An intellect which at any given moment knew all the forces that animate Nature and the mutual positions of the beings that comprise it, if this intellect were vast enough to submit its data to analysis, could condense into a single formula the movement of the greatest bodies of the universe and that of the lightest atom: for such an intellect nothing could be uncertain; and the future just like the past would be present before our eyes.

P. S. Laplace (1749-1827), Philosophical Essay on Probabilities [78].

Chapter 1

Introduction

1.1 Motivation

The advances in medical imaging beginning from the discovery of X-rays for more than 100 years ago, open nowadays new perspectives for the improvement of the computer assisted surgery planning (CASP). Meanwhile, modern medical imaging techniques, such as computer tomography (CT) and magnetic resonance imaging (MRI), are widely-used for diagnostic and visualization purposes enable the derivation of useful 3D models of human anatomy. 3D body models provide the information on the *geometrical* disposition of different anatomical structures only. However, the main goal of computer assisted surgery (CAS) is to simulate *physical* interactions with virtual bodies. In particular, the realistic simulation of soft tissue deformations under the impact of external forces is of crucial importance. It is the task of the biomechanical modeling to assign reliable physical properties to virtual anatomical structures in order to make them interact according to underlying physical laws. The nearer a physical model approaches the properties of a living tissue the more realistic the simulation results can be obtained. This predication is the central paradigm of the physically based soft tissue modeling.

In cranio-, dento-maxillofacial surgery, there is a great demand for efficient computer assisted methods, which could enable flexible, accurate and robust simulations of surgical interventions on virtual patients, including the realistic prediction of their postoperative appearance. The computer assisted surgical planning has many advantages in comparison with conventional planning systems. Once the virtual model of a patient is generated, various case scenarios of the surgical impact and their outcomes can be extensively studied. Better preparation, shorter operation time, lower costs are the immediate benefits. Since the improvement of the patient's aesthetics is one of the main aims in craniofacial surgery, the realistic prediction of the patient's postoperative appearance is an important feature of the planning system giving the surgeon unique feedback already during the planning stage.

In addition to the static soft tissue prediction, the estimation of individual facial emotion expressions is another important criterion for the prediction of postoperative results as well as for patient compliance. In certain cases, as for instance facial paralysis treatment, the estimation of single muscle actions is even of primary interest for the surgical planning.

1.2 Problem Description

The topic of soft tissue modeling has been the subject of intensive investigations of many research groups within the last three decades. Because of the complexity of soft tissue behavior and diverse types of application fields, a wide spectrum of approaches has been developed. In Table 1.1, a brief overview of the range of problems arising within the scope of soft tissue modeling is given. From this overview, it is already evident that there is no general modeling approach, which could cover the whole spectrum of soft tissue biomechanics and serve for all various medical applications. In fact, modeling complex living systems implies many intrinsic controversies. For instance, the requirement of the increasing realism of the simulation is often associated with the decrease of the efficiency and/or the robustness of a more sophisticated modeling approach. The real-time performance can hardly be realized on low-cost hardware platforms, etc. Consequently, the way of simplification of the original complex problem is usually preferred. Which particular aspect or property of a complex soft tissue model has to be considered, and, which can be neglected, essentially depends on the order of priority of the concrete characteristic of the given problem.

The goal of the present thesis is the development of a biomechanical model of facial tissue tailored to the particular needs of the craniofacial surgery planning,

- the static soft tissue prediction and
- the estimation of individual facial emotion expressions.

Such problem definition has already certain important consequences for the choice of an adequate modeling approach, which in turn paves the way for some substantial simplifications. In the following, we formulate some important statements, which give a more detailed description of the problem to be studied in the present work and range the preliminary scope of further investigations.

Table 1.1: Soft tissue modeling. Range of problems

Tissue Type	Field of Application
brain-liquor	neurosurgery
parenchymal organs	inner surgery
cardio-vascular system	cardiology
connective tissue	sport-medicine
musculoskeleton	biokinematics
skin, fat, muscles	craniofacial surgery
Typical Dimensions	
space:	from 10^{-1}mm to 10^{2}mm
time :	from 10^{-2}s to months
General Material Properties	
anisotropic	
non-homogeneous	
non-linear plastic-viscoelastic	
Special Properties of Living Tissues	
thermodynamically open systems	
self-repairing	
self-adapting	
Boundary Conditions	
prescribed displacements	
applied force density	
mixed boundary conditions	
Required Capability Characteristics	
realism	
efficiency	
robustness	
real-time ability	
low-cost hardware platforms	

Quasi-static. Due to the restrictions of adaptive abilities of living tissues with respect to mechanical rearrangements, craniofacial operations are normally performed

- ”at once” in the case of small deformations or

- stepwise over a longer period of time, if deformations are large.

