Generic Approach for Biomechanical Simulation of Typical Boundary Value Problems in Cranio-Maxillofacial Surgery Planning

Evgeny Gladilin[1], Alexander Ivanov[2], and Vitaly Roginsky[2]

[1] Zuse Institute Berlin (ZIB), Takustr. 7, D-14195 Berlin, Germany,
[2] Moscow Center of Children's Maxillofacial Surgery,
Timura Frunse 16, 119992 Moscow, Russia

Abstract. In this work, we present a generic approach for biomechanical simulation of two typical boundary value problems arising in cranio-maxillofacial surgery planning, i.e. the prediction of patient's postoperative appearance for a given rearrangement of bones and the reverse optimization of individual facial implants for a desired correction of facial outline. The paper describes the basic methodology for the generation of individual geometrical models from tomographic data, incorporation of the boundary conditions, finite element modeling of tissue biomechanics and experimental results of applied clinical studies.

Keywords: cranio-maxillofacial surgery planning, soft tissue biomechanics, finite element analysis, implant optimization, rapid prototyping

1 Motivation

In cranio-maxillofacial surgery, there is a great demand for efficient computer assisted methods which could enable flexible, accurate and robust simulations of surgical interventions. Modern medical imaging techniques, such as computer tomography (CT) and magnetic resonance imaging (MRI), enable the derivation of useful 3D models of human anatomy. 3D body models provide the information on *geometrical* disposition of different anatomical structures and represent rigid bodies, which only allow rigid and affine transformations. However, the main goal of computer assisted surgery (CAS) is to simulate *physical* interactions with virtual bodies. In particular, the realistic simulation of non-rigid tissue transformations (deformations) under the impact of real or fictitious forces is of crucial importance. Typical boundary value problems arising in the planning of cranio-maxillofacial surgery interventions can formally be subdivided into two major groups:

– "direct problems", e.g. the soft tissue prediction for a given rearrangement of facial bones,
– "inverse problems", e.g. the optimization of individual facial implants for a desired correction of facial outline.

C. Barillot, D.R. Haynor, and P. Hellier (Eds.): MICCAI 2004, LNCS 3217, pp. 380–388, 2004.

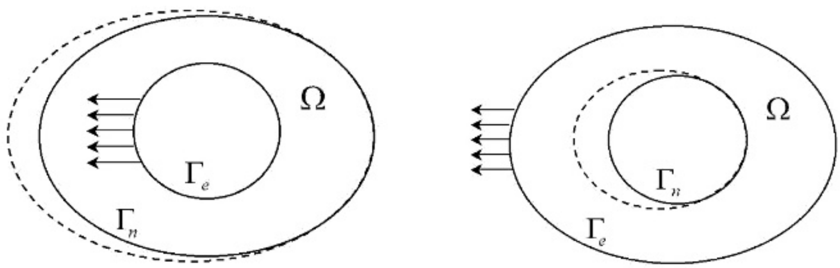

Fig. 1. Typical boundary value problems (BVP) arising in the craniofacial surgical planning: find the deformation of a domain Ω with the natural boundary Γ_n for the boundary conditions given by the prescribed displacements of the essential boundary Γ_e. Left: a direct BVP, e.g. soft tissue prediction for given displacements of bones. Right: an inverse BVP, e.g. find the displacements of bones inducing the desired correction of facial outline.

Both direct and inverse problems are basically of the same nature and can be reduced to a well known boundary value problem (BVP) of structural mechanics: "find the deformation of a domain Ω with the natural boundary Γ_n for the boundary conditions given by the prescribed displacements of the essential boundary Γ_e", see Fig. 1.

In this paper, we present a generic approach for solving typical BVPs of the computer assisted surgery planning (CASP), which is based on the generation of individual geometrical models from tomographic data and the finite element (FE) modeling of deformable biological tissues.

2 Material and Methods

2.1 Geometrical Modeling

Geometrical models of the patient's head are derived from CT data consists of triangulated boundaries between essential soft tissue and bone layers. For the generation of surface models, a standard segmentation technique based on Hounsfield value thresholding as available with Materialise Mimics 6.3 is used [Mimics]. For the subsequent numerical simulation of soft tissue biomechanics, a volumetric grid is required. An unstructured tetrahedral grid for a multi-layer surface model is generated with the help of the multipurpose visualization and modeling system Amira 3.1 [Amira].

