Journal of Computation and Artificial Intelligence in Mechanics and Biomechanics ISSN 2184-8971
Volume 1, Issue 3, Page 64-70, 2021

Cupula response to otoconia debris in the semicircular canal

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Abstract

The vertigo symptoms are commonly related with inner ear diseases and it affects 20%-30% of the world population, and its prevalence increases with age. In this work, a three-dimensional computational model of the semicircular canal of the vestibular system, containing the fluids which promote the body balance, was used. The smoothed-particle hydrodynamics method was the computational process used to simulate the fluid behaviour, in which the elements are represented by particles and have constant mass. The other vestibular components were discretized using the finite element method. The movement performed to endolymph/cupula interaction analysis was reproduced in the simulation through the acquisition of the displacement field based on image analysis. The results obtained with the frames of the video recorded during the process is the appropriate method to simulate the real moves, due to the analysis of the region of interest located near the inner ear. The data obtained from the video acquisition were the input in the simulation with the semicircular model. The principal stress cupular response allowed to understand the interaction of the vestibular structures during a vertigo episode, and the influence of the otoconia in the cupula displacement. This model is the first step to improve the vestibular rehabilitation and the quality of life of patients suffering from vertigo.

***DOI**: 10.5281/zenodo.5710398*

Article Info

Keywords
Finite element method
Meshless methods
Biomechanics
Inner Ear
Vestibular System

Article History
Received: 22/01/2021
Revised: 26/03/2021
Accepted: 11/05/2021

1. Introduction

The main sensory component of the vestibular system is the cupula, located in the semicircular canal (SCC). This structure combined with the macula in the vestibule, comprise the human balance system, which is fulfilled by a fluid called endolymph. The vestibular system, placed in the inner ear, coordinate the gait and body balance function, associated with visual and proprioceptive systems. The vestibular system sends signals primarily to the neural structures that control eye movements, and to the muscles that contributes to keep upright position. Our movements consist of rotations and translations, which are processed in cupula and macula respectively [1]. The macula is a gel layer membrane that contains calcium carbonate crystals called otoconia and have substantially more mass than the cupula. The mass of the otolithic membrane causes the maculae to be sensitive to gravity and linear acceleration. When the otoconia debris is detached from the macula and lost in the SCC, it will influence the endolymph flow and consequently the cupula oscillatory movements will change. This will be translated in an electrical signal distinct from the one that occurs when just the endolymph influences the cupula movement, which will lead do vertigo. According to the body movement performed, a specific electrical signal is expected, however the otoconia in the SCC will change this information and it will not pair with the muscle signal, which will lead to mismatch information in the brain, translating in a vertigo episode. It will lead to a perception of spinning motion, an impression of displacement of the environment to the individual or an intensive sensation of rotation inside the head [2]. The otoconia influence in cupula displacement is not fully understood, which combined with the incapacitate condition of a vertiginous syndrome, turn this an issue of utmost importance regarding a biomechanics point of view.

There are several disorders affecting the vestibular system, most of them lead to vertiginous syndrome, which is the most common symptom in older people. Since vertigo episodes lead to a false sense of rotation, it is important to avoid that kind of symptoms, which in severe cases could cause a fall [3], [4]. Falls are the second leading cause of accidental or unintentional injury deaths worldwide, according to World Health Organization [5]. The vestibular system research

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could be a partner in prevention strategies development to reduce or avoid the risk of fall. The main treatment applied in the vertigo symptoms caused by otoconia in the SCC is the vestibular rehabilitation procedure, which consists in a set of personalized programed exercises, known as the otoconia repositioning manoeuvres [6]. After the diagnosis, where the affected canal is defined, the suitable manoeuvre is selected. The procedure integrated few evolutions since the manoeuvres creation during the 80's [7], [8]. Some rehabilitation protocols include limitations of movements, until some days after the procedure, which causes anxiety to several patients [9]. Furthermore, the vestibular rehabilitation fails in a certain amount of cases.

