# Three-dimensional surgical simulation

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In this article, we discuss the development of methods for computer-aided jaw surgery, which allows us to incorporate the high level of precision necessary for transferring virtual plans into the operating room. We also present a complete computer-aided surgery system developed in close collaboration with surgeons. Surgery planning and simulation include construction of 3-dimensional surface models from cone-beam computed tomography, dynamic cephalometry, semiautomatic mirroring, interactive cutting of bone, and bony segment repositioning. A virtual setup can be used to manufacture positioning splints for intraoperative guidance. The system provides further intraoperative assistance with a computer display showing jaw positions and 3-dimensional positioning guides updated in real time during the surgical procedure. The computer-aided surgery system aids in dealing with complex cases with benefits for the patient, with surgical practice, and for orthodontic finishing. Advanced software tools for diagnosis and treatment planning allow preparation of detailed operative plans, osteotomy repositioning, bone reconstructions, surgical resident training, and assessing the difficulties of the surgical procedures before the surgery. Computer-aided surgery can make the elaboration of the surgical plan a more flexible process, increase the level of detail and accuracy of the plan, yield higher operative precision and control, and enhance documentation of cases. (Am J Orthod Dentofacial Orthop 2010;138:361-71)

Orthognathic surgery involves repositioning segments of the jaws. Reconstructive procedures entail replacement of missing or damaged anatomic structures by grafts or implants. Each patient in craniomaxillofacial surgery has unique properties and requires careful preparation. Conventional methods to prepare for orthognathic surgery rely on lateral and frontal radiographic images. These are only of limited help for understanding complex 3-dimensional (3D) defects and planning appropriate corrections.[1,2] Cone-beam computed tomography (CBCT) allows acquisition of 3D images of the patient's head.[3] CBCT is now used routinely for the diagnosis of severe abnormalities of the craniofacial skeleton. Even with the availability of CBCT, the surgical plan is still normally prepared by using 2-dimensional (2D) radiographic images. In the past 10 years, some research centers and commercial companies have strived to provide software environments that allow preparation of the operative plan on 3D models of the skeletal base extracted from the CBCT. As these planning systems begin to be used in clinical practice, it is important to validate their clinical applications and critically assess the difficulty of transferring virtual plans into the operating room.

In this article, we discuss methods for computer-aided jaw surgery and present applications of a complete computer-aided surgery (CAS) system, the CMFApp software,[4-10] under development at the Maurice Müller Institute, Bern, Switzerland. The applications and adaptation of this CAS system result from the collaboration of our research center at the University of North Carolina with the Maurice Müller Institute.

## MATERIAL AND METHODS

The methods for CAS systems in jaw surgery follow procedures from the image scanners to the operating room (Fig 1): (1) data acquisition: collection of diagnostic data; (2) image segmentation (ITK-SNAP open source

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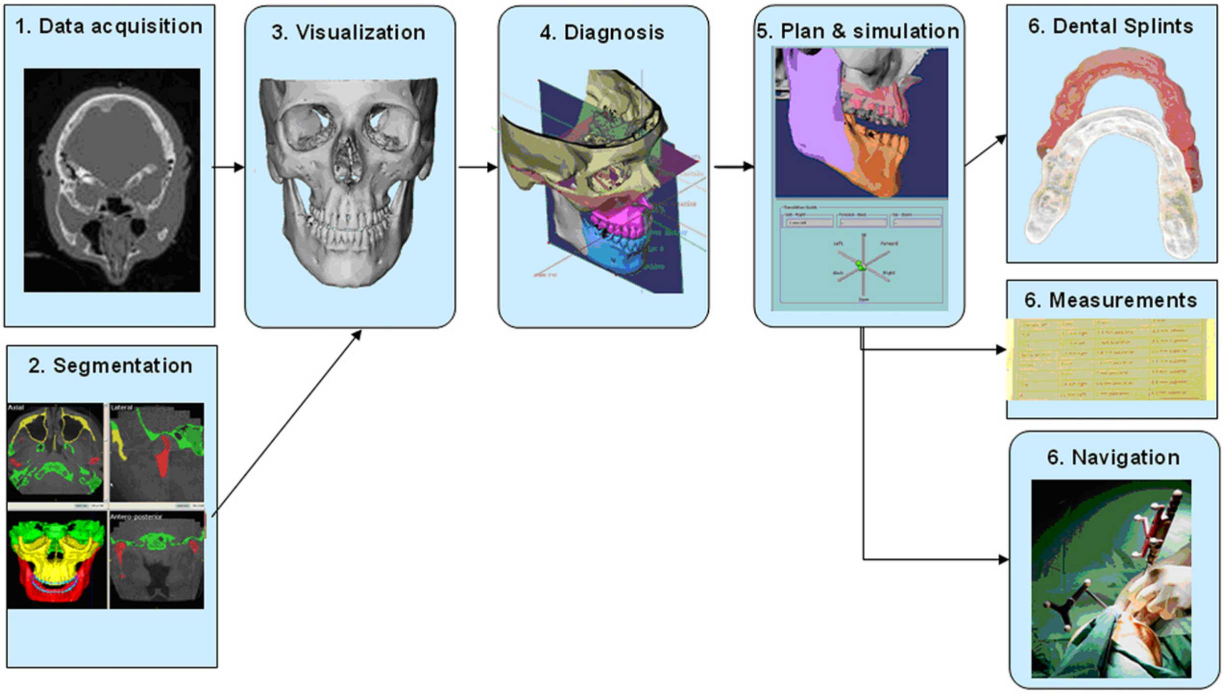

**Fig 1.** *1*, CBCT images are taken for each patient; *2*, segmentation involves delineation of the anatomic areas of interest; *3*, visualization of the 3D skull; *4*, diagnosis occurs in 3D; *5*, preparation of an operative plan and simulation of the actual surgery; *6*, measurements, dental splints, and intraoperative guidance can then be used for intraoperative realization of the virtual surgical plan.

software, www.itk-snap.org)[11]: identification of anatomic structures of interest in the image data sets; (3) visualization (CMFApp software)[4-10]: 3D display of the anatomic structures; (4) diagnosis (CMFApp software)[4-10]: extraction of clinical information from the 3D representations of the anatomy; (5) planning and simulation (CMFApp software)[4-10] : preparation of an operative plan by using the virtual anatomy and a simulation of the outcome; and (6) intraoperative guidance (CMFApp software)[4-10]: assistance for intraoperative realization of the virtual plan.

