Finite Element Face Model Conformed to Patient Morphology

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Abstract

A surgical simulator for plastic and maxillofacial surgery, that gathers the dental analysis (orthodontia) and the maxillofacial analysis (cephalometry) into a single computer assisted procedure, has been recently developed. This simulator proposes a semi-automatic diagnosis for facial bone structure repositioning.

This paper presents the next step of this work, i.e. predicting the consequences of the simulated bone structures displacements onto the patient face appearance and functionality. A generic Finite Element model of the face integrating skin layers and muscles is presented. This model is then automatically conformed to patient data using elastic registration. Finally, a mesh correction algorithm is used to correct the mesh irregularities resulting from the registration, so that Finite Element analysis can be computed with the patient model.

1. Introduction

Orthognathic surgery deals with face dysmorphosis arising from congenital malformations or accidents. For example, in the case of mandibular prognathism (dento-facial deformity of the lower third of the face resulting from excess mandibular growth), orthognathic surgical treatment is required to correct the occlusion (dental position) with an osteotomy of the mandible [Bel92]. Several Computer-Aided systems have been developed to assist surgeons in the definition of the surgical pre-operative planning [Cut86, Mar86, Udu91, Lo94, Van96]. They are based on a 3D reconstruction of the patient skull out of Computer Tomography (CT) images. The surgeon can simulate skull osteotomies in a way that reflect actual surgical procedure. Bone segments can therefore be mobilized with six degrees of freedom. In this framework, our research group has developed a surgical simulator for plastic and maxillofacial surgery, that gathers the dental analysis (orthodontia) and the maxillofacial analysis (cephalometry) into a single computer assisted procedure [Bet00].

In order to evaluate the consequences of the bone repositioning onto patient face appearance, physical models of facial soft tissues have been developed. The first ones focused on computer animation and were motivated by a need for external realism [Lee95]. Their modeling was mainly based on discrete mass-spring structures, regularly assembled inside facial tissue.

These kind of discrete models were introduced in the framework of computer assisted maxillofacial surgery [Wat96, Kee96, Koc98, Tes99, Bar00]. Then, arguing that a precise modeling of soft tissues deformation requires a continuous description, Finite Element (FE) models were developed [Kee98, Rot98, Sch00, Zac00].

From our point of view, these models suffer from shortcomings in terms of a numerical, mechanical and modeling point of view. This paper addresses these shortcomings and introduces our methodology. This methodology is based on the definition of a generic 3D Finite Element model of the patient face, integrating different anatomical structures. A model adapted to the patient morphology is then obtained by elastically deforming this generic model to patient data.

2. Methods

Once the surgeon has defined a bone repositioning planning, the consequences of this planning on the facial soft tissues have to be evaluated. A very important point is to predict the aesthetic face appearance after surgery. Another issue consists in evaluating the functional consequences of the intervention, i.e. the way bones repositioning affect the facial mimics of the patient, its mastication and speech production. The latter 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 issues, an accurate biomechanical face model integrating muscles must be defined for each patient.

The first subsection gives some information about face anatomy. Then, the shortcomings of the Finite Element face models proposed for computer-aided surgery are addressed. Finally, we introduce our methodology based on the development of a "generic" Finite Element face model, automatically adapted to the patient morphology.

2.1. Face anatomy

Facial skin has a layered structure composed of epidermis, dermis and hypodermis. Many facial muscles, involved in speech production and face expression, are inserted between these skin layers and the underlying bones (figure 1). More than ten muscles are involved in the deformations of the lower part of the face. 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.

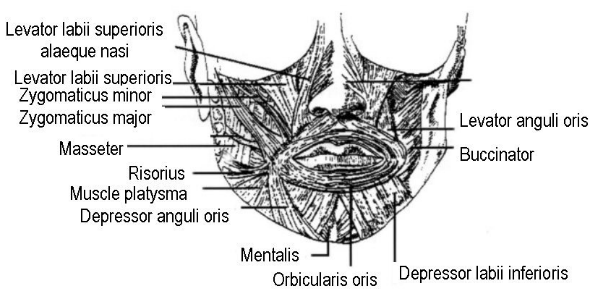

Figure 1. Face anatomy (from [Bou72]).

2.2. Previous works

In the framework of computer-assisted maxillofacial surgery, a 3D mesh adapted to each patient morphology must be defined. Therefore, Finite Element face models proposed in the literature [Kee98, Rot98, Sch00, Zac00] are built from patient CT or MRI images using automatic meshing methods. It is well known in the biomechanical community that for very complex shapes, such as the face skin tissues between the skull and skin surfaces, the generated mesh can present singular regions, that is to say with an extremely 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 [Cra96]. 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. As a consequence, the existing Finite Element models are isotropic, as the face anisotropy due to muscle fibers orientation cannot be taken into account. Moreover, as muscular structures are not modeled, functional consequences of the bone repositioning cannot be evaluated.