2.2 General Soft Tissue Model

Biological tissues exhibit, in general, a very complex biomechanical behaviour. In different experiments with different tissue types, non-homogeneous, anisotropic, quasi-incompressible, non-linear plastic-viscoelastic material properties are described in the literature [Fung 1993]. However, in the range of small deformations soft tissues can be approximated as a St.Venant-Kirchhoff material, which is basically characterized by the linear stress-strain relationship [Ciarlet 1988]:

$$\boldsymbol{\sigma}(\boldsymbol{\varepsilon}) = \frac{E}{1+\nu}\left(\frac{\nu}{1-2\nu}\mathrm{tr}(\boldsymbol{\varepsilon})\mathbf{I} + \boldsymbol{\varepsilon}\right), \tag{1}$$

where $\boldsymbol{\sigma}$ denotes the Cauchy stress tensor, $\boldsymbol{\varepsilon}$ is the strain tensor, E is the Young's modulus, which describes the material stiffness, and ν is the Poisson's ratio, which describes the material compressibility. Typical values for Young's modulus are varying in the range $E \in [2, 200]$kPa. The Poisson's ratio for water-rich soft tissues lies in the range $\nu \in [0.3, 0.5[$. In general, material constants depend on particular tissue type, age, sex and other factors. However, for the quasi-geometrical boundary value problems, i.e. if both boundary conditions and unknowns are the displacements, the simulation results are not sensitive with respect to variation of material constants within "reasonable value ranges" [Gladilin 2003].

The strain tensor in (1) is generally a nonlinear function of the displacement $\mathbf{u}$:

$$\boldsymbol{\varepsilon}(\mathbf{u}) = \frac{1}{2}\left(\boldsymbol{\nabla}\mathbf{u}^{\mathrm{T}} + \boldsymbol{\nabla}\mathbf{u} + \boldsymbol{\nabla}\mathbf{u}^{\mathrm{T}}\boldsymbol{\nabla}\mathbf{u}\right). \tag{2}$$

In the case of small deformations, i.e. $\max|\boldsymbol{\nabla}\mathbf{u}| \ll 1$, the quadratic term in (2) can be neglected, and the strain tensor can be linearized: $\boldsymbol{\varepsilon}(\mathbf{u}) \approx \frac{1}{2}\left(\boldsymbol{\nabla}\mathbf{u}^{\mathrm{T}} + \boldsymbol{\nabla}\mathbf{u}\right)$.

The deformation of a body occupying the domain Ω is obtained as a solution of the boundary value problem (BVP), which is given by (i) the equation of static equilibrium between external loads $\mathbf{f}$ and inner forces (stresses) $\boldsymbol{\sigma}$:

$$\mathbf{div}\boldsymbol{\sigma} + \mathbf{f} = 0 \tag{3}$$

and (ii) the boundary conditions (BC). The boundary conditions in craniofacial surgery simulations are typically given implicitly in the form of node displacements of essential boundaries Γ_e:

$$\mathbf{u}(\mathbf{x}) = \hat{\mathbf{u}}(\mathbf{x}) \quad \mathbf{x} \in \Gamma_e\,. \tag{4}$$

The essential boundary conditions of structural mechanics correspond to the better known Dirichlet BC of classical potential theory. The Neumann-like BC on "free boundaries" are called the natural BC:

$$\mathbf{t}(\mathbf{x}, \mathbf{n}) = 0 \quad \mathbf{x} \in \Gamma_n\,, \tag{5}$$

where $\mathbf{t}(\mathbf{x}, \mathbf{n}) = \boldsymbol{\sigma}(\mathbf{x})\mathbf{n}$ is the Couchy stress vector or the traction. In the case of the soft tissue prediction, essential BC are given by the prescribed displacements of rearranged and fixed bones, whereas skin-layer

