Automatic generation of patient-specific finite element meshes of the face and oral cavity for orofacial digital twins

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1. Introduction

Digital Twins, i.e. digital models that precisely simulate the behavior of physical systems, are increasingly used to better understand the properties of the systems and predict how they would behave under unknown conditions (Jones et al. 2020). This concept is particularly useful in the *a priori* evaluation and planning of clinical treatments, which impacts can be simulated in a patient-specific manner, by using Digital Twins that are specifically adapted to reproduce the physical characteristics of each patient (Lauzeral et al. 2019).

In this paper we present a method for the design of patient-specific biomechanical models of the orofacial region (oral cavity and face) starting from a thoroughly validated reference Finite Element (FE) model. This method is based on an iconic image registration process (Bijar et al. 2016). Some anatomical landmarks are introduced to improve the registration while the human face and the entire oral cavity are transformed with the method.

2. Methods

2.1. General process

The segmentation of the different mechanical structures of the orofacial region on 3D medical images is particularly difficult and long lasting, because many of them are made of soft tissues and are in contact with each other. This is why our approach in designing patient-specific biomechanical models of these structures consists in applying a non-rigid geometric transformation on a reference biomechanical model that has been designed from carefully segmented MR and CT 3D images recorded from a male subject. Our method uses patterns of grey levels as well as anatomical landmarks on bone structures in both images to determine the best geometrical transformation that registers the reference image into the patient-specific one. The registration process uses the Elastix library (Klein et al. 2010). It returns a 3D displacement field that can be in turn applied to the FE mesh of the reference subject (Calka et al. 2023), using the library called Transformix, part of the Elastix library, in order to obtain a patient-specific mesh.

2.2. Registration parameters

A non-rigid landmark assisted B-Spline transformation is used. The optimization process consists of 5 steps that rely on 5 different image resolutions, with a grid size varying from 256 mm to 16 mm (256 mm, 128 mm, 64 mm, 32 mm, 16 mm). A multi-metric approach is used made of a normalized cross correlation (NCC) commonly used for images of the same modality and a landmark mapping based on Euclidean distance (SCP) for rigid alignment such as:

$$S = \alpha NCC + \beta SCP$$

During the 5 steps the parameters α and β vary: in the 1st step only the SCP metric is used and only the NCC metric is used during the last two steps; for steps 2 and 3 a ratio 0.95/0.05 is chosen for α and β. A Gaussian pyramid ($\sigma =$ 16.0, 8.0, 4.0, 2.0, 1.0) is used during the different steps to subsample the image.

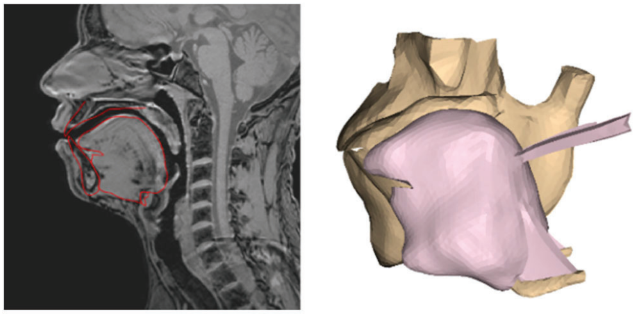
A random sampling extracted 5000 voxels samples, which corresponds to about 0.0005% of the image. It allows us to drastically reduce the computation time. The interpolation is performed using a B-Spline interpolator of order 3. Finally, the optimization of the transformation is done using a stochastic gradient descent method as advised in Klein et al. (2010).

