Published in final edited form as:

Am J Orthod Dentofacial Orthop. 2010 September ; 138(3): 361–371. doi:10.1016/j.ajodo.2009.08.026.

3D Surgical Simulation

Lucia Cevidanes, DDS, MS, PhD^a, Scott Tucker, DDS, MS^b, Martin Styner, PhD^c, Hyungmin Kim, MS^d, Jonas Chapuis, PhD^e, Mauricio Reyes, PhD^f, William Proffit, DDS, PhD^g, Timothy Turvey, DDS^h, and Michael Jaskolka, DDSⁱ

^a Assistant Professor, Department of Orthodontics, School of Dentistry, University of North Carolina, Chapel Hill, NC ^b Assistant Professor, Bowman Gray School of Medicine, Wake Forest University, Winston-Salem, NC ^c Assistant Professor, Departments of Psychiatry and Computer Science, University of North Carolina, Chapel Hill, NC ^d PhD Student, Maurice Müller Institute, Bern, Switzerland ^e Software Engineer, NEXThink, Parc Scientifique PSE-B Lausanne, Vaud 1015 Switzerland ^f Head, Medical Image Analysis Group at ARTORG Center for Biomedical Engineering Research, Basel, Switzerland ^g Kenan Professor, Department of Orthodontics, School of Dentistry, University of North Carolina, Chapel Hill, NC ^h Professor, Department of Oral & Maxillofacial Surgery, School of Dentistry, University of North Carolina, Chapel Hill, NC ⁱ Resident, Department of Oral & Maxillofacial Surgery, School of Dentistry, University of North Carolina, Chapel Hill, NC

Abstract

This paper discusses the development of methods for computer-aided jaw surgery. Computer-aided jaw surgery 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 (CAS) system developed in close collaboration with surgeons. Surgery planning and simulation include construction of 3D surface models from Cone-beam CT (CBCT), dynamic cephalometry, semi-automatic mirroring, interactive cutting of bone and bony segment repositioning. A virtual setup can be used to manufacture positioning splints for intra-operative guidance. The system provides further intra-operative assistance with the help of a computer display showing jaw positions and 3D positioning guides updated in real-time during the surgical procedure. The CAS 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 prior to the surgery. CAS has the potential to 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. Supported by NIDCR DE017727, and DE018962

INTRODUCTION

Orthognathic surgery involves repositioning segments of the jaws. Reconstructive procedures entail replacement of missing or damaged anatomical structures by grafts or implants. Each case in craniomaxillofacial surgery has unique properties and requires

Corresponding Author: Dr. Lucia H.C. Cevidanes, Department of Orthodontics, UNC School of Dentistry, 201 Brauer Hall, CB7450, Chapel Hill, NC 27599, Cell: (919) 357-8603 Fax: (919) 843-8864, cevidanl@dentistry.unc.edu.

Conflict of Interest Statement

There is no conflict of interest for any of the contributing authors.

careful preparation. Conventional methods to prepare for orthognathic surgery rely on lateral and frontal radiographic images. These are only of limited help for the understanding of complex three-dimensional defects and for the planning of appropriate corrections.^{1, 2} The advent of Cone-beam computed tomography (CBCT) imaging 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 preparation of the surgical plan is still normally carried out using 2D radiographic images. In the past ten years, a number of 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 the clinical application of these methods and critically assess the difficulty of transferring virtual plans into the operating room.

This paper discusses methods for computer-aided jaw surgery, and presents applications of a complete computer-aided surgery (CAS) system, the CMFApp software,⁴⁻¹⁰ under development at the Maurice Müller Institute (MEM), 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 MEM.

METHODS

The methods for computer-aided surgery systems in jaw surgery follow procedures from the image scanners to the operating room (Figure 1):

- Data Acquisition: collection of diagnostic data.
- Image Segmentation (ITK-SNAP software):¹¹ identification of anatomical structures of interest in the image datasets.
- Visualization (CMFApp software):⁴⁻¹⁰ 3D display of the anatomical structures.
- Diagnosis (CMFApp software):⁴⁻¹⁰ extraction of clinical knowledge from the 3D representations of the anatomy.
- Planning & Simulation (CMFApp software):⁴⁻¹⁰ preparation of an operative plan using the virtual anatomy and a simulation of the outcome.
- Intra-operative Guidance (CMFApp software):⁴⁻¹⁰ assistance for intra-operative realization of the virtual plan.

