FINITE ELEMENT MODEL OF THE FACE SOFT TISSUE FOR COMPUTER-ASSISTED MAXILLOFACIAL SURGERY

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1. ABSTRACT

In orthognatic surgery, patient mandible and maxilla are repositioned to correct face dismorphosis due to congenital malformation or traumatism. An important issue is to evaluate the consequences of these bone repositioning on the face soft tissue, in order to predict the post-operative aesthetic aspect of the patient. This problem is addressed using a biomechanical model of the patient skin tissue. A generic 3D Finite Element model of the face is presented, integrating skin layers and muscles with specific mechanical properties. This generic model is then automatically deformed to fit the patient morphology, using an elastic registration algorithm. The elements irregularities arising from the registration are automatically corrected. Therefore, a Finite Element model of each patient is available to simulate the face soft tissue deformation resulting from bone repositioning.

2. INTRODUCTION

Orthognathic surgery is directed to patients suffering from dysmorphosis of the lower part of the face, due to congenital malformation or traumatism. The consequences of these malformations are both aesthetic and functional (with a bad dental occlusion). Bone structures, namely the mandible and/or the maxilla, must be cut and repositioned in a surgical procedure, to reset the equilibrium of the face. A computer-aided system has been developed to assist surgeons in the definition of the surgical pre-operative planning, based on orthodontic and craniofacial analysis [1]. Once the bone repositioning planning is defined, its consequences on the facial soft tissues must be evaluated. A first point is to predict the aesthetic face appearance after surgery. This

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step is important for the surgeon as the prediction of facial tissue deformations might modify a planning based only on skull and dental analysis. Moreover, one of the main patient request is a reliable prediction of his post-operative aesthetic aspect. Another issue consists in evaluating the functional consequences of the intervention, i.e. the way bone repositioning affect the facial mimics of the patient, its mastication and speech production. This issue, not addressed so far in the literature, is very challenging and requires an accurate modeling of the facial muscular structures. To address these two problems, an accurate biomechanical face model integrating muscles must be defined for each patient. A new 3D Finite Element model of the patient face is then introduced in this paper. First results to simulate the outcomes of a surgical procedure or the face deformation resulting from muscular contractions are presented.

3. METHOD

3.1 Face anatomy

Facial skin has a layered structure composed of epidermis, dermis and hypodermis. Many facial muscles, involved in mandible movements and production of facial mimics, are inserted between these skin layers and the underlying bones (figure 1). Their organization is complex, with specific insertion points and orientations, and fibers interweaving. Moreover, their mechanical properties differ from skin layers ones. As a consequence, face tissues are highly anisotropic.

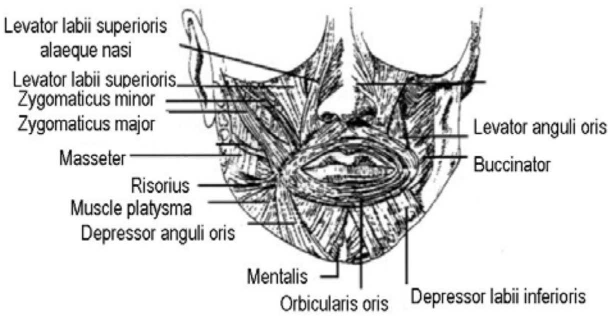

Figure 1. Face anatomy (from [2]).

3.2 Previous works

The first face models were developed for computer animation purpose [3], then applied to maxillofacial surgery [4]. These models, mostly motivated by a need of external realism, were based on discrete mass-spring structures. Then, arguing that a precise modeling of soft tissues deformation requires a continuous description, Finite Element models were developed [5,6,7,8]. However, these models suffer from numerical, mechanical and modeling shortcomings. For computer-aided surgery, a model of each patient must be defined. Therefore, existing models are based on a 3D mesh built out of patient CT images using automatic meshing methods. It is well known in the biomechanics community that for very complex shapes, such as the face skin tissue, generated mesh can present singular regions, with a high density of elements. Besides increasing the number of degrees of freedom (hence the computation time), these singular regions can lead to artificial anisotropy inside the mesh and over-stressed areas [9]. In addition, such automatically generated meshes are composed of unorganized tetrahedral elements that make difficult the identification of facial anatomical structures (skin layers or muscles) within the mesh. Since muscular structures are not modeled, the face anisotropy due to muscle fibers orientation cannot be taken into account, and functional consequences of the bone repositioning cannot be evaluated.