Diagnosis of skeletal discrepancies is based on visual data from various sources: clinical examination, 3D photographic examination, CBCT, and digital dental models. A CAS must integrate many records to characterize the orthodontic diagnosis and formulate the treatment plan. The first advantage of a software-based solution is its capacity for data organization. The different sources of anatomic and diagnostic data can be stored in 1 location, correlated, and viewed as a combined display. As image modalities and sources of data multiply, these information-handling abilities will prove even more valuable, particularly if connected with planning and intraoperative guidance functions.

Multi-modality registration is available for several commercial software programs, such as 3DMDvultus (3DMD, Atlanta, Ga), Maxilim (Medicim, Mechelen, Belgium), Dolphin Imaging (Dolphin Imaging & Management Solutions, Chatsworth, Calif), InVivoDental (Anatomage, San Jose, Calif), and SimPlant OMS (Materialise, Leuven, Belgium). We focus specifically on the surgical simulation procedures executed on 3D surface models built from CBCT. However, the CMFApp software (developed with funding from the Co-Me network[12]) provides a uniform medical data-handling backbone to collect all anatomic, diagnostic, planning, and intraoperative guidance and monitoring information in a structured file in XML format. This includes preoperative CBCT images, skeletal models, acquired dental occlusion, operative plans, diagnostic data (3D cephalometry, mirrored structures), planning data (osteotomy lines, repositioning plans), guidance data (registration points and transformations), postoperative CBCT images, and so on. This file can be shared among different CAS applications. This data-handling mechanism is part of a modular software framework that permits seamless assembly of software components and sharing of data between these components, and it facilitates system extension.

For CBCT images, once they are acquired, the DICOM files can be imported into the 3D image-analysis software. Next, in a process known as image segmentation, we identify and delineate the anatomic structures of interest in the CBCT image. In orthodontics and orthognathic surgery, the goal of segmentation is to obtain a 3D representation of the hard and soft tissues that is usable for virtual planning.

Currently available 3D image-analysis software tools offer many manual, semiautomatic, and fully automatic segmentation techniques. For routine clinical use, a fully automated segmentation protocol is preferable because it requires only limited interaction with the user. Segmentation is a preparatory step for surgical planning and should be performed as quickly as possible. A simple way to segment bone in CBCT is thresholding. This is the technique used in commercial software such as Dolphin, 3DMD Vultus, and Maxilim. Thresholding classifies a voxel (element of volume in a 3D image) depending only on its intensity.[4] A certain intensity range is specified with lower and upper threshold values. Each voxel belongs to the selected class (eg, bone) if, and only if, its intensity level is within the specified range. The appropriate value range must be selected for each patient because bone density varies between patients, and intensity values of bone can vary between scanners.

The major limitation of thresholding is that it is prone to artifacts. These artifacts are created because different densities in a voxel are averaged and then represented by 1 CBCT number.[13] Therefore, the CBCT numbers of thin bony walls tend to drop below the thresholding range of bone because their density is averaged with that of surrounding air. This effect causes artificial holes in 3D reconstructions of the condyles and areas of thin cortical bone, such as the internal ramus of the mandible and much of the maxilla.[13] Another source of artifacts is metal in the face (orthodontic appliances, dental fillings, implants, surgical plates). Metal artifact intensity values fall into the thresholding range of bone and are included in CBCT images as pronounced star-like streaks. The morphology and position of the condyles, and internal surfaces of the ramus and the maxilla, are critical for careful virtual surgery planning. To best capture these and other areas, our method of choice for the segmentation procedures uses ITK-SNAP software.[11] ITK-SNAP was developed, based on the National Institutes of Health Visualization Tool Kit and Image Tool Kit, as part of the National Institutes of Health Roadmap Initiative for National Centers of Biomedical Computing. The automatic segmentation procedures in ITK-SNAP use 2 active contour methods to compute feature images based on the CBCT image's gray level intensity and boundaries (Fig 2). The first method causes the active contour to slow down near edges, or discontinuities, of intensity. The second causes the active contour to attract to boundaries of regions of uniform intensity.

After obtaining the segmentation result, manual postprocessing is normally necessary. Artifacts from metallic elements need to be removed. The 2 jaws are usually connected because of insufficient longitudinal image resolution and must be separated in the temporomandibular joint and on the occlusal surface in particular. For this reason, it was recommended that the CBCT image should be taken in centric occlusion with a stable and thin bite-registration material.[14] On a laptop computer equipped with 1 GB of RAM, the initial mesh generation step typically takes about 15 minutes. Manual postprocessing usually takes longer, up to several hours (separation of the jaws can be particularly tedious). Currently, this manual postprocessing step is too time-consuming and not practical for the surgeon. However, some groups have recommended that these steps can be outsourced to radiology technicians at imaging centers.[15] Further research in advanced segmentation methods is essential to reach the ideal of an accurate and continuous individual segmentation of the skeletal base, with only a few mouse clicks. This needs to be possible with images of even poor quality.

After segmentation of the anatomic structures of interest, 2 technological options are available to visualize these structures 3 dimensionally. The first are surface-based methods, which require the generation of an intermediate surface representation (triangular mesh) of the object to be displayed. The second are volume-based methods, which create a 3D view directly from the volume data.[16]

The advantages of surface-based methods are the detailed shading of the facial surfaces at any zoom factor. Also, any other 3D structure that can be represented by a triangular mesh can be easily included in the anatomic view (eg, implants imported from computer-aided design implant databases). Most Cranio-maxillofacial (CMF) surgery-planning software programs (including the CMFApp described here) use surface-based visualization. An obvious disadvantage of surface-based methods is the need for an intermediate surface representation.

