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NUMERICAL VIBROACOUSTICAL ANALYSIS OF THE HUMAN MIDDLE EAR UNDER DISEASED CONDITIONS

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ABSTRACT
This work aims to investigate the vibrational response of the human middle ear caused by an acoustical excitation under two pathological conditions: stapes fracture and stapedial tendon ossification. To perform this analysis, a previously validated Finite Element model of the human middle ear was used for modeling both pathologies. Results of stapes velocity transfer function under normal and diseased middle ear conditions were compared to hearing losses audiograms from literature which good agreements were observed. Furthermore, the Total displacement of the stapes and its footplate at specific frequencies are analyzed for a better understanding of diseased middle ear mechanics.

RESUMEN
O objetivo deste trabalho é investigar a resposta vibratória da orelha média humana causada por uma excitação acústica sob efeito de duas patologias: fratura no estribo e ossificação do tendão estapedial. Para isso, um modelo em Elementos Finitos da orelha média humana, previamente validado, foi utilizado para modelar as patologias. Resultados de velocidade de vibração do estribo foram comparados a audiogramas encontrados na literatura e boas concordâncias foram observadas. Por fim, foi analisado o deslocamento total do estribo e sua platina em frequências específicas para um melhor entendimento da mecânica da orelha média em condição patológica.

1. INTRODUCTION

The human middle ear is an important part of human peripheral auditory system. The middle ear has two well-known anatomy-physiological purposes. Firstly, middle ear transmits the acoustical energy from the outer ear to the inner ear by means of mechanical vibrations and works to allow for low reflectance propagation of the acoustical energy between these systems, matching their severally different impedances (von Békésy, 1960). As second purpose, the middle ear also works in order to protect the inner ear against high static pressure and high impulsive stimuli. This protective function can still be divided into its passive and active working. The passive working is lead through the flexible ossicular chain and its synovial joints (Gottlieb *et al.,* 2018) while the active protective function is made by the two muscles connected to ossicular chain through their respective tendons (Mason, 2013).

Pathological conditions related to the middle ear can cause conductive hearing losses, meaning a decrease of the human hearing (Luers and Huttenbrink, 2016). Hearing losses can impact in a person life in many ways, such as: generating social isolation, communication difficulties and sometimes yielding a cognitive decline (WHO, 2017). Treatment of diseased middle ears can be made through clinical procedures or surgery intervention by means of several devices such as hearing aids, middle ear prosthesis and cochlear implants (Luers and Huttenbrink, 2016; Calero *et al.,* 2018). Following the World Health Organization (WHO, 2017), it is estimated that 360 million people around the world have some form of hearing loss. This data revealed that hearing loss poses substantial costs to the health care system and to the economy as a whole. Based on these data, tools which allow predictions of how diseases can change physiological functions of the middle ear as well as to evaluate several restorative techniques could be useful for academic and clinical applications. Therefore, numerical models of the human middle ear have been developed over the past 30 years, whereas the Finite Element Method (FEM) stands out due to be a potential tool to investigate the middle ear mechanics (Puria, 2018; de Paollis *et al.*, 2017).

In order to understand the human middle ear mechanics under pathological conditions, this work aims to investigate the vibrational response of the human middle ear, caused by an acoustical excitation, under two stapedial disorders: stapes crus fracture and stapedial tendon (ST) ossification. An usually measure used in the literature to characterize the middle ear frequency response, called in this work as $H_{\text{footpalte}1}$, was used to evaluate the middle ear response under pathological conditions. In addition, Total Displacement u of the stapes and its footplate is evaluated for a better understanding of the changes in the middle ear mechanics caused by the two stapedial pathological conditions.

2. STAPEDIAL DISORDERS

As mentioned previously, this work aims to evalutae the middle under pathological conditions retated to the human stapes. In this section, Stapes fracture and ST ossification are described and hearing losses audiograms from literature are shown to be used as reference data to the obtained results and analysis.

Yetiser *et al.* (2008) studied about the etiology of traumas at human ossicular chain, indicate that these traumas are related to head injuries, usually caused by traffic accident. Furthermore, Yetiser *et al.* (2008) point Stapes fracture out as one of the frequent disorders at human ossicular chain. Stapes fracture characterizes as a disruption normally located in the stapes cruses or footplate and has been reported by Aussedat et al. (2017). In this work, authors describe an isolated fracture of the posterior crus of the stapes caused by head injury and the related conductive hearing loss, that can be seen in Figure 1(a).

