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Biomechanical study of the vestibular system of the inner ear using a numerical method

Carla F.Santos[a], Jorge Belinha[a], Fernanda Gentil[b], Marco Parente[a], Bruno Areias[a], Renato Natal Jorge[a,c,] *

[a]*INEGI – Institute of Mechancial Engineering and Industrial Management, Porto, Portugal*
[b]*Escola Superior de Tecnologia de Saúde do Porto, Porto, Portugal*
[c]*FEUP-Faculty of Engineering of University of Porto, Porto, Portugal*

Abstract

The inner ear has two main parts, the cochlea, dedicated to hearing, and the vestibular system, dedicated to balance. Dizziness and vertigo are the main symptoms related to vestibular disorders, which commonly affects older people. In order to eliminate these symptoms a vestibular rehabilitation is performed; this consists in a range of movements of the head, known as maneuvers, performed by a clinical professional. This procedure does not always work as expected. The aim of this work is to contribute to a better understanding on how the vestibular system works. This knowledge will help in the development of new techniques that will facilitate a more efficient rehabilitation. In order to achieve that goal, a three-dimensional numerical model of the vestibular system, containing the fluids which promote the body balance, was constructed. The vestibular components will be discretized using the finite element method and the fluid flow will be analyzed using the Smoothed Particle Hydrodynamics

The results obtained with the numerical model of the semicircular canal built to study the rehabilitation process are presented and compared with other authors. The solution achieved is similar with literature.

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Keywords: Inner ear; vestibular system, numerical methods

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* Corresponding author:
E-mail address: rnatal@fe.up.pt

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1. Introduction

The vestibular system is located in the posterior region of the inner ear and is a key to our sense of balance and movement. Any changes in this system can cause symptoms such as dizziness, blurred vision, imbalance and nausea, which are vertiginous syndrome indicators. Vertigo is reported as one of the most common symptoms in the world. It is considered the third most frequent complaint in medicine, transmitting a sense of inadequacy and insecurity[1].

1.1. Vestibular System

The vestibular sensory organs are located in the petrous part of the temporal bone, connected to the cochlea, and consists of two labyrinths, the membranous labyrinth and the bony labyrinth. The membranous labyrinth is lodged within the bony labyrinth and they have the same general shape. In order to support the membranous labyrinth there is perilymphatic fluid and connective tissue between both labyrinths. The membranous labyrinth is filled with endolymphatic fluid (resembles intracellular fluid), while the bony labyrinth consists of three semicircular canals (SCCs), the cochlea, and a central chamber called the vestibule. In Fig. 1 it is possible to see five sensory organs of that labyrinth: the membranous portions of the three SCCs (called ampullas) and the two otolith organs, the utricle and saccule[2].

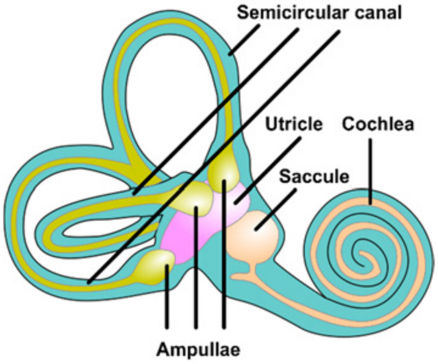

Fig. 1. Vestibular system.

The fluid structure interaction simulation of the endolymph and cupula during head rotation allows the measure of the fluid interactions between the three ducts and the displacement of the cupula during the move. This model could be considered useful to understand the physiological and mechanical aspects of semicircular canal, and it could be described as a band-pass filter relating the displacement of the cupula to the angular velocity of the head[3]. In Fig. 2 it is possible to observe the detailed structure of the hair cells inside the ampulla of the SCC.

The semicircular canals indicate rotational movements, and the otoliths, located inside the utricle and the saccule, indicate linear accelerations.

The mechanical properties of the otolith particles are important to understand and interpret vestibular neurophysiological behavior. The development of a numerical model will permit to calibrate those properties and also will allow to investigate the orientation and shape of the otolith maculae. Another layer of this structure is the specialized hair cells, contained in the gel layer, which are biological sensors that convert displacement, due to head motion, into neural firing.

The hair cells of the saccule and utricle register forces related to linear acceleration. These cells are located on the medial wall of the saccule (related to horizontal movements) and the floor of the utricle (associated to vertical movements)[4].

The vestibular system sends signals primarily to the neural structures that control eye movements and to the muscles that contribute to keep upright position. The projections to the former provide the anatomical basis of the vestibule-ocular reflex (VOR), which is required for clear vision, and the projections to the muscles that control our posture are necessary to keep us standing[2]. Body balance results from a complex interaction between the vestibular system, eyes and gait.

