Developing finite element head models using advanced blocking techniques: density-changeable high-quality all-hexahedral meshes and fit for individual brain component morphing

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ABSTRACT – Detailed all-hexahedral solid head models were developed using an advanced blocking technique. A strategic O-grid core was implemented facilitating node-to-node connectivity and seamless mesh distribution across all scalp-skull-brain structures. Two models with 549,054 and 231,586 hexahedral elements representing lower- and higher-resolution mesh densities were tested. Additional models explored the effects of mesh density, pattern, as well as features such as variations of dura layer and cerebrospinal fluid. All models have a minimum Jacobian of 0.6, with 67% of elements having a Jacobian above 0.9. Preliminary validation involved two cadaver tests to assess brain pressure and displacement. This new modeling approach supports flexible changes in mesh density and morphing of individual brain components, improving the accuracy of personalized FE brain models when investigating head biomechanics, all with numerical stability even under severe loading conditions.

INTRODUCTION

Researchers have developed detailed brain finite element (FE) models with high-quality meshes to get accurate brain biomechanical responses. Less than 4% of the earlier version head model from Kungliga Tekniska Hoğskolan (KTH) Royal Institute of Technology had Jacobian smaller than 0.5 (Kleiven, 2007).The later KTH model showed that 94% of elements had Jacobian values above 0.5 (Ho et al., 2009). In the recent head model (ADAPT) 95.5% of brain elements have Jacobian values above 0.5 (Li et al., 2021). The Wayne State University (WSU) model (Zhang et al., 2001) and then the Global Human Body Models Consortium (GHBMC) model developed at WSU (Mao et al., 2013b) also used high-quality hexahedral meshes for the brain, with GHBMC model showing a minimum Jacobian above 0.4. The Total Human Model for Safety (THUMS) model (Kimpara et al., 2006) and the updated version demonstrated numerical stability and are also widely used (Atsumi et al., 2018). The element size of the Worcester Head Injury Model (WHIM) V1.0 was 2.9 ± 0.6 mm (Ji et al., 2015) which was later refined to 1.8 ± 0.4 mm (Zhao and Ji, 2019). The updated University College Dublin brain trauma model (UCDBTM) (Horgan and Gilchrist, 2003) increased the number of elements increased from 28,286 to 184,261 with 0.1% of elements having Jacobian values below 0.4, and at least 80% of elements had Jacobian ratios between 0.8 and 1 for the brain parts (Trotta et al, 2020).

However, most of the FE brain models faced a major challenge that it's very difficult or almost impossible to update specific brain component meshes, and overall mesh density, to represent detailed anatomy except for conducting a 1-to-8 or later 8-to-64 splitting. Block-based approach was reported to be effective in generating hexahedral meshes with various mesh densities once the blocks were developed (Mao et al., 2013a). Meanwhile, due to the complex geometry of the brain, cerebrospinal fluid (CSF) spaces, and connections to the membranes, skull, and scalp, it was very challenging to create blocks for all head components while maintaining proper geometry. As such, for the widely used GHBMC brain model, only its brain component was developed using blocks, while the CSF, skull, and scalp parts were meshed using conventional approaches, yielding initially using tetrahedral elements to mesh the CSF space (Mao et al., 2013b) which was later upgraded to hexahedral elements (Lyu et al., 2022). Another head model commonly available in the field is the THUMS head model (Atsumi et al., 2018), which however has some sharp non-uniform mesh distributions with several brain elements having over 300 times larger volume than the neighboring elements near the inner cortex region. Thus, to improve brain response prediction, and to develop head models that bring flexibility for continuously improving local meshes and overall mesh densities,

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this study attempted to deliver all-hexahedral solid, block-based FE head models.

METHODS

Pipeline of mesh generation

The initial brain geometry was verified according to an atlas with detailed brain anatomy (Schaefer et al., 2018). A multi-block-based approach was then applied on the geometry using ANSYS ICEMCFD (ANSYS, Inc., Canonsburg, Pennsylvania). The full pipeline to generate the final FE head model is shown in Figure 1A. To maintain the proper shape of the geometry and uniform mesh distribution throughout the whole model, the core of the O-grid was strategically adjusted to ensure a seamless mesh distribution across all head-brain structures as shown in Figure 1B. Such O-grid was not implemented in a previous effort in developing an all-hexahedral head model (Cai et al., 2019).

