Model-Based Simulations of the Insertion of Tensor Threads in Patient-Specific Human Face: A Proof of Concept

Marie-Charlotte Picard[1,2,4](✉), Mohammad Ali Nazari[1,3], Pascal Perrier[2], Michel Rochette[4], and Yohan Payan[1]

[1] Université Grenoble Alpes, CNRS, Grenoble INP, TIMC, 38000 Grenoble, France
marie-charlotte.picard@univ-grenoble-alpes.fr

[2] Université Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, 38000 Grenoble, France

[3] School of Mechanical Engineering, University of Tehran, Tehran, Iran

[4] Ansys, 69100 Villeurbanne, France

Abstract. Facial paralysis, *i.e.* the inability to activate facial muscles, results in face tissue sagging under the effect of gravity, with aesthetic and functional consequences, which deeply degrades quality of life. In order to compensate for sagging, a minimally invasive clinical procedure involves inserting and anchoring biodegradable tensor threads under the facial skin to restore tissue tension. This paper presents a proof of concept of a software tool that uses simulations with a Finite Element (FE) biomechanical model of the face in order for the surgeons to (1) predict how tensor threads mechanically interact with facial tissue and (2) visualize preoperatively in real-time the postoperative aesthetic appearance of the patient's face using a Reduced Order Model of the FE model.

Keywords: Finite Element Method (FEM) · Human face · Tensor threads · Biomechanical model · Facial Paralysis · Reduced Order Models (ROM)

1 Introduction

Our project aims to help remedy face tissue sagging under the effect of gravity due to facial paralysis, defined as the inability to activate facial muscles, affecting 127,000 people a year in the United States, according to Bleicher et al. [4]. The loss of muscle force generation capability weakens muscle tone, *i.e.* a fundamental mechanism that counteracts the effects of gravity, so that soft tissues of the face tend to fall down with a combination of aesthetic and functional consequences. Dynamic reanimation techniques are available to restore surgically muscle tone, by decompressing and repairing the facial nerve, or transferring nerves or muscles to local areas [12]. This surgery is necessary for complete facial paralysis, affecting the whole face. Most of the time, facial paralysis is asymmetric, due to damage to a nerve branch innervating half of the face. It impacts the behavior of healthy tissue in the other half of the face, sometimes resulting in difficulty

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to speak or to swallow. In such cases, static reanimation solutions can help alleviate the consequences of paralysis by inserting an external component, such as a tensor thread, to restore tension in the affected areas. These techniques are minimally invasive, while considerably improving the patient's quality of life [5]. One of the limitations of such facelift techniques is the difficulty to quantitatively predict the surgical outcome. It depends on the number of inserted threads as well as on the location of the anchoring points of the threads in the patient's face. It is also highly patient-dependent. To help clinicians to predict the functional outcome of thread insertion for each patient, we propose a method that uses a patient-specific biomechanical Finite Element (FE) model of the facial soft tissues coupled with a mechanical model of the tensor thread [13], in order to evaluate these functional outcomes with FE simulations [2].

2 Generation of Patient-Specific FE Models

For many years, our group has been working on the design of a FE model [6,15–17] that accurately accounts for the facial biomechanics of a subject, called *reference subject*, for whom various medical images of the orofacial region have been collected [6,14]. It consists of 10,068 nodes and 17,145 hexahedral elements (Fig. 1a). The choice of a hexahedral mesh aims to avoid numerical locking phenomena, which can occur in linear tetrahedral elements with quasi-incompressible materials. The model has been developed in the ANSYS® APDL environment. It is composed of four layers which represent skin, dermis, hypodermis and muscles (Fig. 1b), modeled as Yeoh hyperelastic quasi-incompressible materials which their parameters are based on the experimental data from the literature [1]. A set of fixed nodes was defined to model the interaction between soft tissues and bones, assuming that soft tissues are attached to the bones. Contacts between soft tissue and bone have been neglected, and this may have a slight impact on force, since friction was neglected. This will be taken into account for further more accurate modeling of facial deformation.

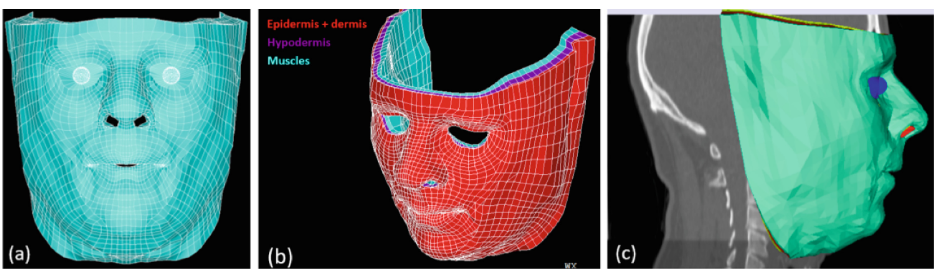

Fig. 1. FE model of the reference subject. (a) Full model, (b) Visualization of tissue layers, (c) FE mesh superimposed on a CT-image of the reference subject.

