Computer-Assisted Planning in Cranio-Maxillofacial Surgery

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In cranio-maxillofacial surgery physicians are often faced with the reconstruction of massively destroyed or radically resected tissue structures caused by trauma or tumours. Also corrections of dislocated bone fragments up to the complete modeling of facial regions in cases of complex *congenital* malformations are common tasks of plastic and reconstructive surgeons. With regard to the individual anatomy and physiology, such procedures have to be planned and executed thoroughly in order to achieve the best functional as well as an optimal aesthetic rehabilitation. On this account a computer-assisted modeling, planning and simulation approach is presented that allows for preoperative assessment of different therapeutic strategies on the basis of three-dimensional patient models. Bone structures can be mobilized and relocated under consideration of anatomical and functional constraints. The resulting facial appearance is simulated via finite-element methods on the basis of a biomechanical tissue model, and visualized using high quality rendering techniques. Such an approach is not only important for preoperative mental preparation, but also for vivid patient information, documentation, quality assurance as well as for surgical education and training.

Keywords: cranio-maxillofacial surgery, computer-assisted surgery planning, osteotomies, bone relocation, soft tissue prediction, finite-element simulation, visualization

1. Introduction

A constantly increasing public mobility with always faster transportation systems, as well as an increasing level of sport activities with all accidents that might result thereof lead to a growing number of complex fractures in the cranio-maxillofacial region. A surgeon's primary concern is to reconstruct the original situation as close as possible. For that purpose photographs or any other source of information that documents the previous state is used. The functional and aesthetic rehabilitation of *congenital* malformations, however, is much more difficult to achieve, since any individual reconstruction template is missing (Fig. 1).

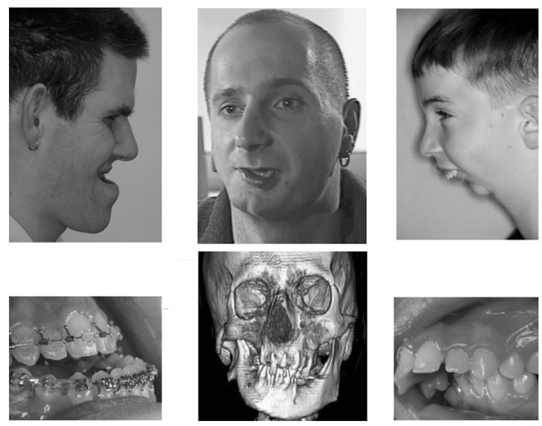

Fig. 1. Complex congenital skull deformities.

Especially for children or youths, the psychosocial consequences of an appearance, that is deviating from the respective standards, are of extremely high relevance for their personal development and the later social acceptance. Therefore, a surgeon has to model a functional anatomy under consideration of a harmonious facial appearance. Such a modeling task requires a high level of surgical expertise, a distinct sense of aesthetics, artistic skills, and extensive communication with the patients and their relatives. Due to the individuality of patients, the complexity of anatomy and physiology of the human organism, as well as the demand for optimal functional and aesthetic rehabilitation, cranio-maxillofacial surgery must be

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carefully planned under utilization of all available planning aids. Reliable methods and tools are needed to prejudge the overall result of facial surgery to its full extent.

2. Surgery Planning

The surgical correction of facial disproportions requires profound knowledge of a normally developed anatomy. Among many physiognomic investigations, Albrecht Dürer and Leonardo da Vinci already did accomplish elaborate studies on facial proportions and the characterization of harmonious faces, that even today still have its validity [1]. Meanwhile a comprehensive database of healthy or pathologic proportions as a result of anthropometric or cephalometric studies provide sufficient information for the characterization of anomalies [2, 3]. To assess an individual situation, anthropometric and cephalometric landmarks are identified on the skin surface as well as on X-ray images, and are set in relation to each other for a comparison to the normal range.

Starting from anatomic landmarks and lateral or frontal X-ray images, cephalometric analysis is typically performed on 2D projections of 3D anatomy. Traditionally, contours, landmarks, distances, and angles were manually traced on radiographs using acetate overlays, and these tracings were copied, cut and rearranged. Later on, in the 1970's, this process was adapted to a computer using a digitizer tablet and 2D image processing software [4] (Fig. 2). That way profile corrections could be planned, however, without any possibility to *reliably* assess implications on the facial soft tissue.

Fig. 2. 2D Planning of orthognathic surgery.

From the 1980's on, computer-assisted planning methods have been developed that allow for a combined use of anthropometric and cephalometric landmarks to predict soft tissue *profiles* on the basis of heuristic ratios that have been observed over time [5]. Advanced image processing tools distort digital 2D profile images according to the estimated profile changes, leading to a rough, but often grotesque approximation of a patient's postoperative appearance. For complex facial dysplasia, 2D planning methods with profile analysis are generally not sufficient. Especially symmetry aspects, as in cases of hemifacial microsomia (cf. Fig. 1, center), are only assessable in a frontal view. Thus, the goal should be to plan any complex facial surgery on a 3D model of a patient's head, and to assess any changes in a 3D view from arbitrary perspectives.