2.3. Methodology

In biomechanics, a response traditionally given to these shortcomings 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…). Moreover, hexahedral and wedges elements can be used. These types of elements have better numerical properties (convergence, error estimation and computation time) than tetrahedral ones [Zie89, Cra96].

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. The automatically generated patient mesh has then to be regularized in order to perform Finite Element computation.

2.4 Generic Finite Element face model

A multi-layers volumetric mesh (figure 2) is used to model the fat and dermis layers [Cha00]. Biomechanical properties are chosen to replicate observations made on human skin [Fun93]: quasi-incompressibility and elasticity set with a Young modulus equal to 15 kPa. Main face muscles are defined within this mesh by elements located along the courses of the muscles. These elements have specific properties to model the linear transverse elasticity of the muscles, in the fibers directions. Moreover, as measured by [Duc90], this elasticity depends on muscle activation, raising linearly from 6 kPa at rest to 110 kPa when activated. Figure 5 presents dynamic simulations of the generic face model deformations under muscles activation.

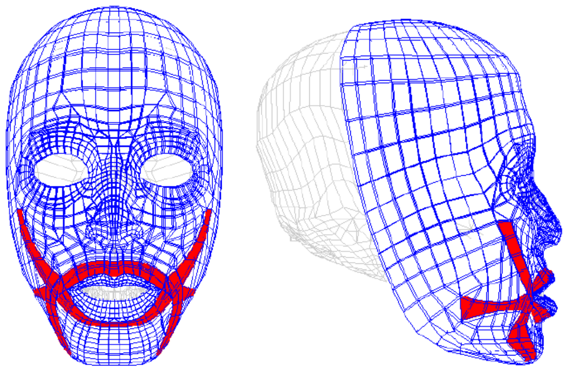

Figure 2. The generic 3D face mesh. Highlighted: main muscles integrated in the model.

2.5 Adaptation to patient morphology

The next step after the complete generation of the generic model is to adapt it to each patient morphology. Registration methods have already been proposed in the literature to adapt a generic face model to patient anatomy [Lee95, Bar00, Mao00]. These methods rely on feature-based correspondence techniques, which require the manual definition of landmarks on patient data. Although, these algorithms were defined for mass-springs models and cannot be applied to Finite Element models. Indeed, the mesh regularity is not ensured during the registration, which means that some elements can be geometrically distorted (figure 4). 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 [Tou84, Zie89].

A new conformation method has therefore been developed by our group. It uses the Mesh-Matching algorithm [Cou00] to fit the generic mesh to specific patient data. The resulting deformed mesh is thus regularised so that Finite Element analysis can be performed.

2.5.1 Mesh adaptation

The M-M algorithm [Cou00] is based on the *Octree Spline* elastic registration method, originally developed for applications in computer-aided surgery [Sze96]. 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.

To adapt the generic model to the patient morphology, skin and skull surfaces of the patient are automatically extracted out of CT images. Then, the 3D mesh of the patient model is generated in two steps (figure 3) :

1. First, an elastic transformation is computed to fit the external surface 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 surface 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.

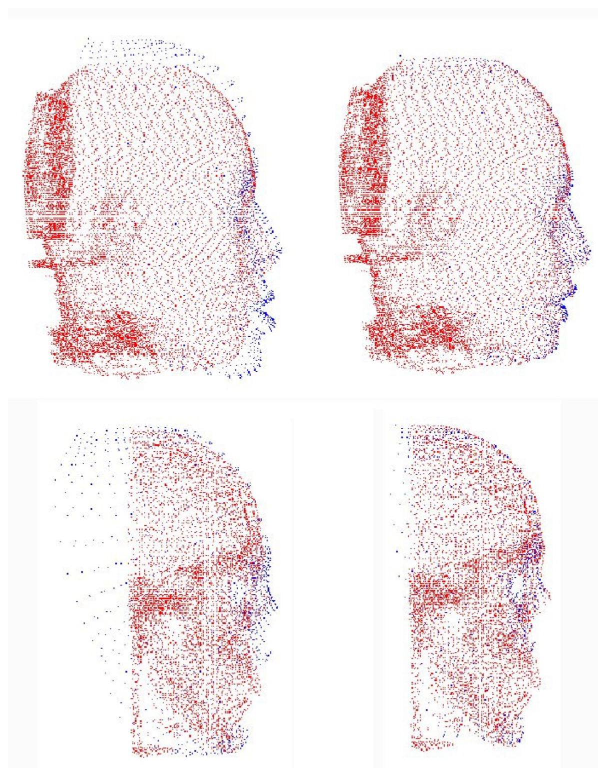

Figure 3. Nodes of the "external" surface of the generic mesh are elastically matched to the patient skin surface (top). Then, "internal" nodes are fitted to the patient skull surface (bottom).

2.5.2 Correction of mesh irregularities

Using this method, a model conformed to patient morphology is provided, still integrating skin layers and muscles and with anisotropic mechanical properties. However, some elements can be highly distorted (figure 4), disabling one to use the Finite Element method. Thus, an automatic algorithm was developed to correct the mesh irregularities [Lub01]. Based on a study of the singularity of the elements jacobian matrix [Zie89], nodes of the mesh are slightly displaced until every element is regular. Therefore, a regularized patient mesh is obtained, which enable Finite Element computations.