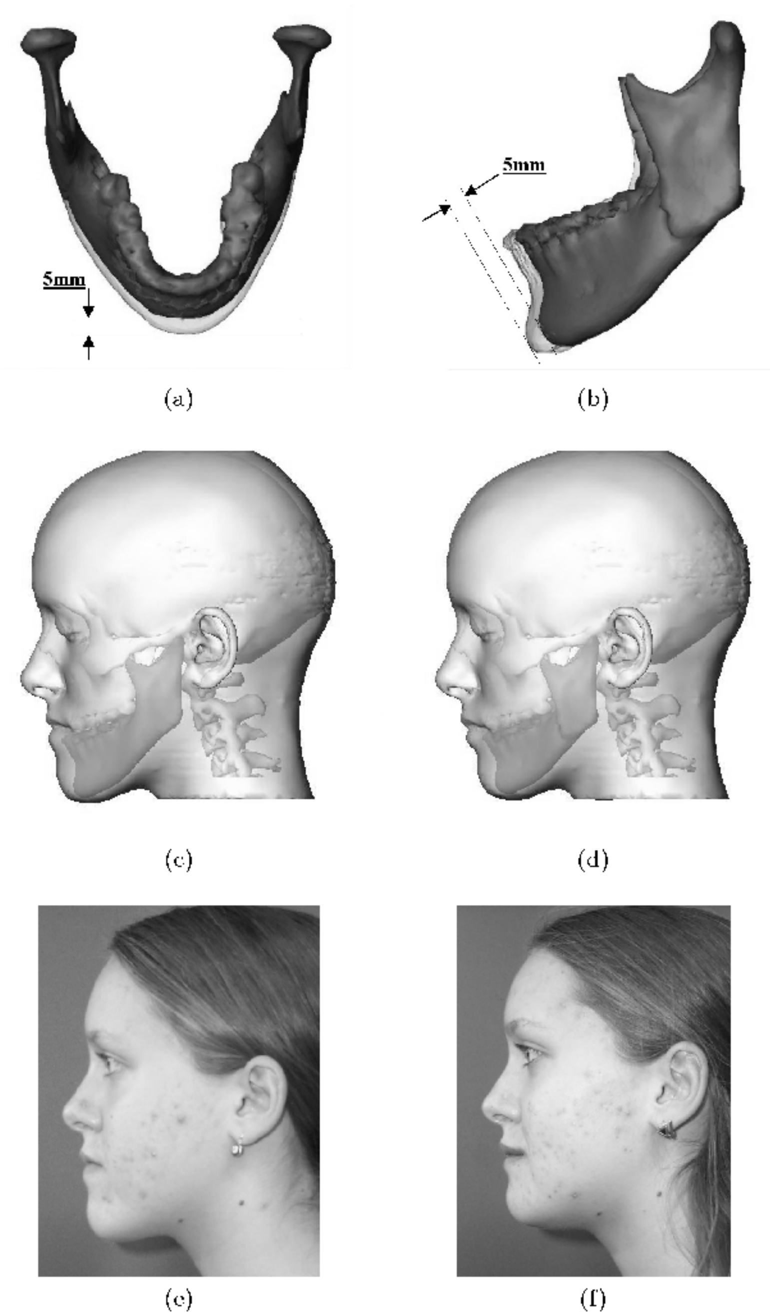

Fig. 2. Setting back mandibula for the correction of lower prognatism (a,b). Geometrical model of preoperative anatomy (c) and the result of the numerical soft tissue prediction (d). Preoperative (e) and postoperative (f) patient profiles, respectively.