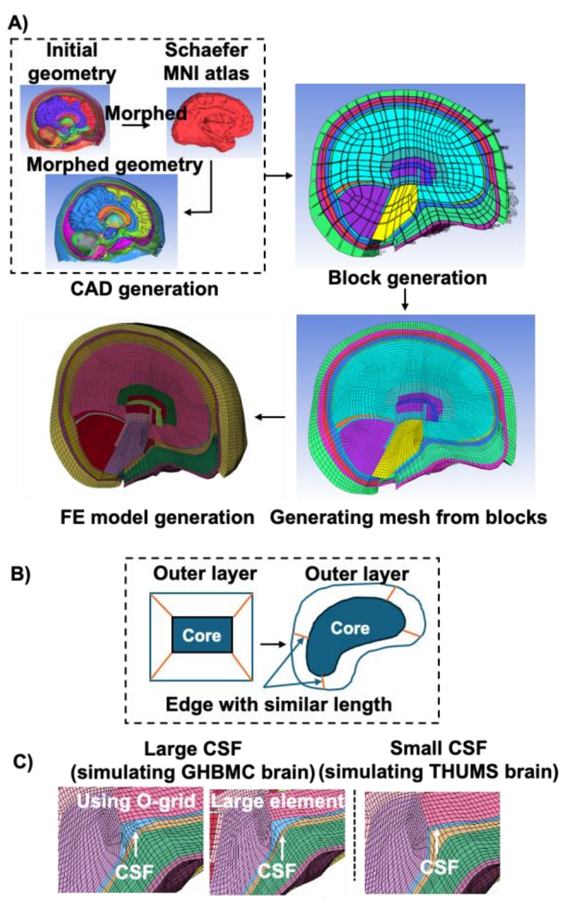

Figure 1: A) Pipeline to create block-based all hexahedra solid elements for head models B) Strategic O-grid shape distribution to match brain geometry. C) various CSF junctions

FE head models

A total of seven FE head models were developed. These models have detailed anatomical regions including deep brain structures such as the corpus callosum, basal ganglia, thalamus, hippocampus, ventricular system, and fornix. The blocking technique can adapt to the profiles of internal brain structures. In this study, blocks were arranged to represent major internal components while smaller ones have a zig-zag boundary shape. As the developed blocks allow generating FE meshes with various mesh sizes, two FE head models with 549,054 and 231,586 hexahedral brain elements were tested to investigate the biomechanical response of lower- and higher-resolution mesh. The block-based models allowed individual component refinement. Hence, we developed a solid- dura model and a conventional shell-dura model. Additionally, as GHBMC and THUMS models showed different CSF junctions near the brainstem-cerebrum region, we developed three models representing different CSF junctions and mesh patterns (Figure 1C) while keeping other brain regions not affected. All these models were simulated according to the loading conditions of two cadaveric tests related to brain motion (Hardy et al., 2001) and brain pressure (Nahum et al., 1977) to understand their biomechanical responses using the material property specified previously (Mao et al., 2013b). A total of 14 simulations were conducted using LS-DYNA R 9.3.1 (LSTC/ANSYS).

PRELIMINARY RESULTS

Mesh quality comparison

The minimum Jacobian for all hexahedral elements in the developed models is 0.6, with approximately 67% of the elements having Jacobian values between 0.9 to 1. This represents a significant improvement over the GHBMC model, which has a minimum Jacobian of 0.4, and the THUMS v4.02 head model, which has the minimum Jacobian of 0.25. In addition, the distortion element quality metric, which measures the twisting of hexahedral elements from their ideal shape, was compared for these three models. Our models achieved superior mesh distortion scores than the GHBMC and THUMS models.

Preliminary validation

The model-predicted pressure (Nahum case 37) and brain displacement (Hardy case 755-T2) were comparable to the cadaver test as shown in Figure 2. Peak brain displacements were in the order of 5-8 mm (Figure 2A). A typical coup and contra-coup pressure pattern was observed (Figure 2B).