In contrast to Stapes fracture, the ossification of the stapedial tendon is a less reported disease in literature and two case studies of ST ossification are related by Grant and Grant (1991). Grant and Grant (1991) reported two cases of the stiffening of the ST after a exploratory tympanotomy referring to the ST as a "solid bony bar fixing the stapes". Figure 1(b) shows the conductive hearing loss measure by Grant and Grant (1991) in these two case studies.

1 This measure is also called "stapes velocity transfer function" in the literature.

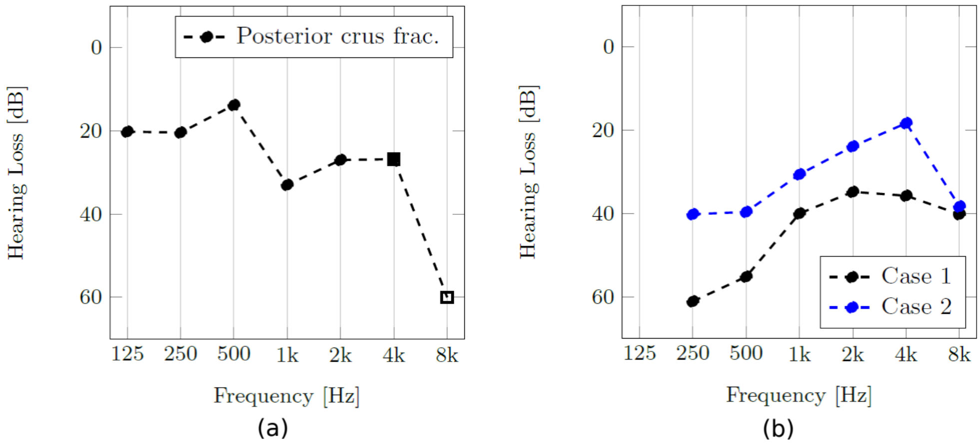

Figure 1: Conductive hearing loss of case studies of (a) Stapes fracture from Aussedat *et al.* (2017) and (b) ST ossification from Grant and Grant (1991).

3. FINITE ELEMENT (FE) MODELS OF THE MIDDLE EAR

3.1 FE Model Under Normal Condition

In order to analyze the vibroacoustical behavior of the human middle ear, an accurate three-dimensional FE model is used for modeling the middle ear under normal and pathological conditions. The geometries employed in both normal and diseased FE models of the human middle ear were obtained from a cadaveric temporal bone via micro computed tomography made by Biophysics and BioMedical Physics research group from University of Antwerp, and are available in their website[2]. All geometries were meshed defining solid, three-dimensional and tetrahedral elements. The model was meshed and solved using the software COMSOL Multi-physics 5.2 with Solid Mechanics modulus.

Our FE model is composed by all middle ear structures excepted the superior malleus ligament (SML), as can be seen in Figure 2(a). Therefore, the SML was represented by a lumped spring at the malleus head. For all ligaments and tendons, the elements that represent the connection to the tympanic cavity wall had their displacement set to zero. The same was true to the peripheral elements of the stapedial annular ligament and tympanic annulus. On the other hand, to represent the cochlear load, a complex impedance based on the experimental data obtained by Nakajima *et al.* (2008) was defined on the medial surface of the stapes footplate. Other details about mechanical properties and boundary conditions of the FE model can be seen in Lobato *et al.* (2018).

As shown in details in Lobato *et al.* (2018), our FE model was validated comparing the numerical results of $H_{footplate}$ as well as displacement of lateral surface of the tympanic membrane to experimental data from the literature. Figure 2(b) shows the comparison of numerical $H_{footplate}$ obtained with our FE model of the human middle ear under normal condition to the experimental $H_{footplate}$ obtained by Aibara *et al.* (2001).