Data Acquisition

Diagnosis of skeletal discrepancies is based on visual data coming from different sources: clinical examination, 3D photographic examination, Cone-beam CT (CBCT) and digital dental models. Computer assisted systems must integrate different records in order to characterize the orthodontic diagnosis and formulate the treatment plan. The first advantage of a software-based solution lies in its capacity for data organization. The different sources of anatomical and diagnostic data can be stored in one 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 intra-operative guidance functions.

Multimodality registration is available for a number of commercial software programs, such as 3DMDvultus (3DMD, Atlanta, GA), Maxilim (Medicim, Mechelen, Belgium), Dolphin Imaging (Dolphin Imaging & Management Solutions, Chatsworth, CA), InVivoDental (Anatomage, San Jose, CA), and SimPlant OMS (Materialise, Leuven, Belgium). This paper focuses specifically on the surgical simulation procedures executed on 3D surface models

built from CBCT. However, the CMFApp software (developed under the funding of the CoMe network¹²) provides a uniform medical data handling backbone that was developed to collect all anatomical, diagnostic, planning and intra-operative guidance/monitoring information in a structured file in XML format. This includes preoperative CBCT, 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, etc. This file can be shared among different computer aided surgery (CAS) applications. This data handling mechanism forms part of a modular software framework which permits seamless assembly of software components, sharing of data between these components, and facilitates system extension.

Cone-beam CT Image Segmentation

For CBCT images, once the images 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 anatomical 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, semi-automatic and fully automatic segmentation techniques. For routine clinical use, a fully automated segmentation protocol is preferable because it only requires 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 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 (bone for example) if, and only if, its intensity level is within the specified range. The appropriate value range has to 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 artifact-prone. These artifacts are created because different densities within a voxel are averaged¹³ and then represented by a single CBCT number. Therefore, the CBCT numbers of thin bony walls will 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 reconstructions¹³ of the condyles and areas of thin cortical bone, such as the internal ramus of the mandible and much of the maxilla. Another source of artifacts is the presence of metallic material 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, internal surface of the ramus and maxilla are critical for careful virtual surgery planning. In order to best capture these and other areas, our method of choice for the segmentation procedures utilizes ITK-SNAP (11) software. ITK-SNAP was developed, based on the NIH Visualization Tool Kit (VTK) and Image Tool Kit (ITK), as part of the NIH Roadmap Initiative for National Centers of Biomedical Computing. The automatic segmentation procedures in ITK-SNAP utilize two active contour methods to compute feature images based on the CBCT image gray level intensity and boundaries (Figure 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 post-processing is normally necessary. Artifacts resulting from metallic elements need to be removed. Lower and upper jaws are usually connected due to insufficient longitudinal image resolution and must be separated in the temporomandibular joint and on occlusal surface in particular. For this reason, it has been recommended that the CBCT be taken in centric occlusion with a stable and thin bite registration material.¹⁴ On a laptop computer equipped with 1GB of RAM, the initial mesh generation step typically takes about 15 minutes. Manual postprocessing usually takes longer, up to a couple of hours (separation of the jaws can be particularly tedious). Currently, this manual post-processing 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, obtained with only a few mouse clicks. This needs to be possible with images of even poor quality.

Visualization

After segmentation of the anatomical structures of interest, two technological options are available to visualize these structures three 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 very detailed shading of the facial surfaces at any zoom factor. Also, any other three-dimensional structure that can be represented by a triangular mesh can be easily included in the anatomical view (e.g., implants imported from CAD implant databases). The majority of existing CMF surgery planning software programs (including the CMFApp described in this paper) 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, e.g., the commercial Voxim® (IVS Solutions AG, Chemnitz, Germany), which is based on a highly optimized volume representation showing good detail and performance on clinical datasets. The advantages of volumetric methods are that not only do you have direct visualization of volumetric operations in 3D, but also on cross-sectional image views. Virtual osteotomies are applied on the original image dataset. However, it is difficult to establish the boundaries between tissues and assign the proper color/transparency values to obtain the desired display. Moreover, the image intensity for a given tissue can vary between patients and scanners (e.g., bone density varies with age; there are variations in scanner calibrations; etc...). Virtual cutting operations are much more difficult to simulate in voxel-wise representations. Further evolutions in software and graphics hardware that combine both surface- and volume-based visualization technologies have great potential.