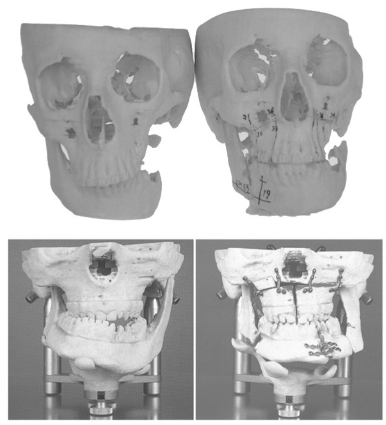

Fig. 3. 3D planning of maxillofacial surgery.

The prerequisites for a 3D planning are 3D imaging techniques, as available with computed tomography. Due to the high X-ray absorption rate of bone, skeletal structures can almost automatically be reconstructed from a consecutive set of CT slices. This layered, three-dimensional information can be converted to a life-size replica of a patient's skull via so called rapid prototyping techniques (Fig. 3). On such models, surgeons are able to practically perform bone cuts (osteotomies) and bone relocations to preoperatively assess functional rehabilitation [6, 7]. However, rapid prototyping techniques are rather expensive, especially when different therapeutic concepts are to be evaluated. Furthermore, neither the impact of an osteotomy on vulnerable structures, like nerves, vessels or, for example, the roots of the teeth, nor the facial soft tissue arrangement resulting from bone relocations, can be assessed. These requirements are additional important reasons for *computer-assisted planning methods* in cranio-maxillofacial surgery.

3. Computer-Assisted 3D Planning

From the late 1980's on, computer-assisted 3D planning of cranio-maxillofacial surgery became a topic of interest [8, 9, 10, 11, 12]. Besides the 3D reconstruction of individual anatomy from tomographic data, a major focus was on predicting soft tissue changes due to bone relocations [13, 14, 15, 16, 17, 18, 19, 20]. Only a few research groups did focus on an integrated 3D planning approach [21, 22, 23, 24].

In the following we present such an integrated approach for 3D surgery planning on *virtual* patient models, addressing three major problems: i) authentic reconstruction of adequate 3D patient models from tomographic data, ii) intuitive surgery planning of bone cuts and bone relocations, and iii) reliable and fast simulation of the resulting facial appearance. Our planning environment is based on the 3D modeling and visualization system AMIRA [25], that has been developed at Zuse-Institute Berlin (ZIB).

3.1. 3D Patient Models

Advanced visualization techniques like direct rendering of scalar fields (e.g. stacks of tomographic images containing HOUNSFIELD values) using texture hardware or polygon rendering of automatically generated iso-surfaces allow for an immediate display of anatomic structures within 3D image data. These techniques are well suited for diagnostic purposes, but cannot compensate for imaging or reconstruction artifacts that might occur due to metal shadowing or partial volume effects (cf. Fig. 4).

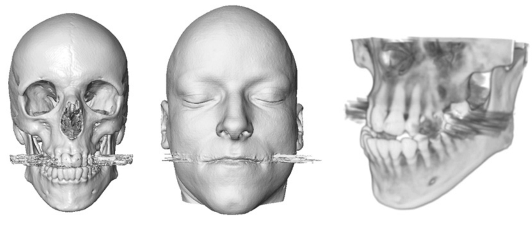

Fig. 4. 3D visualization of tomographic data: left) iso-surfaces, right) volume rendering.

For a meaningful planning of surgical procedures, *reliable* patient models are the basic requirement. Such models, reconstructed from stacks of tomographic slices, must represent all relevant details of an individual anatomy, i.e. the correct surfaces of bony structures and teeth, as well as of all soft tissue boundaries. Therefore, advanced segmentation tools are needed, as, for instance, provided with AMIRA.

In view of a functional rehabilitation, the 3D model of bony structures and teeth is the foundation for an interactive three-dimensional planning of osteotomies and subsequent relocations of mobilized bone segments. The bone-tissue, interface is needed to peg bone relocations to surrounding soft tissue whose volume is defined by its boundaries to hard tissue and air. A volumetric representation of soft tissue is the prerequisite for a reliable 3D simulation of soft tissue deformation and hence for a preoperative assessment of an aesthetic rehabilitation.

