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Technical Note
Orthognathic Surgery

Computer-assisted three-dimensional surgical planning: 3D virtual articulator: technical note☆

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Abstract. This study presents a computer-assisted planning system for dysgnathia treatment. It describes the process of information gathering using a virtual articulator and how the splints are constructed for orthognathic surgery. The deviation of the virtually planned splints is shown in six cases on the basis of conventionally planned cases. In all cases the plaster models were prepared and scanned using a 3D laser scanner. Successive lateral and posterior-anterior cephalometric images were used for reconstruction before surgery. By identifying specific points on the X-rays and marking them on the virtual models, it was possible to enhance the 2D images to create a realistic 3D environment and to perform virtual repositioning of the jaw. A hexapod was used to transfer the virtual planning to the real splints. Preliminary results showed that conventional repositioning could be replicated using the virtual articulator.

Keywords: dysgnathia; cephalometry; registration; articulator; virtual reality; planning; 3D.

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In many fields, computer-assisted planning has enabled surgeons to perform complex interventions[3,5]. New techniques, such as navigated surgery [1,4,6] have been established in craniofacial surgery.

To improve treatment and results, systems such as Gaertner's[2] virtual articulator have been used to simulate static or dynamic occlusion. This project used natural reference points acquired by means of a pointer device. The relation between the models is established by means of a registration imprint and movement is recorded by a jaw-motion-analyzer (Zebris Medical GmbH, Isny, Germany), but the results cannot be retransferred to reality.

In another project[7], plaster models were set up in the articulator; they were conventional in respect to the calibrated double-base method – muensteraner model operation system (KD-MMS). The models were later placed into the hexapod and transformed by an operation planning tool to find the optimum position. The pneumatically fixed models were fixed into their final position by applying plaster. The surgeon can reference the real cement models and the displayed transformation data in the program.

Most comparable projects are restricted to soft-tissue simulation based on CT data with the corresponding exposure dose. Even if the jaw is reposition, the main aim of these projects is improved post-operative aesthetic appearance and function of the patient's stomathognatic system.

The project presented here requires only two routine cephalometric images, signif-

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icantly minimizing the X-ray and radiation dose to the patient, and non-invasive fixation of the patient during exposure. Using the two images, the authors developed a virtual articulator including anatomical registration and controlled repositioning of the jaws. The transformation ends with the creation of a real-world splint for intra-operative use. The aim is to improve the accuracy of orthognathic surgery by advancing 2D images with the addition of the third dimension, and using the enhanced 3D environment in the computer-assisted planning system.

Material and methods

Six patients whose treatment had been planned conventionally were divided into two groups of three patients; one group requiring reposition of a single jaw and the other repositioning both jaws. The radiological images described below were taken from all six patients, and two pairs of plaster models of the jaws were built. One model pair was used for conventional planning using a semi-adjustable articulator and the other pair for the virtual planning method. The implemented virtual articulator orientates on the selected rotation points of the caput mandibulae.

In the conventional method, a wax imprint of the patient was created and, to achieve an exact anatomical constellation, a face bow (KaVo, Biberbach, Germany) was used.

Cephalometric X-ray

Patients were examined routinely by means of a digital radiological device (ORTHOPHOS XG^{Plus}, Sirona, Bensheim, Germany) with a cephalometric attachment using mainly Sidex version 5.54 (Sirona, Bensheim, Germany). This attachment has a three-point fixation unit (left/right porion and glabella) which is fixed to a rotation table at the top of the cephalometric attachment giving a virtual rotation axis through the patient. With the help of this unit the patient is always positioned at the same distance from the image-plane and in the field of view of the X-ray. For this study, one digital image was taken from the posterior-anterior and one from the lateral direction.

Positioner and initialization object

In order to be able to transfer the virtually planned splints into reality, the plaster models have to have a well-defined position and orientation, which has to be reproducible in the virtual environment.

The X1med3D positioner (Med3D, Heidelberg, Germany; Fig. 1) has six arms enabling the user to set up every movement (including rotations, tilting, moving) with an accuracy of 1/10 mm (manufacturer's information). On the arms, there is a scale for setting up defined positions of the table. The table consists of an embedded Adesso-split (Baumann Dental GmbH, Keltern-Ellmendingen, Germany) and three linear, independent landmarks that simplify the referencing of the center and orientation of the table. Above the table, there is a stamp-like attachment (Fig. 1) with an Adesso-split.

For specifying a fixed working area and to fix the orientation of the stamp, an initializing object was created (Fig. 1). It consists of a cylinder with a height of 10 cm with a fixed Adesso-split plate on either side. The split plates are mirrored on an axis going through the center of the cylindrical object. By positioning this object on the table, setting all arms of the hexapod to the same length and pushing the stamp onto the object, the working area was defined and was fixed by the distance holder (Fig. 1). The adjustable range is between 7.5 cm and 14 cm.