Diagnosis

3D Cephalometry—Correction of dentofacial deformities often requires rotational movements, which 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 CBCT, defining landmarks, lines, planes and measurements.^{17–19} Definition of individual coordinate systems is possible, which are used to express all displacement values during movement planning and intra-operative navigation (Figure 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 anatomical meaning or from an abstract definition (such as middle point between two other points). Surface and shape data available in 3D imaging provide new characterization schemes, based on higher order mathematical entities (e.g., spline curves and surfaces). For example, 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 very rich and compact information, which tend to correspond to natural anatomic features. Lines of high curvature are typical reference features in the craniofacial skeleton.

Future studies will establish new standards for three dimensional 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 4D shape information which integrates evolution over time in the analysis.

Mirroring—Mirroring can be a valuable technique in the treatment of asymmetries. This allows the normal contra-lateral side to be used as a reference. The conventional definition of the symmetry plane is the mid-sagittal plane. In 2D cephalometry, the midline is defined with a number of anatomical landmarks on the frontal cephalogram, and used as a reference to measure the distance to laterally-positioned landmarks. Presence and extent of 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 mid-sagittal plane showed that the definition of the mid-sagittal plane is a reliable procedure.²² However, the choice of landmarks used to determine the mid-sagittal plane will have a marked impact on the asymmetry quantification. In a particular face, symmetry is often better described by several regional symmetry axes (e.g., symmetry between jaw and midface regions often differs) for which no defining landmark set exists.²³ In severe mandibular asymmetries, as in craniofacial microsomia, entire regions of the anatomy might be missing or severely dislocated. In these cases, 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 (Figure 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 in order to obtain as close a match as possible between mirrored healthy structure and affected site.

Dental Assessment—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 methods²⁴ or CBCT¹⁴). The CMFApp software has the capability of integrating high resolution dental surface data that will make quantitative evaluations of occlusion quality possible, and it can be utilized for optimization of jaw movements in orthognathic surgery planning.

Surgical Planning and Simulation

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 in which 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 intra-operatively. In reconstructive procedures, problems consist in determining the desired implant or graft shape. Reconstructive procedures will be assessed in a future paper.

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 bio-compatible 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

Virtual Osteotomy—The resulting mesh from a segment remains 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 (e.g., mandibular nerve canal) are often included in the surface model. For this reason, virtual osteotomy using the CMFApp software⁴⁻⁶⁻¹⁰ utilizes a robust cutting algorithm, able to cope with triangular meshes of any complexity.

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 serves as an individually based planning of the anatomic cuts prior to the surgical procedure. This allows for planning of position and size of fixation screws and plates. The osteotomy tool in CMFApp supports any type of cut with reliable detection and separation of resulting segments. Cutting planes are defined with three or more landmarks selected on the surface (Figure 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, either by drawing on the line, or by clicking on connected line sections. The latter selection mode simplifies selection of closed intersection lines, often encountered when simulating osteotomies of closed skeletal structures (e.g., maxilla buttresses in Le Fort I osteotomy).