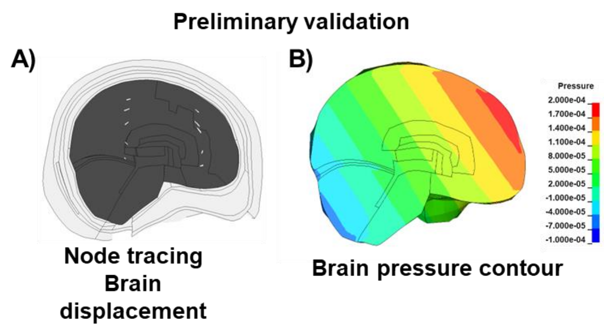

Figure 2: Pressure and brain displacement

Parametric results on corpus callosum mesh density, solid vs. shell dura, and CSF junction

There were comparable changes in strain development for coarser and finer models, particularly for internal brain structures such as the corpus callosum (Figure 3A). Modelling the dura as a solid layer induced less internal brain strain but more strain on the surface of the cerebrum as compared to using a shell dura (Figure 3B). Interestingly, there was little deviation in strain development for three variations of CSF models (Figure 3C).

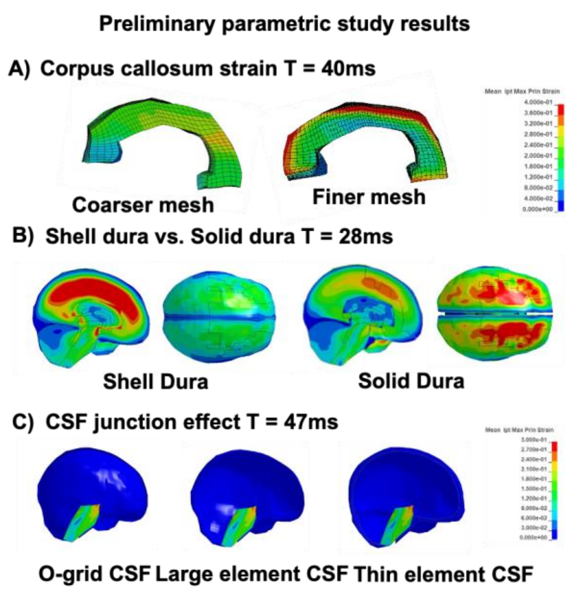

Figure 3: Strain development of A) coarser vs finer corpus callosum B) solid vs shell dura models C) various CSF junctions

DISCUSSION

In this preliminary study, we delivered all-hexahedral solid, node-matching, FE head models based on blocking techniques. One of the main benefits is its ability to efficiently update local components, addressing issues such as relatively coarser meshes of the corpus callosum in the GHBMC brain model. In addition, we were able to quantify the effect of solid vs. shell dura, and the effect of different CSF junctions presented in the GHBMC (Mao et al., 2013b) and the THUMS head model, while maintaining the geometry and meshes of other head components, hence avoiding introducing confounding factors during the comparison. These models allow updating mesh density without being constrained by conventional 1-to-8 splitting. Also, as the whole head model is block-based, such updates on brain meshes could be conveniently achieved together with CSF, skull, and scalp meshes.

In addition to block based meshing technique, other methods such as voxel-based meshing (Ho et al., 2009, Miller et al., 2016) and octree-based meshing (Li et al., 2021), along with personalized mesh morphing technique (Ji et al., 2011, Giudice et al., 2020) were also applied to develop head models in literature. Different from voxel-based method which led to a zig-zag pattern of brain outer and inner surfaces, octree-based meshing techniques provide the advantage of accurately conforming to the boundaries of brain components, enabling a detailed representation of anatomical structures with a minimum Jacobian of 0.45 reported for the ADAPT model (Li et al., 2021). The block-based approach proposed in this study yielded a smooth cortical surface with a minimum Jacobian of 0.6. In addition, the flexibility in individual component meshing and high-resolution meshes are particularly beneficial for subject-specific morphing. Our models will support precise customization for individual brain structures. Also, node sharing across all head parts and node-to- node connectivity was meticulously implemented, together with Jacobian values above 0.6 for all hexahedral elements, supporting a high numerical stability. Per in-house testing, our models remained stable under some extreme rotating scenarios. Furthermore, the convenience of adjusting mesh density in the blocking technique rather than being constrained by 1-to-8 splitting will help in performing mesh density convergence studies. Ongoing and future studies include assigning nonlinear anisotropic brain materials, extensive validation across a wide range of experiments, and understanding the local strain development for finer models, such as the one with the gyri and sulci.

ACKNOWLEDGMENTS

We acknowledge NSERC, New Frontiers in Research Fund, and the Canada Research Chairs Program.

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