Some developments in computer-aided CMF surgery use volume-based visualization—eg, the commercial Voxim (IVS Solutions AG, Chemnitz, Germany)—based on a highly optimized volume representation showing good detail and performance on clinical data sets. The advantages of volumetric methods are direct visualization of volumetric operations not only in 3D, but also on cross-sectional image views. Virtual osteotomies are applied on the original image data set. However, it is difficult to establish the boundaries between tissues and assign the

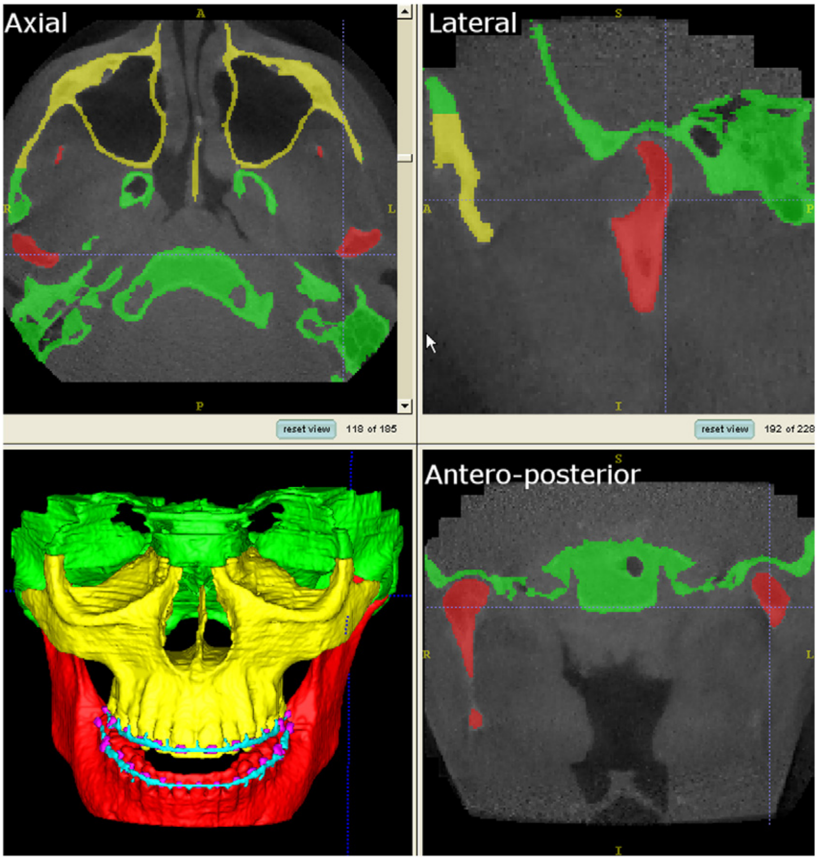

**Fig 2.** CBCT images are imported as DICOM files into ITK-SNAP. In a process called semiautomatic segmentation, anatomic areas of interest are identified and delineated. Manual editing is performed to ensure accuracy of the segmentations. The images can be viewed in 3 dimensions and as axial, coronal, and sagittal slices of each image.

proper color or transparency values to obtain the desired display. Moreover, the image intensity for a tissue can vary between patients and scanners (eg, bone density varies with age, and there are variations in scanner calibrations, and so on). Virtual cutting operations are much more difficult to simulate in voxel-wise representations. Further evolutions in software and graphics hardware that combine both surface-based and volume-based visualization technologies have great potential.

Correction of dentofacial deformities often requires rotational movements of the 3D cephalometry; deformities are impossible to represent correctly in lateral or frontal planes only. In the CMFApp software, cephalometry is performed on the 3D skeletal model generated from the CBCT image, defining landmarks, lines, planes, and measurements.[17-19] Definition of individual coordinate systems is possible; these are used to express all displacement values during movement planning and intraoperative navigation (Fig 3).

The use of computers for cephalometric analysis allows new assessment methodologies. Morphometrics is the branch of mathematics studying shapes and shape changes of geometric objects. Cephalometrics is a subset of morphometrics. Clinical cephalometric analyses have been based on a set of points, either of anatomic meaning or from an abstract definition (such as the middle point between 2 other points). Surface and shape data from 3D imaging provide new characterization schemes, based on higher-order mathematical entities (eg, spline curves and surfaces). Cutting et al[20] and Subsol et al[21] introduced the concept of ridge curves for automatic cephalometric characterization. Ridge curves (also known as crest lines) of a surface are the loci of the maximal curvature in the associated principal curvature directions. The ridge lines of a surface convey rich and compact information, which tends to correspond to natural anatomic features. Lines of high curvature are typical reference features in the craniofacial skeleton.

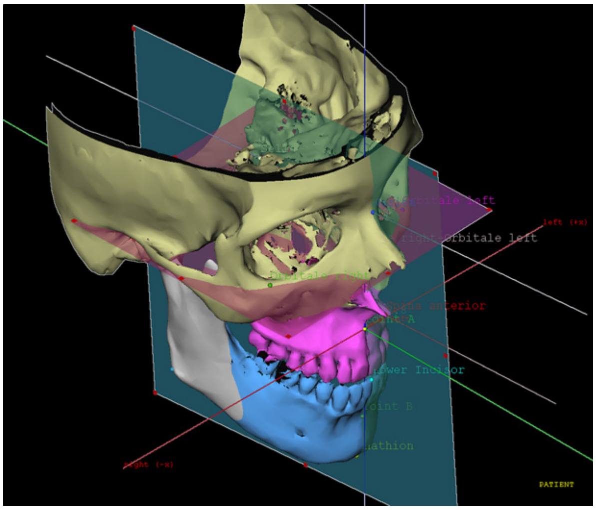

**Fig 3.** Cephalometry can be performed on the 3D skeletal model formed from the CBCT image. This allows the user to define landmarks, lines, planes, and measurements.

Future studies will establish new standards for 3D measurements in the craniofacial skeleton. New developments in this area might lead to comprehensive 3D morphometric systems including surface-based and volume-based computed shape measurements. They could also lead to 4-dimensional shape information that integrates evolution over time in the analysis.

