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Investigation of Balance Disorders Through the Clinical Sudden Stop Test: Influence of the Kinematics and the Boundary Conditions

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1. Introduction

The inner ear hosts a fundamental component of the mechanisms regulating balance and maintaining gaze: the vestibular system. It can detect motion thanks to three semi-circular canals and two cisterns, which act as sensors of angular and linear acceleration of the head, using deflection of the cupular diaphragm and of both cistern maculas to generate neural information. That peripheral information is processed in the central nervous system to modulate muscle tone in order to allow postural adaptations and eye motion. Impairment of these peripheral sensors leads up to a state of instability commonly known as vertigo.

The cupula's deflection can be influenced by many parameters in a given head motion scenario among which the real head kinematics and the potential damping role of the suspensory fibers which exist between the perilymph and the petrous bone and can be seen as one boundary condition of the soft tissues of the vestibule of the inner ear. Thus, this study tries to clarify the role of these two parameters on the cupula deflection in a given clinical diagnosis test: the Sudden Stop Test, as it is described in Van de Berg et al. (2018). In particular, this work uses a 2.5D finite element (FE) model of the lateral semi-circular canal (LSCC) of the human inner ear to identify what happens to the cupula during an extended range of head rotational decelerations in the axial plane and various stiffness of the suspensory fibers.

2. Method and material

The FE model of the LSCC used here has been previously developed and validated against clinical observations, as largely described in Baumgartner et al. 2025. This 2,5 D model consists in two fluids–endolymph and perilymph–and four tissue structures–labyrinth membrane, cupula, crista and petrous bone. It mimics a human LSCC, and it is made of 10,339 hexahedral elements and 21,201 nodes. The membranous labyrinth, forming a small tube with an enlarged part called utricule, contains the endolymph and bathes in the perilymph, itself embedded in the petrous bone of the skull base. Mechanical properties of water are assigned to both fluids. Besides, structures (membranes, crista and skull bone) are assumed to follow Hooke's law and are also assumed to be quasi-incompressible. Eventually, the cupula is modeled as a Zener viscous-elastic material because it is mainly composed of water and soft gelatinous glycoproteins. The value of the variables of this behavior are taken from the literature (Selva et al., 2009).

All nodes are constrained in the normal direction of the LSCC. That constraint is supposed to represent the boundary condition of the modeled slice, i.e. the presence of medium on both sides of the slice, so as to contain the slice motion in its plane. The model is subjected to the Sudden Stop Test, i.e. a deceleration (axial rotation of the head) in 100 ms starting from an initial velocity of 180°/s, thus generating a level of deceleration of 1,800 °/s².

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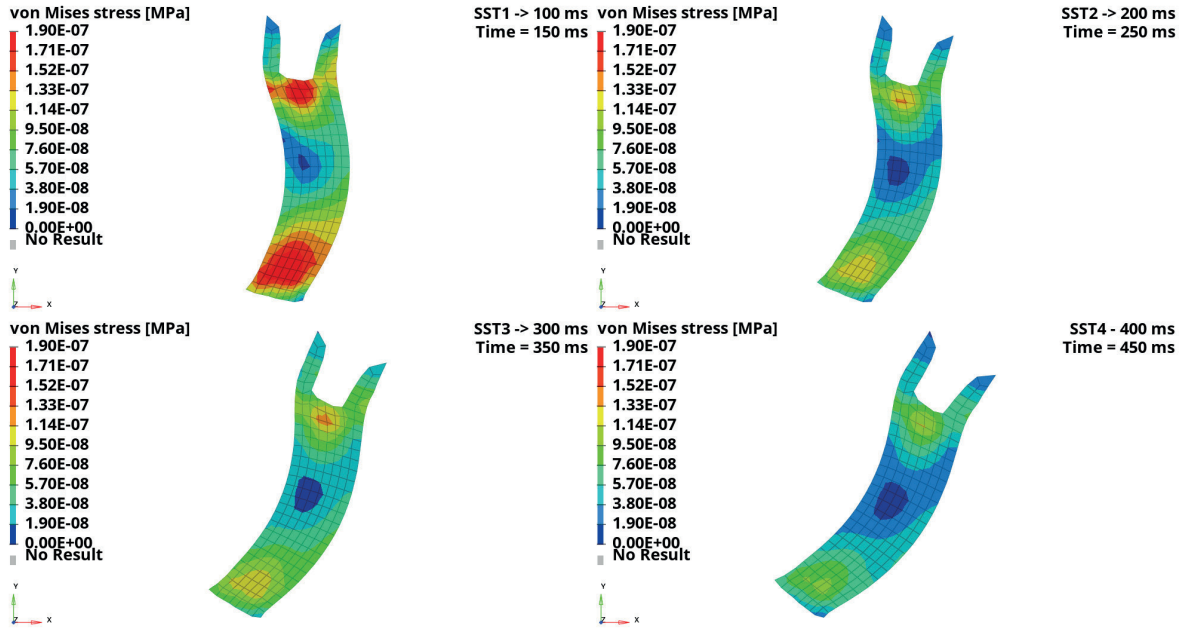

Figure 1. Cupula Von Mises stress 50 ms after deceleration end for various head deceleration durations ranging from 100 ms (SST1) to 400 ms (SST4).