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2 https://www.uantwerpen.be/en/rg/bimef/downloads/

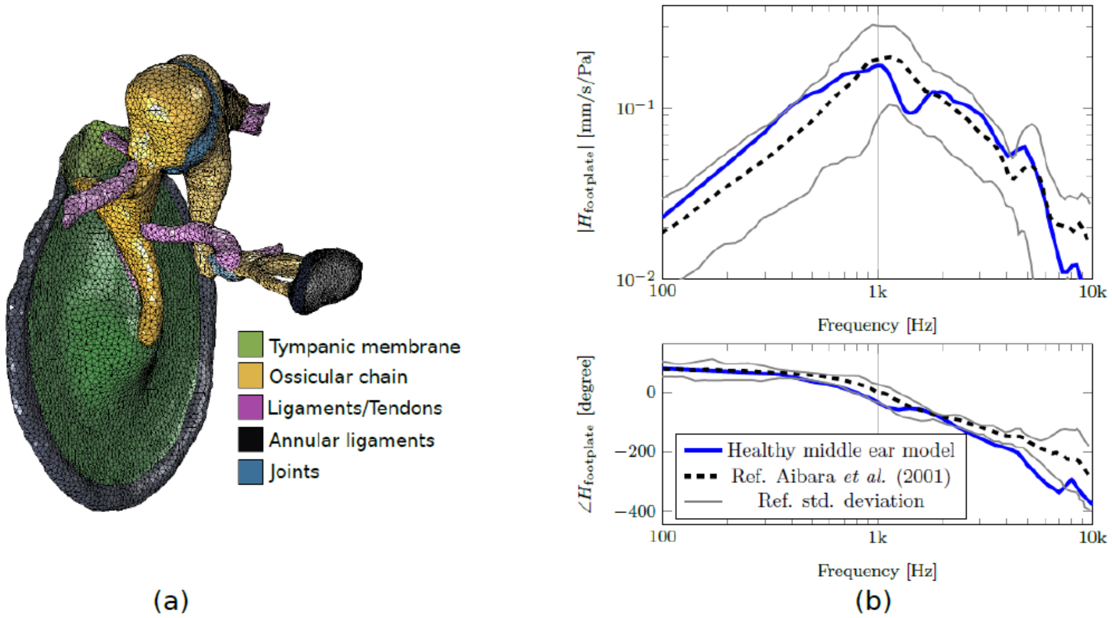


Figura 2: (a) FE model of the human middle ear and (b) numerical $H_{footplate}$ compared to experimental data.

3.2 FE Model Under Pathological Condition

The FE model described in Section 3.1 was modified in order to represent the stapedial disorders described in Section 2 for assessing their influence on middle ear mechanics. Firstly, for modeling Stapes fracture, a portion of posterior crus of the stapes was withdrawn with h_{frac} equal to 1 [mm] and d_{frac} equal to 0.2 [mm], as shown in Figure 3. On the other hand, for ST ossification the tendon had its Young's modulus increased up to the Young's modulus of the ossicular chain (14.1 [GPa]).

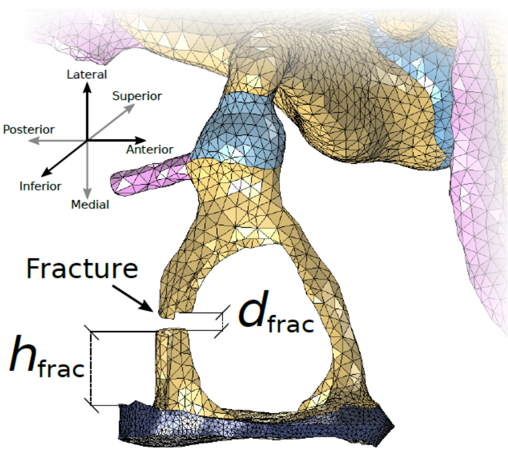
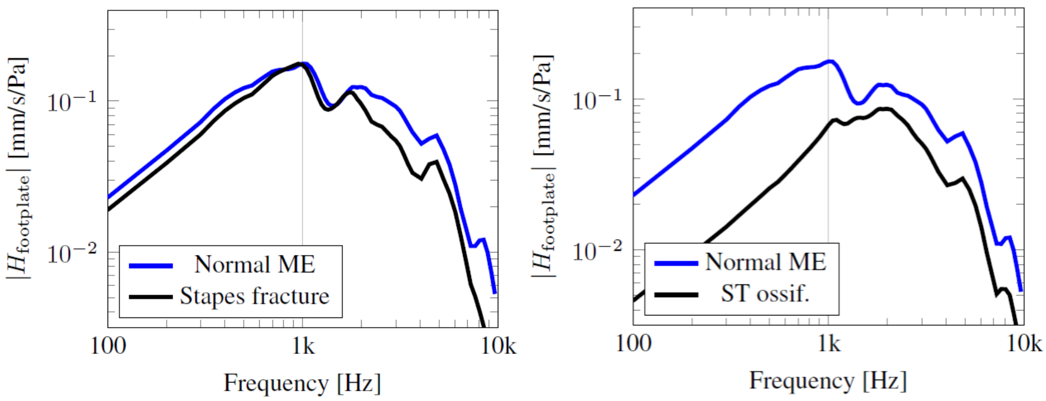


