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Modelling and analysis of cerebrospinal fluid flow in the human brain

Mariusz Ptak [1*], Claudia Sbriglio[1], Mateusz Dymek [1] and Artur Kwiatkowski [2,3]

[1]Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Łukasiewicza 7/9, 50-371 Wroclaw, Poland;
[2]Department of Neurosurgery, Provincial Specialist Hospital in Legnica, Iwaszkiewicza 5, 59-220 Legnica, Poland
[3]Faculty of Medicine, Wroclaw University of Science and Technology, Hoene-Wrońskiego 13c, 58-376 Wroclaw, Poland
*Correspondence: mariusz.ptak@pwr.edu.pl

ABSTRACT: Traumatic brain injury (TBI) presents a major health concern, requiring an in-depth comprehension of its mechanisms and effects. The cerebrospinal fluid (CSF) protects the brain and maintains central nervous system homeostasis. Progress in computational biomechanics has enabled the creation of sophisticated finite element models, including the aHEAD model, which incorporates anatomical data to accurately simulate head biomechanics under diverse conditions of sudden acceleration. This research study advances the aHEAD model by incorporating smoothed particle hydrodynamic (SPH) elements to simulate CSF flow during vehicle impacts. The study was enriched by comparing the model with a) CSF modeled as, SPH, b) without CSF, and c), without CSF yet with an additional component – arachnoid trabeculae, which serves as a rigid connection between the brain and skull. The numerical model of cerebrospinal fluid and the formulation of conclusions have been verified and calibrated with the experiment conducted in the final phase. The findings contribute valuable insights into the field and highlight the need for continued development of advanced modeling techniques and experimental validations. The goal of understanding the flow dynamics of the cerebrospinal fluid and its role in traumatic brain injuries has been achieved, yet some future studies are necessary.

KEYWORDS: Traumatic Brain Injury (TBI), Cerebrospinal Fluid (CSF), Smoothed Particle Hydrodynamics (SPH) Finite Element Model (FEM)

1. INTRODUCTION

Traumatic brain injury (TBI) is a serious health problem with millions of new cases globally each year. The 2019 Global Burden of Disease Study reported 27.16 million new TBI cases worldwide.

For TBI, falls were the leading cause in 74% (150/204) of countries/territories, followed by pedestrian road injuries (14%, 29/204), motor vehicle road injuries (5%, 11/204), and conflict and terrorism (2%, 4/204) [1], [2], [3].

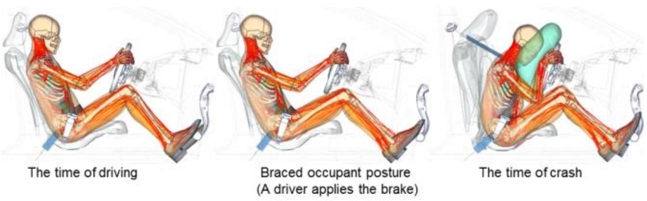

Fig. 1. Stages of a car accident in the perspective of vehicle occupants [4]

An important aspect of TBI is the dynamics of cerebrospinal fluid (CSF), which protects the brain from injuries. Understanding CSF dynamics and their numerical modeling is key to improving diagnostic and therapeutic strategies, ultimately enhancing the quality of life for TBI patients.

2. Methods

Conventional models use hexahedral or tetrahedral solid elements to depict cerebrospinal fluid, simplifying its representation. To assess the finite element head model's accuracy in representing CSF, two approaches were considered: comparing the SPH-based aHEAD model [5], [6] to one without CSF, as well as generating arachnoid trabeculae, beam elements that rigidly connect the brain to the skull. These methods aim to evaluate the effectiveness of SPH in simulating fluid properties and account for the rigidity of internal head structures, crucial for accurate crash simulations.