3D laser scanner

Scanning of the defined models was performed by a DigiScope (3D Alliance Inc., Bischoffen, Germany), which is a laser-based 3D coordinate-measuring device with a measuring volume of $200 \times 200 \times 200$ to $600 \times 600 \times 600$ mm with 3 (maximum 6) movement axes. The digital optical sensors have a recurrence accuracy of 8 μm.

Microscribe G2x

For measurement of the deviation between conventional and computer-assisted planned splints, a MicroScribe G2X (Immersion Corporation, San Jose, USA) was used. This is a high-performance sensor for tracking the position and orientation of the stylus tip. Its working space is a sphere of 1.27 m and it has an accuracy of 0.23 mm measured on 100 points ANSI sphere (manufacturer's information).

Procedure

The scheme (Fig. 2) shows the different stages, such as data acquisition, preparation of registration, reposition and return of the planned splints into the real world. Data acquisition and preparation of the models are described above.

Planning was carried out by a surgeon and a technician. The surgeon identified the points on the models and images and undertook the planning. The technician used the same segmented points and could refer to the real models and the conventionally planned splints.

Preparation of the models

After initializing the X1med3D (Fig. 1), the mandible and the maxilla were cemented to the Adesso assembly disc using the wax imprint or, in two cases, the conventionally planned starting splint for fixing the relation. The stamp was fixed in this position, resulting in a horizontal-only volume expansion while the cement dries.

Through this procedure, the authors held the stamp at a set distance and fixed the models at a specific distance and defined unambiguous orientation to the plate.

Transfer of the models into the virtual word

Before the scanning procedure, the plate of the hexapod carrying the cement model was mounted onto the table of the scanner. Starting with the three landmarks on the plate, each model was scanned from different sides with a small advancement of the scanner and a high resolution using the ScanOS (3D Alliance Inc., Bischoffen, Germany) software.

For performance reasons, the number of points was reduced from 2.75 million to a maximum of 362,000. This was achieved by removing doubled points, unneeded points and by a substantial reduction of points at less important sites, such as the palate. The software used was Rapidform2006 (INUS Technology, Seoul, Korea). The number of points was reduced and the surface smoothened, without geometric loss.

Transformation of the 2D images into a 3D environment

In order to be able to reference radiological images to each other at the time the patient was scanned, information on the fixed geometric metrics of the ORTHOFLOW XG^{PLUS} and on the images' size and resolution was required. With the information on the size and resolution, which can be found in the Sidex files, the images can be aligned (Fig. 3). For finding the rotation axis of the images, the user has to pick the porions in each of the