In the context of clinical applications, one of the major issues is to generate quasi-automatically a 3D face mesh specific to each patient. For this, the

FE mesh of the reference subject (Fig. 1) is morphed to the patient's anatomy through a 3D geometrical displacement field, inferred from a non-rigid image-based 3D registration of the CT-scans of the reference subject and the patient. This registration aims at maximizing the similarities between the intensities of the voxels of both volumes. It was implemented using the open-source *Elastix* library [10] and is described in Fig. 2. A first non-rigid geometrical transformation is carried out based on Thin Plate Splines (TPS) [9] to register six anatomical landmarks located on bony structures. It deals with the largest differences between the two sets of images. Then, a non-rigid B-Spline transformation is performed to achieve a more precise registration by maximizing the similarities between the two volumes on a 3D grid. The global transformation is finally applied to the reference mesh in order to generate the FE mesh of the patient.

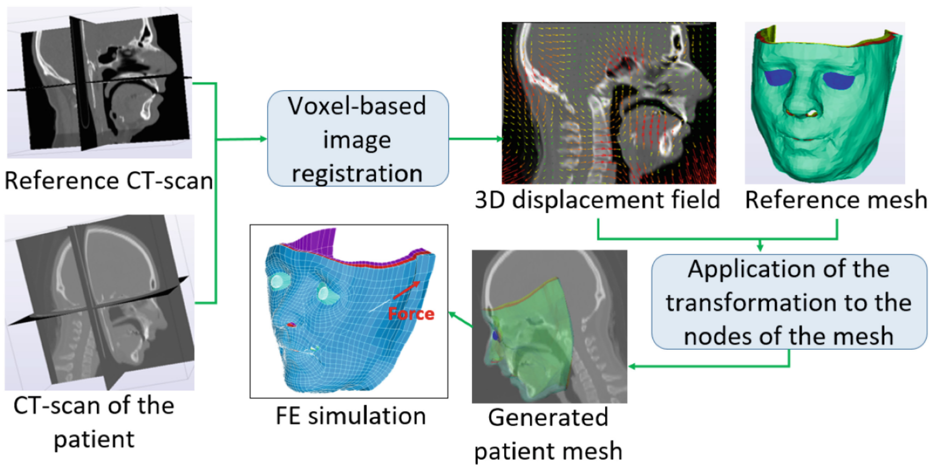

Fig. 2. Patient-specific mesh generation [3].

After registration, it is necessary to ensure that the patient's FE mesh (1) correctly matches his/her CT-scan and (2) is of good quality. The first point is verified through the computation of the Hausdorff distance between the outer surface of the generated patient's FE mesh and the outer surface of the patient's 3D scan (Fig. 3a), reconstructed with a marching cube algorithm from the CT-scan [11]. The error is smaller than 2 mm in the regions concerned by the face lifting. Ensuring a good quality mesh consists of avoiding irregularities in the mesh after registration, which would make FE simulations impossible. Irregularities can be detected using the determinant of the Jacobian matrix of the transformation, which should be strictly positive at any point of the elements (Fig. 3b). Once the patient-specific FE mesh is obtained, numerical simulations can be launched to evaluate the face lifting effect after insertion of threads. The procedure is based on the method developed by Nazari et al. [13]. To do so, a FE replica of the thread is inserted in the hypodermis layer of the model. It is made of a wire (diameter: 0.4mm) on which 4 hollow cones (height: 2.54 mm; diameter of the basis: 1.27 mm; diameter at the top: 0.53 mm; thickness of the material: 0.13 mm) are attached. Contacts between the thread and facial tissue are modeled by constraint equations that impose a rigid link.

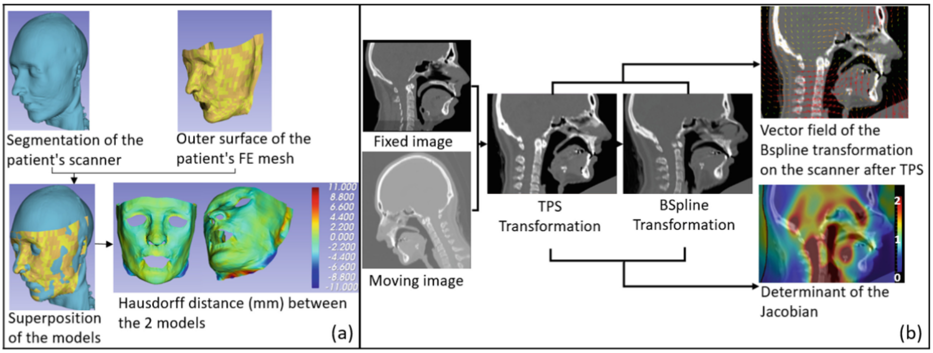

Fig. 3. (a) Computation of the Hausdorff distance between two surfaces, (b) Results of the TPS and B-Spline transformations (with a 16mm grid spacing) vector field of the B-Spline transformation; determinant of the Jacobian matrix.