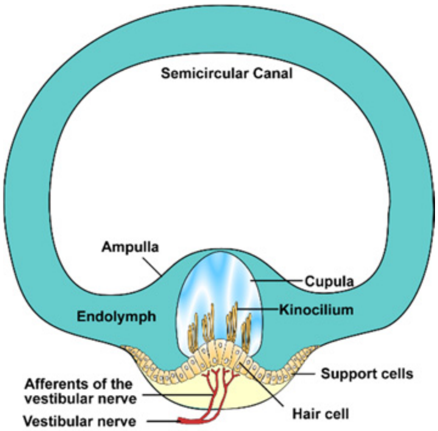

Fig. 2. Semicircular canal.

A balance disorder has recurrent episodes with vertigo and other symptoms like hearing loss[3]. The patients who suffer from dizziness are not aware of the environment and are very sensitive to small movements, which leads to a sensation of rotation inside the head[5]. The main concern in these episodes is to avoid falls that can lead to more severe problems. These symptoms are often related with nausea and can cause difficulties to stand or to walk if it is associated with central lesions[6].

Vertigo can be classified into peripheral or central depending on the location of the dysfunction of the vestibular pathway, although it can also be caused by other factors[7], the most common cause being benign paroxysmal positional vertigo (BPPV)[6].

To diminish the symptoms, drugs that suppress the activity of the inner ear are frequently used. In severe cases, manoeuvres in a specific forming part of a vestibular rehabilitation program are also performed.

1.2. Vestibular Rehabilitation

The main therapy used when the patients show BPPV symptoms is vestibular rehabilitation. The goal of this kind of therapy is to diminish the symptoms and attenuate the pain. Recovering the balance will allow the patients to maintain a daily routine[8,9].

The first developments in vestibular rehabilitation area were made during 1940 by Cawthorne-Cooksey, which comprised a set of simple and progressive exercises of head rotation[10]. The aim of the maneuvers is to replace the otoconia in the vestibule, which are lost in the SCC inducing vertigo by a false sensation of movement[11].

Nowadays, there are detailed maneuvers for each canal. There is evidence that they improve nystagmus, control postural dizziness and all other vertigo symptoms, making it the definitive treatment for most patients[12,13]. The exercises choice is guided by the patient symptoms and by the related physiopathological mechanisms.

The results of vestibular rehabilitation can be influenced by factors such as age, functional integrity of the central nervous system, individual disposition and time available to perform the exercises[6]. Despite the effectiveness of this process there are some reports of a non-successful rehabilitation process[14], which could be justified by the used empiric process without any real control of what happens inside the canal.

More recently, techniques have been developed to address specific problems with gaze, postural instability, motion sensitivity and vertigo in patients with a variety of different vestibular disorders such as BPPV, Meniere's disease, brain injury, and others.

2. Methods

Since vertigo, caused by dysfunctions in the vestibular system, has such a detrimental role in a person's routine, in this work the aim is to define new ways of helping to treat it. The membranous labyrinth of the vestibular system is filled with fluid. Simulating this inner fluid is a challenge and is of extreme interest for the subject. For this, we propose to simulate this fluid using the smooth particle hydrodynamics (SPH) method, which is part of a 3D model based on the finite element method (FEM) (simulated using ABAQUS software) built to simulate and improve vestibular rehabilitation [15].

2.1. Numerical model

The developed numerical model is composed of two main components, the exterior part of the membrane, represented as a ring shell with the ampulla (Fig.3) and the fluid inside represented by the white particles in the same figure. The measures used in the SCC model were based in the work of O.W. Henson *et al.*[16].

The properties used in the model were found in the literature[3]. For the membrane values of 5.0 Pa for Young's Modulus and 0.48 for Poisson's ratio were considered. The endolymph properties were defined as having a density of 1.0×10^{-3} kg/m^3 and a viscosity of 4.8×10^{-3} Pa.s.

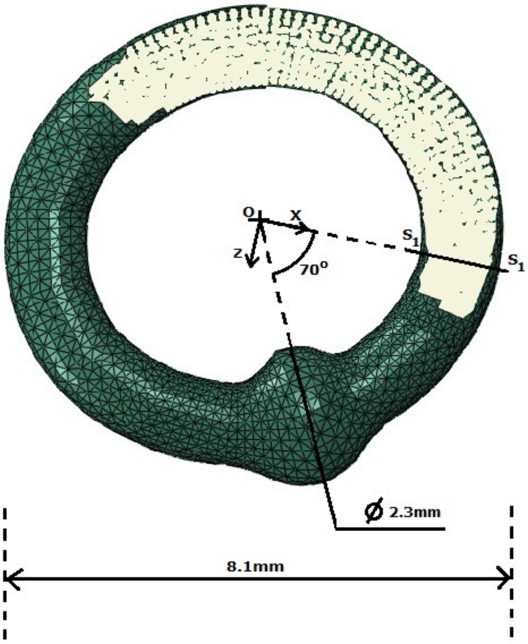

Fig. 3. Numerical model of the semicircular canal.