The present work goes further than others existing in the literature on obtain a personalized movement of the manoeuvres performed and used it combined with a computational model. This allow to study the cupular movement with less costs compared to other methods (as animal models [10], [11]) as a first step towards a personalized medicine tool, as we could evaluate which movement achieve faster results in the patient, restoring the otoconia back to the vestibule. The aim of the present work is to simulate and analyse the influence of lost otoconia in the cupula activity using computational models, with the last goal of improve quality of life of patients suffering from vertigo, through improved rehabilitation procedures.

2. Methodology

2.1. Geometrical model and properties

The 3D model of the SCC was developed with finite element method (FEM) and composed of three main parts (Fig. 1); a small shell ring that represents one SCC, particles that represent the endolymph fluid inside (simulated with smoothed particle hydrodynamics (SPH)) and the cupula. A mesh with 4478 elements was used to simulate the endolymph as a convergence analysis was performed in the previous SCC model [12]. The model represents the vestibular membrane of the SCC and it is defined as rigid body. In table 1, can be found the properties of the model, as described in the literature for the components of the vestibular system. The model dimensions were defined according the human vestibular system. An otoconia particle is also modelled and included in the SCC, sized 0.15 mm.

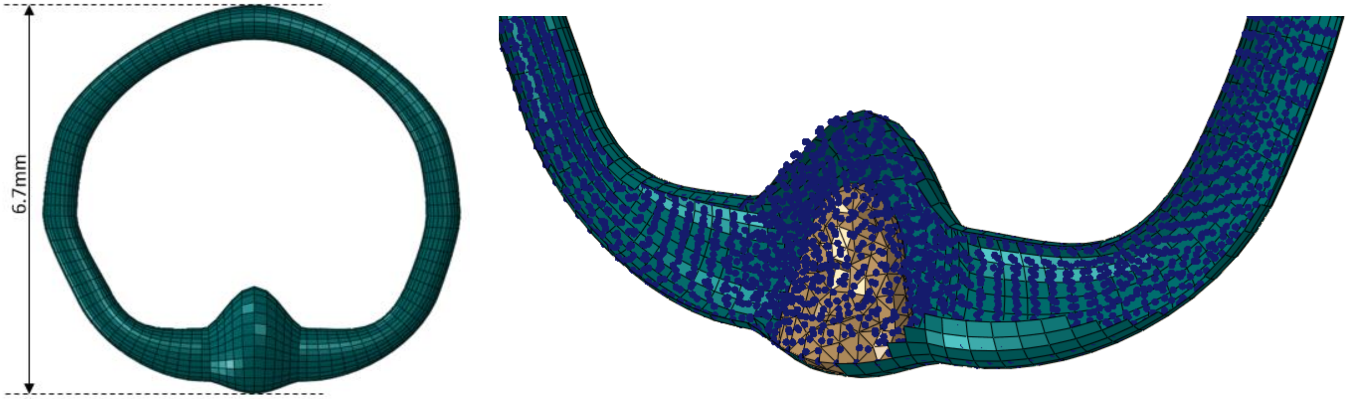


Fig.1 - Semicircular canal with endolymph particles (blue) and the cupula (orange).

Table 1: Properties used in the model [13].

	Young's Modulus (Pa)	Poisson's ratio	Density (kg/m3)	Viscosity (Pa.s)	Element type
Fluid	-	-	1.0x10^{-3}	4.8x10^{-3}	PC3D
Cupula	5.0	0.49	1.0x10^{-3}		C3D4
Membrane	13.7	0.3	1.85x10^{6}	-	S4R
Otoconia	6.6	0.45	3.0x10^{-9}		C3D4

2.2. Numerical method and boundary conditions

FEM is one of the most common discrete numerical tool used to solve complex problems, such as domains with irregular geometries or structures built with materials showing a non-linear behaviour, which are common features in biological systems such as the vestibular system. This method is widely used in some scientific fields, including several biological researches to reproduce human systems, due to its great flexibility and efficiency, since cellular level [14] to organs [15] or fully body models [16]. Combined with a constitutive equation, FEM allows the analysis of displacements, stresses and strains, among other measurements [17]. Achieve reliable results without use animal's models in the research performed is another advantage of FEM models.