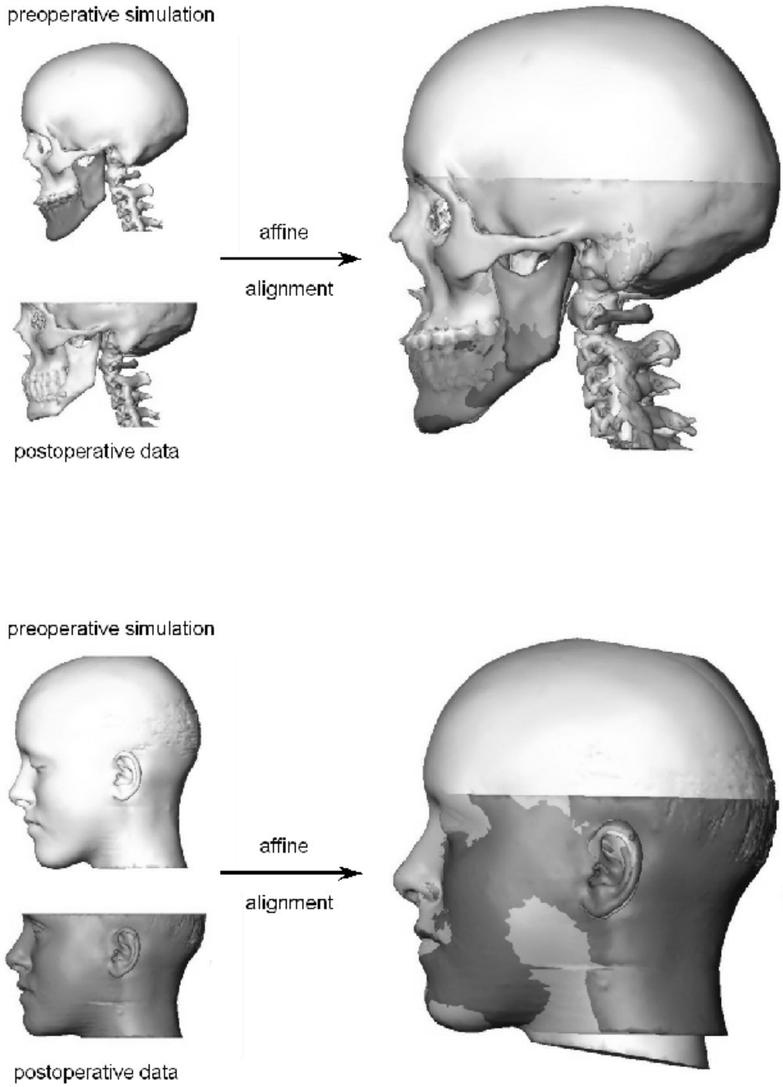

Fig. 3. Top: affine alignment of preoperatively simulated and postoperative skull surfaces. Bottom: superposition of preoperatively predicted and real postoperative facial outlines obtained as a result of the affine alignment of skull surfaces. Since the boundary displacements in this case are comparatively small, the linear elastic model yields a sufficient approximation of soft tissue behavior and the simulation result matches well with the postoperative patient's outline.

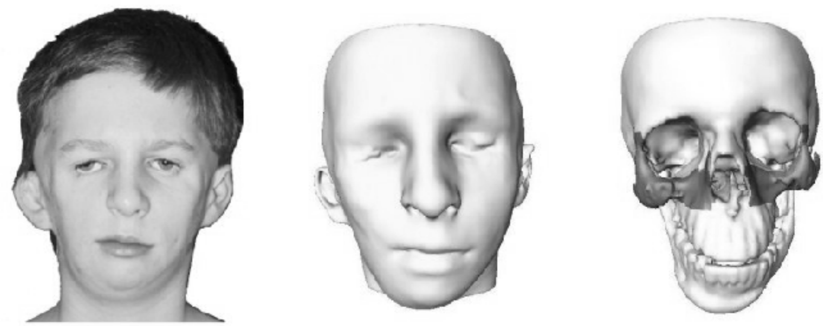

Fig. 4. Left: patient with a Treacher-Collins syndrome. Middle: geometrical model of patient's head with the "virtually corrected" facial outline. Right: initial implant areas.

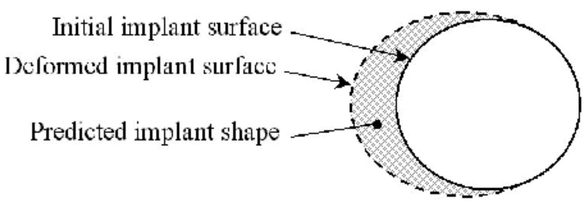

Fig. 5. The volume enclosed by the initial and deformed implant surfaces forms the implant shape, cf. Fig. 1(right).

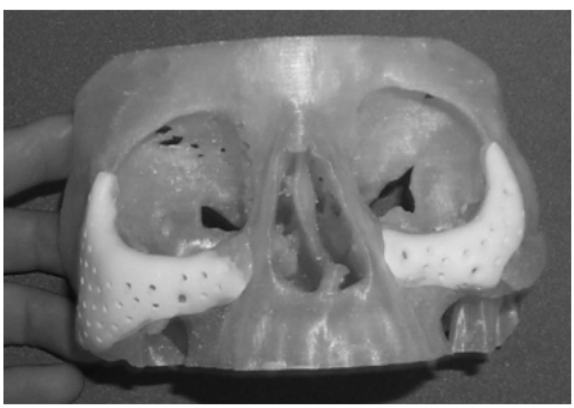

Fig. 6. 3D lithographic model of patient's head including check-bone implants, which were manufactured using the results of the reverse shape optimization.

nodes are set to natural BC. In an inverse BVP, essential boundaries correspond to the warped skin-layer and fixed bones, whereas natural BC are set to the mesh nodes of the initial implant area, cf. Fig. 1(right). To solve the BVP given by (3) and the boundary conditions, the finite element method (FEM) on tetrahedral grids is used [Gladilin et al. 2002].

3 Experimental Results

3.1 Direct Problem. Static Soft Tissue Prediction

In the case of a direct BVP, the patient's postoperative appearance for a given rearrangement of bones has to be predicted. Fig. 2 illustrates the CAS planning for a 15 y.o. female patient with a lower prognatism. The surgical correction consisted in sagittal split osteotomy followed by setting back mandibula by 5mm, see Fig. 2(a,b). The geometrical model derived from CT data consists of a surface mesh corresponding to skin, mandible and skull layers, which has been filled up with approximately 10^6 tetrahedrons. In Fig. 3, the comparison between the result of the soft tissue prediction and an 8 months CT control expertise is shown. Since the boundary displacements in this case are comparatively small, the linear elastic model yields a sufficient approximation of soft tissue behavior and the simulation result matches well with the postoperative patient's outline.