Mirroring can be a valuable technique in the treatment of asymmetries. This allows the normal contralateral side to be used as a reference. The conventional definition of the symmetry plane is the midsagittal plane. In 2D cephalometry, the midline is defined with a number of anatomic landmarks on the frontal cephalogram and used as a reference to measure the distance to laterally positioned landmarks. Facial asymmetry is assessed and determined by the differences between measurements on both sides. Transposition of this conventional 2D landmark-based definition scheme in 3D works well to obtain a plane that accounts for global symmetry of the entire face. Previous work on a landmark-based midsagittal plane showed that the definition of the midsagittal plane is reliable.[22] However, the choice of landmarks used to determine the midsagittal plane has a marked impact on the asymmetry quantification. In a particular face, symmetry is often better described by several regional symmetry axes (eg, symmetry between the jaw and midface regions often differs) for which there is no defining landmark set.[23] In patients with severe mandibular asymmetries, as in craniofacial microsomia, entire regions of the anatomy might be missing or severely dislocated. Thus, selection of landmarks in the mandible could result in an incorrect quantification of asymmetry.

For this reason, the CMFApp software also allows surface-based definition of symmetry planes.[4-6] This allows the user to select equivalent surface regions on both sides (Fig 4). An automatic optimization process calculates the symmetry plane, which is most able to reflect the correspondence of these regions. This is a key requirement for the usability of mirroring techniques. The symmetry plane should be adjusted to the selected symmetrical structure to obtain as close a match as possible between the mirrored healthy structure and the affected site.

Recently proposed methods aim at full digitization of the dental arches and elimination of physical dental models, thanks to the integration of digital dental data (acquired with high-resolution surface scanning methods[24] or CBCT[14]). The CMFApp software can integrate high-resolution dental surface data that will make quantitative evaluations of occlusion quality possible, and it can be used for optimization of jaw movements in orthognathic surgery planning.

After establishment of the diagnosis, the next step is to use the 3D representations of the anatomy to plan and simulate the surgical intervention. In orthognathic surgery, a distinction should be made between the tasks involved in corrective and reconstructive interventions. Corrective intervention designates procedures that do not require an extrinsic graft, and reconstructive interventions are designated for situations when a graft is used.

In corrective procedures, it is important to determine the location of the surgical cuts, to plan the movements of the bony segments relative to one another, and to achieve the desired realignment intraoperatively. In reconstructive procedures, problems include determining the desired implant or graft shape. Reconstructive procedures will be assessed in a future article.

In the case of an implant, the problems are to select the proper device and shape it, or to fabricate an individual device from a suitable biocompatible material. With a graft, the difficulties lie in choosing the harvesting site, shaping the graft, and placing the implant or graft in the appropriate location.[4]

In a virtual osteotomy, the resulting mesh from a segment is complex for several reasons: (1) cranial anatomy is intrinsically complex; (2) regions of thin (or absent) bone, such as the orbital floor, create sudden discontinuities in the mesh; and (3) inner structures (eg, the mandibular nerve canal) are often included in the surface model. For this reason, a virtual osteotomy with the CMFApp software uses a robust cutting algorithm, able to cope with triangular meshes of any complexity.[6-10]

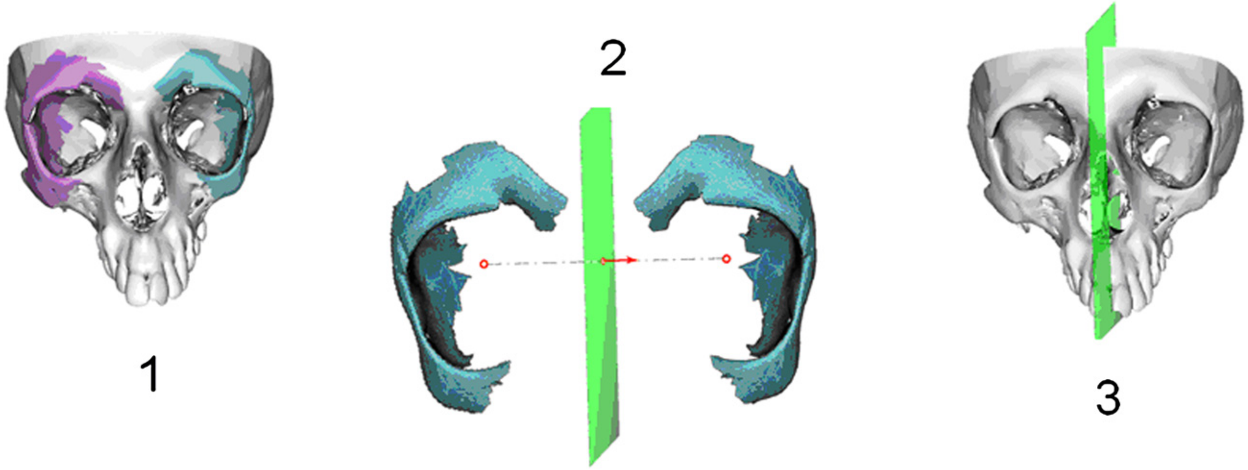

**Fig 4.** Mirroring can be a valuable technique in the treatment of asymmetries: *1*, the lateral orbit has been delineated on each side; *2*, the left orbit was mirrored onto the right side by using the CMF application's mirror function, and the midsagittal plane was defined for the image; *3*, the lateral left orbit was then reincorporated back into the whole skull model with the right side recreated as a mirror of the left side.