The SPH method used to simulate the endolymph fluid is a meshless method that works by dividing a continuous field into a set of discrete sample points, with a defined spatial distance, over which their properties are "smoothed" by a kernel function. This approximation is based on the following two steps: the kernel approximation and the particle approximation [18]. The result of the first step is the following quantity function:

$$f(x) = \int_{N} f(x')W(x - x', h)dx' \tag{1}$$

Where x is any point in the support domain (N), and W(x-x',h) is a smoothing kernel function. The influence area of the smoothing function W(x-x',h) is defined by the smoothing length (h), which can be fixed in space and time. The SPH potential was obtaining by assigning to each particle its own smoothing length (variation with time), which can lead to an automatic adaptation of the simulation resolution depending on the domain conditions [18]. W(x) and f(x) as demonstrated below lead to equation 1. The three dimensional position vector x, is the root of integral representation of a function used in SPH:

$$f(x) = \int_{N} f(x')\delta(x - x')dx' \tag{2}$$

Where $\delta(x - x')$ represents the Dirac delta function given by

$$\delta(x - x') = \begin{cases} 1 & x = x' \\ 0 & x \neq x' \end{cases} \tag{3}$$

If the delta function of equation 3 is replaced in the equation 2 by the smoothing function $W(x - x', h)$, it is possible to obtain the equation 1. The particle approximation plays an important role within the SPH method. The mass of a particle is defined by the relation of density and volume ($m = V\rho$). Thus, the approximation function for a particle i can be represented by the following equation, being the infinitesimal volume dx' in the above equations replaced by the finite volume of the particle j. Where the ρ_j in the density of each particle in the domain N and m_j is the mass of each particle.

$$f(x_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j)\, W(x_i)\, W(x_i - x_j, h) \tag{4}$$

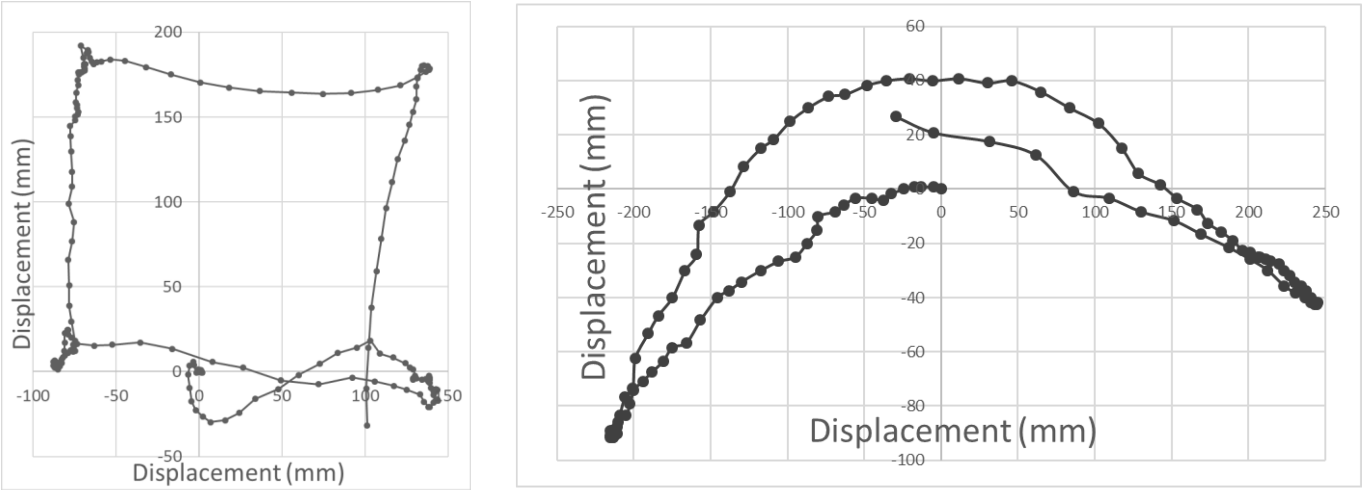
The boundary conditions imposed in the model include the general contact between the fluid, the membrane and the cupula. The otoconia contact with all the structures is also defined. The gravitational force is imposed to act as a real environment, and finally the angular movement to reproduce the head movement detailed in next sub-section.

