Biomechanical model of the human face with a perspective of surgical assistance

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1. Introduction

Our group has been working on the biomechanical modeling of the human face soft tissue for more than 20 years, with two main applications: surgical assistance (Chabanas et al. 2003) and speech production (Nazari et al. 2011).

The first version of our face model was designed to predict the aesthetic and functional consequences of bone repositioning in the context of maxillofacial surgery (Chabanas et al. 2003). It included a hexahedral-dominant Finite Element (FE) mesh made of two layers representing the dermis and hypodermis tissues. Muscle activations used for speech production or for facial mimics were functionally modeled through a set of external forces applied to nodes along the muscle courses.

Twenty years later, we must unfortunately admit that such kind of modeling tools are still not used by surgeons in their clinical practice. Some commercial products such as Materialise® software propose modeling options for predicting passive and active face tissue deformations after bone repositioning. However, such options are currently not used by most surgeons who consider them as not sufficiently realistic.

This paper aims to address this limitation, coming back to the design of a patient-specific face model, with a special focus on the accuracy of the model, including:

- 1) the identification and differentiation of anatomical structures involved in face deformations, skin, muscles and hypodermis tissues, in which we include in a first approximation as a whole fat and connective tissue;
- 2) the meshing of the volume represented by each of these anatomical structures with a full tetrahedrons FE mesh which convergence has been studied;
- 3) the accurate design of the course of each face muscle, based on muscle contours observed on a CT and an MRI exams of the patient, to study as a perspective the functional aspect of the patient's soft tissues after surgery;
- 4) the definition of accurate boundary conditions with the face FE mesh fixed onto specific locations of the skull and with sliding contacts between lips and teeth.
- 5) experimental tensile tests carried out on tissues extracted from a human cadaver head, in order to propose constitutive laws as inputs to the FE model.

2. Methods

2.1. Finite element (FE) face model

The global geometry of the FE face model, extracted from 3D CT images of the patient's head, represents a 3D FE mesh composed of tetrahedral elements that are supposed to model the hypodermis and muscle tissues. On the top of this FE volume are defined shell elements that represent the skin (with a thin thickness of 1 mm). Bony surfaces (mandible and maxilla) are added and modeled by shell elements.

The volumetric and surface FE meshes were generated using Hypermesh® software, making sure that the elements were of good quality. Indeed, a poor quality mesh can lead to numerical errors during a FE analysis and thus to distorted visual results. In order to check the quality of the mesh, geometrical criteria such as the ones proposed by ANSYS® FE solver were used. A convergence analysis was performed to determine what element sizes to put in our FE model in order to find a good compromise between accuracy and computation time. A mesh that includes 132,736 elements and 27,696 nodes was therefore used for the simulations.

2.2. Muscles inserted into the FE mesh

Starting from this 3D tetrahedral mesh, the courses of most muscles involved in the human face were defined as follows. A set of points along muscle tracks were manually positioned in 3D using information from the literature (Hutto and Vattoth 2015) but also with the use of CT images of the patient, on which it was possible to distinguish the contours of some muscles. Eleven muscles were then implemented by selecting the sets of elements along the course of these points: zygomaticus major and minor, orbicularis oris peripheral and marginal, levator anguli oris, buccinator, levator labii superioris alaeque nasi, risorius,