Credit: Daniel Baumgartner.

Nevertheless, this ideal scenario is sometimes criticized since some author claim that either the deceleration may last more than 100 ms, or the deceleration is damped by the existing of suspensory fibers or tethers. In fact, one can observe a fibrous trabecular meshwork of connective tissue within the perilymphatic space surrounding the membranous labyrinth as described by Smith et al. (2022). To take into account these two facts, 8 new scenarios were developed:

- 4 scenarios in which the duration of the deceleration varies from 100 ms (reference model) to 400 ms by steps of 100 ms: SST1 to SST4.
- 4 scenarios in which a layer of soft material is introduced in the reference model between the rigid skull and the perilymphatic compartment to mimic the suspensory fibers. The Young modulus of that layer decreases from 500 MPa in SST1E1 to 0.0005 MPa in SST1E4 by division steps of 100.

For the 8 scenarios, two variables are computed: the angle between the initial position of the kinocilium (normal to the crista top) and its deflected position, and the cupula von Mises stress, with a focus on the cupula base.

3. Results

Significant variations and non-variations are observed for both variables in these 8 rotational impact scenarios. Namely, increasing the deceleration time of the head from SST1 to SST4 leads to:

- a lower angle between the initial position of the kinocilium (normal to the crista top) and its deflected position, ranging from 35° for SST1 to 29° for SST4 (Tab. 1).
- a lower level of the maximal value of the cupula von Mises stress, ranging from 1.754 Pa for SST1 to 0.546 Pa for SST4 (Fig. 1 and Tab. 1).

Table 1. Cupula von Mises stress (final values and maximal absolute) and kinocilium angle between its initial position (normal to the top of the crista) and its maximal deflection, as well as relative value (relref) to the reference scenario (SST1 or SST1E1).

Scenario	von Mises *max-final* [Pa]/relref	von Mises *max* [Pa]/relref	Deflection *max* [°]/relref
SST1	0.194/1	1.754/1	35/1
SST2	0.138/0.71	0.948/0.54	33/0.94
SST3	0.123/0.63	0.677/0.39	31/0.89
SST4	0.116/0.60	0.546/0.31	29/0.83
SST1E1	0.194/1	1.754/1	35/1
SST1E2	0.194/1	1.754/1	35/1
SST1E3	0.194/1	1.753/1	35/1
SST1E4	0.199/1.03	1.749/0.99	35/1

Credit: Daniel Baumgartner.

Besides, the introduction in the model of suspensory fibers seems to leave unchanged the values reached by both variables under study compared to the reference model (Tab. 1).

4. Discussion and conclusion

Variations in the way the Sudden Stop Test is considered may induce variations in the cupula answer. In fact, when the head deceleration duration is increased, thus when the deceleration itself decreases, the shearing stress and the cupula deflection is lowered. Shearing stress and transverse motion at the cupula base trigger a signal to the central nervous system, funding the vestibular ocular reflex, itself responsible for vertigo and instability when altered. Thus, lower levels of these two variables mean reduced perception of rotation. It would therefore be necessary to be able to measure the "true" head movement for each single clinical test and for each patient rather than assuming that the head is always animated by the same idealized movement from one patient to another.

Besides, taking into account suspensory fibers between surrounding rigid and inner soft features does not modify both variables under study. This means that this supposed damping link between the rigid petrous bone and the soft inner tissues may not modify the mechanical answer of the cupula to a rotation in the axial plane of the head.

In fact, a remaining challenge is to enhance this study with other, more general, types of pulses (and not only pure single decelerations) at different levels and in various directions and also for both others semi-circular canals, as well as for the utricule and the saccule, to complete the knowledge on vertigo and instabilities.

Conflict of interest statement

The authors have no conflicts of interest to declare.

Contributor roles

Daniel Baumgartner and Manon Blaise developed the finite element models and the methodology, achieved the simulations and produced the results. Anne Charpiot provided the initial clinical expertise and analyzed the results from a medical and surgical point of view.

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Data, software, code availability

The software used in the present study is the Altair Hyperworks 2022.3 suite (www.altair.com).

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