The software used to build the model of the vestibular system with finite elements is ABAQUS [19]. This software is one of the most well-known and robust computational frameworks developed for finite element analysis, mainly used for solid models but also successfully used to study biological models [20], [21].

2.3. Video acquisition of the manoeuvres

The movement performed by the audiologist expert during the rehabilitation process will be numerically obtained through video image acquisition. The data retrieved from the video frames, recorded during the therapy, will be used to identify and define analytically the spatial position along time of the interest region located near the inner ear.

A small blue object placed over the ear, in this case a blue bottle cap, was used to trace the head displacement in the sagittal plan by video acquisition. Each point in Fig. 2 represent a step along time during the movement performed. The imposed movements in the SCC model are represented in Fig. 2. The Fig 2(a) corresponds to a benchmark square shape example of the method developed for the present work. The Fig. 2(b) was obtained when the blue bottle cap was placed in the outer ear, and a flexion extension neck move was performed. The algorithm was able to choose the bluish pixels of the video, as it selects 30 frames per second of the video to identify the coordinates in the plane of the bluish pixel (by a RGB analysis) and save all the data sequentially to trace the displacement of the object in the sagittal plan, which was used as an input in the computational model of the SCC. There are two limitations in the present method, one is that the physician should guarantee that there isn't any other blue area in the frames captured in order to not bias the result and the other is the inability to obtain three-dimensional data.



(a) (b)

Fig.2 - Object displacement in sagittal plane obtained with the frames of video acquisition. (a) benchmark, square shape, (b) flexion-extension neck movement.

The two axis correspond to the axial and sagittal planes. The first displacement obtained (Fig. 2(a)) was used in the SCC without otoconia, to notice the fluid flow inside the canal and also the cupula endolymph interaction. The displacement corresponding to a human physiologic motion (Fig. 2(b)) was simulated with the otoconia inside the canal. The results obtained inside the canal, the fluid flow and the otoconia path are shown in the next section.