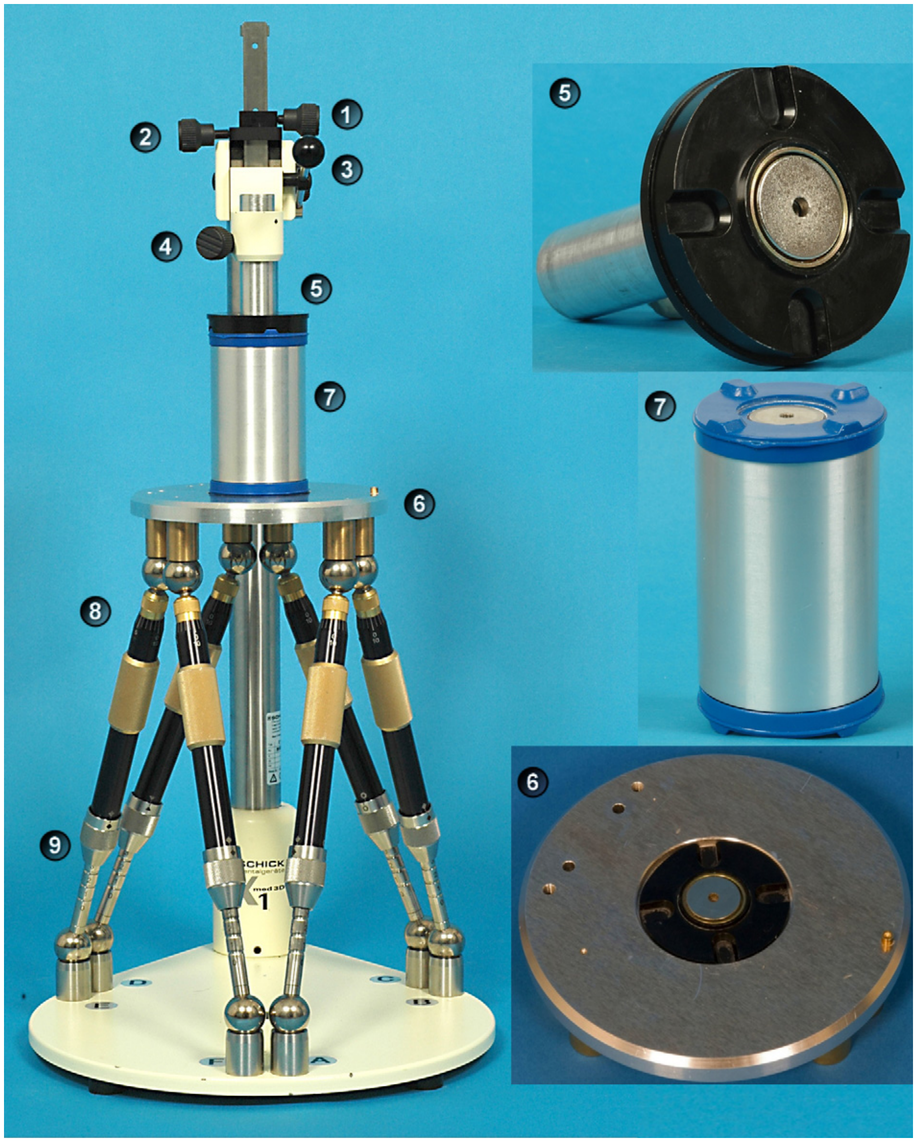


Fig. 1. The X1med3D with the modified plate and stamp using the Adesso mounting plate while initializing the distance with the initialization object. Also shown are the fixations for downward distance. (1) Fixation of translation in the z-direction, (2) fixation to hold the distance on the z-axis, (3) lever to adjust the distance in the z-direction, (4) fixation of the stamp, (5) stamp with Adesso-split plate, (6) the modified plate with Adesso-split plate, (7) initialization object with two Adesso-split discs, (8) mm scale and (9) cm scale of the X1med3D.

images, which can be accomplished in a separate dialog showing the appropriate image in full resolution. Reconstructing the path of the X-ray, beginning at the center of the line connecting the left and right porions of each image and the virtual source of the X-ray, at a distance of 230 mm (manufacturer's information) the intersection with the virtual rotation axis can be found. By bringing these points onto one point and rotating one of the images by 90° the 3D environment is established (Fig. 3). The scene now shows the situation at the time the patient was scanned, including the rotation the patient performed before the second image was taken.

The 3D points of the selected porions are the intersection points of the reconstruction of the corresponding X-ray paths of each image.

The center of the left and right caput mandibulae (Fig. 3) are selected to construct the rotational axis of the virtual articulator. In the case of planning to reposition the maxilla, the spina nasalis anterior has to be selected, building the Camper's line for a possible transformation in the posterior-anterior direction.

Another group of three points have to be picked, including the incisal and buccal hunches of the teeth 16 and 26, for placing the maxilla models into the environment.

The origin of the coordinate system was transferred to the center of the line connecting the selected 3D points of the center of the caput mandibulae. The x-axis was rotated into this line intersecting the two points and creating the rotation axis for dynamic closure of the mandible by means of the virtual articulator.

Registration

In order to reproduce the real initialized position of the models in the 3D scenario, the virtual models were matched with the origin by using the automatically selected landmarks on the virtual table (Fig. 4). The upper model was rotated around the center