Surgical Plan—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 anatomical segments with six degrees of freedom (DOF) is tracked for each of the bone fragments. This allows for the correction of the skeletal discrepancy for a given patient and simultaneous tracking of measurements of X, Y and Z rotational and the rotation about each of these axes. 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 each 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 mathematical programming techniques may be found. For example, Cutting *et al.* proposes that to optimize bone segment positions, one should best fit an appropriate age/race-matched ideal

morphometric form defined in numerical terms. In his proposition, the sum of square distances between landmarks on a particular patient to corresponding landmarks in the normal form would provide the quantitative deviation measure.²⁰

Simulation of Soft Tissue Changes—Methods that attempt to predict facial soft tissue changes resulting from skeletal reshaping utilize approximation models, since direct formulation and analytical resolution of the equations of continuum mechanics is not possible with such geometrical complexity. Different types of models have been proposed:

- Purely geometrical 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
- Multi-layer mass-spring models (MSM): These models rely on the assumption that the material constituting an anatomical structure can be represented by a set of discrete elements, each having individual properties. Each discrete element bears a mass, and relations between these masses are characterized by stiffness values. These models suffer from stability problems, lack of conservation of volume, and a certain mismatch between model parameters and real physical properties.^{27–29}
- Finite element models: Finite element models are intensively used for the analysis of bio-mechanical systems. The finite element method (FEM) can offer a numerical approximation of viscoelastic deformation problems. FEM models consist in 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 which 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, which usually entails substantial computational times and resources.^{29–32}
- Mass Tensor Models (MTM): MTM can be defined as a mixture of the easy architecture of the MSM and the biomechanical relevance of FEM.^(20·29)

Due to their solid physical base, FEM models and Mass Tensor Models are the most likely to provide reliable simulation results. In any case, 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. However, the current integration of the accurate positioning control ensured by the CMFApp system will allow thorough validation studies in the future.³³

3D photographs can also be texture mapped onto the skin surface from CBCT images to provide photo-realistic rendering of soft tissue changes (3DMDvultus (3DMD, Atlanta, GA); Maxilim (Medicim, Mechelen, Belgium); Dolphin Imaging (Dolphin Imaging & Management Solutions, Chatsworth, CA); InVivoDental (Anatomage, San Jose, CA). Alignment of the 3D photograph with the CBCT skin surface (registration) utilizes surface matching algorithms.

Other functionalities that have been incorporated into different software systems include: simulation of muscular function,³⁴ distraction osteogenesis planning³⁵ and 4D surgery planning.³⁶ Many corrective treatments are planned long-term. This involves several surgical interventions distributed over time with periods of healing and growth between surgeries. A generic growth model based on statistical data collected with longitudinal

studies can also be utilized in future studies, although its relevance in regard to the variations in growth factors and bone density should be evaluated. Such a generic model could be individualized progressively by collecting clinical/image data over time.

Intra-operative Guidance: Surgical Navigation Systems

In corrective procedures, achieving the desired bone segment realignment freehand is difficult. Also, segments must often be moved with very limited visibility, e.g., under the (swollen) skin. Approaches used currently in surgery rely largely 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 implant in the planned location also arises. 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 anatomical bodies, instruments, or devices in the operative scenario. They provide an augmented view of the current operative situation. This can incorporate pre-operatively, or intra-operatively acquired images, operative plans, and real-time measurements, in order 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. In order 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.

Tracking Technology—Different tracking technologies³⁸ for the tracking of the displacement of a mobilized fragment in the course of an osteotomy can be used with the CMFApp with respective advantages and disadvantages:

- 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, which is not possible in practice.
- Ultrasound: an array of three 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 value can vary with temperature changes and the calibration procedure is very delicate.
- 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 strongly with these systems, distorting the measurements in an unpredictable way. Newer systems claim reduction of these effects and feature 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, Louisville, CO, and Aurora, Northern Digital Inc., Ontario, Canada).
- Optical: infrared (IR) optical tracking devices rely on pairs or triplets of charged coupled devices that detect positions of IR 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 6DOF position tracking. Optical tracking offers reliability, flexibility, high accuracy (as low as 0.2mm), and good OR-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 LEDs with more than one camera simultaneously.

