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Biomechanical Modeling of Semicircular Canals for Fabricating a Biomimetic Vestibular System

G. Ciaravella, C. Laschi, *Member, IEEE*, P. Dario, *Fellow, IEEE*

Abstract— **This paper presents a biomechanical model of the semicircular canals of the human vestibular system and the design of a 3D biomimetic structure that mimics the biological system. Starting from anatomical and physiological data, mechanical and structural parameters have been identified and a mathematical model has been formulated, by considering the semicircular organ as a canal filled by a liquid. The mathematical and mechanical models were used to simulate the behavior of the semicircular canals under known conditions of angular velocity and acceleration along three axes. Furthermore, the membrane inside the semicircular canals was simulated to understand what the mechanical properties of the membrane are and if polymeric materials can reproduce the mechanical characteristics of the biological organ. The results obtained from the model allow to design a biomimetic organ, as a part of a biomimetic vestibular system, by following this biomechatronic approach.**

I. INTRODUCTION

IN Humans, and most animals, the vestibular system is a sensory apparatus which detects head motion and posture in order to keep balance and to stabilize gaze (by the well-known VOR, Vestibulo-Ocular Reflex) [1]. It is located in the inner ear and comprises of 5 organs, 3 semicircular canals (SCCs) and 2 otolithic organs which measure angular velocities and linear acceleration, along three axes, respectively. Its role is crucial during locomotion and posture maintenance, as well as during complex movements when the foot base is not available to stabilize the head in the space [2]. It can be said that the vestibular system creates the reference frame for the coordination of the body and the limbs [3]. A number of mathematical models describing both the transfer function of the human vestibular organs and the processing of visual and vestibular information about head motion have been proposed [4-7]. These models provide a very powerful tool for designing artificial vestibular systems [8].

In robotics, the study of artificial vestibular systems has been pursued by developing specific solutions for achieving the different functions of the biological vestibular system [9,10]. Most of them make use of inertial sensors, based on MEMS technologies, used either to keep balance or to stabilize images. Few examples exist of artificial vestibular systems with the whole functionality as the biological one, i.e. detecting angular velocities and linear accelerations along three axes [11]. Research on the development of artificial vestibular systems based on the study of the biological organs has been carried out with the aim of realizing vestibular prostheses [12,13].

The development of a biomimetic vestibular system could provide sensory signals comparable to the biological ones and then provide one artificial organ for VOR, balance and posture, to humanoids and walking robots.

The objective of the work presented here is the biomechanical modeling of human semicircular canals, as the first critical step for the design and development of biomimetic organs, and finally of a biomimetic vestibular system, for robotic heads. Biomimetism favours the implementation of neurophysiological models for VOR, balance and vestibular processing, in general, on robots.

II. METHODS AND TOOLS

A biomechatronic approach is proposed to design and develop the biomimetic artificial vestibular system. According to this approach, an important initial phase is the study and characterization of the biological model, from the anatomical, neurophysiological, biomechanical and functional points of view.

In the development of a biomimetic vestibular system, the nature of the structure and of the materials that compose the biological system represent critical issues. Preliminary studies are required to understand which is the best solution to model a structure that senses the same physical quantities in the same way and has the same behavior of the biological one; furthermore, the materials used to fabricate the sensors and components that best achieve the behavior of the biological system need to be accurately selected, as this should respect the same principles of transducing physical quantities.

The biomechanical modeling of human semicircular canals presented here considers the morphology of the organs and the composition of the biological tissues and their viscoelastic and mechanical properties. This biomechanical study is aimed at improving the quantitative knowledge on these organs, from the perspective of mimicking them in the design and fabrication of biomimetic

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Gaetano Ciaravella is PhD Student at the PhD School in Biorobotics Science and Engineering of the IMT Institute of Advanced Studies, Lucca, Italy.

Cecilia Laschi is with the ARTS (Advanced Robotics Technology and Systems) Lab of the Scuola Superiore Sant'Anna, Pisa, Italy.

