Mesh Convergence Depends on the Element Formulation of Finite Element Brain Models.

Azilis Even, Zhou Zhou, Svein Kleiven

I. INTRODUCTION

Finite element (FE) head models are virtual tools to study brain biomechanics, but one prerequisite before their usage is that these numerical surrogates have a convergent behaviour. Previous convergence studies primarily focused on the influence of element size on brain pressure [1–2], displacement [2–3], and strain [4–5], of which the latter two were considered to be more relevant to injury [3][6]. The element formulation is known to influence the model's prediction, yet no consensus has been reached among existing FE head models [5]. For example, most models used the constant stress solid formulation, whereas the KTH head model [6] employed the selectively reduced (S/R) integration. This short communication aims to evaluate the influence of element formulation on the model convergence responses.

II. METHODS

Brain Meshes

The base model for this study was the KTH Head model, with brain mesh size as 6.4 ± 1.9 mm [6]. We modified the mesh in the original model to generate three derivatives, all of which had the same mesh topology but different element sizes (Fig. 1), i.e., a coarse model (mesh size: 12.2 ± 3.9 mm), a medium model (mesh size: 3.2 ± 0.97 mm), and a fine model (mesh size: 1.6 ± 0.48 mm). In order to eliminate compounding factors and focus on the influence of mesh size and element formulation, all intracranial components were merged. The brain was modelled as a homogeneous structure with nonlinear behaviour using a second-order Ogden-based hyperelastic constitutive law with six Prony-series terms to account for its rate dependency [6], and the cerebrospinal fluid was modelled as a nearly incompressible elastic fluid [7]. Three commonly used element formulations (i.e., constant stress solid [reduced integration] with exact volume integration viscous hourglass control, S/R integration, and fully integrated elements) were implemented to the brain elements in these models.

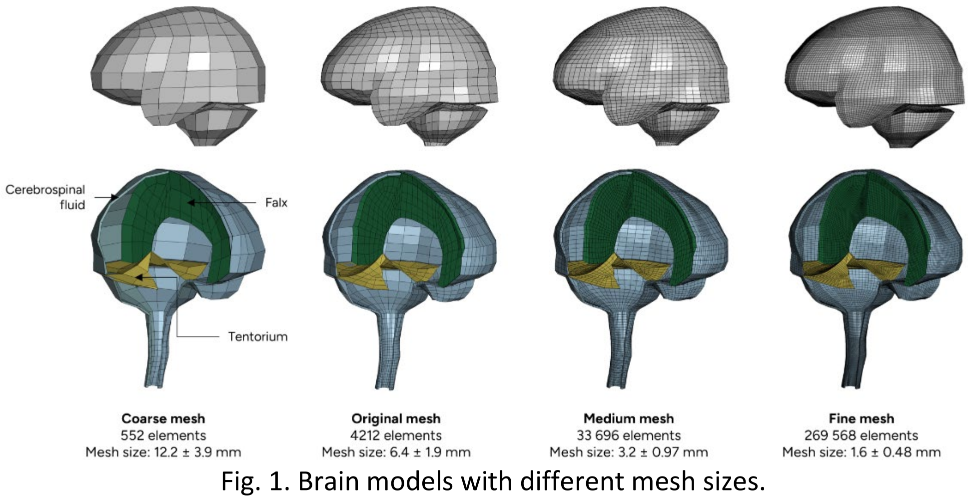

Fig. 1. Brain models with different mesh sizes.

Evaluation of the Convergence Behaviour

An experimental rotational loading profile (angular velocity peak: 40 rad/s, duration: 30 ms) along three anatomical directions (i.e., axial, coronal, and horizontal) was imposed to all 12 models [8], resulting in a total of 36 simulations. All simulations were solved using the massively parallel processing version of LS-Dyna R15.0.

To evaluate the convergence behaviour of the models, the maximum resultant displacement relative to the skull was extracted from one representative brain node. Then, the 95th percentile maximum principal strain (MPS) over the entire brain was analysed and compared for all three loading directions.

A. Even is doctoral student (e-mail: aeseven@kth.se; tel: +46 0793434084), Z. Zhou is Assistant Professor and S. Kleiven is Professor, all at the Division of Neuronic Engineering, KTH Royal Institute of Technology, Stockholm, Sweden.

