PhD proposal 2026-2029

Title of the project

Biomechanics of peripheral vertigo: from numerical modeling and simulation of various diseases to patient specific surrogate - BioPeriVer

Supervisors of the project

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Short accessible summary of the project

This project aims to consolidate and improve diverse (2D-slice and 3D) existing anatomical finite element models of the vestibule of the human inner ear in order to reproduce well known clinical tests, and thus confront simulation results to real world observations. Once validated, the objective is to use the renewed models to increase the knowledge of the physiology of various common pathologies such as endolymphatic hydrops and benign paroxysmal positional vertigo, as well as Meniere disease. To this end, various biomechanical models and numerical simulations are explored to lead to more relevant and accurate diagnostic and therapeutic tools through a patient specific approach.

Context of the project

Human balance in a moving environment corresponds to a state of stability of the body and the gaze. It requires the mobilization of a set of mechanisms that modulate muscle tone in order to allow postural adaptations and eye motion. In particular, the human balance system is based on two reflexes: the Vestibular Occular Reflex (VOR) and the Vestibular Spinal Reflex (VSR). Impairment of these reflexes leads up to a state of instability commonly known as vertigo or dizziness. A great variety of reasons can conduce to dizziness and vertigo, thereby inducing a wide range of treatments. Thus, to identify the fundamentals of vertigo and dizziness in order to diagnose it and to treat it properly, it is necessary to know in detail the behavior of the human balance system in normal conditions, and its dysfunction relying on pathology or trauma. Therefore, the investigation of the balance system has to be led both on its central (neurological processing of information) level, and on its peripheral (recording sensory information) areas.

Objectives and originality of the project

This project considers the entire understanding of the functioning of the main peripheral sensor of both the VOR and the VSR: the labyrinth of the inner ear, more simply called the vestibule. This sensor consists of three semicircular canals (SCC) and two cisterns: the utricle and the saccule. It is usual to admit that the semicircular canals measure the angular acceleration of the head, while the utricle and saccule measure the linear acceleration of the head. These two components of acceleration make it possible, through complex central nervous system processing of information, to subjugate the three pairs of eye muscles (per eye), so that a fixed image of a moving environment can be maintained on the retina. This signal processing chain constitutes the VOR, which thus ensures the balance of the body through stable target tracking. When this acceleration sensor is damaged, either through pathology or through trauma, the measurement is erroneous and the enslavement of the eye muscles is in fact distorted: a state of vertigo or dizziness sets in.

1 – Fundamental objective

So, the primary objective of this project is to improve the knowledge on the biomechanical behavior of this acceleration sensor (SCC, utricle and saccule), this based on diverse existing finite element (FE) models (2D-slice and 3D) which have to be developed further. In particular, the following concerns will have to be addressed: the boundary conditions of the soft membranes, i.e. the perilymphatic fluid compartment, the endolymphatic sac and the cochlear aqueduct, which communicate both with the intracranial area. The goal here is to better understand the volume and pressure variations that can be either observed, or sometimes measured, in human medical imaging as well as in animal models like rodents. There is a real lack of knowledge on the biomechanical behavior of the global peripheral component (SCC, utricle and saccule + boundary conditions) of the balance system:

- Does a volume variation induce a pressure variation, or is it the other way around?
- Could there be a volume or a pressure leak through the endolymphatic sac and/or the cochlear aqueduct?
- How does the intracranial pressure influence the biomechanical behavior of the whole system since the intracranial space, i.e. the cerebral spinal fluid, is linked to the inner ear?
- How do these volume and pressure variations modify the cupula deformation for a given head motion, itself linked to a given clinical routine test or consecutive to a head trauma? And how will these variations modify the human balance?

Many and many questions that require answers to improve the knowledge on the biomechanical behavior of the peripheral component of the balance system.

2 – Applied objective

Secondly, it is also a matter of identifying all the possible malfunctions of this sensor, especially for various frequent pathologies such as endolymphatic hydrops and benign paroxysmal positional vertigo, or Meniere disease, as well as through a patient specific approach (but not exclusively). Again, particular attention should be paid to volume and pressure variations in the vestibule linked to the surrounding soft membranes permanent deformation, as well as otoconia migration and sedimentation (fluid/structure interaction).

3 – Ultimate objective

This knowledge of fine biomechanics will lead to the final and global objective that sounds like the following leitmotif: developing better diagnoses and more appropriate treatments for vertigo and dizziness!

Planned timetable of the project

The vestibule in its accurate anatomy (exact geometry) and in its physiology (behavior) is understood in a relatively poor way. This is due to its small size (around 10 millimeters) and the difficulty of accessing it because it is deeply embedded in the petrous bone at the base of the skull. It is also particularly fragile because it is very flexible, its membranes being made of a single layer of cell epithelium containing two fluids: the endolymph and the perilymph. It is thus difficult to carry out a mechanical experiment on this sensor to identify its mechanical behavior. This is why, to best approach this anatomical structure, this project uses the FE method to achieve biomechanical modelling and numerical simulation of the vestibule in various scenarios.

To begin with, the previously developed FE models of the vestibule have to be validated in depth against clinical observations and experimental measurements, this in their actual state and in normal conditions: Sudden stop test, Head Impulse Test (HIT), sinusoidal pseudo-random binary sequence, …

Then, these models have to be improved to take into account the surrounding perilymphatic fluid compartment on the one hand and the two communication canals with the intracranial medium on the other hand. This is of particular importance since the pathologies under study rely on volume and pressure variations. These variations are even badly known; shall it be in their amount or in their time evolution/history.

Eventually, the here developed and improved models with their entire environment, will then constitute an original tool when transferred to, and used in clinical routine, moreover if they are patient-specific. They will help to address better diagnoses and to propose more suitable therapies. However, before that, an industrial transfer has to be undertaken to implement such complex tools in a simple and existing investigation device/equipment.