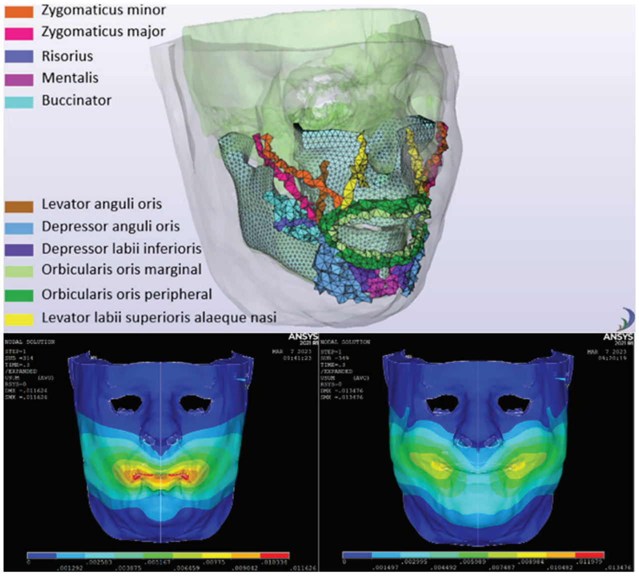

Figure 1. Top panel: Model of the human face (gray: soft tissues, light blue: mandible and maxilla, light green: skull, other colors: muscles). Lower panel: Face deformations during the contraction of the orbicularis oris peripheral OOP, responsible for smiling (left) and the zygomaticus ZYG major and minor, responsible for lip protrusion (right). Simulations are provided by the ANSYS software with the material parameters of Barbarino et al. (2009).

depressor anguli oris, depressor labii inferioris, and mentalis, represented in Figure 1 (top panel).

Muscle activations are modeled using the ANSYS UserMat element designed by Nazari et al. (2022). Such a model generates active stress along muscular fibers assuming a transverse isotropic behavior for the muscle.

2.3. Experimental tensile tests

To the best of our knowledge, no mechanical *ex vivo* experimental test has been provided in the literature as concerns the human facial tissues. We propose here preliminary tests on a single specimen. In accordance with French regulations on post-mortem testing, a face anatomical dissection was performed at the Anatomy Laboratory, Grenoble Faculty of Medicine, on a female cadaver head (95 years old, 160 cm tall and 55 kg). The dissection occurred 8 days after the death. Samples from skin, hypodermis tissue and muscles (zygomaticus and masseter) were extracted and dog-bone shape samples were used to carry out tensile tests in a 37 °C bath of saline solution (MTS criterion model 41 machine, Figure 2). Since this work is preliminary, a single sample was tested for each tissue, without any details as concerns variability.

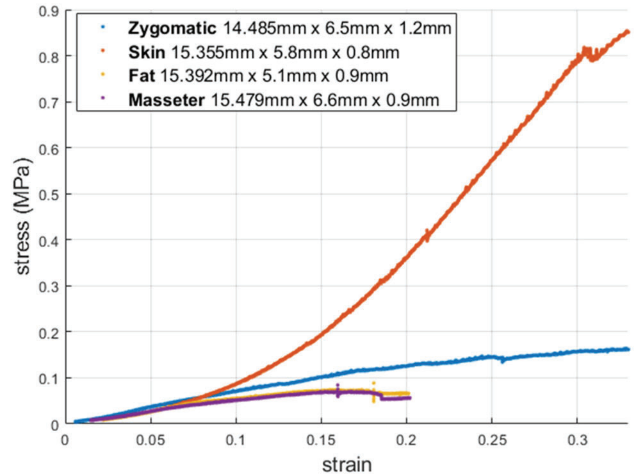

Figure 2. Experimental stress/strain measurements of skin, fat, zygomatic and masseter muscles. Strain rate was 10%/min.

3. Results and discussion

The lower panel of Figure 1 plots face deformations after the activation of two muscles, namely the orbicularis oris peripheral (left) and the zygomaticus (right). The corresponding face deformations are coherent with what is expected from these muscles, namely lip closing and protrusion from OOP, and a smile from ZYG (Nazari et al. 2011).

Figure 2 plots the nominal stress-strain curves recorded for four tissue samples corresponding to skin, fat, and the zygomatic and masseter muscles. As expected (Barbarino et al. 2009), skin appears stiffer in tension than fat and muscles.

Finally, it seems important to note that the various steps described in this paper to generate a generic subject-specific FE model of the face have to be done one time only. For any new patient to study and to model, an automatic image-based non-rigid registration technique will be used to morph the generic FE model to the anatomy of that new patient.

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