Conclusion

We have carried out theoretical and experimental investigations leading to the development of the numerical model of facial tissue biomechanics for the prediction of the patient's static postoperative appearance and facial emotion expressions in craniofacial surgery planning.

Since soft tissue generally shows a very complex biomechanical behavior, an *adequate simplified model* tailored to the particular range of problems is formulated. In craniofacial surgery planning, the essential input for the numerical modeling is usually given in the *quasi-static* and *quasi-geometrical* form, i.e., no information on the timing of bone rearrangement, the acting forces or any other physical terms describing the "physics" of the surgical impact is available. The postoperative patient's appearance has to be predicted on the basis of 3D geometrical models derived from tomographic data and the prescribed displacements of relocated bone structures. For the estimation of facial expressions, the geometric model of patient's anatomy is the only input for the further modeling.

Our approach for the general modeling of deformable facial tissue is based on the non-linear elastic approximation of tissue biomechanics. Different tissue types are modeled as a homogeneous, isotropic, quasi-incompressible *St. Venant-Kirchhoff material* characterized by two elastic constants, the Young modulus E describing the material stiffness and the Poisson ratio ν describing the material compressibility. In our approach, we substitute the absolute material stiffness by the non-dimensional *relative stiffness* rE, which can be easier estimated and reduces the number of unknowns. Low compressibility of soft tissue is modeled by a Poisson ratio in the range $\nu \in [0.4,\ 0.45]$.

The numerical solution of the associated boundary value problem on tetrahedral grids is obtained via the finite element method (FEM). The linear elastic FEM widely used in previous works is generally limited by the assumption of small deformations and produces a substantial error by ad hoc calculations of large deformations, which are usual in the craniofacial surgery. Since the non-linear elastic

FEM is computationally very expensive, an *adaptive numerical scheme* is developed. In order to achieve the efficient and robust performance, the adaptivity of the numerical scheme on different levels of problem solving is required. In our approach, we have implemented (i) the adaptive mesh refinement, (ii) the adaptive linear/non-linear assembly of the stiffness matrix and (iii) the adaptive solving scheme, whereby (i-ii) are based on efficient numerical indicators for the monitoring of the local deformation. For the solution of the resulting linear or non-linear elastic problem, the preconditioned conjugate gradient method (PCG) with Jacobi preconditioner, the Newton method and the simplified Newton method have been implemented.

The developed FE model has been validated in the experiments with the artificial objects as well as by the direct comparison with the patient's postoperative facial outline. The outcome of the surgical impact on soft tissue induced by small and large rearrangements of bone structures has been simulated. The resulting soft tissue prediction has also been positively evaluated by collaborating surgeons.

In addition to the static soft tissue prediction, the modeling approach for the estimation of individual facial emotion expressions has been developed. We assume consistent biomechanical mechanism of facial expressions that is the impact of contracting muscles on remaining facial tissue. Numerous unknown parameters such as direction and magnitude of muscle forces, geometry of insertion area of muscles as well as the material constants for a multi-layer model have to be estimated for the realistic simulation of facial tissue mechanics. The first step in our modeling approach is the simulation of single muscle contraction. Since the information about microscopic structures, e.g., muscle fibers, cannot be obtained from tomographic data, any suitable construction considering the correct muscle anatomy and biomechanics may be applied for the interpolation of muscle forces resulting from fiber tensions. The shape-based, heuristic technique of *virtual fibers* developed in this work enables the interpolation of muscle forces for an arbitrarily shaped muscle. In the general model of deformable soft tissue, muscles are represented by the force density acting along the fiber tangents. Using this technique, elementary facial emotion expressions resulting from single muscle actions have been simulated. On the basis of this 'database of single muscle actions', complex facial emotion expressions are modeled.

The investigations carried out in the present thesis have their origin in the clinical application and do provide the methodological basis for further application-oriented developments.

Outlook

The biomechanical modeling of living objects is a very challenging problem, which requires a comprehensive knowledge of different fields of study, e.g., biology, continuum mechanics, numerical mathematics. Especially, the advances in experimental biomechanics providing more detailed constitutive models of living tissues are the essential prerequisite for the development of more sophisticated modeling approaches. Quantitative, comprehensive and differentiated description of static and time-dependent constitutive properties of different tissues is still missing.

Since this work is primarily devoted to the modeling, a numerical platform for the FE simulation, which is relatively easy to implement and to control, is used. For the dimension of problems studied within the present work, i.e., grids of $\leq 10^7$ elements, this technique enable an acceptable performance. For significantly larger grids, the application of more sophisticated numerical methods, e.g., multi-grid techniques, should be taken into consideration.

A general problem that remains the potential object of future research is the accurate and efficient computation of large deformations. The appropriate handling of numerical problems associated with the calculation of the smooth orientation-preserving displacement gradient on large deformed FE grids should improve the robustness of the non-linear elastic FE calculation, which is essential for clinical applications.

Finally, the whole set of problems related to the increasing realism of facial expression simulations still remains an interesting object of further investigations. Due to the encouraging results of experimental studies carried out in this work, we see a high potential for more detailed simulations of muscle-based facial expressions on the basis of highly resolved geometrical models of human anatomy and more sophisticated biomechanical approaches. The modeling of numerous subtle details of human face, such as individual material properties depending on age, sex, nationality etc., wrinkles as well as various contact and obstacle phenomena, offers practically unlimited possibilities for perfectioning of simulation results. There is still a lot of work to do.