An efficient strategy for modeling the human auditory system from Micro-Computed Tomography Imaging.

Caminos, Luis[1]; Chaves, Gonzalo[1]; Lima-Rodriguez, Antonia[1]; Garcia-Manrique, Jose[1]; Gonzalez-Herrera, Antonio[1]

ABSTRACT

Finite Element modeling is a widely used methodology to build numerical models and simulate the behavior of the human auditory system; this has allowed essential advances in understanding the biomechanics of that complex system. There are two key points in modeling: the construction of an adequate geometry that allows efficient meshing and the correct use of mechanical properties of the materials. This research aims to show a new strategy for automating the build Finite Element Model process of the human auditory system using the FEM from Micro-Computed Tomography (Micro-CT) Imaging. The idea behind this methodology is to build a Finite Element Model with a computational and temporal low cost. This work allowed us to design the first semi-automatic algorithm to build a finite element model of the human middle ear that will later be used to incorporate the other components of the auditory system for different types of studies.

Keywords: human hearing, middle ear, finite element model

1. INTRODUCTION

The intricate human auditory system necessitates the application of finite element models for comprehension [1]. Nevertheless, generating these models is a challenging undertaking that demands precise geometry creation and optimal coupling between components. Proportions must remain accurate to avoid meshing issues, while the element count should be balanced to achieve computational efficiency. This study seeks to automate the process of constructing the finite element model for the human auditory system, serving as a crucial initial step towards this objective.

A semi-automatic algorithm is designed to build a finite element model of the human middle ear (tympanic membrane, ossicular chain, tendons, and ligaments). The geometric model is built from images taken from Micro-CT provided by the University of Antwerp [2].

Although some human decisions are necessary, the process has been designed and partially automated. The following sections provide a brief description of the methodology, results, and conclusions.

[1] *Departamento de Ingeniería Civil, de Materiales y Fabricación. Universidad de Málaga (España).*
lfcaminos@uma.es (Corresponding author). *chaves.h.gonzalo@gmail.com. tlima@uma.es. josegmo@uma.es. agh@uma.es*

2. METODOLOGY

The structure of the algorithm is shown in Fig. 1. It is divided into four stages that are described below.

2.1. Input data

The input data is obtained from Micro-CT of the auditory system, in our case provided by [2]. These data are ***.stl*** files of the tympanic membrane, ossicular chain, ligaments, and tendons that were generated through Micro-CT image processing, the latter is outside the scope of this research.