All tissue boundaries are initially reconstructed from a sequence of tomographic images with subvoxel accuracy [26, 27]. A resulting surface model typically consists of several million triangles (Fig. 5), depending on the amount of slices and the voxel size, i.e. the inner-slice resolution and the inter-slice distance. Since high resolution surface models are very demanding in view of interactive visualization and manipulation, and also lead to very high resolution volumetric grids, being far too large for fast finite element simulations, a *mesh simplification* based on error quadrics is applied [28]. That way, planning models with a resolution of 75 000 to 250 000 triangles are constructed (Fig. 5, center). The simplification error, measured as deviation between initial and reduced surface

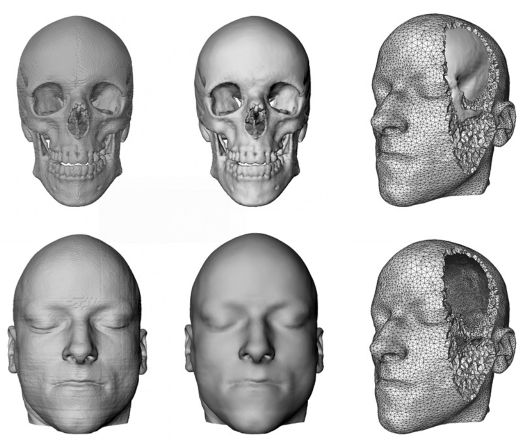

Fig. 5. left) high resolution surface model consisting of approx. 5 million triangles, center) simplified model with 250 000 triangles, right) volumetric soft tissue grid consisting of 650 000 tetrahedrons.

models, depends on the voxel size and in our implementation amounts to a few tenths of a millimeter, thus being rather negligible.

To locally control the mesh resolution, i.e. to make sure thin tissue layers can be filled with a sufficient amount of undistorted volume elements, the original algorithm of Garland and Heckbert [28] has been extended to consider a maximum edge length information per triangle as an additional cost value. Such maximum values can be specified for certain tissue regions and are automatically adjusted with regard to local soft tissue thickness. During simplification, the triangulated surface model is optimized with regard to triangle distortion. That way, suitable surface meshes of finite-element compatible triangles are generated (Fig. 6). These closed triangle meshes are the basis for the generation of unstructured tetrahedral grids. For grid generation a modified *Advancing Front* algorithm is used [29, 30]. Since a major requirement for fast finite-element analysis is a coarse mesh with optimally shaped elements, the placement of inner nodes is controlled via a 3D scalar field of edge length information, which is computed from the resolution of the simplified surface model up to a given maximum inner element size. The resulting soft tissue grids typically consist of 175 000 to 750 000 tetrahedrons, leading to computing times of 1 to 10 minutes on a standard PC for a linear elastic modeling approach (see Sect. 3.4.).

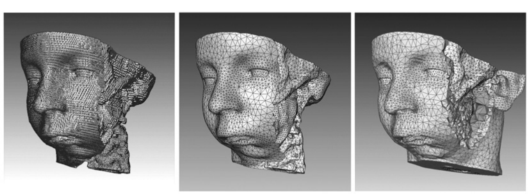

Fig. 6. 3D patient model for surgery planning.

Anatomically and topologically correct patient models, which not only represent tissue *surfaces*, but also mixed tissue *volumes* in a consistent manner, are the first major requirements of our integrated planning and simulation approach. With such a combined representation of individual anatomy, where tissue interfaces (polygonal boundary surfaces) and tissue volumes (tetrahedral grids) are generated and optimized concerning spatial resolution and mesh quality, we are able to perform interactive surgery planning as well as fast finite-element analysis.

3.2. Cephalometric Analysis

Authentic three-dimensional models of individual anatomy (so called *virtual* patient models) and tomographic images, in combination with interactive 3D visualization techniques, have a tremendous diagnostic value for cranio-maxillofacial surgeons. Anomalies or asymmetries are immediately apparent and can be quantified by measuring distances and angles between characteristic points. Such measurements are very common in anthropometric studies as well as in two-dimensional cephalometric analysis, where lateral X-ray images are acquired in a standardized way [31, 32]. Reference points are either located on the facial skin surface or on cephalograms. An individual arrangement of these points is compared to a statistical reference for the assessment of dysplasia (cf. Fig. 7, left).

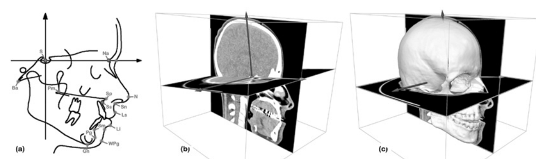

Fig. 7. Cephalometric reference frames: a) 2D according to [32], 3D with sagittal median and b) Sella-Nasion, resp. c) Frankfort Horizontal plane.