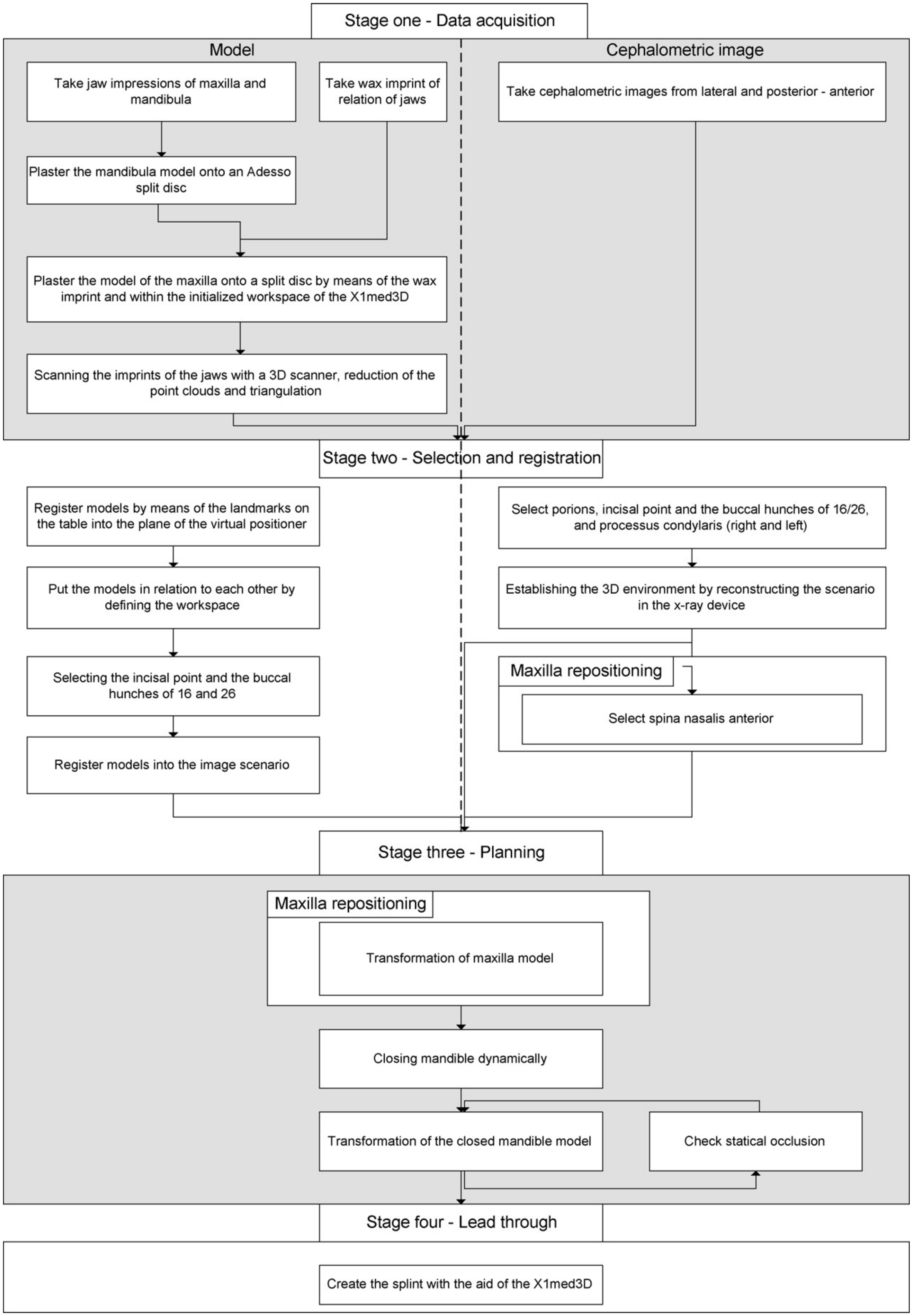


Fig. 2. The four stages of the method and its main steps.

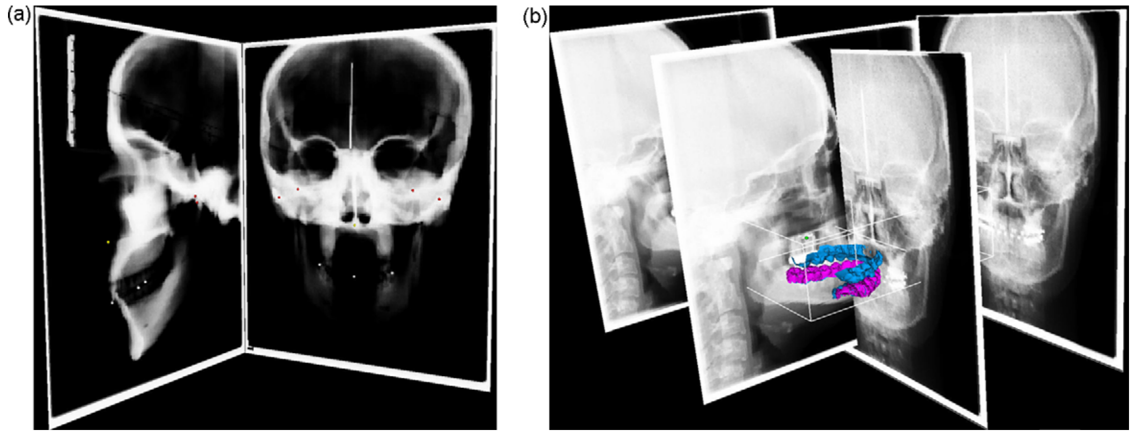


Fig. 3. The initialized view of the software shows the two cephalometric images and their relation in the second stage before (a) and after (b) registration corresponding with the size of the real cement models.