3.3 Methodology

An alternative to the automatic generation of tetrahedral mesh consists in manually building a mesh. This enables to arrange the elements inside the mesh so that they can be associated to specific anatomical entities (dermis layers, fat, muscles, mucosa, etc.). Moreover, hexahedral and wedges elements can be used, which have better numerical properties (convergence, error estimation and computation time) than tetrahedral ones [9,10]. However, such manual elaboration of the model is extremely complex, long and tedious. Hence, it cannot be considered for each patient in a Computer-Assisted clinical protocol. Our methodology consists, first, in manually building one generic model of the face, integrating skin layers and muscles. Then, the mesh of this generic model is conformed to each patient morphology, using an elastic registration method and patient data segmented from CT images. The automatically generated patient mesh has then to be regularized in order to perform Finite Element computation.

3.4 Generic Finite Element mesh

A volumetric mesh was manually designed to represent the soft tissue of a “standard” human face. This mesh is composed of two layers of hexahedral elements representing the dermis and hypodermis (subcutaneous fat) (fig. 2). Elements are organized within the mesh so that the main muscles responsible of facial mimics are clearly identified.

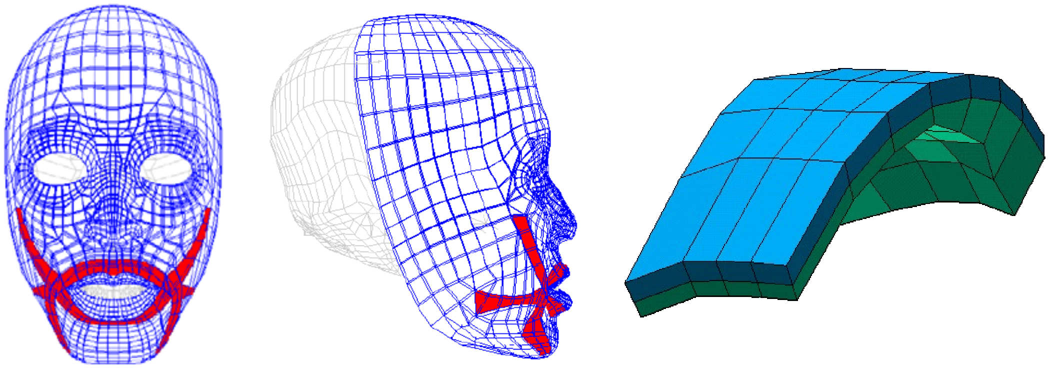

Figure 2. The generic 3D layered mesh, with embedded main facial muscles.

3.5 Conformation of the generic mesh to patient morphology

Manually building a 3D mesh is an extremely long, complex and tedious task, that obviously cannot be achieved for each patient in a clinical protocol. Therefore, once a generic mesh is available, our strategy is to fit it to each patient morphology. The Mesh-Matching algorithm [11] is used. This method is based on the Octree Spline elastic registration algorithm, originally developed for applications in computer-aided surgery [12]. A hierarchical and adaptive 3D displacement grid is used to compute a non-rigid transformation between two 3D surfaces, based on position and gradient features. 3D surfaces representing the external skin and skull surfaces of the patient are automatically built out of CT images using the Marching Cubes algorithm [13]. Then, the patient mesh is generated in two steps (figure 3) :

1. First, an elastic transformation is computed to fit the external nodes of the generic model to the patient skin surface. This transformation is applied to all the nodes of the mesh.

2. Then, another transformation is calculated between the internal nodes of the mesh and the patient skull surface. This second transformation is applied to the internal nodes of the mesh that must be rigidly fixed to the skull, i.e. not located in the lips and cheeks area.