In the second case, each step is associated with small deformations of soft tissue and is performed ”at once”. Since no information on the timing of bone rearrangements during the surgical impact is available in our approach, we are not interested in real-time simulations of the soft tissue deformation, but in a general *long term prediction* of patient’s postoperative appearance, which remains unchanged after the surgical impact, and consequently can be considered *quasi-static* (nearly time-independent). Such assumption is natural, since facial tissue as every living system retains its constant shape (except for periods of growing, healing or aging).

Quasi-geometric. Furthermore, input data for the numerical simulation in our approach are given exclusively by

- the 3D model of patient’s anatomy derived from tomographic data and

- the prescribed displacements of bone structures.

This means that the boundary conditions as well as the unknowns of the deformation we are seeking are both the displacements. Neither the applied forces nor other physical terms describing the ”physics” of the surgical impact are available. Thus, the physical problem we are concerned is basically given in a *quasi-geometric* form.

Starting point. Since surgeons basically avoid undergoing soft tissue large deformations ”at once”, the modeling of small deformations as the first approximation of facial tissue biomechanics seems to be a reasonable starting point for further investigations.

Adequate simplified model. Soft tissue generally shows a very complex mechanical behavior (cf. Table 1.1). However, the relevancy of each ever observed property for the modeling of a particular problem has to be analyzed first. The goal of the present work is not the formulation of a ”most general approach”, but an *adequate simplified model* of deformable facial tissue tailored to the range of problems stated.

Applicability aspects. The application in a clinical environment generally requires that numerical computations have to be performed on comparatively low-cost hardware platforms. Nevertheless, a numerical model should be sufficiently fast in order to be suitable for the clinical application. Also, it should be robust, i.e., not sensitive with respect to small variations of material parameters and boundary conditions. Furthermore, it is highly desirable that the model requires as few external parameters as possible to be justified for each simulation. Finally, the resulting soft tissue deformation has to be realistic, which usually means that at least the predicted facial surface has "sufficiently" to match with the real post-operative outcome.

1.3 Contributions

The contributions of the present thesis consist in the theoretical and experimental investigation of the stated problem. The major contributions of this work are as follows.

Adaptive non-linear elastic FE model. The linear elastic approach known from the previous works and widely used in soft tissue modeling yields an insufficient approximation of soft tissue behavior, especially in the case of large soft tissue deformations. The investigations carried out in this work lead to the development of a more accurate adaptive non-linear elastic model. Based on the finite element method (FEM), this approach yields more realistic results and provides a robust and flexible platform for the general modeling of deformable facial tissue.

Sensitivity analysis and model validation. The derivation of an adequate simplified model is an important part of this work. Various case studies as well as the analysis of the model sensitivity with respect to the different material parameters and boundary conditions are carried out to validate and to optimize the chosen approach.

Static soft tissue prediction. The numerical model of deformable soft tissue developed in this work is primarily applied for the prediction of the patient's postoperative appearance within the scope of the craniofacial surgery planning. Several clinically relevant studies with 3D models derived from individual tomographic data are carried out.

Biomechanical muscle model. For the simulation of individual facial emotion expressions, a correct biomechanical model of contracting muscles and their interaction with remaining facial tissue is needed. In this work, a new modeling technique for the simulation of contracting facial musculature based on the natural relationship between "the form and the function" is developed.

Muscle-based modeling of individual facial emotion expressions. In addition to the general model of deformable soft tissue, a consistent biomechanical approach for the estimation of individual facial expressions on the basis of tomographic data is developed. Using this approach, experimental studies for the estimation of individual facial emotion expressions are carried out.

1.4 Overview

The structure of the present thesis is as follows. We start with a review of the existing approaches for modeling of deformable objects (**Chapter 2**). In **Chapter 3**, we present an overview of the essential background knowledge in soft tissue modeling and simulation, including the basics of soft tissue anatomy and biophysics, continuum mechanics and the FEM, which build the basis of our modeling approach. **Chapter 4** is concerned with the geometrical modeling of human anatomy from tomographic data. In **Chapter 5**, a detailed description of our numerical soft tissue model and its implementation is presented. **Chapter 6** is devoted to the validation of linear and non-linear elastic models based on *St. Venant-Kirchhoff hyperelasticity*. Various feasibility studies with artificial objects as well as the experimental results of craniofacial surgery planning simulations, including the static soft tissue prediction, are presented. In **Chapter 7**, we describe our approach for the simulation of contracting muscles and muscle-based facial expressions. Finally, we conclude the thesis and make outlook of future research.