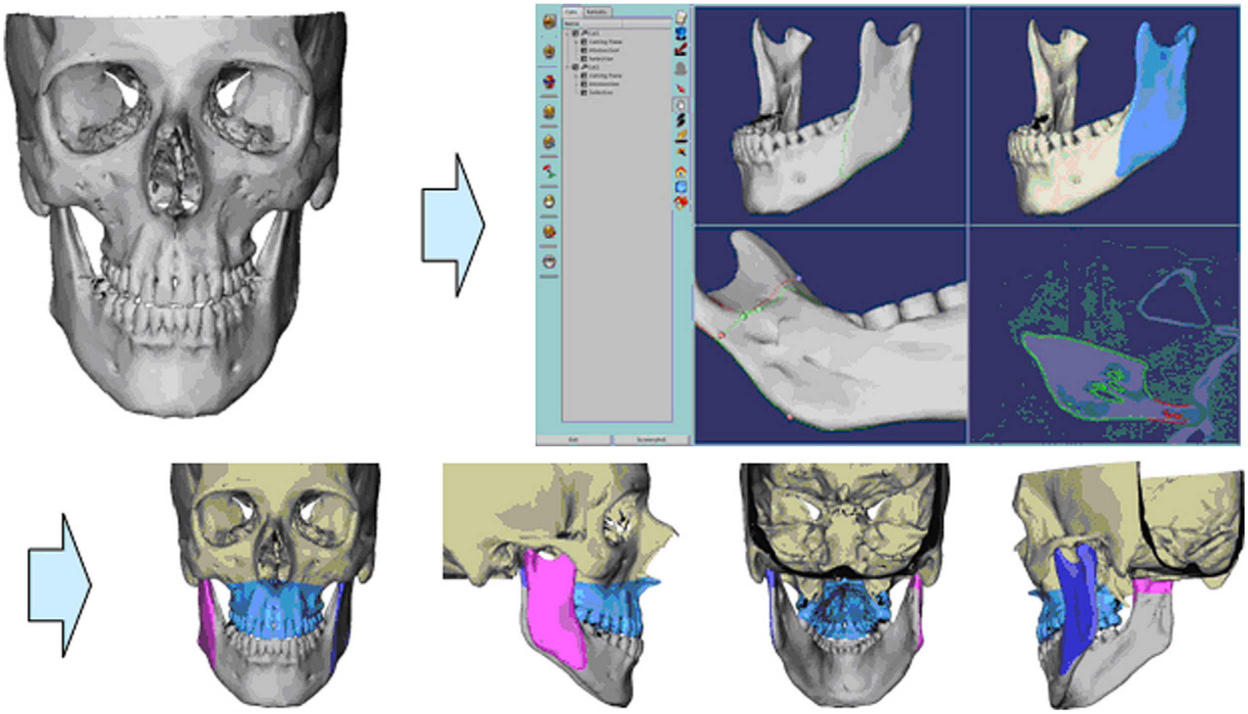

**Fig 5.** Virtual surgical cuts were placed in the 3D skull models by placing 3 or more points in the desired orientation of the cuts. The newly cut segments were then painted different colors to allow better visualization of the cuts. Each segment can then be relocated and tracked with precise control by using movements with 6 df (x, y, and z in rotational and translational planes of space).

Osteotomies are simulated in the CMFApp software with combinations of planar cuts into the skeletal model. The aim of the osteotomy simulation is a set of realistically separated bone segments for relocation planning. This step is an individually based plan of the anatomic cuts before the surgical procedure. This allows for planning of the position and the size of the fixation screws and plates. The osteotomy tool in

CMFApp supports any type of cut with reliable detection and separation of the resulting segments. Cutting planes are defined with 3 or more landmarks selected on the surface (Fig 5). The intersection between the plane and the model is computed, and inner structures and surface discontinuities are clearly visible in cross-sectional views. The location of the cut can be selected on the intersection line, by either by drawing on the line or clicking on connected line sections. The latter selection mode simplifies selection of closed intersection lines, often encountered when simulating osteotomies of closed skeletal structures (eg, the maxilla buttresses in LeFort I osteotomy).

After the virtual osteotomy, the virtual surgery with relocation of the bony segments can be performed with quantification of the planned surgical movements.[4-10] Relocation of the anatomic segments with 6 df is tracked for each bone fragment. This allows for the correction of the skeletal discrepancy for a patient and simultaneous tracking of measurements of the x, y, and z rotational axes and the rotation about each axis. The segment repositioning produced can be used as an initial suggestion to the surgeon and for discussions of the 3D orthodontic and surgical treatment goals for the patient. Standard measurement tools are available for performing the cephalometric analysis in 3D as in 2D radiographic images. In the CMFApp, a modification in the position of a landmark is immediately reflected on the 3D cephalometric measurements, aiding quantification of planned changes. With the integration of morphometric data in surgical planners, interesting applications for mathematic programming techniques might be found. For example, Cutting et al[20] proposed that, to optimize bone segment positions, one should best fit an appropriate age- or race-matched ideal morphometric form defined in numeric terms. In that proposition, the sum of square distances between landmarks on a patient to corresponding landmarks in the normal form would provide the quantitative deviation measure.

Methods that attempt to predict facial soft-tissue changes resulting from skeletal reshaping use approximation models, since direct formulation and analytic resolution of the equations of continuum mechanics are impossible with such geometric complexity. Several models have been proposed.

1. Purely geometric models: In these models, the displacements of soft-tissue voxels are estimated with the movements of neighboring hard-tissue voxels,[25] or bone-displacement vectors are simply applied on the vertices of the soft-tissue mesh.[26]
2. Multi-layer mass-spring models: These models rely on the assumption that the material of an anatomic structure can be represented by a set of discrete elements, each having individual properties. Each discrete element bears a mass, and relationships between these masses are characterized by stiffness values. These models have stability problems, lack of conservation of volume, and a certain mismatch between model parameters and real physical properties.[27-29]
3. Finite element models: These models are intensively used for the analysis of biomechanical systems. The finite element method (FEM) can offer a numeric approximation of viscoelastic deformation problems. FEM models consist of a discretization of the geometry in a set of discrete subdomains, for which continuum mechanics equations can be formulated. In this way, the partial differential equation characterizing the deformation can be written as a matrix equation that can be solved by the computer. Although the problem is broken down in simpler elements, the number of necessary elements to obtain results of satisfying accuracy can be elevated; this usually entails substantial computation times and resources.[29-32]
4. Mass tensor models: These are a mixture of the easy architecture of the multi-layer mass-spring models and the biomechanical relevance of FEM.[20,29]

Because of their solid physical base, FEM models and mass tensor models are the most likely to provide reliable simulation results. However, thorough validation reports for all these methods are still lacking. Comparisons of the simulation with the postoperative facial surface have not yet been performed. Surgical-planning functions generally do not fulfill the requirements enumerated above for preparation of quantitative facial-tissue simulation for surgical planning. No such facial-tissue simulation method has been integrated in the CMFApp software, but the current integration of the accurate positioning control ensured by the CMFApp system will allow thorough validation studies in the future.[33]

Three-dimensional photographs can also be texture mapped onto the skin surface from CBCT images to provide photo-realistic rendering of soft-tissue changes (3DMDvultus, Maxilim, Dolphin Imaging, and InVivoDental). Alignment of the 3D photograph with the CBCT skin surface (registration) uses surface-matching algorithms.