The boundary condition imposed in the model, besides the contact defined between the parts, was an angular velocity of $\pi/2$ rad/s in point O marked in Fig.3.

Two different angular velocity functions (step 1 and step 2 – see Fig.4) were used with the purpose of analyzing the SCC model and compare it with other authors. The steps chosen were used before by P. Selva et al.[17] and Cai-qin, WU et al.[3].

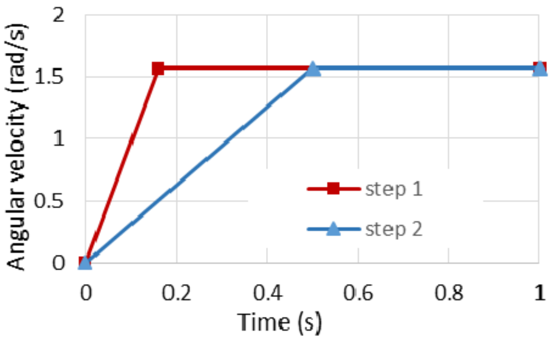

Fig. 4. Angular velocity applied to the model.

In order to validate the model, three discretizations of the endolymph, with a different number of particles, were tested: 1790 particles (mesh M1); 7410 particles (mesh M2); and 13637 particles (mesh M3).

The segment analysed in the validation was the S1 section represented in Fig.3.

In order to compare the results of the performed different simulations the discharge variable was used, which is defined as the volume rate of fluid flow transported through a given cross-sectional area.

2.2. Smoothed Particle Hydrodynamics

SPH is a computational method used for simulating fluid flows[18]. The SPH method works by dividing a continuous field into a set of discrete sample points, called particles. These particles have a spatial distance, over which their properties are "smoothed" by a kernel function. The particles are identified with some characteristics like mass, position, velocity, etc., but can also carry estimated physical properties depending of the problem, like mass-density, temperature and pressure.

These variables are in the form of partial differential equations, but it is not always possible to obtain an analytical solution for those problems. In order to provide a better result, an approximation (kernel function) is applied to produce a set of ordinary differential equations. The kernel function helps to ensure the stability of the numerical solution[15].

3. Results

The simulations of the rotational velocity imposed in the 3D model of the SCC were performed and the results were compared with the works of Selva, P.[17] and Caiqin, WU.[3], which used the same boundary conditions in similar models of the SCC. The results obtained in their work can be found in Table 1.

Table 1. Results in the literature used to validation of the model.

Selva , P. (2010)		Caiqin, WU. (2011)	
Time (s)	Discharge (m^3/s)	Time (s)	Discharge (m^3/s)
0.010	2.011E-12	0.004	1.414E-13
0.025	4.825E-12	0.008	7.069E-13
0.030	9.651E-12	0.012	2.827E-12
0.040	1.850E-11	0.014	4.948E-12
0.050	2.654E-11	0.016	7.067E-12

The results of the discharge obtained in the simulations of the three different meshes with the two different time steps (step 1 and step 2) are presented in Table 2, where it is possible to observe that the simulations performed with the model of the SCC with both angular velocity steps and with all the three meshes (M1, M2, and M3) shows similar results. The results obtained are more similar to the range values of Selva, P.[17].

Table 2. Comparison of the discharge obtained with all the meshes in both steps.

Step 1				Step 2			
Time (s)	Discharge (m^3/s)			Time (s)	Discharge (m^3/s)		
	M1	M2	M3		M1	M2	M3
0.011	1.986E-12	1.524E-12	3.390E-13	0.010	1.924E-12	1.432E-12	3.079E-14
0.016	2.201E-12	1.863E-12	1.090E-12	0.015	1.909E-12	1.536E-12	4.156E-13
0.021	3.233E-12	2.432E-12	1.170E-12	0.020	2.124E-12	1.627E-12	4.618E-13
0.026	6.204E-12	5.357E-12	1.910E-12	0.025	2.171E-12	1.801E-12	6.466E-13
0.032	1.370E-11	1.179E-11	4.330E-12	0.030	2.509E-12	1.909E-12	8.467E-13
0.037	2.586E-11	2.377E-11	9.310E-12	0.045	4.002E-12	3.171E-12	1.108E-12
0.042	4.557E-11	3.110E-10	1.790E-11	0.060	9.190E-12	8.544E-12	3.895E-12

In order to understand the model behavior during the imposed rotation, it was considered the velocity of the fluid inside the canal along time.