Figure 3: Model of fracture at posterior crus of the stapes with d_{frac} equal to 0.2 [mm] and h_{frac} to 1 [mm].

4. RESULTS AND DISCUSSIONS

Figure 4 shows the numerical stapes velocity transfer function $h_{footplate}$ obtained from FE model of the middle ear under normal condition as well as under pathological conditions. Figure 4(a) compares $h_{footplate}$ of the middle ear with a fracture at posterior crus of the stapes, as shown at Figure 3, to $h_{footplate}$ from normal middle ear model. It can be seen that the sound transmission is decreased mainly above 2 [kHz], being greater at 8 [kHz] (note that *y*-axis is in log scale). This result agrees with experimental hearing loss audiograms shown at Figure 1(a), which shows a greater conductinve hearing loss at 8 [kHz] frequency band. On the other hand, for the ST ossification, in both cases shown at Figure 1(b), conductive hearing losses are higher in low frequencies, mainly below 2 [kHz], and numerical result goes in this direction. Figure 4(b) compares $h_{footplate}$ from normal and ST ossification FE models and results show that the ossification of the tendon causes a great reduction of the sound transmission at low frequencies, mainly below 1 [kHz].



(a) (b)

Figure 4: Results of $H_{footplate}$ of normal middle ear (ME) and (a) Stapes fracture and (b) ST ossification.

For a better understanding of results presented at Figure 4, Total displacement *u* of the stapes and its footplate is used to. Total displacement is defined as

$$u = \sqrt{u_x^2 + u_y^2 + u_z^2},$$

being u_x, u_y and u_z the magnitude of velocity at *x*, *y* and *z* cartesian coordinates. Firstly, Figure 5 shows Total displacement *u* of stapes and its footplate at 125 [Hz] (low frequency) and 8 [kHz] (high frequency) under normal, ST ossification and Stapes fracture condition. At 125 [Hz], ST ossification showed a great and Stapes fracture showed a low reduction of sound transmission $H_{footplate}$. In healthy case, the stapes presents the \piston-like" movement, since its posterior and anterior cruses as well as all footplate surface move with the same magnitude of total displacement u. The same is true for the ST ossification case, but the magnitude is quite minor compared to the healthy case. On the other hand, in Stapes fracture case, the anterior crus (non-fractured cruse) presents a high magnitude of total displacement u. However, the magnitude of total displacement u over the footplate surface is not uniform, being greater in the posterior side. In other way, at 8 [kHz] both healthy and ST ossification cases show a resembling behavior comparing one each other (see Figures 5 (d) and (e)). On the other hand, Stapes fracture case shows a rather different behavior at 8 [Hz] when compared to its behavior at 125 [Hz] and 1 [kHz]. At 8 [Hz], the magnitude of total displacement of anterior (non-fracture) crus is quite lower the fracture one, as seen in Figure 5 (f). Consequently, the stapes footplate has a low displacement since the anterior crus could not transmit the vibration. Therefore, the fracture works as a "mechanical ground" at this frequency, filtering the displacement.