A mesh conformed to the specific patient morphology is then available, still integrating the skin and muscles structure.

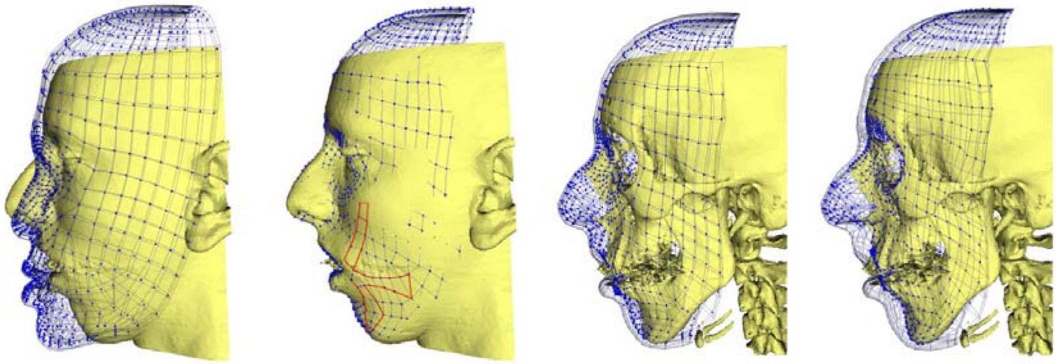

Figure 3. External nodes of the generic mesh are elastically matched to the patient skin surface (left). Then, internal nodes are fitted to the patient skull surface (right). Muscles are still integrated in the new patient mesh.

3.6 Correction of mesh irregularities

Nodes are displaced during the registration phase to fit the patient data. Therefore, some elements can be geometrically distorted during this process. If an element is too distorted, the “shape function” that maps it to the reference element in the Finite Element method cannot be calculated, hence the numerical resolution is not possible [10]. Thus, an automatic algorithm was developed to correct these mesh irregularities [14]. Based on a study of the singularity of the elements jacobian matrix, nodes of the mesh are slightly displaced until every element is regular. Therefore, a regularized patient mesh is obtained, which enable its use for Finite Element computations.

3.7 Finite Element modeling

In a first step, simple modeling assumptions are assumed, with linear elasticity and small deformation hypothesis. However, the anisotropy due to muscle interweaving is taken into account. Once data will be available to validate the simulated deformations, the modeling will be improved in a more realistic way. Biomechanical properties are chosen based on the few measurement of human soft tissue rheology available in the literature. The elasticity of the skin layers elements is set to 15 kPa, with a Poisson ration of 0.49 to model quasi-incompressibility [15]. Muscles elements have specific properties to model the linear transverse elasticity of the muscles, in the fibers directions. As measured in [16], this elasticity depends on muscle activation, with the Young modulus in fibers direction raising linearly from 6 kPa at rest to 110 kPa when activated. As boundary conditions, the internal nodes are rigidly fixed to the skull model, except in the lips and cheeks area. To simulate bone repositioning, nodes fixed to the mandible or maxilla are displaced according to the surgical planning. As muscles are embedded within the mesh, muscular activation can also be simulated by applying distributed forces to the nodes of the muscle elements, in the muscle fibers direction [17].

4. RESULTS

To validate the automatic mesh generation method presented in this paper, models of six patients were built (fig. 4). These models still integrate muscles and skin layers as defined in the generic model. The total amount of time required to build a patient model is about 30 minutes. Although muscles location may vary from person to person, no further data has been used so far to assess the actual patient muscles courses and insertion points. It is assumed that muscles location is still coherent after the registration based on skin and skull surfaces. Similarly, mechanical properties of the generic model are used in the patient model. Further research concerns integrating MRI or Ultra-Sound data to assess actual patient specificity.