Projective techniques, though widely-used, have obvious drawbacks in cases where asymmetric malformations have to be assessed. *En-Face* analysis is also rather difficult to achieve using 2D cephalometry. Thus, for complex cranio-maxillofacial dysplasia, a 3D analysis based on tomographic data and *virtual* patient models is going to become the method of choice [33]. Cephalographic projections can still be computed from tomographic data, and 2D measurements can be performed on such projection images or on any other arbitrarily reformatted slice. In addition, 3D measurements along curved slices or between different slices, as well as on the reconstructed 3D surface model itself are possible. Characteristic points can either be located within the image data (e.g. the center of the hypophyseal fossa — sella turcica), or on the skull and the skin surface respectively. Reference points, or even reference planes, can be constructed from two or more points, as for

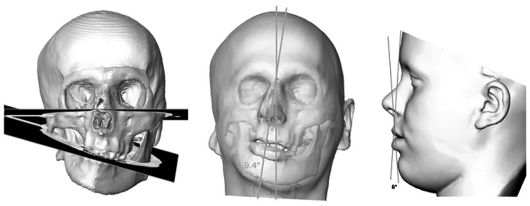

Fig. 8. En-Face symmetry and profile analysis.

instance the Frankfort Horizontal, the median, or an orthogonal plane through the sella point and the nasion (cf. Figs. 7, right and 8).

For a standardized three-dimensional cephalometry, patient models must be aligned within a common reference frame. Such a coordinate system can be easily constructed from reference points and planes. In our case, all models are centered using the sella point, and aligned via the sagittal median and the Frankfort Horizontal plane. Within such a cephalometric coordinate system, measurements can be performed in a standardized way, anomalies or asymmetries can be quantified, and useful guidelines for the relocation of bone segments can be given. A facial profile analysis can also be performed, since extreme values can be uniquely defined (cf. Figs. 7, left and 8, right). In addition, the assessment of dysplasia can be further enhanced using statistical 3D shape models of normally developed anatomy. By comparing an individual skull shape with a statistical reference, deviations might even lead to automatically generated reconstruction proposals [34].

3.3. Osteotomy Planning

Facial regions that deviate from a bilateral symmetry or that show a functional impairment can be identified by cephalometric and functional analysis. The correction of facial dysplasia typically requires relocation, removal, augmentation or even a total replacement of bony structures. Therefore, bone has to be cut (osteotomized) — a procedure that, without any doubt, must be thoroughly planned. In complex cases, such osteotomies are planned on life size replicas of the skull, as shown in Fig. 3. Osteotomy lines are drawn onto the model and cuts are performed accordingly. Mobilized bone segments are rearranged to achieve skeletal symmetry and to re-establish a functional anatomy. However, the assessment of different therapeutic concepts necessitates a set of planning models. Due to increasing costs in health care and a decreasing cost recovery by the governmental health insurance, such approach is not practicable at large.

Our goal was to develop an integrated software system that enables a surgeon to preoperatively plan complex osteotomies and bone relocations on *virtual* patient models. That way, different strategies can be evaluated at almost no additional costs. The computer-assisted osteotomy planning is oriented on the aforementioned *'draw and cut'* principle [35]. Lines can be drawn onto the polygonal surface model of the skull. For a very intuitive specification of such lines, a pen tablet with integrated graphic display can be used, as shown in Fig. 9. Line drawings on a two-dimensional display screen are immediately projected onto the three-dimensional surface, thus giving a surgeon the impression of drawing directly on the planning model. During line specification, the model can be rotated or zoomed at will.

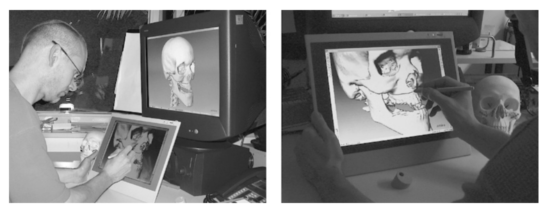

Fig. 9. Intuitive 3D Osteotomy Planning.

After osteotomy lines have been specified, a process that usually takes no longer than a few minutes, cut surfaces are computed from a path the cutting tool must follow to adhere to these lines. To reveal transections of vulnerable inner structures, like nerves, vessels or for example the roots of the teeth, tomographic image data can be mapped onto the cut surfaces

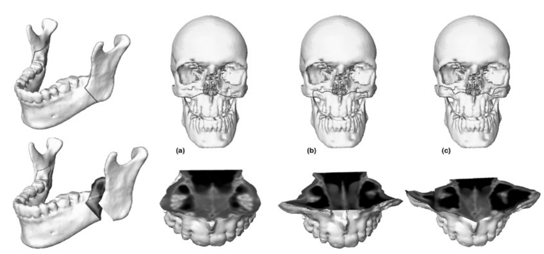

Fig. 10. Osteotomy planning: left) sagittal split of a mandible, right) three variants of a Le Fort-I osteotomy. Assessment with regard to vulnerable inner structures.