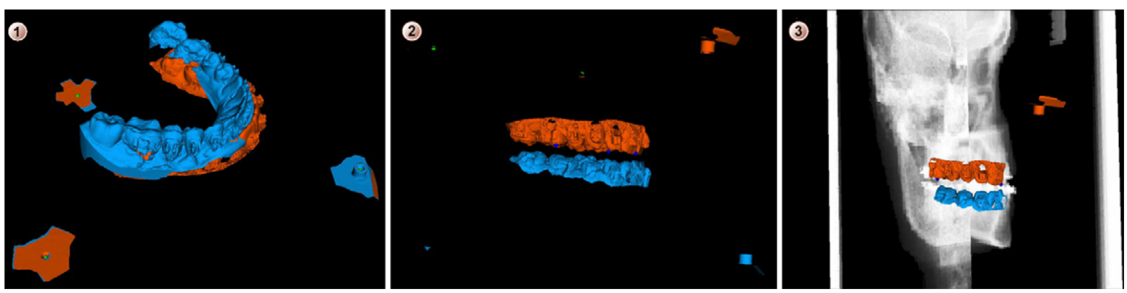


Fig. 4. Registration process. (1) Registered to the table of the virtual X1med3D, (2) initial registration reproduced and (3) matched into the 3D scenario with the registered image planes.

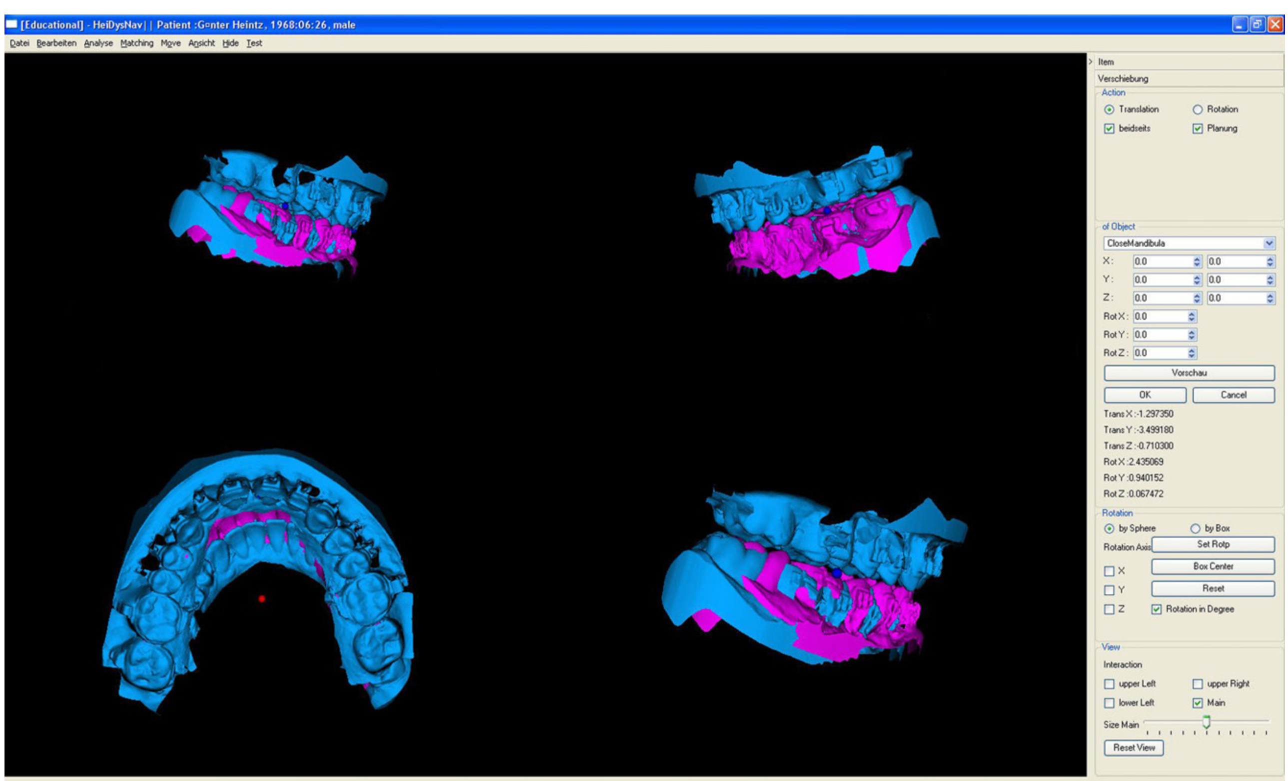


Fig. 5. The transformation mode with four different perspectives for visual control of the applied transformation.

