Computationally Effective Lubrication Theory based Modeling of Cerebrospinal Fluid in Brain Mechanics during Impact on Head

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Finite element head models (FEHM) are increasingly used to gain insights into the mechanisms of traumatic brain injury (TBI). An important component in this context is the realistic modeling of the flow of cerebrospinal fluid (CSF) at the interface of the skull and brain. The CSF is contained in a chamber known as sub-arachnoid space (SAC). One vital function of the CSF is to absorb some energy during head impact and protect the brain inside the skull.

Existing FEHM in the literature characterizes the CSF as a nearly incompressible solid with low shear modulus, to bypass the challenges and computational cost associated with the coupling between a solid mechanics solver (for skull and brain) and a fluid mechanics solver (for CSF). The present work develops a theoretical framework to characterize the CSF flow and the dynamics of the brain and skull motion resulting from an impact to the skull. A simplified geometry of the head is adopted, constituting of the brain, CSF and skull, each being represented by spheres of their representative diameters. The CSF flow in the SAC (thickness is about less than 3 mm) is modeled as a flow through thin gap using the lubrication theory. The inertial component of the Navier-Stokes equation, which is typically ignored in classical lubrication model, is retained in the present formulation. The velocity flow field of the CSF is represented by relying on stream functions. The resulting governing equation for the CSF flow turns out to be a fourth order linear partial differential equation (PDE) [1]. It has been experimentally reported in literature [2] that both the brain and skull solely undergo rigid body motions during the time duration of the impact (~10^{-2} s). Accordingly, the brain and skull are modeled as rigid bodies during this duration of the impact. The rigid body dynamics of the brain is found to be governed by an integro-differential equation (IDE) in terms of the CSF pressure, skull and brain accelerations. The IDE and the PDE form the governing equations for the fluid structure interactions. These equations are solved numerically using the finite element (FE) approach and the associated computational scheme is found to be superior and more effective than the simulation of the fluid structure interaction based full-scale FE model. The result of CSF flow is validated against the predictions from the fluid structure interaction module of Abaqus© (v 6.14-5).

References

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