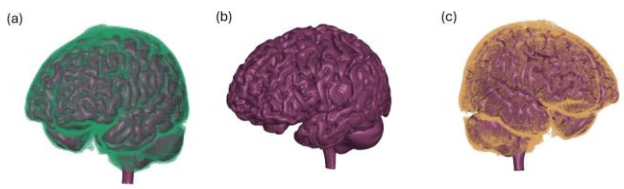

Fig. 2. Representation of cerebrospinal fluid in finite element aHEAD model: (a) CSF as a Smoothed Particle Hydrodynamic (aHEAD 3,156,379 elements); (b) model without CSF (aHEAD 3,016,180 elements); (c) model with arachnoid trabeculae connection (aHEAD 3,075,239 elements) Model with arachnoid trabeculae connection (aHEAD 3,075,239 elements)

3. Results

In current experimental research, the study by Hardy et al. (2007) [7] is particularly noteworthy for its detailed examination of the effect of external forces on the response of human brain tissue. Therefore, the C755-T2 test was used as the boundary conditions of the simulation, and the results of this test were achieved by Hardy as a validation of the obtained results.

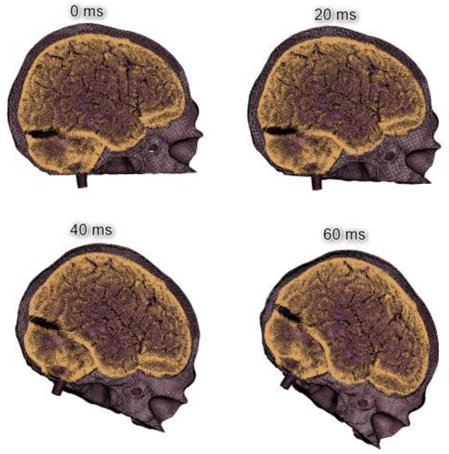

Fig. 3. aHEAD with arachnoid trabeculae connection - course of simulation Hardy C755-T2 test

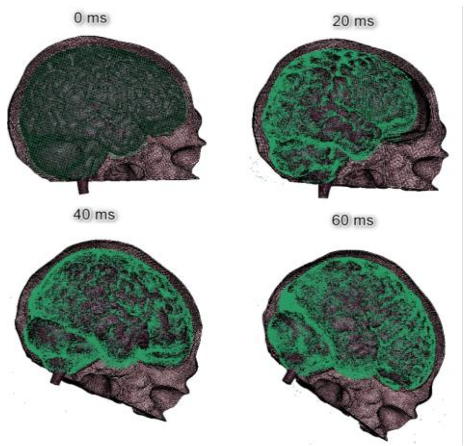

Fig. 4. aHEAD with SPH as CSF - course of simulation Hardy C755-T2 test

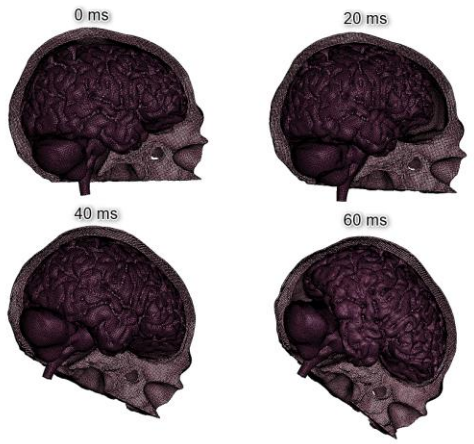

Fig. 5. aHEAD without CSF - course of simulation Hardy C755-T2 test

4. Summary

1) The simulations of the aHEAD model reveal significant discrepancies when compared to experimental data from Hardy's C755-T2 test, particularly in the displacement results. The smoothed particle hydrodynamics (SPH) approach appears to overestimate fluid movement, while the tetrahedral finite element model underestimates it. These variations indicate fundamental issues with both approaches, highlighting the need for improved modeling techniques that can more accurately replicate the complex dynamics of cerebrospinal fluid (CSF) and brain mechanics under extreme conditions.

2) The results from simulations with and without CSF suggest that the presence of CSF may not significantly impact displacement outcomes under extreme acceleration conditions, contrary to expectations. This finding raises questions about the protective role of CSF in traumatic brain injuries. Further investigation is needed to determine whether CSF plays a crucial role in mitigating or exacerbating injury during such events, and whether its dynamic behavior should be more accurately represented in biomechanical models.

3) The differences between the SPH model, the tetrahedral model, and the experimental results highlight the limitations of current modeling approaches. To better simulate physiological conditions and improve the fidelity of finite element models, future research may explore hybrid models that combine the strengths of both flexible and rigid approaches. Additionally, advancements in experimental techniques and computational methods are essential for refining models and enhancing their application in medical and biomechanical research.

Literature

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