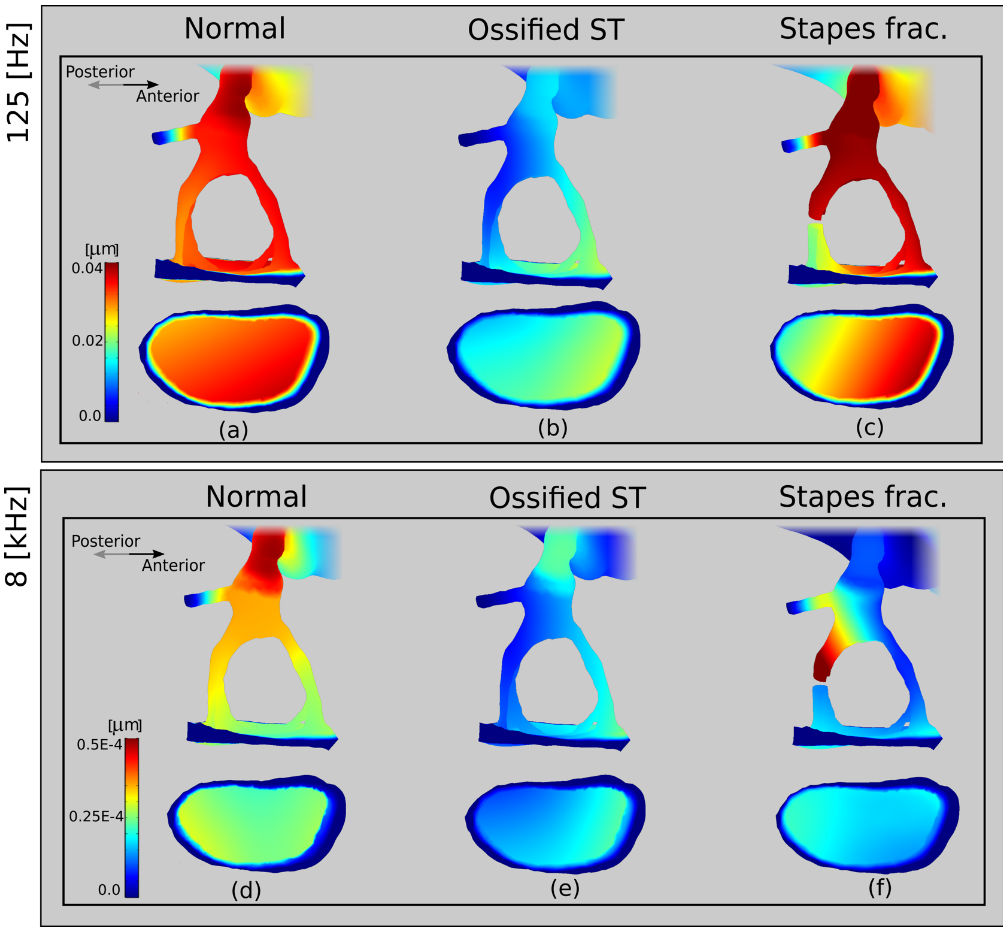


Figure 5: Total displacement u of the stapes (inferior view) and its footplate (medial view) under normal and pathological conditions. Upper panel shows the response at 125 [H] and lower panel shows the response at 8 [kHz]

5. CONCLUSIONS AND FURTHER INVESTIGATIONS

In this work a Finite Element model of the human middle ear was used in order to understand the vibroacoustical behavior of the middle ear under pathological conditions. The work aimed to analyze specifically two stapedial disorders: Stapes fracture and Stapedial tendon ossification. Either Stapes fracture and ST ossification were represented in our FE model separately found results were assessed by means frequency response $h_{footplate}$ and Total displacement u.

Firstly, it could be observed through the frequency response $h_{footplate}$ that the Stapes fracture affects the sound transmission over the middle ear in frequencies above 2 [kHz], mainly at 8 [kHz]. On the other hand, for ST ossification, sound transmission is great affected in low frequencies, mainly below 1 [kHz]. Those two results were observed with agreement when compared to conductive hearing losses from literature. In addition, Total displacement shows that Stapes fracture cause a non-uniform displacement of stapes footplate in 125 [Hz] and "filters" the displacement at 8 [kHz], while the ossificated tendon brakes the stapes in both frequencies.

As further investigations, restorative procedures are going to be analyzed through the FE modeling in order to understand how a restored middle ear works compared to a normal middle ear. For ST ossification the disruption of the tendon is reported in literature as a procedure to restore the stapes mobility (Grant and Grant, 1991). In other way, ionomer cement was reported as method to fix the stapes crus in Stapes fracture case (Aussedat *et al.*, 2017). Therefore, these two restorative methods are able to be evaluated through the FE model of the human middle ear.

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