Other functionalities incorporated into various software systems include simulation of muscular function,[34] distraction osteogenesis planning,[35] and 4-dimensional surgery planning.[36] Many corrective treatments are planned for the long term, involving

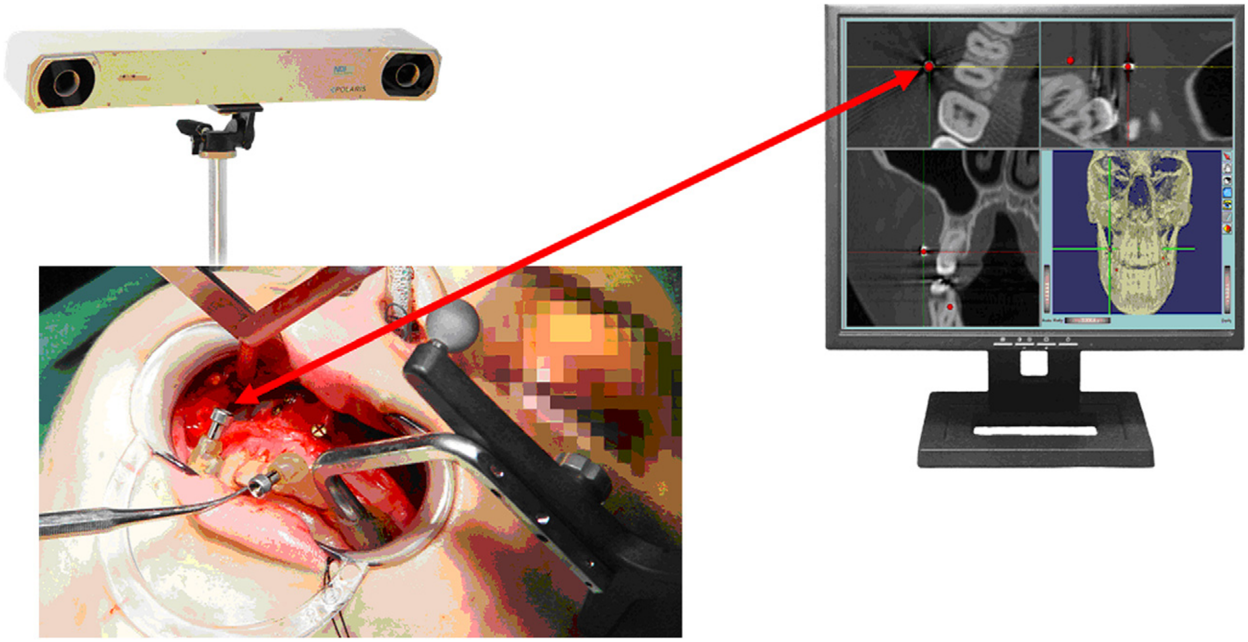

**Fig 6.** Paired-points registration establishes a correlation between virtual images and real anatomy. The initial CBCT images were taken with bite splints that had metallic objects built into the splints. These areas appeared on the radiographic images. A tracked pointer is then used to digitize these points on the patient during the operation. This allows transfer of the virtual surgeries to the operating room.

several surgical interventions with periods of healing and growth between them. A generic growth model based on statistical data collected with longitudinal studies can also be used in future studies, although its relevance for the variations in growth factors and bone density should be evaluated. Such a generic model could be individualized progressively by collecting clinical and image data over time.

In corrective procedures, achieving the desired bone segment realignment in a freehand manner is difficult. Also, segments must often be moved with limited visibility—eg, under the (swollen) skin. Approaches used currently in surgery rely mainly on the clinician's experience and intuition. In maxillary repositioning, for example, a combination of dental splints, compass, ruler, and intuition are used to determine the final position. It has been shown that, in the vertical direction (in which the splint exerts no constraint), only limited control is achieved.[37] In reconstructive procedures, the problems of shaping and placing a graft or an implant in the planned location also arise. Surgical navigation systems have been developed to help accurately transfer treatment plans to the operating room.[5,8-10]

Surgical navigation systems use tracking technology to follow anatomic bodies, instruments, or devices in the operative scenario. They provide an augmented view of the current operative situation. This can incorporate preoperatively or intraoperatively acquired images, operative plans, and real-time measurements to guide the surgeon in the realization of the surgical plan. For this reason, an essential component of any CAS system in this area is guidance for positioning surgical objects such as bone segments, grafts, or implants. To provide such guidance, the system should support tracking of actual object positions in relation to the skull base and the preoperative plan, and assistance for manipulating the object into the desired configuration.

Various tracking technologies for tracking the displacement of a mobilized fragment during an osteotomy can be used with the CMFApp with advantages and disadvantages.[38]

1. Direct contact: The instrument or object is attached to a multi-linkage arm, which measures its position with encoders at each joint of the arm. Such a setup is bulky and would require the installation of an arm for each element to be tracked; this is impossible in practice.
2. Ultrasound: An array of 3 ultrasound emitters is mounted on the object to be tracked. The duration that a sound pulse takes to travel between each emitter and a receiver microphone is measured, but the speed of sound can vary with temperature changes, and the calibration procedure is delicate.

**Fig 7.** Paired-points registration was used to link the virtual surgeries with the operating room. Once they are linked, the software updates in real time the surgical movements on the computer. The object is to guide the hand of the surgeon while maintaining precise control in 3 translational and 3 rotational planes of space.