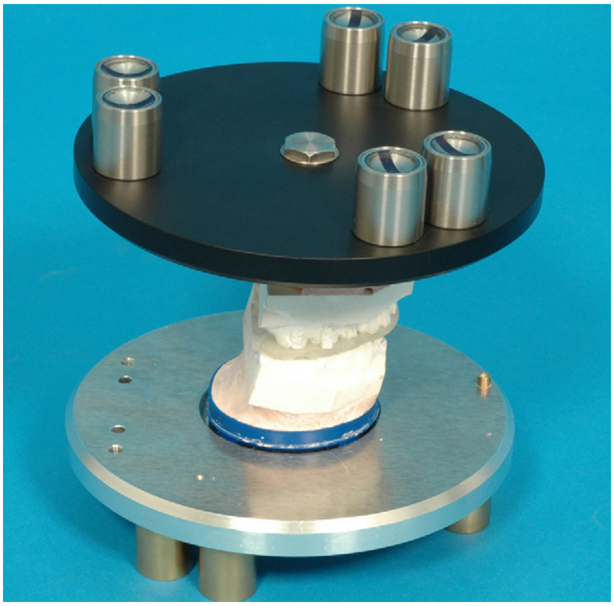


Fig. 6. The validation set up with the two plates and the magnets.

of the distance arising from the arm lengths of the X1med3D at the initial height. The situation when the patient was imprinting his teeth into the wax was reconstructed.

The incisal point and the buccal hunch of teeth 16 and 26 were selected in the same order as in the images before. The maxilla was matched with the 3D coordinates of the images, carrying the mandible along.

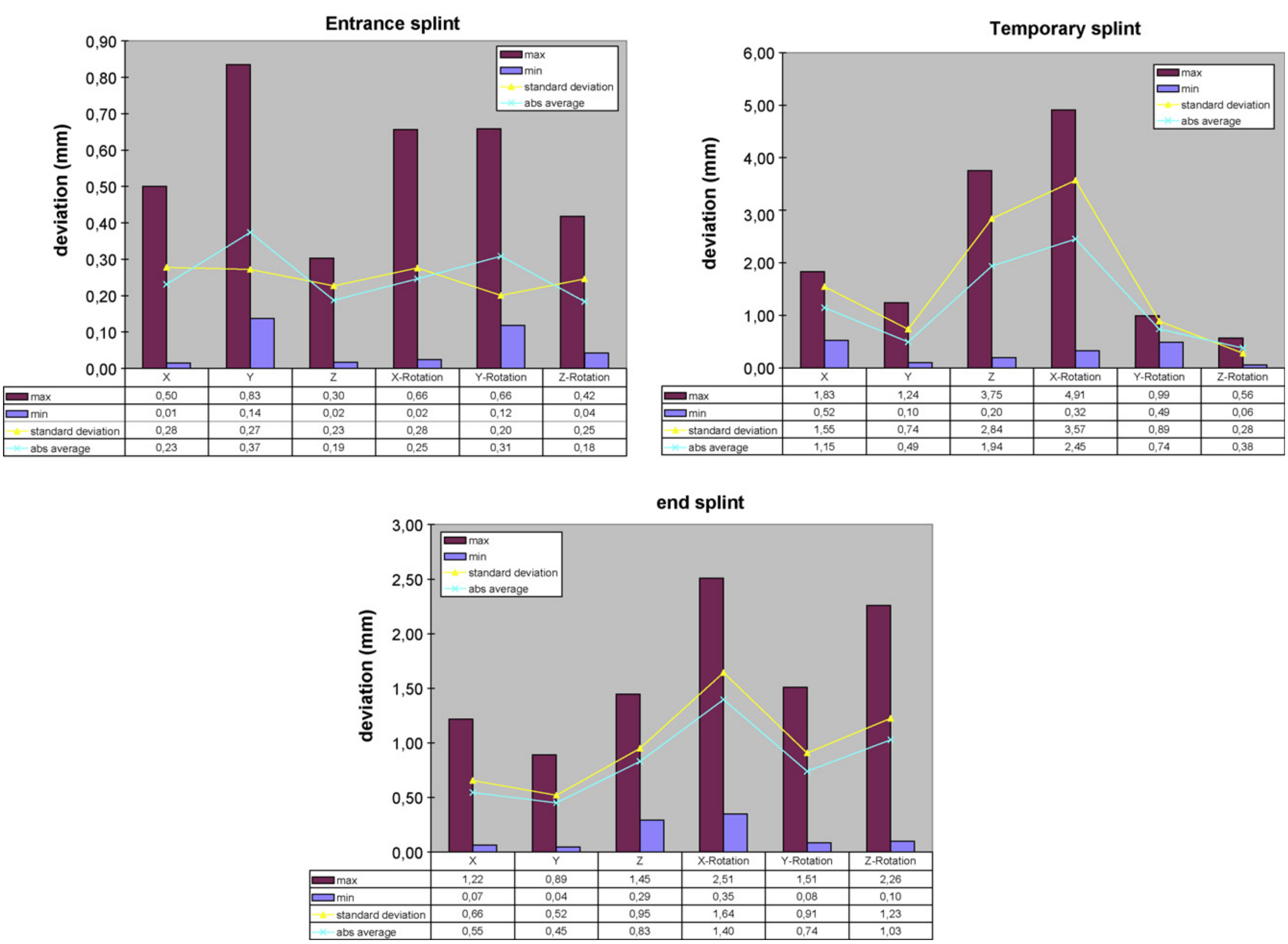
Planning the reposition

In the case of repositioning the maxilla, the origin is changed to the orientation of the Camper's line to perform the transformation with respect to the occlusion plane of the jaw (Fig. 5).