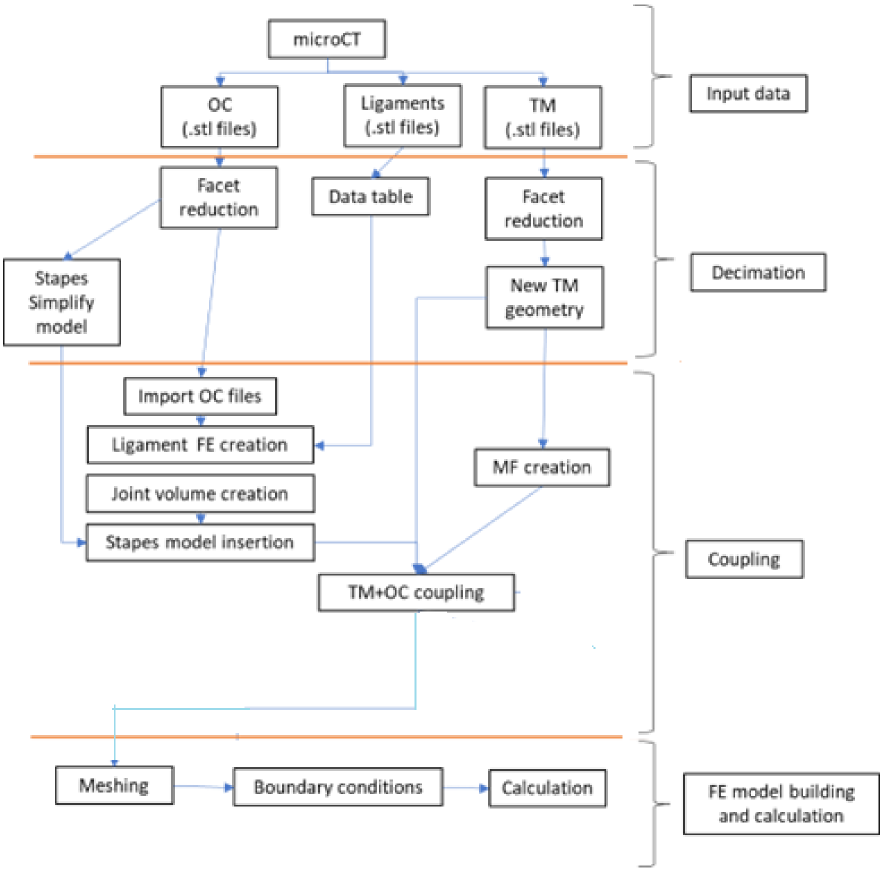

Figure 1. *Algorithm structure*

2.2. Decimation

For FE modeling and calculation, Micro-CT images provide detailed geometries. However, this increases computational cost and it's unclear if the results are of high quality. Thus, a decimation process is necessary to reduce external geometry facet numbers.

For this task, a routine is programmed in MATLAB software. The volumes of the malleus, incus, stapes, and tympanic membrane are treated, and new decimated geometries are constructed in the form of CAD files for the tympanic membrane and ossicles, or data tables for ligaments and tendons in the form of bars.

2.3. Coupling

This stage of the algorithm is the most complex since, each new geometry must be spatially positioned and coupled. Even when the original data comes from the same specimen, this procedure is not easy. This is the point where decision-making automation is most complex. We need to couple geometries with different characteristics, adding ligament, articulation, and at the same time ensuring that the meshing step can be performed efficiently.

2.4. FE model building and calculation.

The methodology used allows different models of material properties to be introduced to each of the parts that make up the system. In this research, this information was taken from the literature and previous works of our research team [3]. It is well known that the tympanic membrane is a critical component in the behavior of the human middle ear, for this reason, a convergence study is necessary [4]. The form factor (relationship between the element and the thickness of the TM) used is 3. On the other hand, the meshing of the other components is done in a specific order.

3. RESULTS

Below are some results from each stage of the algorithm. Fig. 2(a) shows the change in the geometry of the malleus through a faceting process using Matlab; a significant reduction in the number of polygons that make up the solid can be observed.