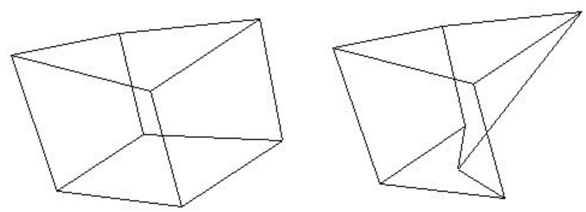

Figure 4. Example of two hexahedral elements after the mesh is adapted to patient data. If an element is too distorted (right), Finite Element computation cannot be performed.

3. Results

As main muscles are integrated in the mesh, muscular activation can be simulated applying distributed forces in the muscles fibers direction [Cha00]. Figure 5 presents face deformation under contraction of Zygomaticus major and Orbicularis oris.

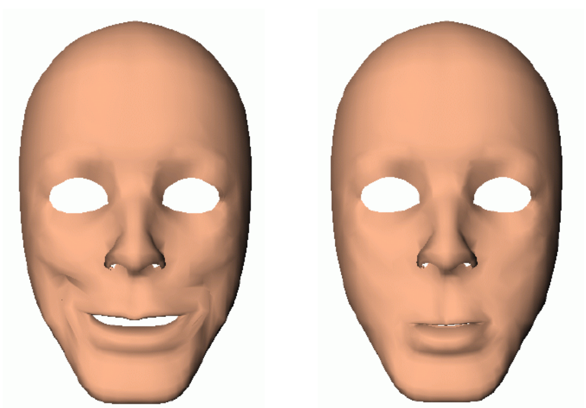

Figure 5. Action of Zygomaticus major and Orbicularis oris muscles on the generic model.

Once the mesh of the generic model has been conformed to patient data, a new model of the patient is available (figure 6). This model incorporates muscles and skin layers as defined in the generic model. 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.

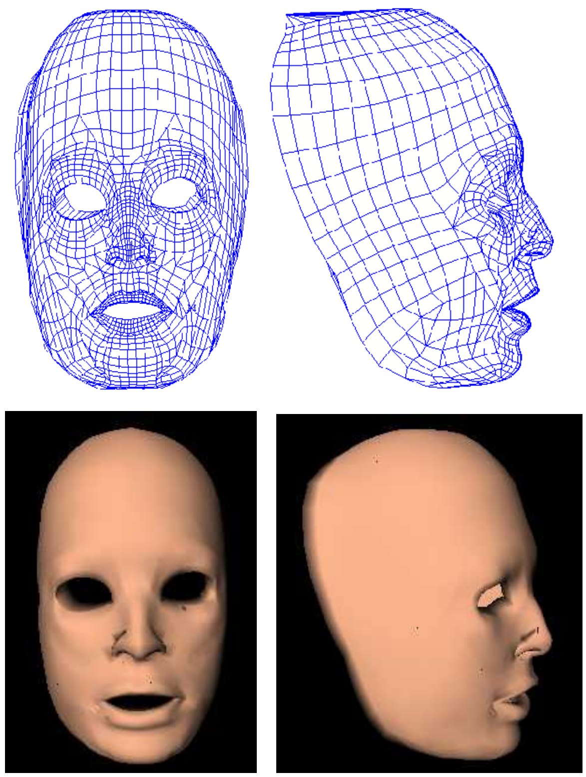

Figure 6. Face model of a patient after registration of the generic model (wireframe and rendered).

The automatically generated patient model can therefore be used to simulate bone repositioning. Figure 7 gives an example of a simulated forward displacement of the mandible.

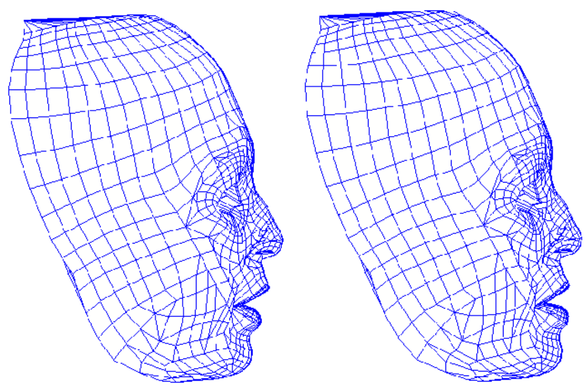

Figure 7. Simulated forward displacement of the mandible on a patient model.

4. Conclusions

A new Finite Element model of the face has been introduced. The method consists in manually designing a generic model integrating skin layers and muscles, with specific mechanical properties. This generic model is then automatically conformed to patient morphology using non-rigid registration and a mesh correction algorithm. First qualitative simulations are provided.

Ongoing works concern integrating this soft-tissue model in a computer aided clinical protocol for maxillofacial surgery. Clinical validation will be carried out using preoperative and postoperative CT exams.

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