(cf. Fig. 10). In case osteotomies have been specified with regard to surgical guidelines and do not harm any structures of risk, the model will be cut, i.e. bone segments are separated.

Mobilized parts of the model can be interactively translated and rotated into the designated positions. Transformations can also be restricted to single degrees of freedom and applied successively for easier control. A center of rotation can be specified as well as a rotational axis (Fig. 11). The latter is especially useful for functional analysis of lower jaw movements. In addition, collision detection and collision avoidance facilitate the planning of bone relocations. In orthognathic surgery, for instance, collision detection is helpful for orthodontic treatment planning, where tooth positions have to be adjusted according to the new relationship of the jaws. Collision avoidance is even more restrictive but very helpful for the re-establishment of a correct dental occlusion. Besides a visual planning of bone relocations, to each bone segment the transformation parameters can be exported for intraoperative navigation techniques [36].

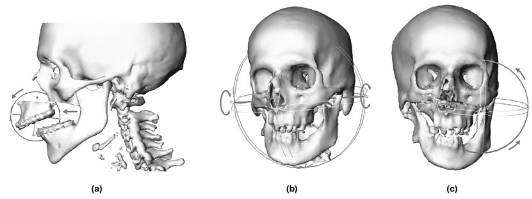

Fig. 11. Interactive bone relocations.

3.4. Soft Tissue Prediction

Functional rehabilitation is the priority objective of osteotomy planning with bone relocations. In cases where multiple bone segments are to be relocated simultaneously and in relation to each other, or different therapeutic concepts are conceivable, facial soft tissue prediction becomes an additional important — for a patient most often *the essential* — criterion in surgery planning. The possibility to preoperatively assess the implications of bone relocations on the facial soft tissue, and thus to consider aesthetic rehabilitation as well, is highly demanded by cranio-maxillofacial surgeons [5]. In view of an improved surgical preparation and patient information, a *reliable* simulation of a patient's postoperative appearance is addressed with our integrated planning approach.

The foundation of a reliable simulation of soft tissue deformation is an adequate geometric model of a patient's individual tissue volume (Sect. 3.1.), as well as a mechanical model that describes deformation of biological tissues in a good approximation [37]. The latter is based on the theory of 3D elasticity, that has its applications in many different engineering fields, as for example in construction design and stress analysis [38].

Soft tissue deformation is caused by the relocation of bone segments. Since bone and surrounding soft tissue share boundaries that are either fixed or transformed, the resulting tissue configuration can be computed from the given boundary displacements $\mathbf{u}|_{\Gamma_D}$, in conjunction with properly assigned boundary types, by minimizing the deformation energy W.

$$W := \int_V \frac{1}{2}\varepsilon : \sigma \, dV - \int_V \mathbf{f}_{ext} \cdot \mathbf{u} \, dV - \int_A (\sigma \cdot \mathbf{n}) \cdot \mathbf{u} \, dA \tag{1}$$

In (1), the first integral term describes the internal energy, being induced by strains and resulting stresses, represented by the two tensors ε and σ respectively. The second term comprises external volume forces, like gravity, acting on the body, and the third contains normal stresses acting on the free part of the body's surface. In a stable static equilibrium, internal and external forces are in balance, and deformation energy attains a local minimum. Since we only prescribe boundary displacements and neglect gravity, the latter two integrals in (1) vanish. Thus, tissue prediction can be reduced to numerically finding the minimum of the first integral (2) as a function of the displacements $\mathbf{u}$ within the computational domain Ω, e.g. using a finite element method. Ω is represented by a volumetric grid of the soft tissue and Γ_Ω by the tissue's boundaries (Fig. 12).

$$W(\mathbf{u}) := \frac{1}{2} \int_\Omega \varepsilon : \sigma \, dV \longrightarrow min \tag{2}$$

Stresses σ are related to strains ε via a constitutive law. In a first attempt, soft tissue is modeled as an isotropic and linear elastic ST. VENANT-KIRCHHOFF material, characterized by only two independent elastic coefficients, POISSON's ratio ν and YOUNG's modulus E. Strains are described by the linearized CAUCHY strain tensor

$\varepsilon(\mathbf{u}) = \frac{1}{2}(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)$ [18]. Based on these assumptions, the following system of partial differential equations (3), the so called LAMÉ-NAVIER equation [42], is solved for the given boundary value problem (4) using fast finite-element methods [43, 44, 45].