Paolo Dario is with the CRIM (MicroFabrication Technology) and the ARTS Lab of the Scuola Superiore Sant'Anna, Pisa, Italy.

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ones. Specifically, this study is focused on understanding what happens during a rotation of the head and in particular on what happens to the thin membrane that separates the SCC from the cupula, with the related movement of the liquid that fills the SCC, i.e. the endolymph.

The first step consisted of a mechanical model of a curved tube filled by a liquid, drawn with a CAD tool (ProEngineer™), considering anatomical and physiological parameters. The mechanical CAD model was created to simulate the behavior of the semicircular canals under known conditions of angular velocity along three axes.

In the second step, a fluidic mathematical model was done of the inner part of the SCC, by inserting biomechanical characteristics of the fluid contained in the canals, like the density and the viscosity. In this way, it was possible to correlate the angular velocity of the SCC with the variation of pressure on the membrane and to estimate the variation of volume of liquid traveling during a rotation.

In the third step, the obtained pressure variation, coupled with the Young modulus and the thickness of the membrane, as known from literature, were used to study the behavior of the membrane with a FEM simulation (Ansys), also based on the results of the first step of CAD modeling. This step allows to identify what are the mechanical parameters of the membrane, in order to find a material that fits the biological characteristics, and to understand how the stress distributes along the radius.

Furthermore, in a fourth step, the shape and the physical characteristics have been used to fabricate a first prototype with a 3D Invision^{TM} HR printer for rapid-prototyping. The modeled SCC contains a hole along his mean radius, where a liquid like the endolymph can be introduced to fill the canal; a thin membrane can be positioned between the end of the canal and the starting contact wall of the cupula, in which the receptors are contained, in order to experimentally measure the pressures applied in response to SCC rotations.

III. THE BIOLOGICAL MODEL: THE HUMAN SEMICIRCULAR CANALS

From an anatomical view, the vestibular system is located within the inner ears, in the two vestibular labyrinths, which are mirror-symmetric structures on the two sides of the head. As mentioned, each vestibular labyrinth comprises of five receptor organs that, complemented by those of the counter-lateral ear, can measure linear acceleration and angular velocity along 3 axes. Linear accelerations, including those produced by gravity and those resulting from body motions, are detected by the otholitic organs (saccule and utricle), while angular velocities caused by rotation of the head or the body are measured by the semicircular canals [14].

The three semicircular canals are small ring-like structures; each forms two thirds of a circle with a diameter of about 6.5 mm and a luminal cross-sectional diameter of 0.4 mm. One end of each canal presents a dilatation, called ampulla, containing a sensorial epithelium, the ampullar crest (see Fig.1).

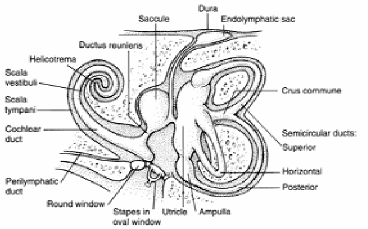

Fig 1 Details of the vestibular organs.

The upper part of each sensorial epithelium contains stereocilia and a kinocilium which are the hair cells that represent the receptor of the vestibular system: the position of the kinocilium respect to the stereocilia confers a functional polarization. The flexion of these stereocilia in the direction of the kinocilium causes a depolarization, due the increasing conductance of their membrane with a consequent generation of action potentials in function of the deflection of stereocilia and kinocilium. Fig.2 shows the depolarization mechanism. The vestibular detectors sense events associated with the results of accelerations of the head and body, sensing in a range of frequencies from few Hz to 10Hz. The semicircular canals detect angular velocities of a rotation along in the three axes The range of detection varies for angular velocities and acceleration respectively from 0.5 to 500 °/sec [15].

Each rotation of the head causes a relative motion of the endolymph in the semicircular canals with a movement of a volume of endolymph as a consequence. This relative movement of fluid creates a mechanical deflection of the membrane which transmits the pressure impulse to the liquid contained in the cupula. As a consequence of this mechanical impulse there is a deflection of both the kinocilium and stereocilia and a relative generation of a sequences of impulses. This happens in the inner part of the two SCCs but in opposite directions.