In the case where the transformation of the maxilla was finished, the mandible was closed by rotating a copy of the mandible until it intersected with the upper jaw. Afterwards, the position of the closed mandible could be manipulated in the transformation mode. The calculated deviation between the jaws results in a coloured map projection to one of the jaws, representing the intersecting points in red. This helps to assess the quality of occlusion.

Creation of the splint

To create the splint, the closed mandible is opened by a rotation equivalent to 1 mm. Applying the transformation between the initialized and the closed position of the



Entrance splint

	X	Y	Z	X-Rotation	Y-Rotation	Z-Rotation
max	0,50	0,83	0,30	0,66	0,66	0,42
min	0,01	0,14	0,02	0,02	0,12	0,04
standard deviation	0,28	0,27	0,23	0,28	0,20	0,25
abs average	0,23	0,37	0,19	0,25	0,31	0,18

Temporary splint

	X	Y	Z	X-Rotation	Y-Rotation	Z-Rotation
max	1,83	1,24	3,75	4,91	0,99	0,56
min	0,52	0,10	0,20	0,32	0,49	0,06
standard deviation	1,55	0,74	2,84	3,57	0,89	0,28
abs average	1,15	0,49	1,94	2,45	0,74	0,38

end splint

	X	Y	Z	X-Rotation	Y-Rotation	Z-Rotation
max	1,22	0,89	1,45	2,51	1,51	2,26
min	0,07	0,04	0,29	0,35	0,08	0,10
standard deviation	0,66	0,52	0,95	1,64	0,91	1,23
abs average	0,55	0,45	0,83	1,40	0,74	1,03

Fig. 7. Deviation between the conventional and virtually planned splints (a) entrance, (b) temporary, and (c) end splint planned by the surgeon.