At some instants of the simulation the maximum fluid velocity in the canal was measured and registered in both steps. This comparison is presented in the Fig.5, where it may be seen that the inner ear fluid velocity increases along time. The obtained results showed, as expected, according with the imposed steps, that the velocity of the fluid inside the canal is always lower in step 2, up until 0.5 seconds where the values of velocity are almost equal for both steps.

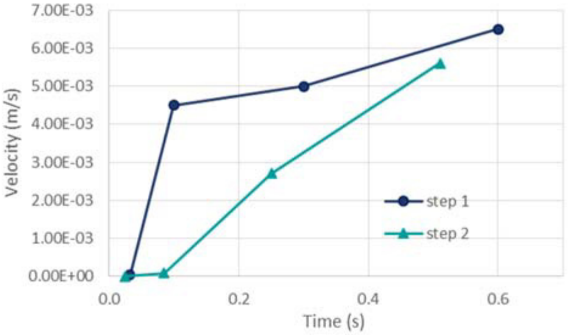

Fig. 5. Velocity (m/s) along simulation in step 1 and step 2.

Analyzing only section S1 of the model (indicated in Fig. 3), similar results were obtained. The maximum velocity of the fluid in that section along time is shown in Fig. 6 for both steps. A higher velocity, for each instant of time, is visible in step 1. At 0.1 seconds the velocity is three times higher in step 1 than step 2, as expected due to the imposed boundary conditions.

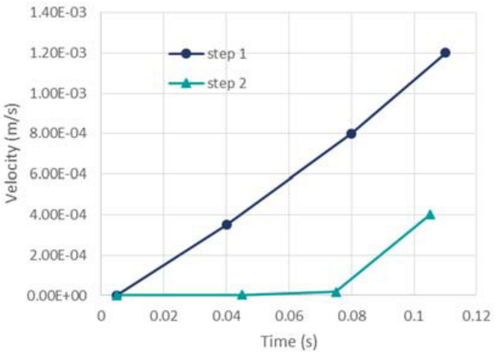

Fig. 6. Velocity (m/s) in section S_1.

Figure 7 shows the velocity profile of the fluid in the lateral section S1 at instant 0.1 seconds during the simulation of step 1 (Fig.7(a)) and step 2 (Fig.7(b)). At this instance, the two velocity profiles are almost fully developed. The fluid shows again, as expected, a higher velocity in the simulation with the step 1 for the same time instant.

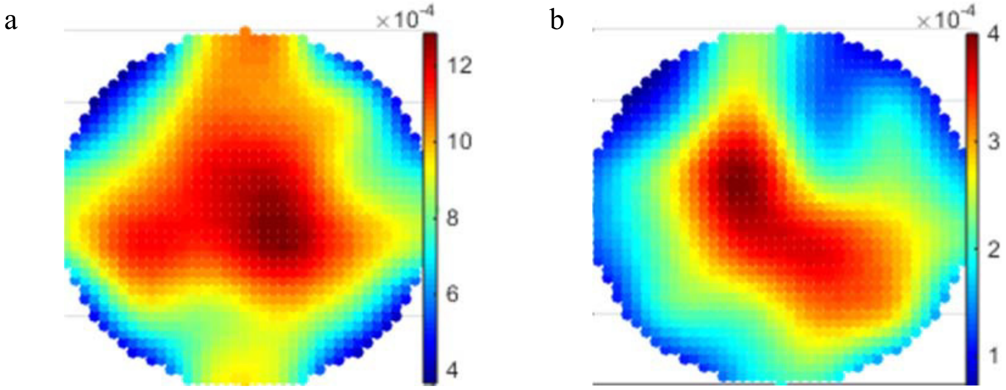

Fig. 7. Velocity profile (m/s) of the fluid at 0.1s in (a) step 1; (b) step 2.

4. Discussion and Conclusions

From the results obtained it is possible to conclude that the methods used to build and analyze the 3D numerical model of the SCC (FEM and SPH) seem to be an adequate option to develop research in this biological area.

The comparison of the results obtained with the ones presented in the literature allow to validate the proposed methodology. This reliable results will permit to use the 3D model in further studies. Another advantage of using a 3D model, is the possibility to obtain results for any point in the model at any time of the simulation.

As previously mentioned, the main aim of this work is to improve the rehabilitation process by understanding the vestibular system behavior. Once the model of the vestibular system is completed it will be possible to reproduce the maneuvers of the rehabilitation process. This will lead to understanding, in more detail, what really happens with this treatment.

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