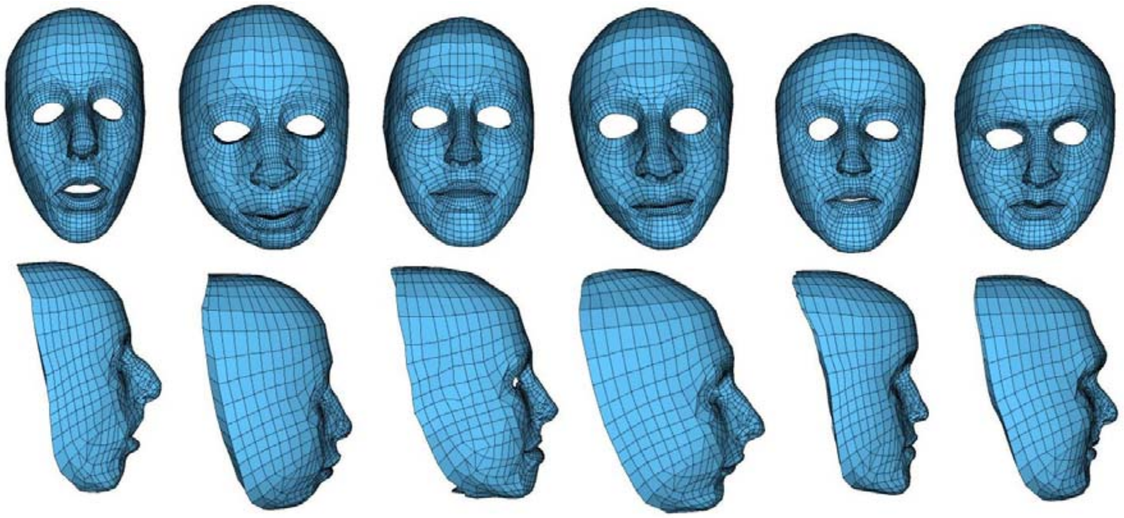

Figure 4 : models were successfully built for six patients with different morphology. Each model was automatically generated in about 30 minutes.

Patient models can be used to perform simulation of the face soft tissue deformation. Simulation of bone repositioning and muscle contraction were carried out, as presented in figures 5 and 6. The validation of these first results will be achieved using post-operative CT data, to quantitatively measure the difference between the real outcomes of the surgery and the simulations. For the functional modeling, muscular activation can be recorded using EMG, while the resulting face deformation are recorded using a video camera and 3D optical localizer [18].

5. CONCLUSION

A new Finite Element model of the face soft tissue has been introduced, as well as a method to automatically conform it to each patient morphology. Ongoing works concern integrating this model in a computer-aided clinical protocol for maxillofacial surgery, to simulate the outcomes of surgical procedures. Clinical validation will be carried out using preoperative and postoperative CT exams.

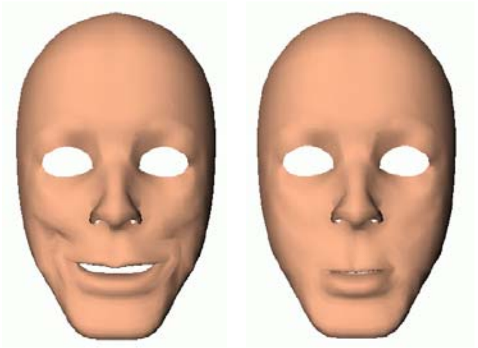

Figure 5. Face deformation resulting from contraction of Zygomaticus major and Orbicularis oris.

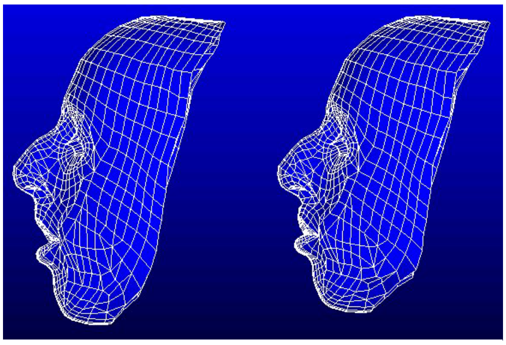

Figure 6. Simulation of face deformation resulting from mandible and maxilla repositioning.

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