Registration

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 relations between these coordinate systems are so-called *rigid* transformations (bone structures can be considered non-deformable), which correspond to a rotation and a translation: a *disparity function dRMS* is defined, which measures the root-mean-square (RMS) 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, using Paired-Points registration (Figure 6). Paired-Points registration¹⁰ consists in finding the rigid transformation that best represents the correspondence between pairs of points identified in the two coordinate systems. A minimum of three pairs of non-collinear points is needed to define the transformation entirely. Generally, points in the image coordinate system (COS) are identified manually on the screen, and corresponding points are digitized during the registration procedure using a tracked pointer. Two categories of points are commonly used:

- **Fiducials:** Fiducials are external physical markers, which provide clearly identifiable points both in image and tracking domains. Fiducials are either attached to or inserted into 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 CBCT acquisition, giving four very precise unambiguous pairs of points.
- **Anatomical landmarks:** Anatomical landmarks are points set on prominent features in the anatomy, which are easily identifiable both, in the image and on the patient with the pointer. Localization of anatomical landmarks is generally less accurate than localization of fiducials.

Navigation Display—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 graphical 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 6DOF movement, which is a difficult task (Figure 7). Interfaces involving stereoscopic displays or auditory feedback can also be envisioned, as well as mechanical aids and augmented reality systems.

Experience from application of CAS systems (such as the CMFApp software) indicates that a lot of time and precision is 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(3):287–309. v. [PubMed: 18088886]
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(4):576–85. discussion 586–7. [PubMed: 8356120]
3. Arai Y, Tammsalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. *Dentomaxillofac Radiol* 1999;28(4):245–8. [PubMed: 10455389]
4. Chapuis, J. Computer-Aided Cranio-Maxillofacial Surgery. University of Bern; 2006. PhD thesis
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(3):274–87. [PubMed: 17521077]
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(7):636–42. [PubMed: 16542822]
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. 3rd International Conference on Computer-Aided Surgery around the Head; Berlin, Germany. 2005 August;
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;
10. Chapuis, J.; Rudolph, T.; Borgeson, B.; De Momi, E.; Pappas, I.; Hallermann, W., et al. 3D Surgical Planning and Navigation for CMF Surgery. SPIE Medical Imaging; San Diego, California, USA. 2004 February;
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(3):1116–28. [PubMed: 16545965]
12. CMFApp software (<http://co-me.ch/>) assessed as of June 1, 2009.
13. Hemmy DC, Tessier PL. CT of dry skulls with craniofacial deformities: accuracy of three-dimensional reconstruction. *Radiology* 1985;157(1):113–6. [PubMed: 3929326]
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(2):297–307. [PubMed: 19276829]
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(12):1780–4. [PubMed: 17113445]
16. Pommert, A.; Riemer, M.; Schiemann, T.; Schubert, R.; Tiede, U.; Hohne, KH. Three-Dimensional Imaging in Medicine: Methods and Applications. In: Taylor, R.; Lavalée, S.; Burdea, G.; Mosges, R., editors. *Computer Integrated Surgery*. MIT press; Cambridge, MA: 1996. p. 155-74.
17. Bettega G, Payan Y, Mollard B, Boyer A, Raphael B, Lavalée S. A simulator for maxillofacial surgery integrating 3D cephalometry and orthodontia. *Comput Aided Surg* 2000;5(3):156–65. [PubMed: 10964087]
18. Swennen, GR.; Barth, EL.; Schutyser, F.; De Groeve, P.; Lemaitre, A. Three-Dimensional (3-D) Cephalometry: The Basics for Virtual Planning. XVII European Congress for Cranio-Maxillofacial Surgery; Tours, France. 2004 September;
19. Swennen, GR.; Schutyser, F.; Hausamen, JE. *Three Dimensional Cephalometry: A Color Atlas and Manual*. 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, R., editors. Computer Integrated Surgery. MIT press; Cambridge, MA: 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(1):37–60. [PubMed: 10638852]
22. Alhadidi A, Cevidanes LHS, Mol A, Ludlow J, Styner MA. 3D Analysis of Facial Asymmetry based on Midsagittal Plane Computation. *J Dent Res* 2009;88(Spec Issue A):311.
23. Tung-Yui, W.; Jing-Jing, F.; Tung-Chin, W. A Novel Method of Quantifying Facial Asymmetry. Lemke, HU.; Inamura, K.; Doi, K.; Vannier, MW.; Farman, AG., editors. Computer Assisted Radiology and Surgery; Berlin, Germany: 2005 Jun.
24. Rangel FA, Maal TJ, Berge SJ, van Vlijmen OJ, Plooi JM, Schutyser F, et al. Integration of digital dental casts in 3-dimensional facial photographs. *Am J Orthod Dentofacial Orthop* 2008;134(6): 820–6. [PubMed: 19061810]
25. Schutyser F, Van Cleynenbreugel J, Ferrant M, Schoenaers J, Suetens P. Image-Based 3D Planning of Maxillofacial Distraction Procedures including Soft Tissue Implications. *Medical Image Computing and 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(4):265–82.
27. Teschner M, Girod S, Girod B. 3-D simulation of craniofacial surgical procedures. *Stud Health Technol Inform* 2001;81:502–8. [PubMed: 11317798]
28. Keeve, E.; Girod, B.; Girod, S. Computer-Aided Craniofacial Surgery. Lemke, HU., editor. Computer Assisted Radiology; Paris, France: 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(3):282–301. [PubMed: 17493864]
30. Westermarck A, Zachow S, Eppley BL. Three-dimensional osteotomy planning in maxillofacial surgery including soft tissue prediction. *J Craniofac Surg* 2005;16(1):100–4. [PubMed: 15699653]
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(2):131–51. [PubMed: 12868618]
32. Schendel SA, Montgomery K. A web-based, integrated simulation system for craniofacial surgical planning. *Plast Reconstr Surg* 2009;123(3):1009–1106.
33. Keeve E, Girod S, Kikinis R, Girod B. Deformable modeling of facial tissue for craniofacial surgery simulation. *Comput Aided Surg* 1998;3(5):228–38. [PubMed: 10207647]
34. Zachow, S.; Gladilin, E.; Zeilhofer, HF.; Sader, R. Improved 3D Osteotomy Planning in Craniomaxillofacial Surgery. *Medical Image Computing and Computer-Assisted Intervention: 4th International Conference Utrecht; The Netherlands. 2001 October;*
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(2):167–70. [PubMed: 15125145]
36. Gateno J, Teichgraeber JF, Xia JJ. Three-dimensional surgical planning for maxillary and midface distraction osteogenesis. *J Craniofac Surg* 2003;14(6):833–9. [PubMed: 14600624]
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, L-P.; Digiola, AM.; Jamaraz, B., editors. Hip and Knee Surgery – Navigation, Robotics, and Computer Assisted Surgical Tools. Oxford University Press; 2004. p. 51-53.
39. Kim, H.; Jurgen, P.; Krol, Z.; Caversaccio, M.; Nolte, LP.; Zeilhofer, HF.; Gonzales, MA. Clinical applications of computer-aided planning and navigation system for cranio-maxillofacial surgery. Leipzig, Germany: CAS-H 2009Book of Abstracts
40. Kim, H.; Nolte, NP.; Gonzalez, Ballester M.; Caversaccio, M.; Zeilhofer, HF. CARS 2008. Barcelona; Spain: p. 031