3. Results

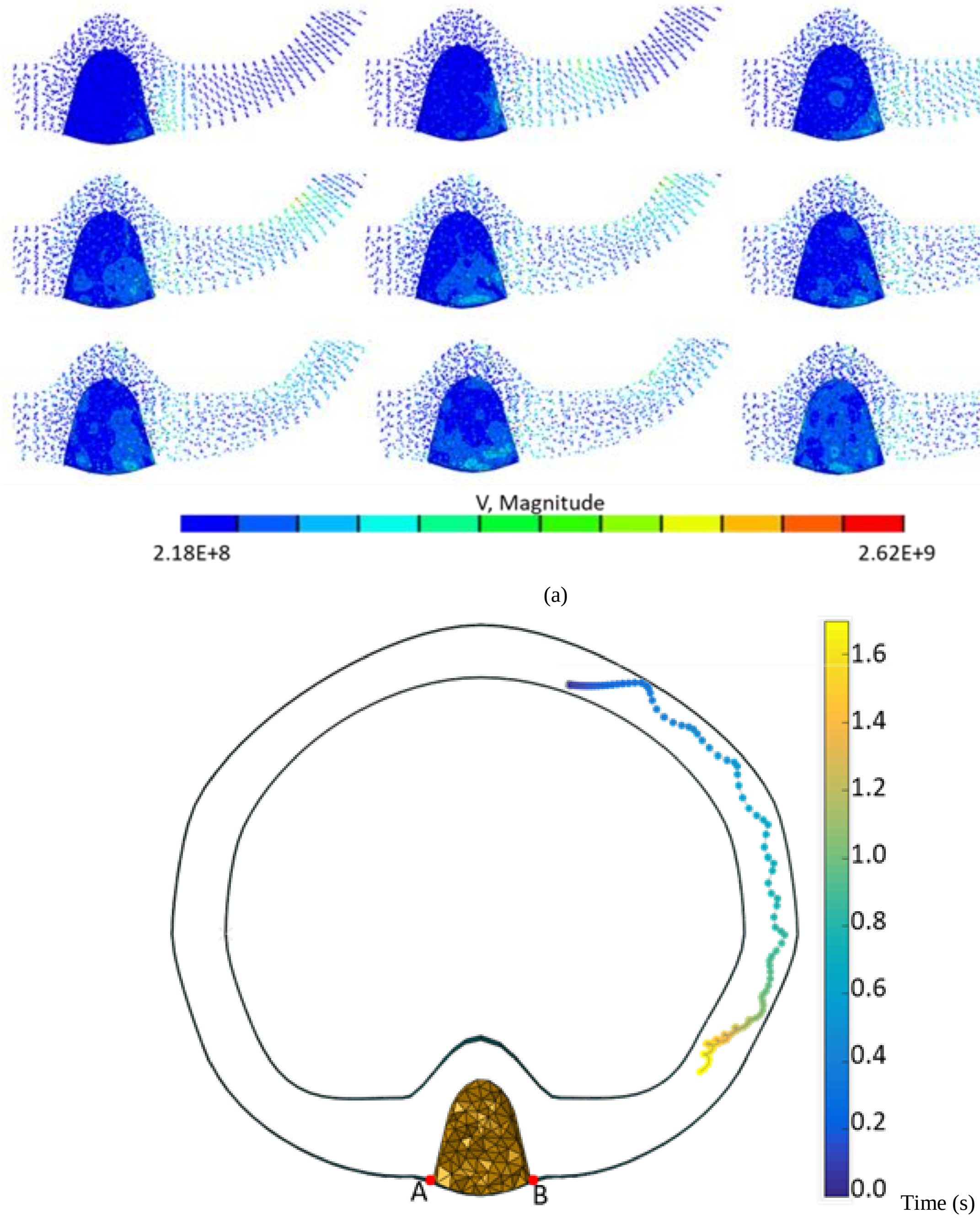
The displacement obtained in the two movements was used as an input in the model of the SCC in two distinct simulations. The square shape movement (Fig 2(a)) was imposed as a boundary condition in the SCC with the cupula and fluid, while the flexion extension neck movement (Fig 2(b)) pretend to simulate a realistic condition with an otoconia inside the canal.

The interaction of the fluid particles with the cupula in the square shape simulation was obtained as expected, and the fluid flow along time was also perceived as could be analysed in Fig.3(a). The results obtained in this benchmark example intends to be a qualitative analysis of the endolymph flow inside the canal and the cupula/fluid interaction under an imposed movement. Fig. 3(a) shows the velocity (magnitude) of the fluid near da cupula during the first horizontal 150 mm section of Fig 2(a), where it is possible to observe an increase in the fluid velocity in the first five steps and then the fluid velocity decline as a change in the direction of the movement occurs. The cupula velocity also increased when the fluid interacts with it as consequence of the experimental displacement input as expected.

In the second simulation, using the displacement of Fig 2(b) as an input, the otoconia pathway inside the canal was obtained and presented in Fig. 3(b). The colour bar legend represents the path evolution along time, the bluish pixel is the initial location of the otoconia at the beginning of the simulation and the yellowish is the final location after the imposed displacement representing the flexion extension neck movement.

Under these results, placing a small blue object near the patient's ear during the manoeuvres will allow to obtain the real movement performed during rehabilitation. When applied to this model, it will allow analysing the interaction of the SCC components. This is an effective and effortless way to obtain the movement performed without disturb the clinical practice. This outcome will improve the rehabilitation since a personalized set of exercises could be prescribed and adapted at each session.

The movement obtained will be applied to this model, it will allow to analyse the interaction of the SCC components, mainly the otoconia path inside the canal. To analyse the cupula behaviour during the flexion extension movement with an otoconia inside the canal, the maximum stress in two nodes in the cupula was obtained (Fig. 4). The nodes A and B where the stress data were obtained are detailed in Fig. 3(b). The max principal stress (MPa) shown in Fig. 4 corresponds to the node A (red) and node B (blue). The stress result obtained in the two nodes shows the cupula oscillation along the simulation with an amplitude increase in the stress values as the otoconia is closer to the cupula, which proves the influence of the otoconia in the cupula signal transduction. In order to support this argument, a conversion from mechanical energy to electrical energy, as an electrical impulse, should be performed, with the purpose of accurately evaluate the difference between both cases, since it is the brain's input signal regarding the body balance position that triggers dizziness symptoms.