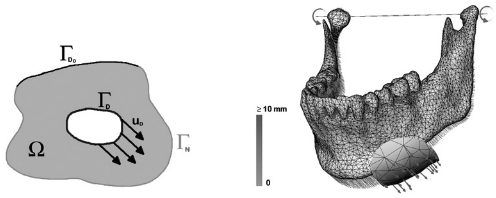

Fig. 12. Boundary displacements.

$$\frac{E}{2(1+\nu)}\left(\frac{1}{1-2\nu}\nabla(\nabla\cdot u(\mathbf{x})) + \Delta u(\mathbf{x})\right) = 0 \quad \textit{in } \Omega \tag{3}$$

$$\begin{aligned} u(\mathbf{x}) &= u_{D_0}(\mathbf{x}), & \mathbf{x} &\in \Gamma_{D_0} \subset \partial\Omega \\ u(\mathbf{x}) &= u_D(\mathbf{x}), & \mathbf{x} &\in \Gamma_D \subset \partial\Omega \\ \sigma(\mathbf{x}) \cdot \mathbf{n} &= 0, & \mathbf{x} &\in \Gamma_N \subset \partial\Omega \end{aligned} \tag{4}$$

Such a rigorous physics-based approach represents a well established method for deformation modeling in continuum mechanics. In combination with an adequate model of a patient's anatomy, resp. soft tissue, the simulation approach in general can be regarded as approved and well suited for that class of problems. The simulation results depend on the choice of appropriate boundary conditions, as well as of suitable mechanical properties of living tissues, that are taken from literature [40,41]. Soft tissue can be modeled as a homogeneous or inhomogeneous material by assigning tissue-dependent elastic coefficients to individual volume elements. Anisotropic tissue properties, non-linear elasticity and more sophisticated tissue models are currently investigated [45], and are to be integrated into our planning system as well.

An example of a three-dimensional soft tissue prediction is depicted in Fig. 13. The top row demonstrates the planing of a bimaxillary osteotomy, where both maxilla and mandible are to be relocated to achieve a correct dental occlusion. The first image shows the preoperative situation with a mandibular prognathism

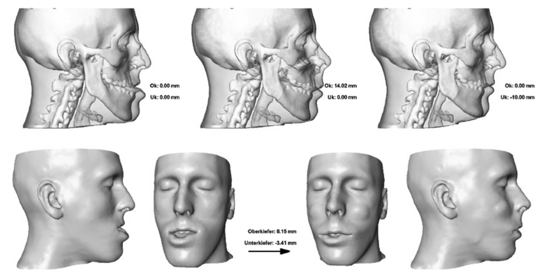

Fig. 13. Planning of a bimaxillary osteotomy with soft tissue simulation.

and a maxillary retrognathism. The middle image shows a correction by maxillary advancement only, and the right image an alternative by mandibular setback. Obviously there are many combinations of bignathic relocations in between, that also lead to a functional rehabilitation. The computer-assisted planning allows for an assessment of *all* possibilities, by continuous variation of bone positions under consideration of the resulting soft tissue arrangement. In the bottom row, the preoperative state is compared to the planned postoperative state, where a maxillary advancement of approx. 8 mm and a mandibular setback of 3.5 mm are simulated. Simulation results can be presented with photo-realistic quality as single images from different perspectives or even as animated sequences.[2] The latter is extremely well suited for indicating subtle changes and leads to a vivid patient information [46].

4. Results

Up to now, more than 30 clinical cases were planned using the previously described approach. All plannings were performed in close collaboration with different clinical partners in Europe. CT data in DICOM format were transferred either with CD or via secure FTP to ZIB, where the 3D patient models were built. The reconstruction process is still the most time consuming task taking up to several hours. Afterwards, the virtual patient models were presented to the surgeons and appropriate strategies for osteotomies and bone reloactions were discussed. In most of the cases, the osteotomy planning, including bone relocation, was performed together with the surgeon in a video

[2] `http://www.zib.de/visual/projects/cas/cas-gallery.html`

conference setting, using remotely controlled planning tools. Such a planning typically takes no longer than 15 to 30 minutes. In all other cases an iterative approach was chosen, exchanging all necessary information via e-mail and a series of annotated 2D images. For each variant the tissue deformation was computed within a few minutes, depending on the size and the quality of the soft tissue mesh. Static images of the simulation, results from different perspectives, were visualized to and assessed by the surgeons, thus getting an impression of the implication of bone relocations on the facial soft tissue.

A *qualitative* comparison of our soft tissue predictions with postoperative results, that have been documented with profile photographs, already yields a good correspondence. Fig. 14 shows a pre- and a postoperative image as well as an overlay view of the predicted 3D facial tissue (semitransparent) with relocated bony structures (opaque) and the photograph of the true outcome, both rendered in a common coordinate system with the photograph positioned at the midsagittal plane. Such an evaluation allows for a comparison of the tissue profile in cases where the bone relocations have been documented with lateral cephalograms.