Figure 1.

(1) Cone beam CT's are taken for each patient. (2) Segmentation involves delineation of the anatomical 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 intra-operative guidance can then be utilized for intra-operative realization of the virtual surgical plan.

Figure 2.

Cone beam CT images are imported as DICOM files into ITK Snap. In a process known as semiautomatic segmentation anatomical areas of interest are identified and delineated. Manual editing is performed to ensure accuracy of the segmentations. The images can be viewed in three dimensions and as axial, coronal, and sagittal slices of each image.

Figure 3. Cephalometry can be performed on the three dimensional skeletal model formed from the CBCT. This allows the user to define landmarks, lines, planes, and measurements.

Figure 4.

Mirroring can be a valuable technique in the treatment of asymmetries. As shown below the lateral orbit (1) has been delineated on each side. (2) The left orbit was mirrored onto the right side using the CMF applications mirror function and the mid-sagittal 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.

Figure 5.

Virtual surgical cuts were placed in the three dimensional skull models by placing three 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 of these segments can then be relocated and tracked with precise control using movements with six degrees of freedom. (X, Y, and Z in rotational and translational planes of space.)

Figure 6.

Paired points registration establishes a correlation between virtual images and real anatomy. In the image below the initial cone beam 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.

Figure 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 three translational and three rotational planes of space.