3. Electromagnetic: A homogeneous magnetic field is created by a generator coil. Receiver coils are mounted to the object to be tracked and measure characteristics of the field at their locations. The main advantages of magnetic systems are the small size of the receivers and the absence of line-of-sight constraints between emitters and receivers. However, ferromagnetic items such as implants, instruments, or the operation table can interfere with these systems, distorting the measurements in unpredictable ways. Newer systems claim reduction of these effects and have receivers the size of a needle head, possibly announcing a renewal of interest for electromagnetic tracking in surgical navigation (examples are the 3D guidance trackstar, Ascension, Burlington, VT; StealthStation, AXIEM, Medtronic, Minneapolis, MN; and Aurora, Northern Digital, Waterloo, Ontario, Canada).
4. Optical: Infrared optical tracking devices rely on pairs or triplets of charged coupled devices that detect positions of infrared light-emitting (active technology) or light-reflecting markers (passive technology). A combination of 3 markers is mounted on dynamic reference bases attached to the objects to be tracked to enable 6-degrees of freedom (df) position tracking. Optical tracking offers reliability, flexibility, high accuracy (as low as 0.2 mm), and good operating-room compatibility. The principal drawback is the absolute necessity of free line-of-sight between cameras and markers. These optical tracking devices are stereo systems that track the light-emitting diodes with more than 1 camera simultaneously.

Registration is the operation that establishes a correlation between virtual and tracking unified coordinate system. Imaged anatomy is matched to real anatomy. Since the preoperative plan belongs to the virtual coordinate system, it is also implicitly registered by this operation. The relationships between these coordinate systems are called rigid transformations (bone structures can be considered nondeformable), which correspond to rotation and translation: a disparity function is defined, which measures the root mean square distance between the reference feature set and the corresponding feature set, the latter set transformed by the (unknown) registration transformation. These features are identified in the CMFApp, by using paired-points registration (Fig 6). Paired-points registration consists of finding the rigid transformation that best represents the correspondence between pairs of points identified in the 2 coordinate systems.[10] A minimum of 3 pairs of noncollinear points is needed to define the transformation entirely. Generally, points in the image coordinate system are identified manually on the screen, and corresponding points are digitized during the registration procedure by using a tracked pointer. Two categories of points are commonly used.

1. Fiducials are external physical markers that provide clearly identifiable points in both image and tracking domains. Fiducials are either attached to or inserted in the structure to be registered before image acquisition. In the CMFApp, a registration bite is equipped with such fiducials and worn by the patient during the CBCT acquisition, giving 4 precise, unambiguous pairs of points.
2. Anatomic landmarks are points set on prominent features of the anatomy that are easily identifiable both in the image and on the patient with the pointer. Localization of anatomic landmarks is generally less accurate than localization of fiducials.

The navigation screen is the interface with which the system communicates with the surgeon. The standard display layout for a typical pointer localization application is a set of image slices, with superimposed representation of the pointer location. In the CMFApp software, for segment positioning assistance, 3D surface representations of the moving segments and schematic graphic movement guides are shown, with cephalometric and landmark movement data updated in real time.[39,40] The objective in that procedure is to guide the hand of the surgeon to match a 6-df movement; this is difficult (Fig 7). Interfaces involving stereoscopic displays or auditory feedback can also be envisioned, as well as mechanical aids and augmented reality systems.

## CONCLUSIONS

Experience from application of CAS systems (such as the CMFApp software) indicates that much time and precision are gained in the surgical procedures. We believe that in the coming years CAS systems will become irreplaceable tools in this field for processing clinical data, and for planning, guiding, and documenting surgical procedures.

## REFERENCES

1. Caloss R, Atkins K, Stella JP. Three-dimensional imaging for virtual assessment and treatment simulation in orthognathic surgery. Oral Maxillofac Surg Clin North Am 2007;19:287-309, v.
2. Altobelli DE, Kikinis R, Mulliken JB, Cline H, Lorensen W, Jolesz F. Computer-assisted three-dimensional planning in craniofacial surgery. Plast Reconstr Surg 1993;92:576-85.
3. Arai Y, Tammisalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. Dentomaxillofac Radiol 1999;28:245-8.
4. Chapuis J. Computer-aided cranio-maxillofacial surgery [thesis]. Bern, Switzerland: University of Bern; 2006.
5. Chapuis J, Schramm A, Pappas I, Hallermann W, Schwenzer-Zimmerer K, Langlotz F, et al. A new system for computer-aided preoperative planning and intraoperative navigation during corrective jaw surgery. IEEE Trans Inf Technol Biomed 2007;11:274-87.
6. De Momi E, Chapuis J, Pappas I, Ferrigno G, Hallermann W, Schramm A, et al. Automatic extraction of the mid-facial plane for cranio-maxillofacial surgery planning. Int J Oral Maxillofac Surg 2006;35:636-42.
7. Krol Z, Chapuis J, Schwenzer-Zimmerer K, Langlotz F, Zeilhofer HF. Preoperative planning and intraoperative navigation in the reconstructive craniofacial surgery. J Med Inform Tech 2005;9:83-9.
8. Chapuis J, Langlotz F, Blaeuer M, Hallermann W, Schramm A, Caversaccio M. A novel approach for computer-aided corrective jaw surgery. Proceedings of the 3rd International Conference on Computer-Aided Surgery around the Head; 2005 Aug 25-27; Berlin, Germany. Berlin: Pro Business Verlag; 2005.
9. Chapuis J, Ryan P, Blaeuer M, Langlotz F, Hallermann W, Schramm A, et al. A new approach for 3D computer-assisted orthognathic surgery—first clinical case. Computer assisted radiology and surgery. Berlin, Germany. 2005 June 22-25, Berlin, Germany. Amsterdam: Elsevier; 2005.
10. Chapuis J, Rudolph T, Borgeson B, De Momi E, Pappas I, Hallermann W, et al. 3D surgical planning and navigation for CMF surgery. Proceedings of the Society for Photographic Instrumentation Engineers (SPIE) Medical Imaging, 2004 Feb 15-17, San Diego, CA. Open access SPIE Digital Library.
11. Yushkevich PA, Piven J, Hazlett HC, Smith RG, Ho S, Gee JC, et al. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. Neuroimage 2006;31:1116-28.
12. CMFApp software. Available at: http://co-me.ch/. Accessed on June 1, 2009.
13. Hemmy DC, Tessier PL. CT of dry skulls with craniofacial deformities: accuracy of three-dimensional reconstruction. Radiology 1985;157:113-6.
14. Swennen GR, Mollemans W, De Clercq C, Abeloos J, Lamoral P, Lippens F, et al. A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning. J Craniofac Surg 2009;20:297-307.
15. Xia JJ, Phillips CV, Gateno J, Teichgraeber JF, Christensen AM, Gliddon MJ, et al. Cost-effectiveness analysis for computer-aided surgical simulation in complex cranio-maxillofacial surgery. J Oral Maxillofac Surg 2006;64:1780-4.
16. Pommert A, Riemer M, Schiemann T, Schubert R, Tiede U, Hohne KH. Three-dimensional imaging in medicine: methods and applications. In: Taylor R, Lavallee S, Burdea G, Mosges R, editors. Computer integrated surgery. Cambridge, Mass: MIT Press; 1996. p. 155-74.
17. Bettega G, Payan Y, Mollard B, Boyer A, Raphael B, Lavallee S. A simulator for maxillofacial surgery integrating 3D cephalometry and orthodontia. Comput Aided Surg 2000;5:156-65.