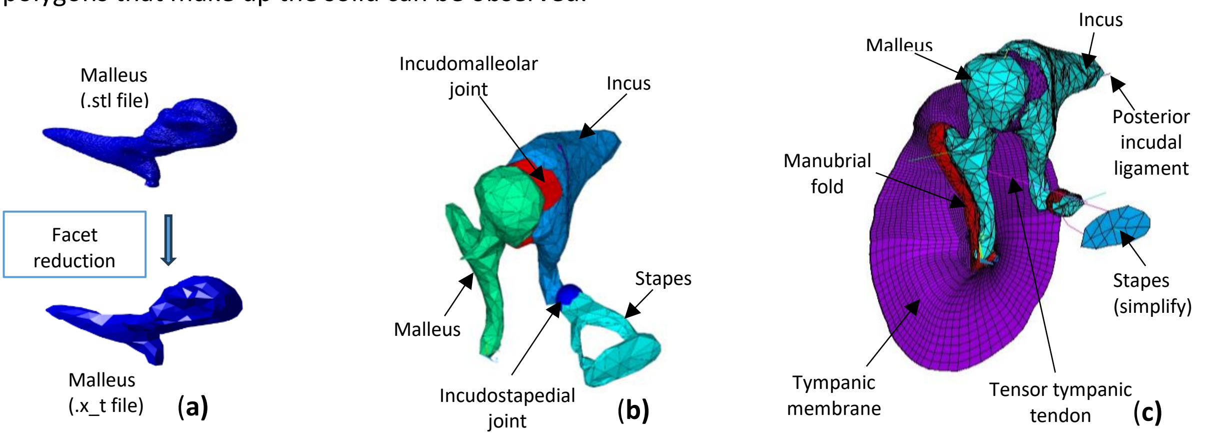

Figure 2. ***(a)*** *Malleus facet reduction.* ***(b)*** *Ossicular chain and joints coupling.* ***(c)*** *Middle ear FEM*

Fig. 2(b) shows the coupling of the ossicular chain and joints. This stage is one of the most complex. Some decisions such as generating contact areas could not be automated.

The complete FEM of the middle ear is shown in Fig. 2(c). Some important simplifications can be observed, such as the use of beam elements for models.

A harmonic analysis was conducted from 100 to 10.000 Hz using the FEM. A uniform harmonic 80 dB_{SPL} stimulus pressure was applied to the lateral side of the eardrum. The amplitude of stapes footplate displacements versus frequency is shown in Fig. 3 compared with experimental measurements [5]. It can be seen that the model curve and the experimental curve are very close.

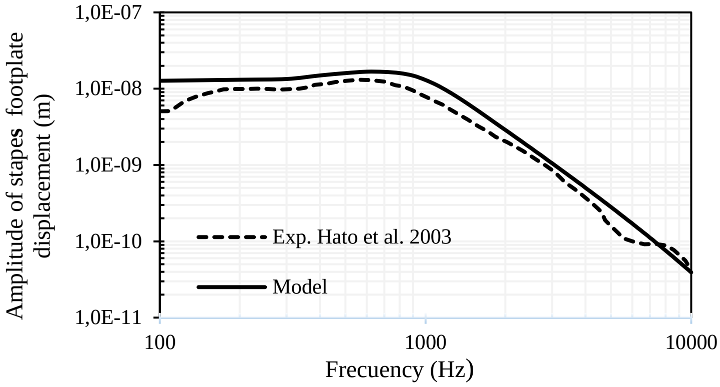

Figure 3. *Amplitude of stapes footplate displacement vs. frequency*

4. CONCLUSIONS

This article describes a methodology to build, from Micro-CT images, a numerical model of the human middle ear. This process is not fully automated because human decisions must be included in the algorithm.

The model obtained could be validated by comparing it with the numerical response of a harmonic analysis and experimental measurements taken from the specialized literature.

This work is the first step in the automation-building process of a numerical model of the human auditory system from images taken from patients with auditory pathologies.

REFERENCES

[1] Garcia-Manrique, J., Furlong, C., Gonzalez-Herrera, A., Cheng. JT., (2023). Numerical model characterization of the sound transmission mechanism in the tympanic membrane from a high-speed digital holographic experiment in transient regime. *Acta Biomaterialia, 159, 63–73.*

[2] Biophysics and biomedical physics. University of Antwerp. https://www.uantwerpen.be/en/research-groups/bimef/.

[3] Caminos, L., Garcia-Manrique, J., Lima-Rodriguez, A., Gonzalez-Herrera, A. (2018). Analysis of the mechanical properties of the human tympanic membrane and its influence on the dynamic behaviour of the human hearing system. *Applied Bionics and* Biomechanics, *2018, 1736957.*

[4] Volandri, G., Di Puccio, F., Forte, P., Carmignani, C. (2011). Biomechanics of the tympanic membrane. *Journal of Biomechanics, 44, 1219–1236*.

[5] Hato N, Stenfelt S, Goode RL. (2003). Three-Dimensional Stapes Footplate Motion in Human Temporal Bones. *Audiology and Neurotology, 8, 140–52*.