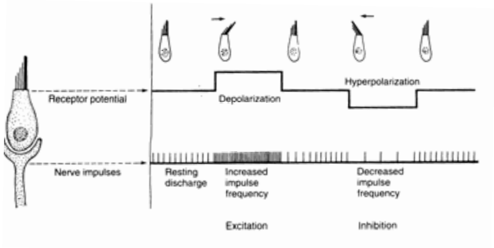

Fig 2 Description of inhibition and excitation of the hair cells contained in the cupula. The range of frequencies varies from 0.5Hz to 10Hz.

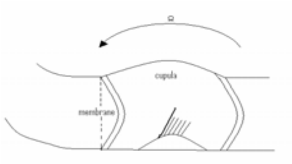

Fig 3 Deflection of the membrane caused by the fluid in canal during a rotation

IV. BIOMECHATRONIC DESIGN

A. Mechanical model

In order to model the mechanical and the dynamical behavior of the endolymph and the membrane it is possible to consider the SCC like a torus. This simplification allows to reduce physical variables as mentioned in Van Buskirk et al [17]. In this work each SCC is then modeled as a torus. The rotation angle of the SCCs is estimated in 250° [16]. Starting from this point, a CAD model with the typical dimensions of a biological system, i.e. the thickness, the two mean radii that constitute the SCC dimensions of the ducts, and the dimension of the cupula that constitute the base of the SCC has been developed (see Fig.4). All these parameters have been considered during the mechanical model formulation.

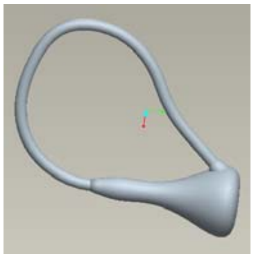

Fig 4 CAD model of a SCC. It is possible to see the anatomical shape of one SCC with anatomical size, while for the mathematical model a toroidal shape was considered.

B. Fluido-dynamical model

The three SCCs are filled with endolymph which has a density ρ and a viscosity μ considered for the model similar to the water: $\rho=1.0$ g/cm^3, $\mu=0.01$ g/cm/s. As explained, the SCCs are separated by a thin membrane from the cupula. When the head turns the liquid in the duct of the canal moves and generates a traveling volume of fluid V_c [17]. During this relative movement it is assumed that the fluid moves with a laminar profile of flow [18]. In this way, we can impose boundary conditions to determine the solution of the system in terms of pressure volume.

Imposing that there is a friction between the fluid and the walls of the duct it is possible to describe the displacement of the traveling volume V_c as a Poiseuille flow. If we consider a linear tract near the membrane it is possible not to consider the rotational component of the acceleration and in this way the fluid moves with a linear velocity v given by $\Omega_0 R$ and the volume that travels through the ducts is:

$$V_c \approx (\pi\beta^2)\Omega_0 R \tau_f \qquad (1)$$

where β is the internal radius, Ω_0 is the angular velocity, R is the external radius of the torus and τ_f is the time in which the vorticity from the walls of the duct transfers to the duct center. The traveling volume V_c causes a variation of pressure over the membrane ΔP_c, which deflects the cupular membrane, producing a mechanical response from the membrane itself. Applying the Poiseuille flow to the duct it is possible to correlate the velocity along the SCC with the variation of pressure to the membrane:

$$v(r) = \frac{\Delta P_c(\beta^2 - r^2)}{4\mu\beta R} \qquad (2)$$

where v(r) is the velocity profile in the duct and r is a general radius that varies from 0 to β.

Consequently, it is possible to correlate the traveling volume and the angular velocity modifying equation (1):

$$V_c = \frac{4\pi d^4 R\alpha}{2^4 \lambda_0^4 \nu}\Omega_0 \qquad (3)$$

where d represents the diameter of the duct, λ_0 is the first zero of the Bessel function J_0, α is a geometric factor equals to 1.3 and $\nu=\mu/\rho$.