18. Swennen GR, Barth EL, Schutyser F, De Groeve P, Lemaitre A. Three-dimensional (3-D) cephalometry: the basics for virtual planning. Proceedings of the XVII European Congress for Cranio-Maxillofacial Surgery; 2004 Sept 14-18; Tours, France.
19. Swennen GR, Schutyser F, Hausamen JE. Three dimensional cephalometry: a color atlas and manual. Heidelberg: Springer; 2005.
20. Cutting CB, Bookstein FL, Taylor RH. Applications of simulation, morphometrics, and robotics in craniofacial surgery. In: Taylor R, Lavallee S, Burdea G, Mosges G, editors. Computer integrated surgery. Cambridge, Mass: MIT Press; 1996. p. 641-62.
21. Subsol G, Thirion JP, Ayache N. A scheme for automatically building three-dimensional morphometric anatomical atlases: application to a skull atlas. Med Image Anal 1998;2:37-60.
22. Alhadidi A, Cevidanes LHS, Mol A, Ludlow J, Styner MA. 3D analysis of facial asymmetry based on midsaggital plane computation. J Dent Res 2009;88(Spec Iss A):311.
23. Tung-Yui W, Jing-Jing F, Tung-Chin W. A novel method of quantifying facial asymmetry. In: Lemke HU, Inamura K, Doi K, Vannier MW, Farman AG, editors. Computer assisted radiology and surgery. Berlin, Germany: June 22-25, 2005. Amsterdam: Elsevier; 2005.
24. Rangel FA, Maal TJ, Berge SJ, van Vlijmen OJ, Plooij JM, Schutyser F, et al. Integration of digital dental casts in 3-dimensional facial photographs. Am J Orthod Dentofacial Orthop 2008;134:820-6.
25. Schutyser F, Van Cleynenbreugel J, Ferrant M, Schoenaers J, Suetens P. Image-based 3D planning of maxillofacial distraction procedures including soft tissue implications. Med Image Comput Computer-Assisted Intervention 2000;1935:999-1007.
26. Xia J, Samman N, Yeung RW, Shen SG, Wang D, Ip HH, et al. Three-dimensional virtual reality surgical planning and simulation workbench for orthognathic surgery. Int J Adult Orthod Orthognath Surg 2000;15:265-82.
27. Teschner M, Girod S, Girod B. 3-D simulation of craniofacial surgical procedures. Stud Health Technol Inform 2001;81: 502-8.
28. Keeve E, Girod B, Girod S. Computer-aided craniofacial surgery. In: Lemke HU, editor. Computer-aided craniofacial surgery. Proceedings of the 10th International Symposium of Computer Assisted Radiology, 1996 June 26-29, Paris, France. Amsterdam: Elsevier/Excerpta Medica;1996.
29. Mollemans W, Schutyser F, Nadjmi N, Maes F, Suetens P. Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation. Med Image Anal 2007;11:282-301.
30. Westermark A, Zachow S, Eppley BL. Three-dimensional osteotomy planning in maxillofacial surgery including soft tissue prediction. J Craniofac Surg 2005;16:100-4.
31. Chabanas M, Luboz V, Payan Y. Patient specific finite element model of the face soft tissues for computer-assisted maxillofacial surgery. Med Image Anal 2003;7:131-51.
32. Schendel SA, Montgomery K. A web-based, integrated simulation system for craniofacial surgical planning. Plast Reconstr Surg 2009;123:1009-106.
33. Keeve E, Girod S, Kikinis R, Girod B. Deformable modeling of facial tissue for craniofacial surgery simulation. Comput Aided Surg 1998;3:228-38.
34. Zachow S, Gladilin E, Zeilhofer HF, Sader R. Improved 3D osteotomy planning in craniomaxillofacial surgery. Medical image computing and computer-assisted intervention. Proceedings of the 4th International Conference of Medical Image Computing and Computer-Assisted Intervention; 2001 Oct 14-17; Utrecht, The Netherlands.
35. Gladilin E, Zachow S, Deuflhard P, Hege HC. Anatomy- and physics-based facial animation for craniofacial surgery simulations. Med Biol Eng Comput 2004;42:167-70.
36. Gateno J, Teichgraeber JF, Xia JJ. Three-dimensional surgical planning for maxillary and midface distraction osteogenesis. J Craniofac Surg 2003;14:833-9.
37. Vandewalle P, Schutyser F, Van Cleynenbreugel J, Suetens P. Modeling of facial soft tissue growth for maxillofacial surgery planning environments. IS4TH 2003;27-37.
38. Langlotz F. Localizers and trackers for computer assisted freehand navigation. In: Picard F, Nolte LP, Digiola AM, Jamaraz B, editors. Hip and knee surgery—navigation, robotics, and computer assisted surgical tools. Oxford, United Kingdom: Oxford University Press; 2004. p. 51-3.
39. Kim H, Jurgen P, Krol Z, Caversaccio M, Nolte LP, Zeilhofer HF, et al. Clinical applications of computer-aided planning and navigation system for cranio-maxillofacial surgery. CAS-H 2009. Leipzig, Germany, Book of Abstracts.
40. Kim H, Nolte NP, Gonzalez Ballester M, Caversaccio M, Zeilhofer HF. CARS 2008. Barcelona, Spain. #031.