3.2 Inverse Problem. Implant Shape Optimization

In the case of an inverse BVP, the displacements of bones or implants have to be obtained from the prescribed correction of facial outline. Facial implants are nowadays widely used in craniofacial surgery interventions for the correction of facial bones and the improvement of the patient's esthetical appearance [Roginsky et al. 2002]. In Fig. 4, the surgical planning of an inverse craniofacial BVP for a 14 y.o. male patient with a Treacher-Collins syndrome is shown. This patient has already been operated two times within last 5 years with an unsatisfactory outcome. The previous operations consisted of the mandible distraction with the subsequent reinforcement of left and right cheek-bones with the help of implants does not lead to the desired correction of the congenital asymmetry of patient's face. The present surgical impact aims at setting a new, suitably shaped cheek-bone implant over the old one. For the prediction of an optimal implant shape, the methods of reverse biomechanical engineering have been applied. First, the skin-layer of the original 3D mesh near cheek-bones was warped into a desired shape using a 3D sculpture tool as available with Maya 5.0 [Maya], see Fig. 4(middle). Thereby, the "virtual correction" of patient's facial outline has been performed by the maxillofacial surgeon himself. The differences of node coordinates between the warped and original facial meshes yield the displacements, i.e. the boundary conditions for the subsequent FE simulation. Furthermore, the boundary conditions (BC) are given by

– homogenous essential BC on fixed bones,
– non-homogenous essential BC on the displaced skin layer,
– natural BC on initial implant surfaces.

The last condition means that one has to subscribe an initial implant area, where an implant has to be attached to, in order to obtain an unique solution of the inverse BVP, see Fig. 4(right). After assembling the FE system of equations and applying the boundary conditions, the displacement field for the entire mesh has been obtained. The resulting deformation of the initial implant area has been computed by applying the corresponding displacements to the coordinates of the initial implant mesh nodes. The volume enclosed by the initial and deformed implant surfaces forms the implant shape, see Fig. 5. After minor shape improvements, e.g. smoothing some sharp edges, two wax implants (for left and right cheek-bones) have been manufactured with the help of the Stratasys FDM 3000 rapid prototyping system. Subsequently, two biocompatible PMMA/HA[1] implants have been substituted for the wax patterns using the investment casting method, see Fig.6.

4 Conclusion

In this work, a general framework for biomechanical modeling of human head in the craniofacial surgery planning is presented. Our approach is based on the generation of individual 3D models of patient anatomy from tomographic data and the finite element simulation of deformable facial tissues. Two typical boundary value problems arising in the CAS-planning, i.e. the static soft tissue prediction for the surgical planning and the reverse implant optimization, were studied. The results of presented clinical studies are very promising. Further comparative investigations on different patients will help to validate and to fit the underlying biomechanical model of deformable soft tissues. The presented approach can also be applied for the soft tissue prediction and implant optimization in other surgical applications.

References

[Amira] Amira. Indeed - Visual Concepts. URL: `http://www.amiravis.com`.

[Ciarlet 1988] Ciarlet, P. G. (1988). *Mathematical Elasticity. Volume I: Three-Dimensional Elasticity*, volume 20 of *Studies in Mathematics and its Applications*. North-Holland, Amsterdam.

[Fung 1993] Fung, Y. C. (1993). *Biomechanics - Mechanical Properties of Living Tissues*. Springer, Berlin.

[Gladilin 2003] Gladilin, E. (2003). *Biomechanical Modeling of Soft Tissue and Facial Expressions for Craniofacial Surgery Planning*. PhD thesis, Freie Universität Berlin.

[1] PMMA/HA - polymetilmethacrylate and hydroxiapatite.

[Gladilin et al. 2002] Gladilin, E. and Zachow, S. and Deuflhard, P. and Hege, H. C. (2002). Adaptive Nonlinear Elastic FEM for Realistic Prediction of Soft Tissue in Craniofacial Surgery Simulations. In *Proc. of SPIE Medical Imaging Conference*, San Diego, USA.

[Maya] Maya. Alias. URL: `http://www.alias.com`.

[Mimics] Materialise Mimics. Materialise. URL: `http://www.materialise.com`.

[Roginsky et al. 2002] Roginsky, V.V. and Popov, V.K. and Ivanov, A.L. and Topolnitzky, O.Z. (2002). Use of stereolithographic and computer biomodeling in children's cranio-maxillofacial surgery. *Journal of Cranio-Maxillofacial Surgery*, 1(1):171–172.