3. Results and discussion

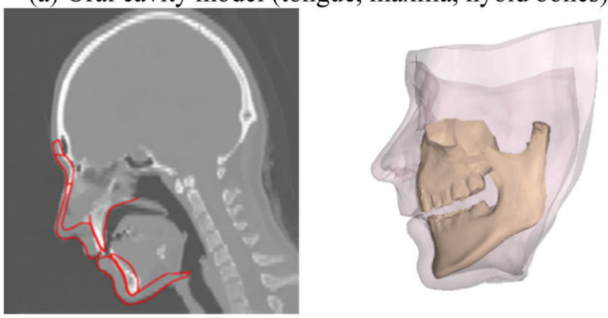
3.1. Registration result

Figure 1a represents the different meshes of a patient-specific oral cavity obtained through our iconic registration process. These meshes are superimposed on a mid-sagital MR image of the patient. The tongue and the mandible obtained are rather precise. The hyoid bone is not perfectly positioned. The maxilla is precise at the level of the teeth but less so on the palate area. We can note that all the contacts tongue/mandible and tongue/hyoid-bone seem to be preserved.

Figure 1b represents the same process applied to the face, the mandible and the maxilla of a second patient. The meshes are superimposed on CT scan images. These two examples show the ability of our registration method to be used for different type of mono-modal transformations (MRI/MRI and CT/CT).



(a) Oral cavity model (tongue, maxilla, hyoid bones)



(b) Face model with mandible and maxilla

Figure 1. Generated patient-specific FE model. Left: Patient-specfic mesh superimposed on MRI data; right: patient-specific FE model.

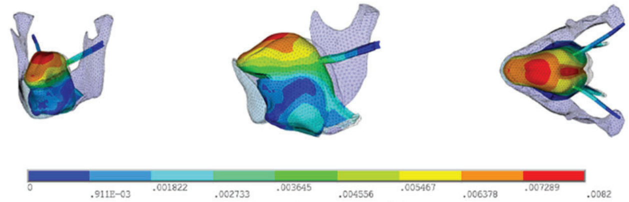
Table 1. Mean, standard deviations, min, max for different quality mesh criteria.

Criteria	Mean	Sd	Min	Max
Aspect ratio (AR)	2.157	0.554	1.197	7.435
Skewness (SN)	0.378	0.164	0.003	0.953
Orthogonal quality (OQ)	0.621	0.161	0.048	0.983
Maximum angle (MA)	102°	12°	72°	153°

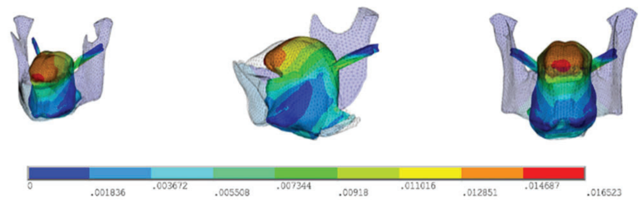
Table 1 shows the quality of the generated FE meshes according to several quality criteria. According to ANSYS criteria, an element is considered to be of poor quality if: AR >20, SN >0.95, OQ <0.14, MA >165°. We can see that some elements exceed the quality thresholds, but these remain in small quantities and do not prevent simulations even if they might reduce their accuracy.

3.2. Patient-specific FE model simulation

Figure 2 shows simulations (ANSYS MAPDL) performed with the patient-specific tongue model generated with our method. These simulations represent two French phonemes (/i/, /u/) involving lingual, mandibular ($\simeq$ 2 mm) and bonded and sliding contacts. In the phoneme /i/, the tongue slides along the mandible toward the teeth. The hyoid bone advances as a result of the genioglossus advancing the tongue. In the phoneme /u/, the tongue has an important backward movement. The hyoid bone lowers due to the action of the sternohyoid muscle allowing the base of the tongue to compress more. All these movements show that the generated patient-specific models are usable in simulations that will be used in the future to generate interactive time simulations.



(a): Phoneme /i/



(b): Phoneme /u/

Figure 2. French phonemes /i/ and /u/ pronounced with the generated patient-specific FE tongue model. The color bar corresponds to the displacements of tongue tissues.

4. Conclusions

The patient-specific mesh generation method based on iconic image registration using the Elastix library shows real capacities to generate quality meshes usable in accurate and realistic FE simulations. These preliminary works need to be validated on several patients. The next step is to generate a reduced order model from the biomechanical model in order to speed up simulations Such a digital twin could then be used in a clinical application like a preoperative simulator for orofacial surgery planning.

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