(a)

(b)

Fig.3 – (a) Fluid flow (velocity) evolution with the square shape input displacement along time. (b) Otoconia pathway inside the canal along time with the flexion-extension neck movement.

4. Discussion

The model used is the first step to the creation of a complex finite element model of the vestibular system, with all the components. The final model will be built using images from Magnetic Resonance Imaging (MRI), this will help to obtain a more realistic model, which allow to get better results. The results obtained with the frames of the video recorded during the process will be the most appropriate method to simulate the real moves, due to the analysis of the region of interest located near the inner ear. The displacement of the particles inside the shell ring that represent one SCC is similar to the expected and follows the ring moves, as the experimental results obtained in controlled environment of the work of Obrist et al [22], which study a canalithiasis condition as the present work. So this method seems appropriated to simulate the rehabilitation manoeuvres. The results will allow to understand the behaviour of the vestibular structures during the rehabilitation process. Regarding the numerical methods, the SPH fluid particle simulation seems to be the most suitable method for this case, apart from the relevance of explore this methodology combined with FEM.

Obtaining the electrical signals from the mechanical stimulus obtained in FEM simulations could open a new research branch to develop new technologies to be applied in vestibular implants. The computational models allow an infinite hypothesis evaluation without using animal models.

After discovering the right cause of the vertigo in specific individual person it is important to start as soon as possible the rehabilitation process. Although rehabilitation process can be influenced by external factors, which can lead to some less effective results, this method is the most used currently. Understand better the biomechanics of the vestibular system is the first stage to could prepare different kind of simulations with the model. The development of one tool that can help audiology experts in the treatments that they use daily is an important step in that scientific field and can contribute to the fast evolution of the patient.

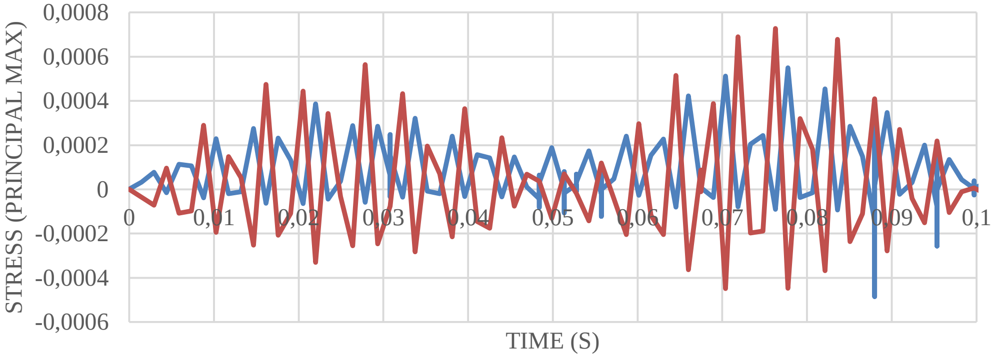


Fig.4 – Maximum Principal Stress of the two nodes in the cupula.

Acknowledgements and Funding

The authors acknowledge the funding by “Ministério da Ciência, Tecnologia e Ensino Superior —Fundação para a Ciência e a Tecnologia , Portugal and POCH —Programa Operacional Capital Humano, comparticipado pelo Fundo Social Europeu e por fundos nacionais do MCTES” under research grants SFRH/BD/108292/2015 and by project funding MIT- EXPL/ISF/0084/2017. Additionally, the authors gratefully acknowledge the funding of Project NORTE-01-0145-FEDER-000022 —SciTech —Science and Technology for Competitive and Sustainable Industries, cofinanced by Programa Operacional Regional do Norte (NORTE2020), through Fundo Europeu de Desenvolvimento Regional (FEDER).

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