In this paper, the results of our simulation tool are illustrated with a unique thread on the face in a given position. The deformations of the face are studied when a force is applied to the upper extremity of the thread, to simulate a lifting effect (Fig. 4a). The evaluation of the lifting effect is based on a variable that is the most intuitive for clinicians, namely the total nodal displacement, *i.e.* the norm of the displacement vector, in the facial regions affected by sagging. The result is presented (Fig. 4b) for a 2N force applied to the tensor thread.

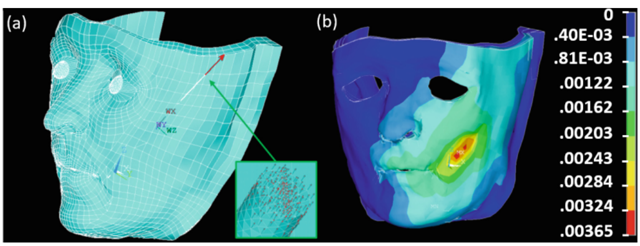

Fig. 4. (a) Modeling the traction of the tensor thread on the patient-specific FE model, (b) Total displacement (m) for a force of 2N applied to the thread.

However, running these simulations directly with the patient-specific biomechanical model and the inserted threads into it is much time consuming (taking a few hours for each simulation) and is therefore incompatible with the time constraints of clinical procedures. Hence, we have worked on training a Reduced Order Model (ROM) [7] of the mechanical model, *i.e.* a computational model that faithfully accounts for the behavior of the mechanical model, without solving the FE model, but by functionally describing its solution.

3 Model Order Reduction

The design of a ROM consists of (1) defining a structure, (2) building a learning set and an evaluation set of simulation data that associate the force magnitude applied by the thread to the face with the nodal displacements resulting from static FE simulations, and (3) supervised learning of the model parameters accounting for the learning data set and providing the best generalization to the evaluation set. Static simulations are used, as the relevant information pertains to the final state of the face after it has reached equilibrium through interaction with the tensor thread. The structure of the ROM is defined by the StaticROMBuilder (SRB) software developed by Ansys®. This software uses a singular value decomposition (SVD) to reduce the dimensionality of the 3D mesh node positions, combined with an interpolation method to continuously reconstruct output values within the range of learned input parameters. The learning and evaluation sets are made of converged 3D field solutions. In our case, 26 tensor thread traction simulations were carried out on a patient with force ranging from 0 to 20N: 7 of them are sufficient to be used as training data; the other ones are considered as validation data. The distribution of the training dataset is determined through an iterative process, progressively increasing the volume of training data until achieving satisfactory generalization to the validation dataset.

In this study, to analyze the quality of the ROM, we focused on the total displacement of a mesh node located on the outer layer of the face, at the level of lip commissure, an area often treated by the insertion of tensor threads. The errors between the six selected validation data and the data obtained with ROM for the same inputs are small (of the order of 0.01 mm) despite the small amount of training data (Fig. 5). This is an encouraging result, but we only addressed in this example the effect of force magnitude on the face mesh for a unique position of the tensor thread. The amount of learning and evaluation data will be a challenge in the context of a comprehensive evaluation of the influence of the thread number and of their positions and orientations in a clinical procedure.

4 Software Proof of Concept Designed on CamiTK Library

An interactive software has been developed using the CamiTK library [8] in order to allow clinicians to (1) build a patient-specific biomechanical face model, (2) insert the tensor threads by controlling their positions and orientations in the model, (3) generate the corresponding ROM and (4) display in real-time the shape of the face resulting from tractions with the tensor threads (Fig. 6).

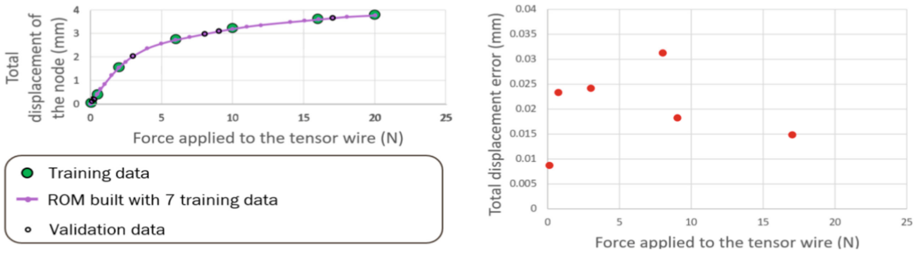

Fig. 5. Left: ROM built from the training data with StaticROMBuilder software. Right: errors between the numerically simulated validation data and the ROM outputs.