In order to determine the three-dimensional prediction accuracy and thus the reliability of our modeling approach, a *quantitative* analysis based on postoperative CT data was performed [47]. For four patients with distinct midfacial hypoplasia and class III dysgnathia a maxillary advancement of up to 15 mm was planned and performed (cf. Fig. 15). With the postoperative CT data the actual results, i.e. the exact courses of the osteotomy lines and the new positions of mobilized bone segments are documented, thus enabling us to exactly reproduce the surgical procedure. Therefore, the pre- and the postoperative models were aligned via the neurocranium, that was not affected by the surgical procedure, using an iterative closest point method [49]. The mean registration error was in the order of 1–2 tenths of a millimeter. Mobile bone segments like the mandible, the hyoid and the spine, as well as the osteotomized maxilla were rigidly aligned via anatomic landmarks. The overall registration error of the bone surface was below 0.5 mm. That way we were able to compare our soft tissue simulations with the postoperative results, as it is described in [48].

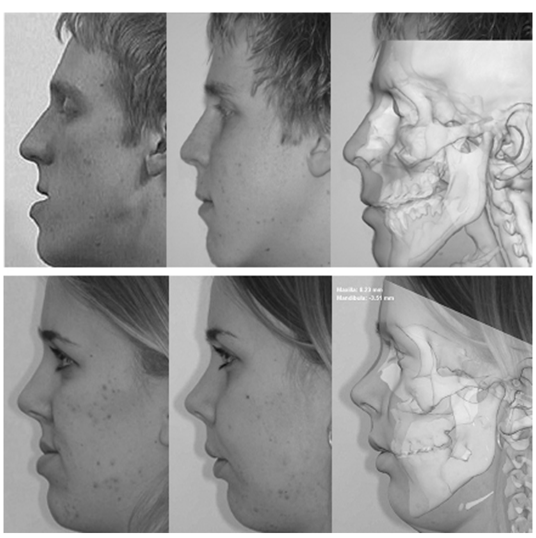

Fig. 14. 2D assessment of tissue prediction using profile photographs and 3D visualization techniques, right) overlay of the postoperative photograph and the altered planning model with predicted facial soft tissue.

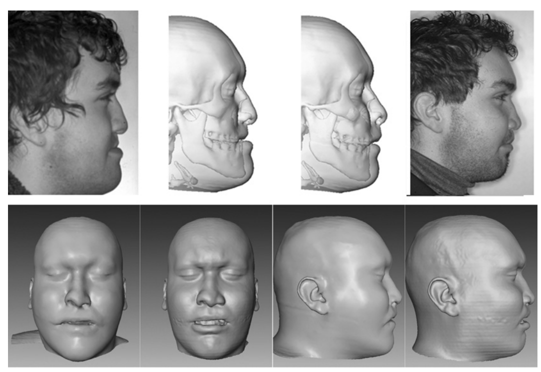

Fig. 15. 3D assessment of soft tissue prediction using postop. CT data: grey) simulation, magenta) actual result.

Among others, the prediction accuracy depends on an appropriately chosen biomechanic model of living soft tissues. Therefore, the histomechanic parameters of soft tissues are required. However, these parameters vary individually and are difficult to obtain *in-vivo*. In the first assumption, soft tissue was modeled as a *homogeneous*, isotropic and linear elastic material. In a homogeneous tissue model, YOUNG's modulus E has no influence at all on the LAMÉ-NAVIER-equation (3). Hence, only the value of POISSON's ratio ν was varied within the range of $[0 \ldots 0.5[$, where a value of 0.5 stands for incompressibility. For all of the four patients the HAUSDORFF-distance $H = \max(d(S_1, S_2), d(S_2, S_1))$ between the retrospectively simulated and the postoperative *facial skin surface* was computed [39]. A minimum deviation $H(\nu)_{min}$ was expected to yield a representative mean value ν for soft tissue compressibility (Fig. 16).

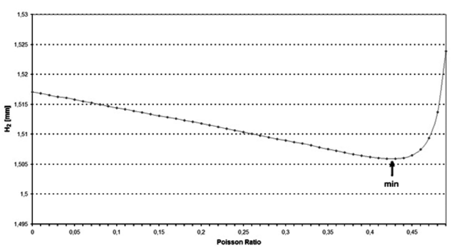

Fig. 16. Prediction quality of a homogeneous tissue model with varying POISSON's ratio ν.

the predicted and the postoperative soft tissue configuration $H(\nu_s, E_s, \nu_m, E_m)$ was computed using a closest points distance. The best correspondence was found with $0.43 < \nu_m < 0.45$ and $E_m \geq 300$ kPa for muscle and with $0.44 < \nu_s < 0.47$ and $E_s \leq 50$ kPa for the embedding tissue (Fig. 17).