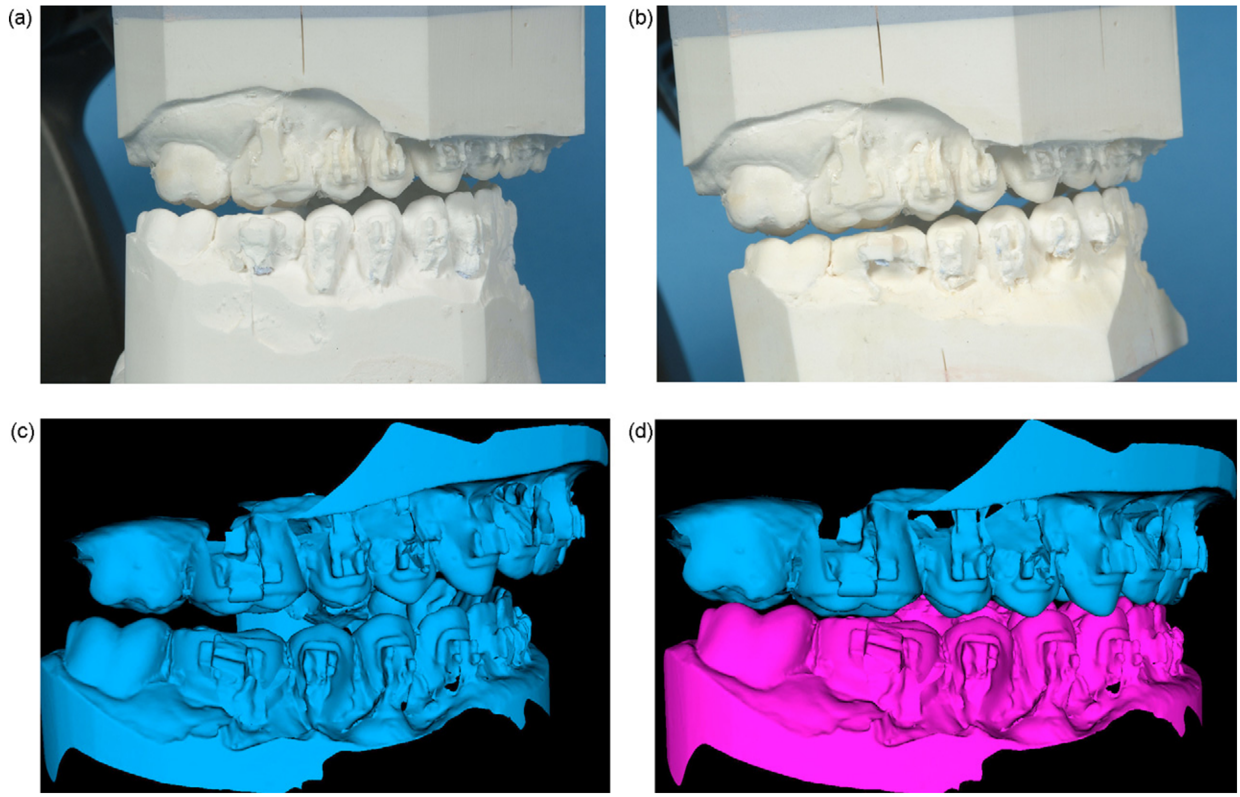


Fig. 8. A patient case planned conventionally (a) preoperative and b) postoperative and virtually (c) preoperative and (d) postoperative.

mandible to a virtual model of the X1med3D gives the set up of the arm lengths of the positioner.

After reinitialization and set up of the arm lengths of the real X1Med3D carrying the models the splints were created by means of pressing the maxilla into the mandible model covered by an ultraviolet scattered-light-sensitive material.

Validation and results

The deviation of the conventionally and virtually planned splint was measured using a MicroScribe G2X (Immersion Corporation, San Jose, USA). For this, the plate of the X1med3D was fixed onto a table. Before and after the measurements of the splints, the landmarks on the plate were measured. To quantify the splint, it was placed between the models of maxilla (on the upper table) and mandible (on the lower table) (Fig. 6). Measuring the borders of magnets of the upper plate results in translation and rotation in respect of the landmarks of the plate.

Fig. 7 shows the sum of all errors of the method compared with the conventional planning method, showing the minimum, maximum, standard and absolute deviation. Fig. 8 gives preoperative and postoperative views of a patient case planned conventionally. The results of the temporary splints are not as satisfactory as the others. One of the patients was not appropriately fixed in the X-ray device and moved, because of this, a correct relation between the images could not be established and the results were hampered significantly. The results of the end splints were good. Omitting this patient, the maximum error for temporary splints would be about 1.8 mm.

The results show that conventional planning by the technician can be reproduced as accurately as listed above. The surgeons' results showed that an inexperienced physician can achieve good results.

Discussion

The success of orthognathic surgery depends on accurate planning. In dysgnathia, the planning of the reposition of the jaw has to be precise.

Gaertner and Kordass[2] is one of the few studies dealing with repositioning of the jaws, with the aim of evaluating the static and dynamic occlusion of the jaws based on the real movement of the lower jaw, which was recorded for reproduction. Their study showed that executing a functional and occlusion analysis was possible. Visualization of movement and occlusion was realized in a 3D environment, in which the user can zoom into a region of interest. This system does not allow repositioning the jaws and retransforming the information gained into the real world. The benefit of the system is limited to the quality of visualization.

Vollmer et al.[7] presented a system using a hexapod for repositioning the jaws. After initialization of the jaws in a conventional articulator, they were fixed to the upper ring of the hexapod. Through movement of the ring, the physician can determine the best position of the jaw by evaluating the values printed on the screen and the occlusion of the plastered models. The software also gives information on whether the position is within the defined limits. Once an optimized position is found, the jaw models are fixed by plaster. When setting up the models within the hexapod, the view of the models becomes restricted through the legs of the device. Visualization of the jaws is lacking in this project.

In the present work, a closed method for computer-assisted planning is presented. As in the work of Vollmer et al.[7], a high-precision hexapod was use, and like Gaertner[2], 3D visualization was integrated into the system. This visualization technique was most useful when planning the repositioning of the jaws and evaluating occlusion. Initially, information is taken from the patient, virtual planning follows, and finally the individualized splints for the repositioning of the patient's jaw are produced. The patient receives routine exposure only, and no face bow is required. Documentary requirements were fulfilled through the digital storage of all data.

The results show that the system can reproduce the conventionally planned splints. In the case where the patient was moving in the X-ray device, the end-splint was still good. This leads to the assumption that such errors would only affect the temporary splint, which needs to be evaluated. Other causes of defects could be the difficulty of marking the points on the images, especially the selection of the center of the caput mandibulae, and the patient having chondrifications. Another cause of defects in the measurements is that, due to documentation, different plaster models were used for creating the splints in the conventional and virtual planning method. This results in the conventionally planned splints having a slide error fitting to the second pair of plaster models.

The main benefit of the system is the omission of the face bow and the conventional articulations, the possibility of easy and fast repositioning of the jaw without using any materials and minimizing the use of X-rays during repositioning.

In the future, selecting points on the X-ray scans will be improved by using markers fixed to the patient during the scanning procedure. This should reduce the error due to selection of bad points and should improve the accuracy of registering the models. The error in planning the temporary splints would be minimized.

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This paper is dedicated to the memory of Prof. Joachim Muehling.

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