Finite Element Analysis of Sex-specific Brain Response to Soccer Heading

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I. INTRODUCTION

Traumatic brain injury (TBI) remains a significant public health concern, exhibiting considerable variation in outcomes based on several demographic factors, including injury severity, genetic factors and sex [1]. Recent studies have elucidated notable sex differences in the incidence and consequences of TBI, underscoring that females may exhibit distinct physiological responses compared to their male counterparts [1-2]. Additionally, sex differences, including variations in brain morphology and material properties, may significantly affect biomechanical responses to head impacts. For instance, a study utilising sex-specific axonal models found that female axons exhibited substantially higher peak strains and associated neurofilament failures compared to male axons, attributed to differences in microtubule configurations [3]. Finite element head models (FEHMs) have become indispensable tools for studying these differences, offering detailed insights into stress and strain distributions during impact scenarios. In this study, we utilised validated female and male FEHMs incorporating different viscoelastic material properties and anthropometric characteristics. Both models were subjected to identical simulation setups replicating one soccer heading scenario, with accelerations applied to the head's centre of gravity (COG). The analysis and comparison of the resulting strain and stress distributions aims to elucidate the impact of sex-specific factors on brain injury mechanisms, thereby contributing to more personalised and effective TBI prevention and treatment strategies.

II. METHODS

The simulation set-up presented in this study was based on the work of Wahlquist *et al.* [4], in which data from youth soccer heading sessions were retrieved from Triax SIM-G sensors positioned within the player's headbands. The sensor starts recording when a linear acceleration exceeds 10 g and post-processing filtering was applied (Moving Average and Savitzky-Golay smoothing). The data were derived from repetitive head impacts exposures involving 27 female youth soccer players over two playing seasons and it was subjected to a selection process based on the severity, including the peak linear acceleration (PLA) and peak rotational velocity (PRV), totalling 81 headers over 30 games and 1,506 headers over 41 practices. For this study, one of the highest g impact cases was selected - 111 g of magnitude. In Abaqus environment, the accelerations and velocities were established as tabular amplitudes with increments for each millisecond, for a total of 61 ms. These were used as boundary conditions (BCs), which were applied to the COG of the head models. The models employed in this study were the YEAHM [5] and the FeFEHM [6], for the male and female head models, respectively. Both represent subjects of the same age (65 years old), with each FEHM exhibiting distinct viscoelasticity parameters from the novel work of Alshareef *et al.* [7]. The new YEAHM employs young male brain material properties for the cerebellum (CB) grey matter (GM) and white matter (WM), and cerebrum GM and WM, while the FeFEHM utilises the young female properties for the same soft tissues. The cerebrospinal fluid (CSF) properties in both models were adapted from Gilchrist [8]. Regarding the interaction between structures, a tangential behaviour friction coefficient (μ=0.2) was considered for both models, to limit unrealistic brain motion. Both models were meshed with elements with reduced integration and hourglass stabilization (C3D8R) for the skull and brain tissues. Injury assessment was conducted by selecting injury criteria, such as the Maximum Principal Strain (MPS). Additionally, the volume fraction of brain regions exceeding a 0.2 strain threshold was calculated, considering the 95th percentile.

III. INITIAL FINDINGS

In the present study there is a volume fraction difference between the models (Fig. 1a), whereas more than half of the female brain elements (52.1 %) are above 0.2 strain, compared to less than a quarter of the male model (23.3 %). YEAHM's pituitary gland (PG) results exhibited no volume because there is no such component in the model, thus excluded from comparison. Comparing the cumulative curves, the FeFEHM consistently showed higher cumulative strain distribution, comparing to the YEAHM curve, meaning that a larger fraction of tissue exceeded any given strain value (Fig. 1b). To further quantify these differences, it was considered four percentiles (100th, 99th, 95th, 90th) of the peak-strain distribution (Fig. 2), which values confirm previous results as the FeFEHM shows higher strain peaks, where large gaps are observed at the 100th percentile (for instance, 0.32 strain in the CB of the FeFEHM, compared to 0.19 in the YEAHM). However, corpus callossum (CC) values are almost overlaid,

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differentiating in 0.02 strain.

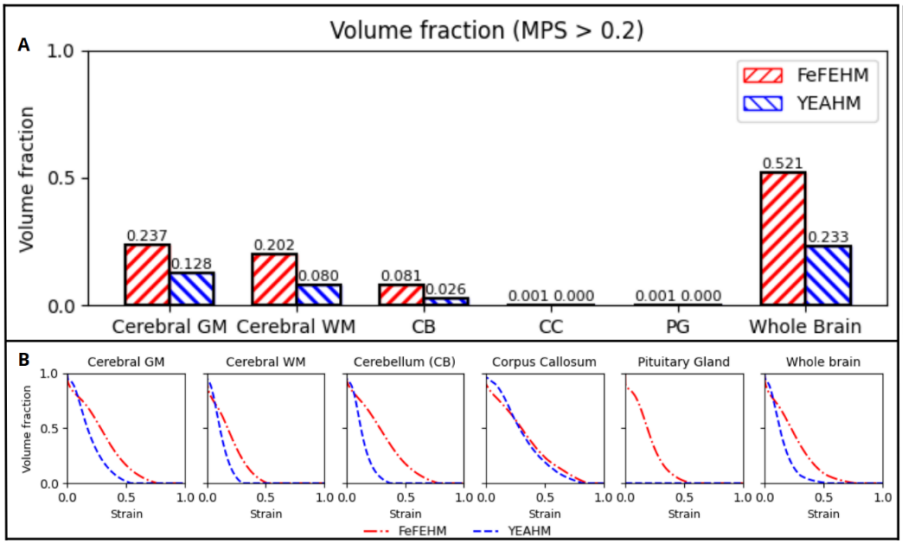

Figure 1 – