ORTHOGNATHIC SURGICAL SIMULATION OF CLASS III PATIENTS USING 3-D CONE BEAM CT IMAGES

Scott F. Tucker, DDS

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Approved by
Advisor: Lucia Cevidanes DDS, PhD
Reader: Martin Styner PhD
Reader: Ray White DDS

ABSTRACT

Scott F. Tucker: Orthognathic Surgical Simulation of Class III patients using 3-D cone beam CT images
(Under the direction of Lucia Cevidanes)

Objective: Our aim is to determine if virtual surgery performed on 3-D cone beam CT models correctly simulated the actual surgical outcome of Class III orthognathic surgical patients. **Methods:** All data was acquired from the UNC orthognathic surgery stability studies. We created segmentations of the maxillofacial hard tissues of twenty class III patients. We performed virtual surgeries on cone beam CT images using the CranioMaxilloFacial Application software. **Results:** The virtual surgical models were superimposed on the models of the actual surgical outcomes. The virtual surgery accurately recreated all surgical movements. Surgery residents showed greater variability in lateral ramus positioning than attending faculty. **Conclusions:** Our methodology demonstrated valid recreation of the subjects' craniofacial skeleton. It allows the surgeon to better predict surgical outcomes. Future validation of occlusal and soft tissue components would be valuable. Virtual surgical training for surgical residents could be beneficial. Supported by NIDCR DE 005215 and the SAO

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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 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 three dimensional 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 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 averaged (12) and then represented by a single CBCT number. Thus, 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 reconstructions (12)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. (13) On a laptop computer equipped with 1GB of RAM, the initial mesh generation step typically takes about 15 minutes. Manual post-processing 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. (14) 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. (15)

An advantage of surface-based methods is the very detailed shading of the facial surfaces at any zoom factor. Any other three-dimensional structure that can be represented by a triangular mesh can also 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 thus 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...). Further evolutions in software and graphics hardware that combine both surface- and volume-based visualization technologies have great potential.

Diagnosis

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3D Cephalometry. Correction of dentofacial deformities often requires rotational movements. These are impossible to represent correctly in only lateral or frontal planes. In the CMFApp software, cephalometry is performed on the 3D skeletal model generated from CBCT, defining landmarks, lines, planes and measurements. (16-18) 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.* (19) and Subsol *et al.* (20) 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. (21) 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. (22) 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 lets the user 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 methods (23) or CBCT(13)). 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.

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. 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)

Corrective Procedures. Craniofacial surgical simulation software allows designing different osteotomies and comparing the simulation visually. This provides qualitative decision making support. The principal advantage has been in allowing the clinician to design unusual osteotomy sets to solve particularly complex reshaping problems, for example, when maxillary impaction is planned. However, quantitative evaluation is the most difficult aspect in procedures involving the midface and mandible. In surgical procedures, the question is not where to cut the bone, but how far the bone segment should be moved or how much bone needs to be removed in the case of maxillary impaction. In the lower regions of the face, the location and shape of the cut is indeed determined by the position of nerves, arteries, and lines of easy fracture. “Best practice” osteotomy shapes exist and are well documented, but how much to move the segment remains a difficult decision. CAS offers solutions to these common problems as will be discussed later in this paper.

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 (4-6, 6-10)software 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 translational planes of space. 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. (19)

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(24), or bone displacement vectors are simply applied on the vertices of the soft tissue mesh.(25)

• Multi-layer mass-spring models: 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. (26, 27)

• Finite element models: Finite element models are intensively used for the analysis of biomechanical 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 sub-domains, 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. (28-31)

Due to their solid physical base, FEM 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.

3D photographs can also be texture mapped onto the skin surface from CBCT images to provide photo-realistic rendering of soft tissue changes. 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,(32) distraction osteogenesis planning(33) and 4D surgery planning.(34) 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.

Reconstructive Procedures

Graft Insertion. In reconstructive procedures, the problem is to design the appropriate shape and then accurately recreate the correct shape of the graft during surgery. With large bone movements, the size of the created gaps between the segments might be too big for proper bone healing. Planning the insertion of a bone graft to replace the missing bone depends on the size of the bone gap, quality and availability of autogenous bone material. Templates to contour the bone graft at the time of surgery can be designed and then fabricated beforehand using rapid prototyping. Custom mandibular implants can also be designed to provide symmetry of bony contours, and surface models of custom made implants can be sent to manufacturers of synthetic implant and grafting materials, such as MEDPOR implants (Porex Corp, Munich, Germany).(1)

With the development of 3D image-based modeling, a wide range of methods exist to create the 3D computer model of the desired implant/graft, and Computer-aided manufacturing (CAM) devices may be used to fabricate the precision custom implant, tissue engineering scaffold, or graft shaping template. The usual procedure for designing the implant or graft involves the application of mirror imaging methods, such as the one in the CMFApp software. (4-10) (Figure 4) Unfortunately, in most congenital craniofacial anomalies, there is no normal side to mirror. In many common craniofacial anomalies (such as Apert, Crouzon's, Treacher Collins) deformities are present on both sides. Mirror imaging in such cases is of little to no value. Therefore, other designing methods need to be developed. For example, the recent developments in statistical shape models allow computing a base shape for reconstruction by registering a "mean" shape to the individual anatomy. The 3D statistical shape model is created from a number of "normal" samples, which represent the mean shape of the structure including all of its variations. The samples are mapped in a common vector space, in which Principle Components Analysis (PCA) can be applied to characterize principal modes of variation in the training set. New shapes can be generated by linear interpolation of these variation modes. By finding an optimal fit for its variations, the statistical shape model can be matched to the malformed body.

For implant fabrication, a new generation of 3D “solid printing” processes exist: stereolithography, selective laser sintering, computer-controlled extrusion, etc. These so-called *rapid prototyping* processes are capable of producing complex shapes with sufficient accuracy and at reasonable cost.

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. (35) 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.

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 technologies (36) 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 camera and markers.

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 registration 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 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. The objective in that procedure is to guide the hand of the surgeon to match a 6DOFmovement, which is a difficult task.(Figure7) 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.

Section II

Manuscript II

INTRODUCTION

Le Fort osteotomy advancements and BSSO setbacks alone and in combination are performed for the correction of skeletal Class III deformities. The conventional treatment planning procedure for these orthognathic surgeries involve making plaster models of the teeth and dentoalveoulus. The desired surgical outcome of the dentition is then determined. A lateral cephalometric radiograph is taken and traced to focus on areas of interest. A relocation plan is then performed. This is frequently performed using computer software. Hard tissue computer predictions from lateral cephalograms for orthognathic surgical procedures have been shown to provide accurate hard tissue prediction. (37, 38) They have also been shown to be a reproducible and a quick method of profile prediction that is useful for treatment planning and patient presentation (39) Current lateral cephalometric models have also been linked to soft tissues. This allows one to make surgical changes in the hard tissues that are then reflected in the soft tissues. (40, 41)The surgery is then performed on the cast as a mock surgery. From these mock surgery casts dental splints are created for use during the surgery. The splints are placed on the relocated dentition during the surgery to confirm that the actual surgery matches the model. In this way, the dentition serves as a guide to confirm correct surgical repositioning of the skeletal structures. During preparation for orthognathic surgery the accuracy of cephalometric tracings and model surgeries is extremely important. The intent is to reduce intra-operative complications and minimize actual surgical time.

This conventional process is satisfactory but it has a number of limitations. As can be seen above it is a manual process with multiple steps. It is only a partial view of the actual surgery because the model surgery is not a true mock surgery. It is a repositioning of the dentition to the desired end result in order to make a splint. It doesn't involve simulated cuts or even the necessary components of the craniofacial complex to make such cuts. The relation to the craniofacial complex is loosely made through estimation of the casts to the lateral cephalometric radiograph. The lateral cephalometric radiograph is a two dimensional image of a three dimensional object. This results in errors of superimposition, distortion, anatomy location, and projection. Vertical positioning of the maxilla is very difficult. (42) It also requires you estimate by hand on the cast movements that have six degrees of freedom. This introduces a great deal of inaccuracy.

With the advent of three dimensional imaging came the possibility for improved diagnosis and treatment planning. Many software systems have been developed that hope to improve surgical treatment and outcomes. (43)Virtual surgeries can be performed pre-operatively. (44)Craniofacial Surgery Planners use a patient's individual preoperative 3-D cone beam CTs for making surgical and other predictions. Noguchi demonstrated that three dimensional simulated surgical repositioning of bones is helpful for analyzing both bone and soft tissue movements. (45)

The future of cone beam technology to enhance surgical prediction and preparation is very promising. Recent advances in imaging technology have made the acquisition of three dimensional images more cost-effective and at a reduced radiation dose. This is particularly the case with cone beam CTs. With the proliferation of cone beam CT 3-D imaging technology we have seen a concurrent expansion of imaging software programs. These software programs have been shown useful for diagnosis, treatment planning, and outcome measurement. CranioMaxilloFacial (CMF) Application software was developed and validated at the M.E. Müller Institute for Surgical Technology and Biomechanics, University of Bern, Switzerland. (11) Using an existing dataset of pre and post-surgery CBCT images from the grant "Influences on Stability following Orthognathic Surgery", NIDCR DE005215, we compared virtual surgical outcomes with actual surgical outcomes by superimposing the two images. Our Null hypothesis is that: The mean surface distance of the simulated surgical models when superimposed on the actual cone beam CT of orthognathic surgical patients at UNC is 0.5 mm. The voxel size of the images is 0.5 mm and thus we anticipate the error in our image superimpositions to be no greater than 0.5 mm. Our aim was to determine if the virtual surgery performed on the Cone beam CT segmentations correctly simulated the actual surgical outcome and to validate the ability of this emerging technology to recreate the orthognathic surgery hard tissue movements in 3 translational and 3 rotational planes of space.

MATERIALS AND METHODS

Fourteen patients who had combined maxillary advancement and mandibular setback surgery and six patients who had one piece maxillary advancement surgery were selected. (11 females and 9 males) Patient ranged in age from 14-35 years with a mean age of 21 years.

- All subjects were taken from a consecutive prospectively collected sample that had one of the above mentioned surgeries on or after November 16, 2004 and consented to participate in an NIH funded project “Influences on Stability following Orthognathic Surgery.”(DE 005215)

- Patients who had cleft lip and palate, asymmetries, and other craniofacial anomalies were excluded.
- Rigid fixation was used in all the surgeries

Image acquisition- New Tom 3G Cone Beam CTs with the patient in supine position were obtained prior to surgery and approximately 4 to 6 weeks after surgery (at splint removal).

Construction of pre- and post-surgery 3D models from the parent grant CBCT dataset. Segmentation involved outlining the shape of structures visible in the cross-sections of a volumetric dataset with the New Tom CBCT-3D images. Segmentation of anatomic structures was performed with ITK-SNAP. (46) 3D virtual models were built from a set of ~ 300 axial cross-sectional slices for each image with the voxels reformatted for an isotropic of 0.5 x 0.5 x 0.5 mm. This resolution was used since higher spatial resolution with smaller slice thickness would have increased image file size and required greater computational power and user interaction time. After the segmentation with ITK-SNAP tool, a 3D graphical rendering of the volumetric object allowed navigation between voxels in the volumetric image and the 3-D graphics with zooming, rotating and panning.

Registration of pre- and post- surgery 3D models. A mutual-information based registration maps one image to another, using a rigid transform to evaluate within subject changes. This task was performed using the registration pipeline within the Imagine Software developed at UNC. (46, 47) Our superimposition methods are fully automated, using voxel-wise rigid registration of the cranial base instead of the current standard landmark matching method, which is observer-dependent and highly variable. After masking out maxillary and mandibular structures, the registration transform was computed solely on the grey level intensities in the cranial base. Rotation and translation parameters were calculated and then applied to register the 3D models.

Surgical simulation. Surgical simulation was performed with the CranioMaxilloFacial (CMF) application software. (M.E. Müller Institute for Surgical Technology and Biomechanics, University of Bern, Switzerland.)

Simulation involved the following procedures:

1. **Registration.** The registered virtual 3D surface models of pre- and post-surgery were extracted from the segementations and imported into CMF.
2. **Simulation of Osteotomies**. Simulated surgeries were performed on the three dimensional pre-surgery models by a single examiner. The cuts for a standard BSSO and Maxillary LeFort I Osteotomy were executed by placing points on the pre-surgery models at the area and in the orientation of the osteotomy cuts. The locations of surgical cuts were determined by the anatomic characteristics of each patient, such as thickness of the mandibular ramus, position of the mandibular canal and proximity to the roots of the second molars.
3. **Simulation of surgical displacements**. The post-surgical model was used as a surgical guide. This was done by changing the color and reducing the opacity of the post-surgery model which was superimposed with the pre-surgery model. The magnitude and direction of the simulated movements were then guided by the registered post-surgical model. Movements for each surgical piece were performed

allowing six degrees of freedom.(Anterior-posterior, Lateral, Superior-Inferior, Yaw, Pitch, Roll)

4. **Quantification of differences between simulated and actual post-surgery models-** We computed the surface distances between simulated and actual post-surgery models at specific anatomic regions (Condyles, Lateral mandibular rami, Lateral mandibular corpi, Anterior mandibular corpi, Chin, Lateral maxillary body, Anterior maxillary body.)

Statistics. Student t tests were performed for all 11 regions of interest to test whether the virtual surgeries showed no greater difference than 0.5 mm when compared to the actual surgeries. Student t tests were also performed to test whether the measurements between two jaw and one jaw surgery patients were statistically significant. The Hotelling T^2 metric was used to test the differences in the amount of movement between one and two jaw surgery patients. Paired F tests were performed to evaluate the difference between right and left lateral rami in patients who received two jaw surgeries. Student t tests were calculated to assess the reliability of the 5 patients who received a second virtual surgery.

RESULTS

The virtual surgical models were superimposed on the models of the actual surgical outcomes. This generated visual displays of magnitude, direction, and location of disagreement between models. (Figure 8) For all statistical testing a P value of $P < 0.05$ was considered statistically significant. The differences between the superimpositions of the simulated and actual surgery images are shown in figure 9. The mean difference for the left lateral maxilla was 0.536 mm and the median was 0.515 mm. The mean and median differences were less than 0.5 mm for the superimpositions of all of the other regions of interest. The 0.5 mm difference was selected because 0.5 mm is the spatial resolution of the cone beam images. For each region of interest power was calculated and a student T test was performed to test if the surface distances between the simulated and the actual surgical models were no greater than 0.5 mm. The results are listed in table 1. For all 11 regions of interest there was no statistically significant difference between the simulated and the actual surgical models. The power calculated in the right lateral maxilla, left lateral maxilla, and chin was less then 0.80. The power was greater than 0.96 for all other regions of interest.

In comparing the two jaw subjects with the maxillary advancement subjects a student t test was performed. The results are listed in table 2. The right lateral ramus was the only region of interest that showed a statistically significant difference when comparing the two jaw and one jaw surgeries. Mean translational and rotational displacements of the one and two jaw surgeries were also calculated. Hotelling T^2 was then performed to test the differences between the two groups. For translational displacements a value of 0.14928498 and an F value of 0.80 showed a Probability > F of 0.538. For rotational displacements a value of 0.22166894 and an F value of 1.18 showed a Probability > F of 0.3477. There was no statistically significant difference between two jaw and one jaw surgeries when comparing translational and rotational displacements.

In two jaw subjects there was very little translational variability in the right and left lateral rami as shown in figure 10. The left lateral ramus showed greater rotational variability than the right lateral ramus as shown in figure 11. The median for translational and rotational displacements in all groups was zero, but significant individual variability was manifest. Paired F-tests were performed to test whether the right and left ramus displacements were significantly different. The F value for translational displacement was

3.2592593 and the probability > F was 0.0633288. The F value for rotational displacement was 1.024251 and the probability > F was 0.4192385. These tests did not demonstrate statistical significance between the right and left lateral rami displacements in two jaw surgery patients.

Five of the subjects were randomly selected to have the surgery repeated. The differences between the repeated surgical simulation and the actual surgical outcomes were recorded. These measurements were then compared to the initial differences in measurements for these patients. All of these measurements showed less than 0.4 mm difference between the initial surgical simulation and the repeated surgical simulation. This is less than the 0.5 mm spatial resolution of the cone beam images. Student t tests were performed and the results are shown in table 3. There was no statistically significant difference between the initial and the repeated measurements for any of the regions of interest.

DISCUSSION

Differences between virtual and actual surgical outcomes were measured utilizing a voxel wise rigid registration of the cranial base. We have validated this method in previous studies. (46) It has been shown to be more accurate than traditional landmark methods for three dimensional superimpositions. The larger the number of points used for superimposition the more accurate it becomes. (48, 49) Only two of the measured differences between pre- and post-surgery models were greater than 1 mm. All differences were less than 2 mm. Differences of less than 2 mm have been shown to not be clinically significant. (50-52)

Pre-surgical predictions do not necessarily reflect the actual surgical outcomes that are produced. Surgery notes although helpful show variation between surgeons as to the estimated amount of movement. Furthermore, their notes do not reflect the necessary degree of precision we desire to accurately assess the validity and reliability of the virtual surgeries. Post-surgical models are the best measure of what movements were actually produced in the surgery. It is for this reason that we used the post-surgical models as a guide for positioning of the virtual surgical models. This limits our ability in this study to generalize our results because we cannot say that we were able to predict the surgical outcomes. Future studies can be used to predict surgical outcomes prior to surgery and thus assess the validity of the surgical predictions. Our technique eliminated surgical error and resulted in an evaluation of the methodology of the computer program itself. These superimpositions allowed us to assess and visually display location, direction, and magnitude of agreement between virtual and actual surgery models. The difference between the actual surgical displacement values and the measured simulated values was smaller than the CBCT image spatial resolution of 0.5mm. We were able to manipulate the images in the necessary six degrees of freedom to accurately reproduce the actual surgical outcome.

Bimaxillary surgery has been shown to be more difficult to predict than single jaw surgery. (53-55) It has been suggested that this is due to the greater complexity of two jaw surgeries. Our research indicates that for the hard tissue structures measured there was no statistical difference between the one and two jaw surgery patients. The only exception was the statistically significant displacement of the right lateral ramus in two jaw surgery patients. There was also no statistical difference in our population in the amount of translation or rotation that was performed in the maxillary body during the surgery. There was also no clinically significant difference between the two groups. Three dimensional surgical planning allows us to overcome many of the limitations of conventional surgical planning. For example an often cited difficulty of maxillary impaction surgery is posterior bone removal for vertical positioning of the Maxilla. The unpredictability of the necessary bone removal can significantly alter surgical time. Our software allows us to visualize the hard tissue structures in the posterior Maxilla and can thus provide better operating room predictability. It allows the surgeon to have a better idea of how much bone removal will be necessary and then plan accordingly. (Figure 12)

We demonstrated greater variability in lateral ramus displacement by the surgical residents. However, the surgery residents' displacement was not statistically significantly different from the attending faculty. Nor was it considered clinically significant. Increased displacement of the lateral ramus during surgery has the potential for decreased stability of the surgical outcome. It could be valuable to incorporate these emerging technologies into surgical training programs.(56) We feel that there is potential for great benefit to residents by allowing them to perform surgical procedures in three dimensions prior to entering the operating room. This allows them to practice procedures as well as attempt different surgical scenarios. A systematic review of the literature by Gurusamy et al. demonstrated that virtual reality training for surgery residents resulted in increased accuracy, decreased operating time, and decreased error. (57) This technology also allows potential for communication between colleagues and training over distances by sharing digital three dimensional records. (58)We see potential value in surgical resident training for surgical procedures to be supplemented through virtual surgical training.

There has been an explosion in recent years of commercially available programs for three dimensional virtual surgery and visualization programs. The biggest drawback to these programs is the lack of validation of outcomes. It is desirable that craniofacial skeletal components, occlusion, and soft tissue outcomes are validated. (59) We demonstrated that CMF application software can correctly simulate the actual surgical outcomes of craniofacial skeletal components of patients. However, the CT does not accurately render the teeth with the necessary precision for surgical simulation and splint fabrication. (60, 61) Three dimensional laser scanning is a noninvasive way to accurately capture the occlusion that has been suggested by multiple groups. (62-64) These images are then superimposed and merged on the cone beam images. (65) Using three dimensional printers' splints can be fabricated from the digital models. (66) Soft tissue predictions also lack validation and are extremely difficult to accurately predict in three dimensions. (42, 67, 67)Commercially available programs utilize spring deformation and morphing programs for soft tissue surgical predictions. This is not biomechanically accurate, nor has it been validated. (68-71) The validation of soft tissue outcomes would greatly improve patient presentation and understanding of surgical outcomes.

Xia et al demonstrated that Computer aided surgical simulation CASS) has lower material costs as well as decreased patient and surgeon time. They foresee even greater time savings by outsourcing to radiology technicians at imaging centers the surgical image processing. (14) Our research allowed us to demonstrate that the computer aided surgical simulations can accurately reproduce with six degrees of freedom the actual surgeries performed for class III correction. This validation of the virtual surgery of hard tissue structures demonstrates the potential for comparable or better surgical outcomes. We see great benefit for this technology in the future as a tool that has been shown to reduce complication and increase predictability. It allows the surgeon to better predict possible surgical complications and adapt accordingly to mitigate potential difficulties. (25, 33, 56, 72-75) It has also been utilized to allow more complex surgeries to be successfully performed in a single procedure rather than the previous multiple staged surgeries. (72) Future benefits also include the fabrication of stereolithographic models and surgical splints. These have the potential to greatly reduce intra-operative time, complications, and surgical surprises. (72)The accuracy of computer assisted surgery has been shown to be within 1 mm when using a referencing splint. (76)A number of these programs such as the CMF application software we tested are also equipped with a surgical navigation feature that allows the surgical simulations to be transferred to the operating room. (70, 74, 75, 77, 78)Many, such as CMF, currently take the form of passive intra-operative orientation and tracking systems. In final form there is potential for robotic execution of specific steps autonomously. (75) Thus we can anticipate the potential for faster, cheaper, and better outcomes through this emerging technology. This rapidly developing technology will have a significant impact on a surgeon’s future work.

CONCLUSIONS

Three dimensional diagnosis and treatment planning has great potential for future benefit to patients and surgeons. The validation of these rapidly emerging technologies is paramount. It is particularly valuable to validate craniofacial skeletal components, the occlusion, and soft tissues.

1. The virtual surgery accurately recreated all surgical movements in 3 rotational and 3 translational planes of space.

2. One and two jaw virtual surgeries were equally valid and accurate.
3. Our virtual surgical methods were reliably reproduced.
4. Preoperative simulation can allow for increased predictability in the operating room.
5. Oral surgery residents could benefit from virtual surgical training.
6. Future validation of occlusal and soft tissue components would be very beneficial

Figure 1. Virtual surgery flow chart: (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. (Image courtesy Dr. Jonas Chapuis (4))

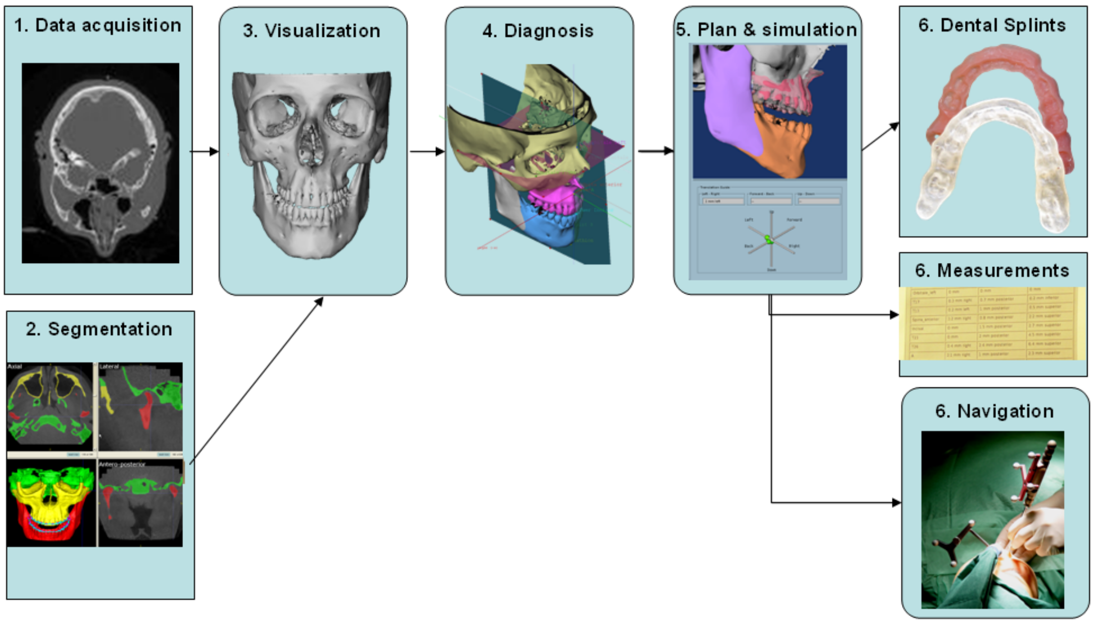

Figure 2. Image segmentation: Cone beam CT images are imported as DICOM files into ITK Snap. In a process known as semiautomatic segmentation anatomical areas of interest are identified and delineated. Manual editing is performed to ensure accuracy of the segmentations. The images can be viewed in three dimensions and as axial, coronal, and sagittal slices of each image.

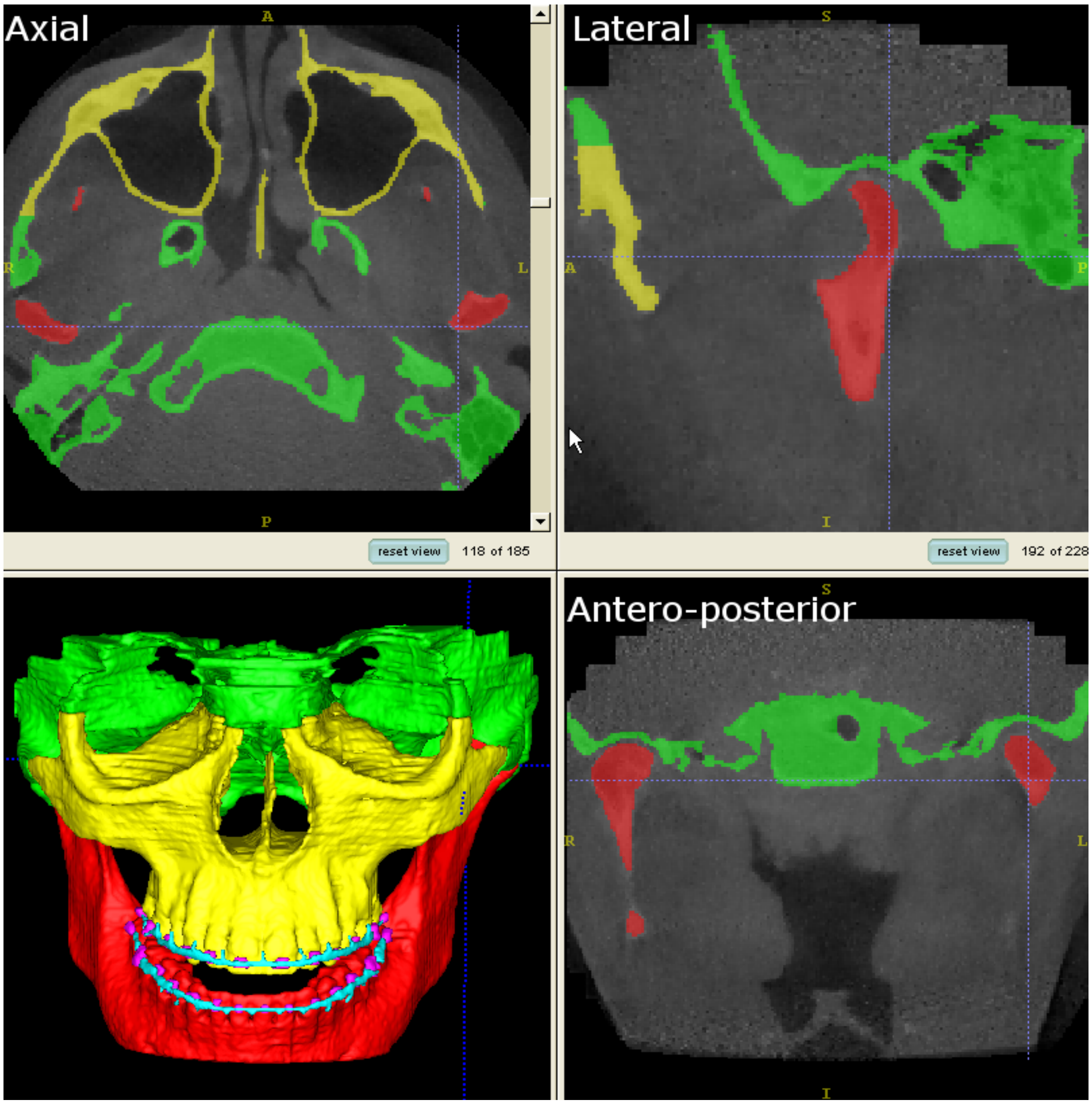

Figure 3. Three-dimensional cephalometry: Cephalometry can be performed on the three dimensional skeletal model formed from the CBCT. This allows the user to define landmarks, lines, planes, and measurements.

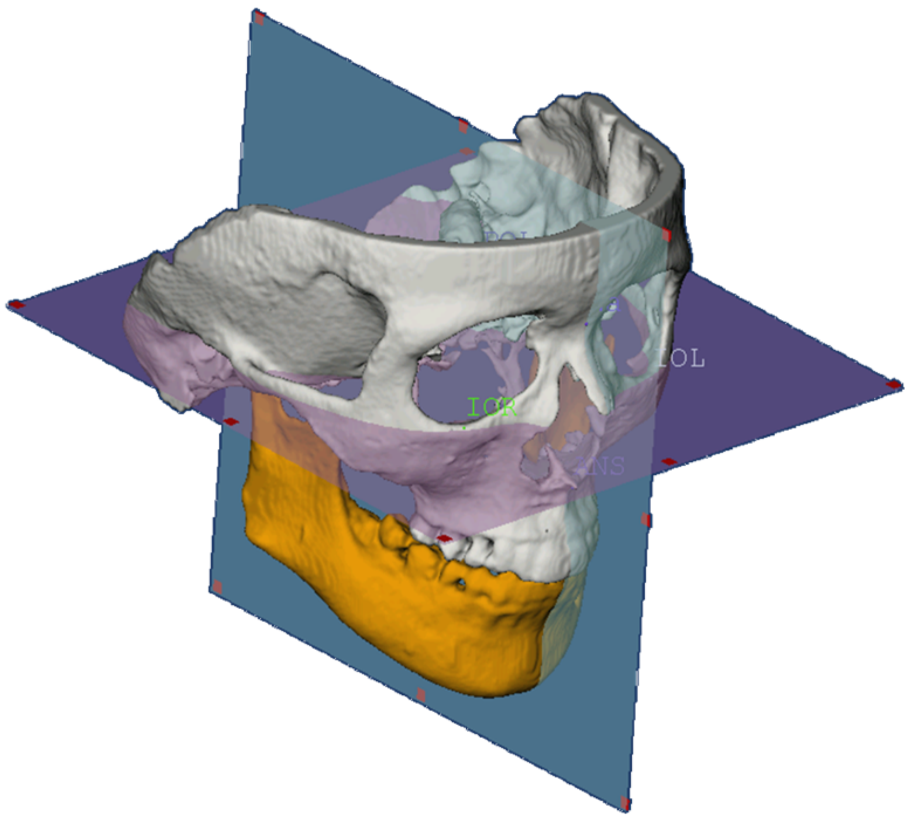

Figure 4. Three-dimensional image mirroring: Mirroring can be a valuable technique in the treatment of asymmetries. As shown below the mandible (A) has been colored yellow. (B) The left ramus was mirrored onto the right side using the CMF applications mirror function and the mid-saggital plane was defined for the image. (C) The right lateral ramus was then reincorporated back into the model with the right side recreated as a mirror of the left side.

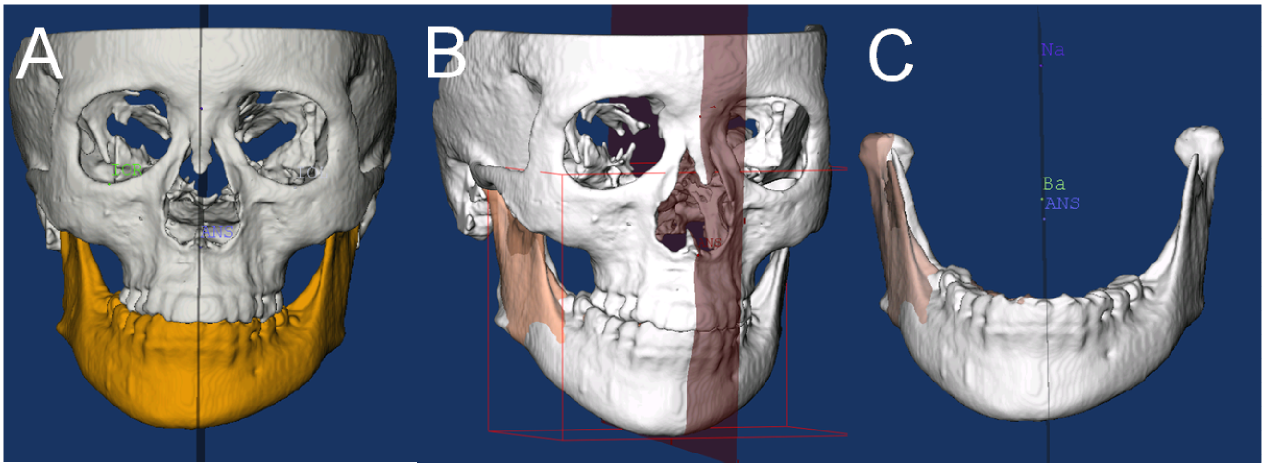

Figure 5. Virtual surgical cuts: Virtual surgical cuts were placed in the three dimensional skull models by placing three or more points in the desired orientation of the cuts. The newly cut segments were then painted different colors to allow better visualization of the cuts. Each of these segments 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.)

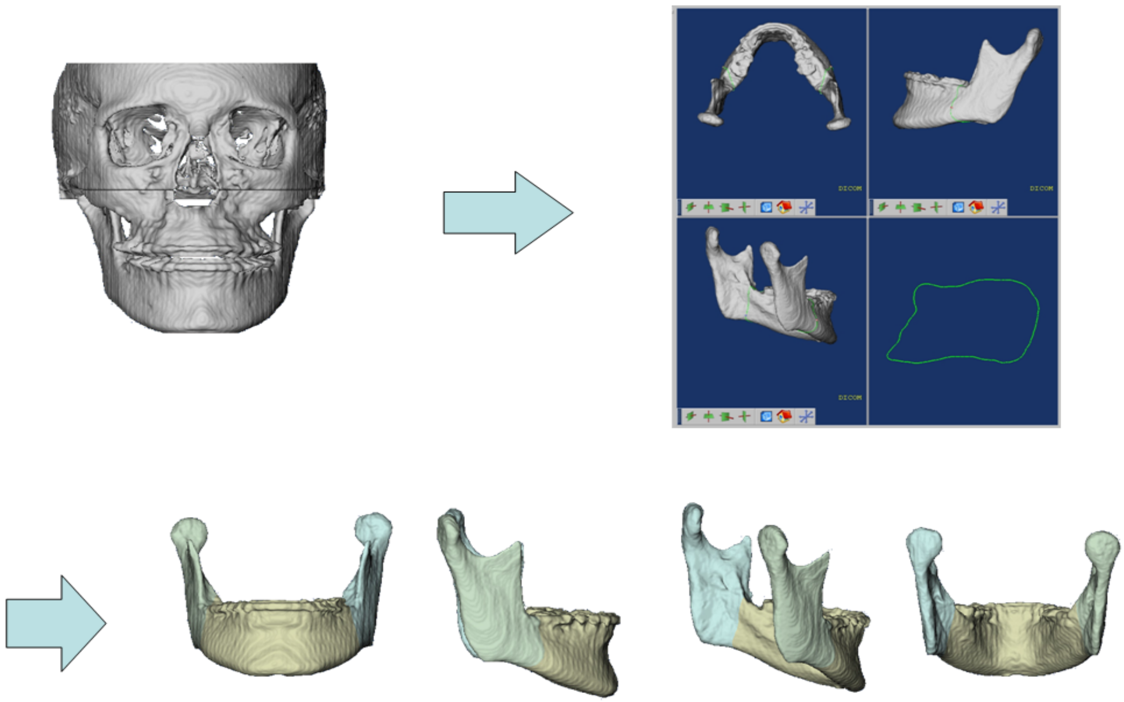

Figure 6. Paired points registration: Paired points registration establishes a correlation between virtual images and real anatomy. In the image below the initial cone beam images were taken with bite splints that had metallic objects built into the splints. These areas appeared on the radiographic images. 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. (Image courtesy Dr. Jonas Chapuis (4))

Figure 7. Surgical navigation: (A and D) the patient below presented with a marked craniofacial asymmetry. (B and E) Reconstruction of the left lateral orbit was performed without surgical navigation. As can be seen in E this resulted in an even greater asymmetry in the axial plane. (C and F) The surgery was repeated with surgical navigation and there was a marked improvement in the symmetry in all planes of space. Future surgeries for the mandibular asymmetries are planned to be performed with surgical navigation.

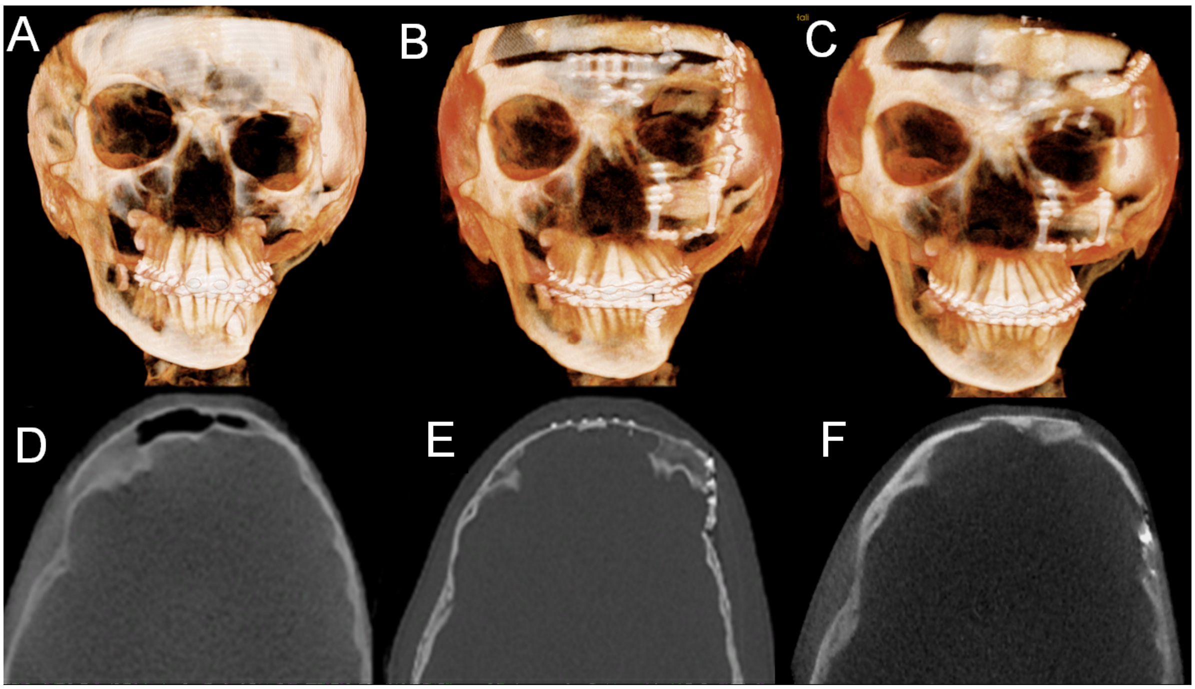

Figure 8. Color map of superimposition of virtual surgery models: Superimposition of virtual surgery models and post surgery models of patients treated with maxillary advancement and mandibular setback. Color maps demonstrate the location, direction, and magnitude of the differences between these models.

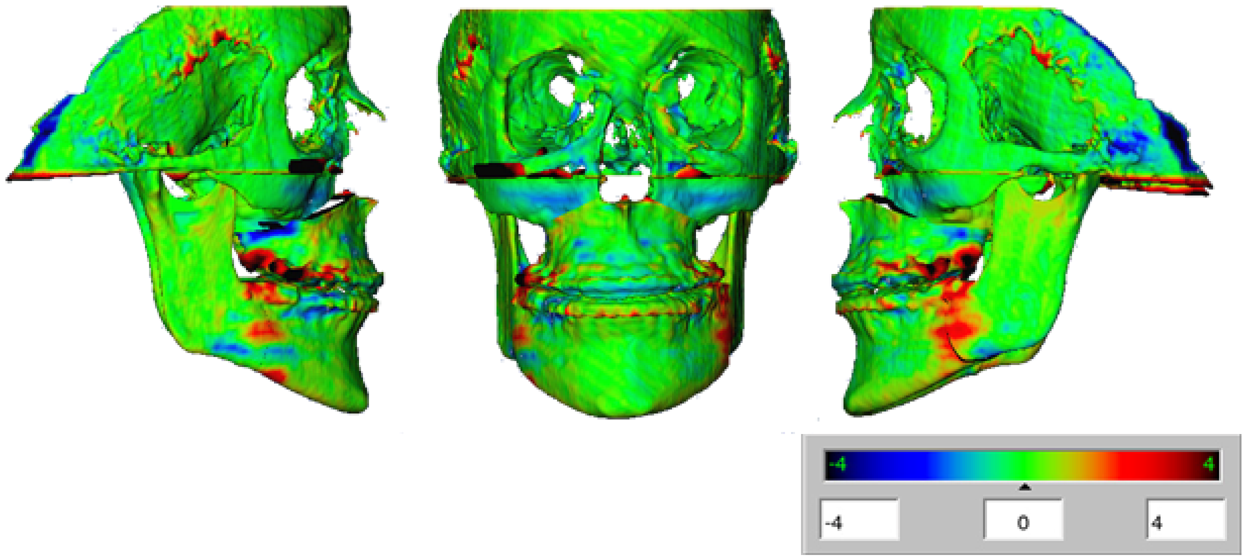

Figure 9. Box plot showing differences between superimposed models: The differences between virtual and actual post surgery models are shown below. The x axis shows the 11 regions of interest and the y axis shows the difference in mm between the two images. All regions of interest except the left lateral maxilla showed a mean and median difference less than the 0.5 mm spatial resolution of the acquired image. (Ant = Anterior Maxilla, RLat = Right lateral maxilla, LLat = Left lateral maxilla, RCon = Right condyle, LCon = Left condyle, RLRam = Right lateral ramus, LLRam = Left lateral ramus, AntC = Anterior Corpus of the mandible, RLatC = Right lateral corpus of the mandible, LLatC = Left lateral corpus of the mandible, Chin = Chin)

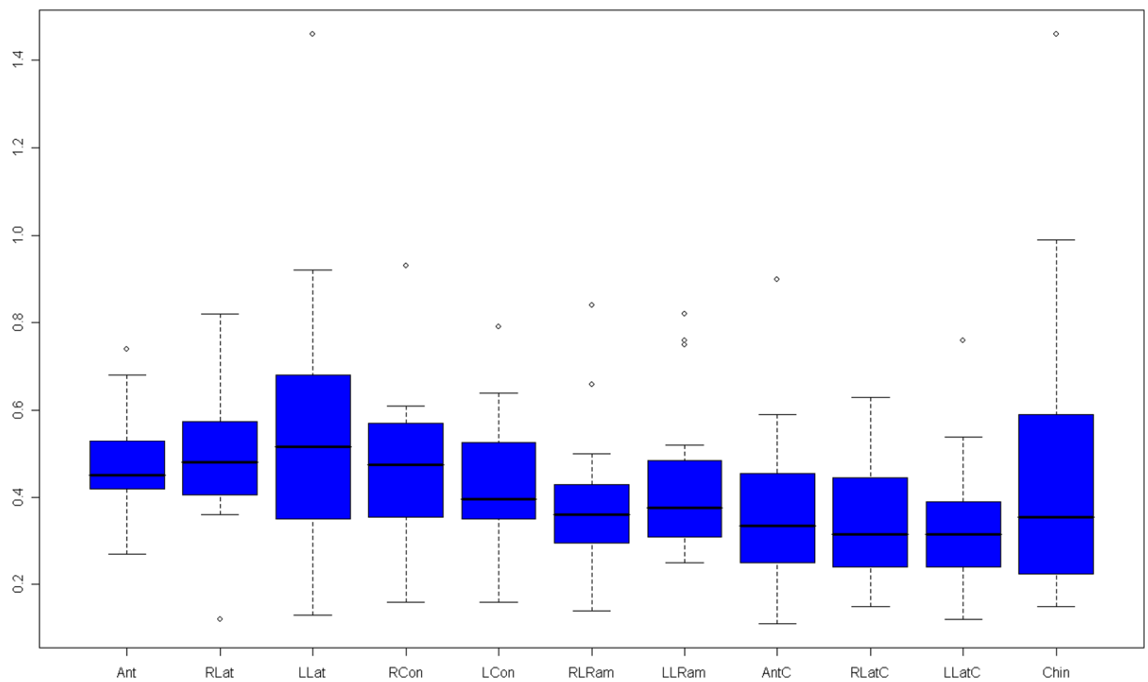

Figure 10. Box plot of translation movements of right and left lateral rami: Translational movements of the right and left lateral rami during mandibular setback surgery. The faculty member operated on the right side and is always shown in the left of the paired columns. (1, 3, and 5) The resident operated on the left side and is always shown on the right of the paired columns. (2, 4, and 6) Directions of movement in mm: (+) left/ (-) right shown in columns 1 and 2; (+) anterior/ (-) posterior shown in columns 3 and 4; and (+) superior/ (-) inferior shown in columns 5 and 6.

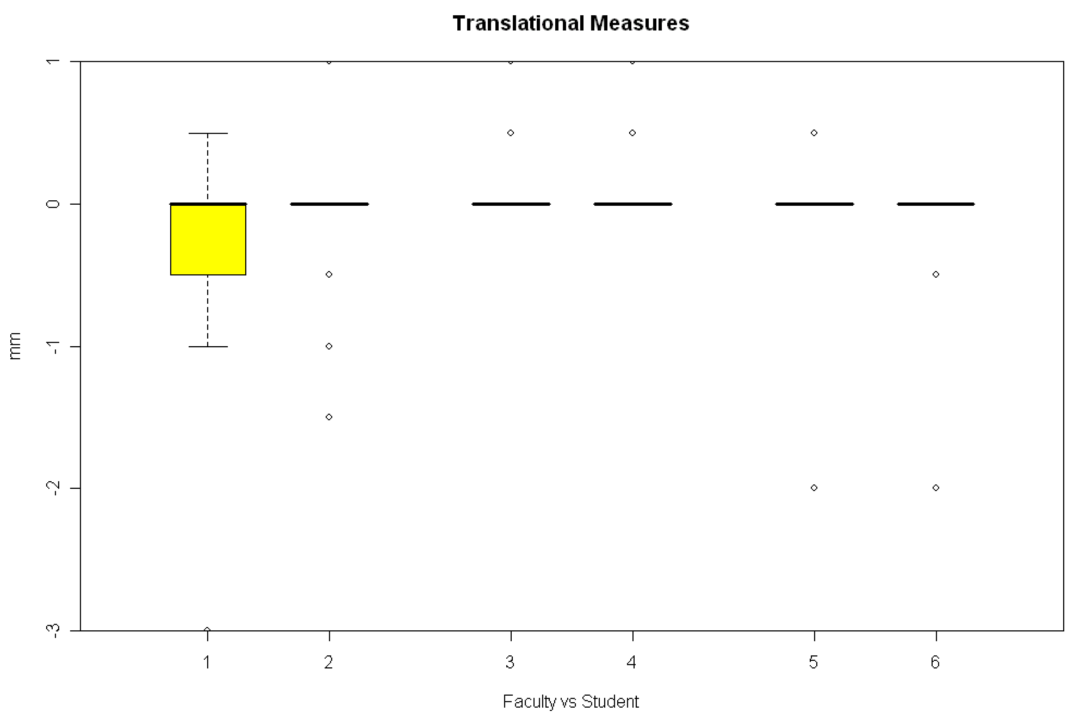

Figure 11. Box plot of rotational movements of right and left lateral rami: Rotational movements of the right and left lateral rami during mandibular setback surgery. The faculty member operated on the right side and is always shown in the left of the paired columns. The resident operated on the left side and is always shown on the right of the paired columns. Amount of rotation in degrees are shown: (+) signifies a clockwise rotation and (-) signifies a counterclockwise rotation. Column X: Axial plane or Pitch, Column Y: Sagittal plane or Yaw and Column Z: Coronal plane or Roll.

