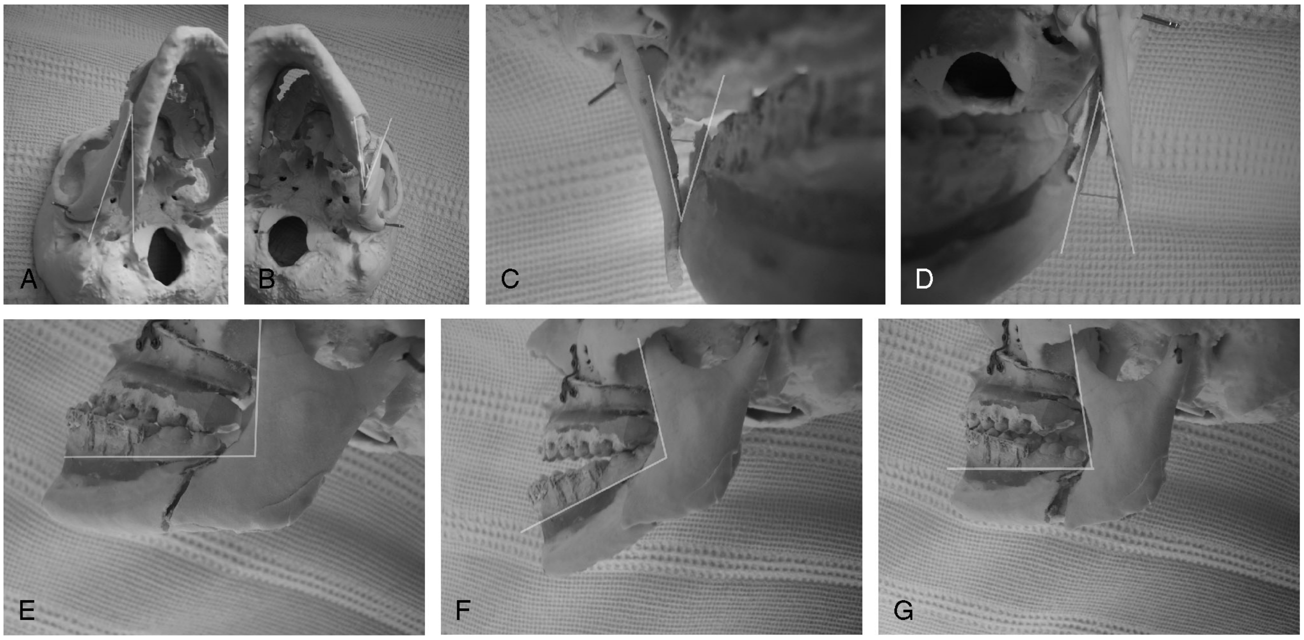

Fig 4 In addition to rotation around the y axis, the distal mandibular segment can be rotated around the x and z axes in space. (A) Angulation between proximal and distal segments of the mandibula on the same side of the rotation around the y axis. Note the bones are in touch with each other anteriorly and a gap develops in between them posteriorly (gap between two red arrowheads) so that angulation faces posteriorly. (B) Angulation between proximal and distal segments of the mandibula on the opposite side of the rotation around the y axis. Note the bones are in touch with each other posteriorly and a gap develops in between them anteriorly (gap between two red arrowheads) so that angulation faces anteriorly. In case of rotation around the z axis, the angulation will face either up or down, rather than anteriorly or posteriorly, depending on the direction of the movement. In case of rotation in the clockwise direction around the z axis (ie, rotation of the right side of the distal mandibular segment up and rotation of the left side of the distal mandibular segment down); (C) on the right side, the distal and proximal segments of the mandibula are in touch with each other inferiorly and a gap develops in between them superiorly (gap between two red arrowheads) so that angulation faces superiorly. (D) On the left side, the segments of the mandibula are in touch with each other superiorly and a gap develops in between them inferiorly (gap between two red arrowheads) so that angulation faces inferiorly. In case of rotation around the x axis, the angle between the ramus and body of mandibula changes. (E) Neutral position without any rotation around the x axis. (F) Downward rotation of the distal mandibular segment (to correct the overbite deformity of incisive teeth) increases the angle between the ramus and the body of the mandibula. (G) Upward rotation of distal mandibular segment (to correct the anterior open bite) decreases the angle between the ramus and the body of the mandibula.

same side of rotation, whereas gapping develops between proximal and distal segments as if the distal segment had anterior advancement on the opposite side of rotation.

Distal mandibular segment may be rotated around the z axis in accordance with maxillary segment to correct the occlusional plane in patients with facial asymmetry as a result of disparity of the vertical heights of each sides of the face such as hemifacial microsomia. Isolated rotational movement of distal mandibular segment around the z axis leads to development of coronal triangular gapping between distal and proximal segments of osteotomized mandibula in such a way that the angulation between bone segments develops at the inferior part of the osteotomized bones (leading to gapping superiorly) on the side of upward rotation (Fig 4C) and at the superior part of the osteotomized bones (leading to gapping inferiorly) on the side of downward rotation (Fig 4D).

To correct an open bite deformity, the distal mandibular segment may be needed to be rotated around the x axis. Although this movement does not cause any gapping between proximal and distal mandibular segments, it still changes the angle of fixation (Fig 4E–G).

Such rotational movements of the distal mandibular fragment does not only make the intraoperative planning more difficult, but also make the preoperative interfragmental relationship estimation of mandibular segments almost impossible. If anteroposterior advancement and the rotational movement around the y axis are required in the same patient, rotational movement will increase the effect of linear movement on one side while hiding its effect on the other side. As an example, in a 4-mm mandibular setback operation, one may expect to observe approximately 4-mm proximal bone juxtapose over the distal segment. In addition to this linear movement, if 4-mm rotational movement to the right side is planned in this patient, then one may observe just an angulation without any gapping on the right side and approximately 8-mm gapping with reverse angulation on the left side.

Prevention of naturally developing interfragmental positional relationships (angulations) after rotational movements around the z and y axes during mandibular bone fixation is important not to apply load to the temporomandibular joints. To keep the correct interfragmental relationship between proximal and distal segments, first bicortical screw should be applied to the point where fragments are in touch with each other. Second and if necessary, third screws should be applied without disturbing the angulation and gapping between the fragments. Gapping may need to be filled with bone grafting or with demineralized bone matrix both to prevent the closure of gapping and to increase bone healing.

By obtaining life-sized, 3D models of our patients preoperatively, we got the chance to perform the planned osteotomies before the operation. Temporomandibular joints of the models were fixed with Kirschner wire application instead of temporomandibular joints of the patients. Therefore, time spent for rigid condylar fixation techniques was spared. Additionally, we were quite sure that we precisely maintained condylar position within glenoid fossa if we could fix the mandibular fragments in the same interfragmental relation with the one we observed on models preoperatively. Although operating on 3D medical models cannot reflect the exactly the same scenario as in the operating room because of lack of effects of soft tissues cannot still be simulated on the medical models, we experienced that there is nothing like a model in your hands preoperatively, no matter how good the 3D graphics are. Performing osteotomies on the models makes the surgeon more acquainted with the anatomy of the region. Additionally, surgical models are inestimable tools for surgical training of the residents.

The authors thank Kutsal Tuac for her contributions in evaluation of raw 3D BT data of the patients with Mimics 9.22 Software (Interactive Medical Image Control System, Materialise, Inc., Leuven, Belgium) and in fabrication of three-dimensional medical models with Spectrum Z 510 3D Color Printer (Z Corporation, Burlington, MA).

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