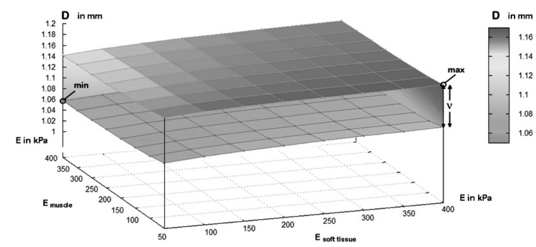

Fig. 17. Prediction quality of an inhomogeneous tissue model with varying POISSON's ratio ν and YOUNG's modulus E with regard to muscle and embedding tissue.

Considering soft tissue as an *inhomogeneous* material, not only compressibility, but also elasticity of each tissue type has to be taken into account. In another study an inhomogeneous tissue model was investigated, where to each tissue element individual histomechanic parameters were attributed. Unfortunately, there is no unique relationship between HOUNSFIELD units and mechanical properties. Determination of appropriate values for different tissue types is still the subject of ongoing research in biomechanics and elastography. Thus, literature values derived from *ex-vivo* experiments were used [47].

In order to preserve the original tissue grid for comparison, tissue elements were relabeled according to the mean HOUNSFIELD values, using a barycentric sampling with selectable refinement of up to 512 sample points per tetrahedron. At first we differentiated between muscle and embedding tissue, since muscle can be easily segmented within a range of $[-30, 100]$ HU. As a result, the tissue grid consists of two different tissue types that can be assigned individual values for ν and E. For each tissue, the POISSON ratio ν was varied within the range of $[0 \ldots 0.5[$ and YOUNG's modulus E within $[50, 450]$ kPa. Again, a parameter study with approx. 2 500 FE simulations of the tissue deformation resulting from maxillary advancement was conducted, and for each simulation the deviation of

For approximately 70 % of the facial skin surface[3], the prediction error was below 1 mm, and only 5 – 10 % showed a deviation larger than 3, up to 4 mm. These areas were mainly subject to postoperative swelling. However, a mean prediction error of about 1 – 1.5 mm already seemed to be an acceptable result for a homogeneous, linear-elastic tissue model. The inhomogeneous model performed slightly better, though the differences were rather marginal. The net improvement of using an inhomogeneous tissue model, or of fine tuning the elastic parameters *does not* seem to significantly influence the prediction of the skin surface [47].

In conclusion we would like to point out that computer-assisted planning *with* soft tissue prediction contributes to an improved surgical preparation. Different therapeutic concepts can be evaluated, thus giving a surgeon more certainty in cases of complex cranio-maxillofacial surgery. The next consequential step is an exact transfer of the planning into the operating room by using innovative navigation techniques that will definitely find their way into cranio-maxillofacial surgery [36].

Besides an improved mental preparation, an integrated computer-assisted approach also contributes to a demonstrative patient information. This in turn enhances the motivation (patient compliance) that again typically leads to better

[3] only the facial region and not the entire head was evaluated

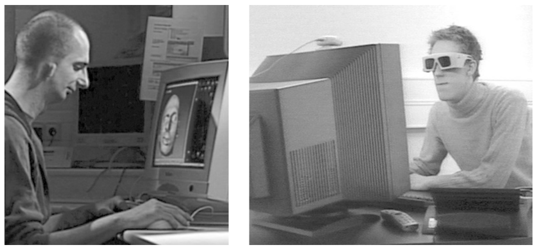

Fig. 18. Improved patient information using advanced 3D visualization techniques.

therapeutic results. In some cases patients did actively participate by using our planning and visualization system themselves (cf. Fig. 18), and in one case a patient even *insisted* on a soft tissue prediction for an intended genioplasty. A reliable simulation with photo-realistic visualization also contributes to an improved documentation and quality assurance. The simulation of the effects of different therapeutic concepts can even be leveraged for surgical education and training. New or unconventional osteotomy techniques, for instance, can be simulated on *virtual* patient models, and the impact on the soft tissue can be studied.

5. Future Work

There is still a lot of work to be done. At first, the modeling of soft tissue deformation can be further enhanced. On that account, anisotropy due to tendons, muscle fibers and skin tension lines are to be investigated, as well as non-linear, or even visco-elastic material properties [45]. Since computational costs are increasing with advanced modeling approaches, concepts for multigrid methods as well as parallelization must be considered as well Tissue remodeling and histogenesis is another important topic that must be taken into account for large deformations. Also, the transfer of boundary displacements from bone relocations to the soft tissue can be improved since tissue regions are detached from bone and lifted off during surgery, and bone segments are re-covered after bone relocations have been accomplished. For such regions, the direct coupling of tissue and bone must be replaced by sliding contact or obstacle modeling. With all these improvements a prediction error of below 1 mm might be attainable, an accuracy that seems quite acceptable for surgery planning.

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