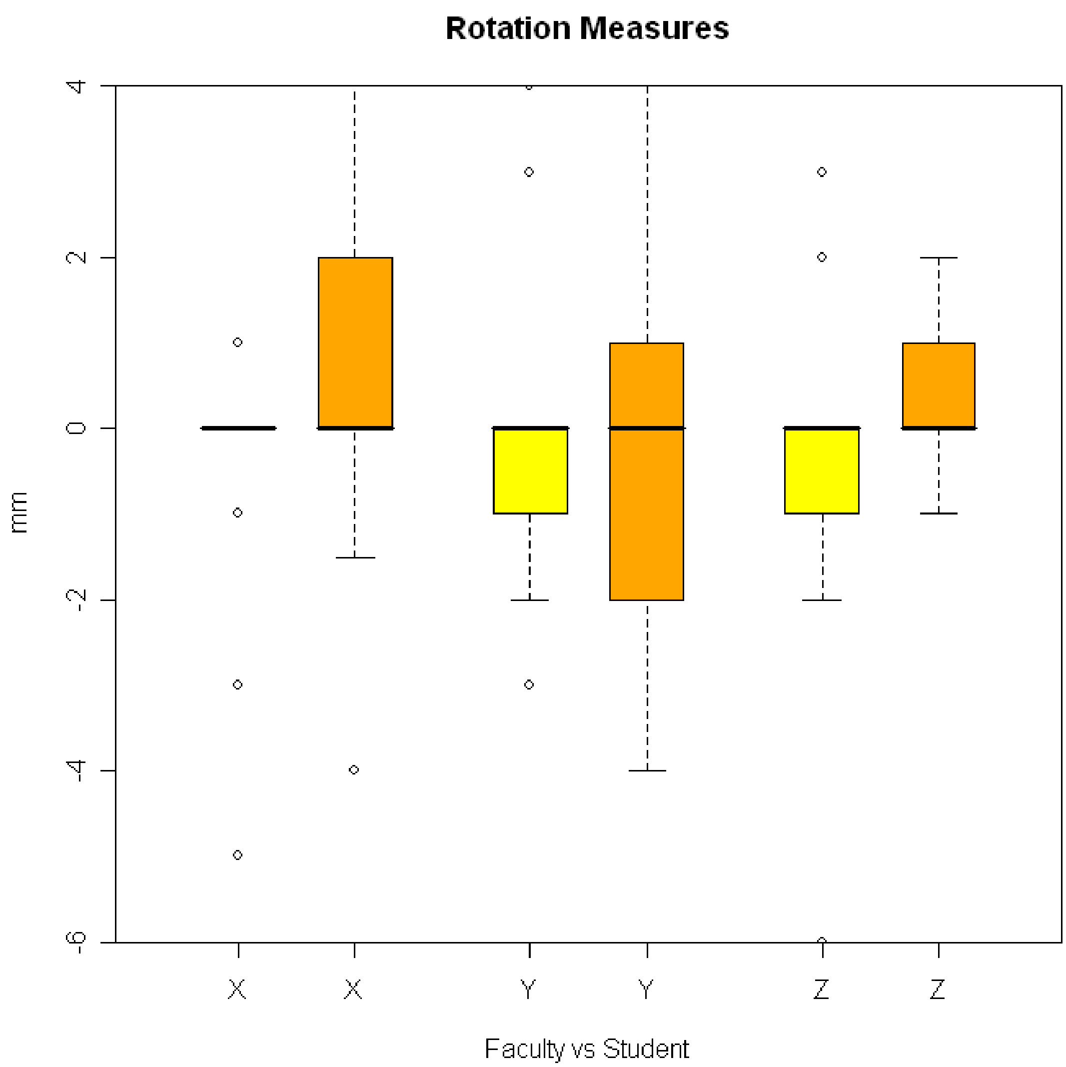

Figure 12. Color map of superimposition of maxillary impaction surgery: Superimposition of maxillary segment of virtual surgery models and pre surgery models of patients treated with maxillary advancement and impaction. The grey image is the pre-surgery model and the image with the color map is the post virtual surgery image. Color maps demonstrate the location, direction, and magnitude of the differences between these models. This allows for visualization of posterior bone removal that will be necessary during the surgery.

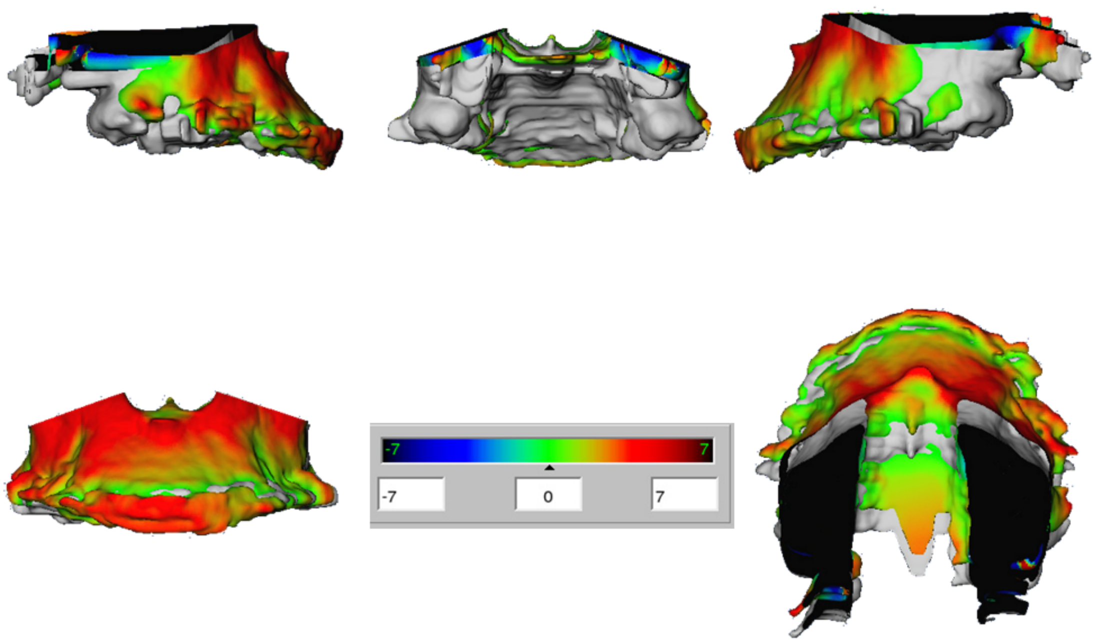

Table 1. Differences between virtual and actual surgical outcomes: Power was calculated. Student t tests were performed for each region of interest to test if the difference of the virtual surgical outcomes when superimposed on the actual surgical outcomes was less than the image spatial resolution of 0.5 mm. P< .05 was used to determine statistical significance between the two images.

	t Value	Probability t	Power
Region of interest			
Anterior Maxilla	-0.79167	0.561677	0.962
Right Lateral Maxilla	-0.18841	0.14745	0.203
Left Lateral Maxilla	0.538988	0.403845	0.151
Right Condyle	-0.8912	0.616033	0.986
Left Condyle	-1.85496	0.920813	0.999
Right lateral Ramus	-3.27984	0.99606	0.999
Left Lateral Ramus	-1.81991	0.915435	0.999
Anterior corpus	-3.29165	0.996163	0.999
Right lateral corpus	-5.62111	0.99998	0.999
Left lateral corpus	-5.27873	0.999957	0.999
Chin	-0.45906	0.3486	0.631

Table 2. Differences between one and two jaw surgical outcomes: Student t tests were performed for each region of interest to test if there was a difference in the virtual surgical outcomes between one and two jaw surgery patients. *P< .05 was used to determine statistical significance between the two images.

	t Value	Probability t
Region of interest		
Anterior Maxilla	-0.88331	0.388712
Right Lateral Maxilla	-0.08929	0.929836
Left Lateral Maxilla	-1.84928	0.080908
Right Condyle	0.351947	0.728965
Left Condyle	-0.81534	0.425536
Right lateral Ramus	2.505062	0.022074*
Left Lateral Ramus	0.638073	0.53146
Anterior corpus	-1.20006	0.245671
Right lateral corpus	1.633646	0.119702
Left lateral corpus	0.605325	0.552519
Chin	0.100442	0.921104

Table 3. **Reliability of repeated surgeries:** Five subjects received a second virtual surgery and measurements for each region of interest were recorded. Student t tests were performed for each region of interest to test the reliability of the repeated surgeries. P< .05 was used to determine statistical significance between the two images.

Region of interest	t Value	Probability t
Anterior Maxilla	0.200548	0.850836
Right Lateral Maxilla	2.046469	0.110131
Left Lateral Maxilla	1.258634	0.276614
Right Condyle	0.043499	0.967389
Left Condyle	0.286611	0.788643
Right lateral Ramus	0.191565	0.857414
Left Lateral Ramus	1.152182	0.313421
Anterior corpus	1.617962	0.180981
Right lateral corpus	-0.55405	0.60906
Left lateral corpus	0.202031	0.849752
Chin	-0.18546	0.861896

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