The first step is to manually select the anatomical landmarks in order to perform the TPS transformation. Then, the registration between the 3D CT-scan images of the reference subject and of the patient is performed automatically and the patient's FE mesh is displayed and superimposed on the CT-images. This allows the clinician to see whether the generated mesh is consistent with the patient anatomy or not. If not, other landmarks and/or another grid size can be chosen to improve the performance of the image-based registration. If the mesh is satisfactory, the next module is used to correctly position the first cone of the thread and allow rotations around this cone to orient the thread. This step can be repeated up to the total number of required tensor threads. The last module generates all the necessary files for the numerical FE simulation, and thus to create the database for the construction of the ROM for the selected thread positioning. This step is done offline since it can require a couple of hours.

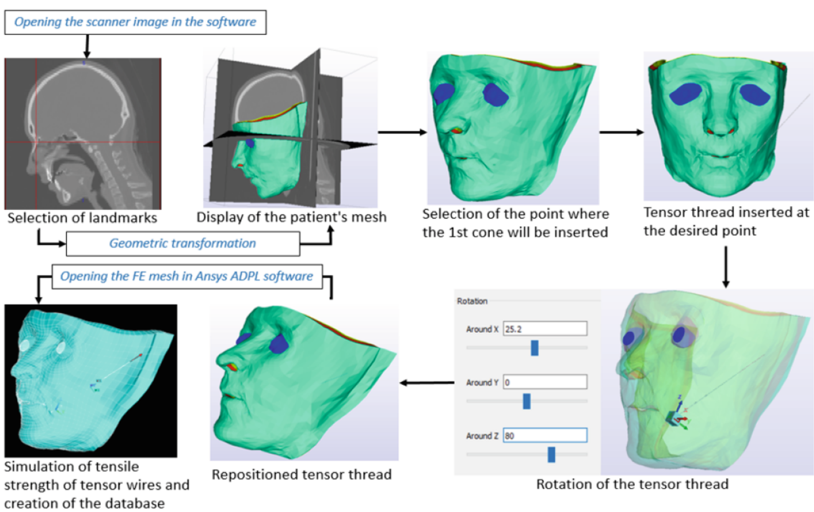

Fig. 6. Steps of 3D image-based registration, generation of a patient-specific mesh and insertion of a thread on the CamiTK software.

Once the ROM is constructed from the simulated training data with Ansys APDL software, a slider is available that allows clinicians to choose the amount of force to apply to the thread to enhance the facial tissue. The result, *i.e.* the total deformation of the face when the tensor thread is pulled, is then automatically displayed in real-time for each force value chosen by the clinician (Fig. 7).

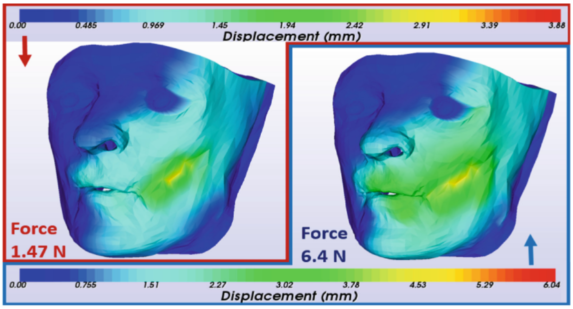

Fig. 7. Simulated face appearance after tensile thread traction at two force levels.

5 Discussion and Conclusion

This paper presents the use of a digital twin of a patient's face to help surgeons predicting the consequences of the clinical treatment. This work integrates the most recent developments now available in computer modeling, including advanced image-based registration, accurate non-linear Finite Element simulation, and machine learning methods for the design of accurate Reduced Order Models that make possible real time simulations of complex physical systems. The clinical treatment of interest in this study is the insertion of tensor threads in the cheek, which aims to lift the tissue of patients suffering from facial paralysis. If limited to a proof of concept with a single patient and a single location for thread insertion, this work has demonstrated the feasibility of a software that allows surgeons to evaluate for each patient the extent to which the position and the orientation of the threads can compensate for facial sagging.

The main challenges for future works are: (1) evaluating the size of the learning and evaluation sets of simulation data that consistently enables ROM to accurately predict the results of FE simulations; (2) deepening the way our software tool can integrate biomechanical patient specificities such as anatomical muscle insertions and tissue properties; (3) evaluating the accuracy of the model-based predictions of the clinical outcomes on the patient's face from an aesthetical and functional point of view. This requires systematic comparisons between data collected from patients in pre- and post-surgical conditions and predictions made with our patient-specific software tool.

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