III. INITIAL FINDINGS

The peak resultant nodal displacements for one node of interest for the axial rotation case are reported in Fig. 2a and the 95th percentile MPS in Fig. 2b, completed by section cuts of the brain meshes showing the element-wise peak strains (Fig. 2c) and volume fractions of brain elements with strain over varying thresholds (Fig. 2d), both for the axial rotation. For all three rotations, using S/R integration led to a slightly higher maximum relative displacement and strain than with the constant stress solid and fully integrated formulations, but all three element formulations were shown to approach similar results for finer meshes. Regardless of rotational directions, S/R integration yielded the fastest convergence results as highlighted by Figs. 2c and 2d, with less than a 5% difference in terms of brain strain between the original and medium meshes. In contrast, the constant stress solid and fully integrated element meshes did not converge when applying a mesh convergence criterion of less than a 5% difference in output between the medium and fine meshes.

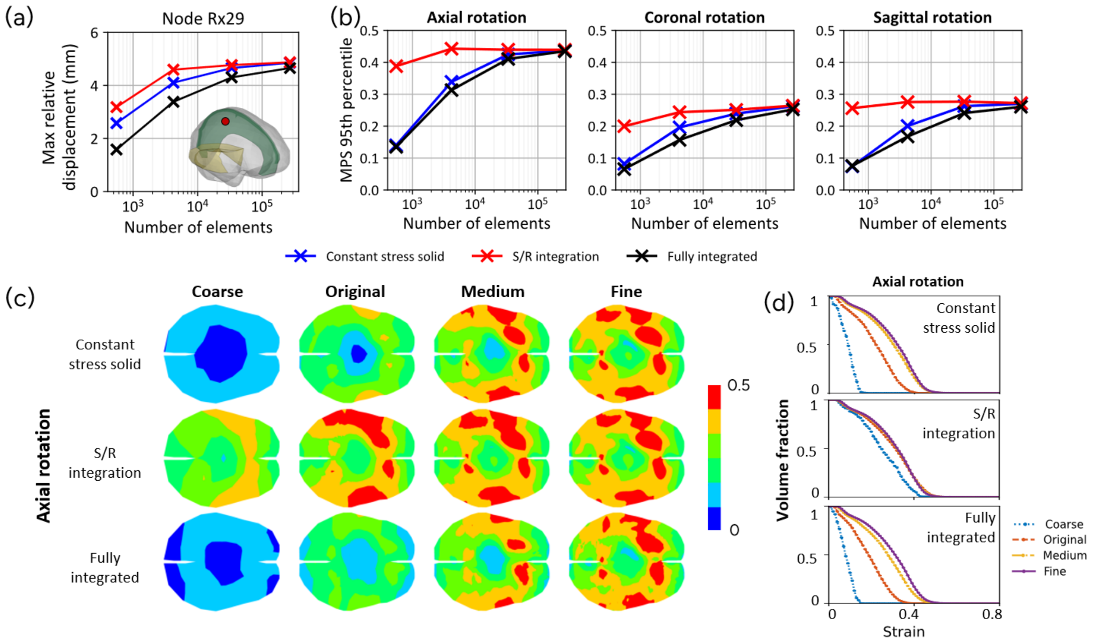

Fig. 2. (a) Maximum relative displacement for one node for the axial rotation, (b) 95th percentile brain MPS in three rotations, (c) Element-wise peak strain predicted by 12 models via the combination of four mesh densities and three element formulations for the axial rotation, (d) Volume fraction of brain elements with the strain over varying thresholds for the axial rotation.

IV. DISCUSSION

This study verified the hypothesis that the mesh convergence behaviour of FE brain models is affected by the choice of element formulation. Originally chosen for the KTH Head model to avoid both hourglass instabilities associated with reduced integration and locking issues accompanying full integration [6], S/R integration yielded the fastest convergence behaviour in terms of nodal displacements and brain strain, followed by constant stress solid formulation then fully integrated elements. When scrutinising the results yielded by the S/R integration (Fig. 2), the differences in brain strain and displacement between the original and medium mesh were less than 5%.

V. ACKNOWLEDGEMENTS

This work was supported by FFI (Strategic Vehicle Research and Innovation), project number no. 2024-03635, funded by Vinnova, the Swedish Transport Administration, the Swedish Energy Agency, and the industrial partners. The simulations were performed with computing resources provided by NAISS [no. 2025/5-147].

VI. REFERENCES

[1] Kleiven S *et al.*, J Biomech, 2002.
[2] Mao H *et al.*, Comput Methods Biomech Biomed Eng, 2013.
[3] Takhounts E *et al.*, Stapp Car Crash Conf, 2003.
[4] Zhao W *et al.*, Ann Biomed Eng, 2019.
[5] Giudice J *et al.*, Ann Biomed Eng, 2019.
[6] Kleiven S *et al.*, Stapp Car Crash J, 2007.
[7] Zhou Z *et al.*, Biomech Model Mechanobiol, 2025.
[8] Alshareef A *et al.*, J Neurotrauma, 2020