C. FEM Analysis of the membrane.

The behavior of the biological membrane, due to its characteristics, it is comparable to a material that has an elastic component (K) and a viscoelastic one (γ). The thin membrane, after a first period of deformation, tries to restore the initial condition by imposing the equilibrium, it is possible to write:

$$-KV_c - \gamma \dot{V}_c + \Delta P_c(t) = 0 \qquad (4)$$

Assuming the behavior of the membrane as an isotropic and elastic medium and under a determined pressure, it is possible to consider a larger deflection in the central part respect to the near regions. With some characteristics of the biological material, like thickness and Young modulus [17], and the physical quantities identified, it is possible to simulate the biological membrane behavior. The simulation gives information regarding the distribution of stress in three dimensions (Fig.5). The knowledge about the mechanical characteristics allows to find a material that performs the behavior like the biological one.

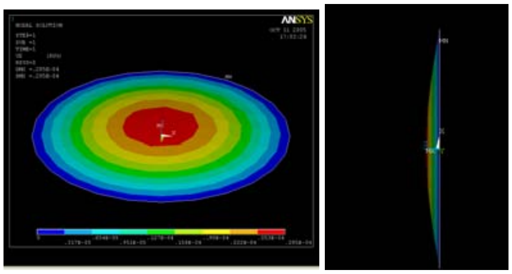

Fig 5 Deformed shape of the membrane plotted with isocurves that indicate in red where the greater stress is (left) and view of the deformed membrane where it is possible to see the directional axis in which the stress increases (right).

Thanks to this model, it is possible to simulate conditions of interest and identify the characteristics of the materials that could be used to prototype and fabricate a bio-inspired model. Moreover it is possible to extract the correlation between the stress distribution and the radius, with a known load (see Fig.6).

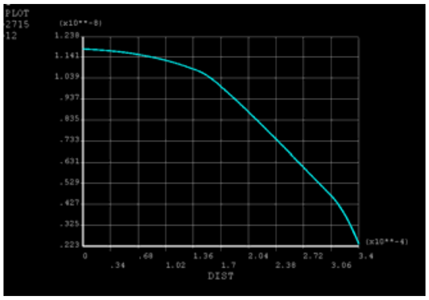

Fig 6. Behavior of thin membrane deflection in function of radius with a constant value of pressure. Along the vertical axis is the strain while along the horizontal axis is the distance from the centre of the membrane

D. The bio-inspired vestibular prototype

The anatomical and fluido-mechanical study brought to model and to fabricate a prototype that respects the biological characteristics of shape and dimensions of a natural vestibular system. Using the same CAD program, basing the dimension on the parameters cited in IV A, a model of the vestibular system was drawn (Fig.7, left) and then this model was printed by a 3D Invision^{TM} HR machine obtaining a definition and resolution of 80μm along X and Y axis and 40μm along the Z axis (Fig.7, right).

Fig 7. The vestibular system CAD model (left): the three semicircular canals are in light color and the two otholitic organs, saccule and utricle, in dark. The microfabricated vestibular system compared with a 10 eurocent coin (right).

The prototype fabricated is empty of material in the inner part of the canals, to be filled with a liquid with the same fluidic and mechanical properties as the endolymph, and there is a thin film composed by a material similar to the biological membrane that separates the semicircular canal from the cupula. A sensor will be attached to the membrane in order to characterize the actual behavior of the membrane under controlled experimental conditions, in order to design and develop the cilia-like transducing units.

V. CONCLUSION

In this paper, a model of the human semicircular canals has been presented and investigated from a mechanical and fluidic perspectives, by identifying important mechanical and fluidic parameters. This kind of investigation represents the first step of the design and development of a new type of biomimetic sensor, with the same sensing capabilities of the analogous biological system. Furthermore, an entire vestibular system has been fabricated by respecting the anatomical and physiological parameters. The data obtained from the simulation and the deep study of the mechanical characteristics of the biological system provide relevant parameters for the development of the biomimetic system. The next steps are represented by the electronic study of the transduction of the mechanical stimulus into an electric signal.

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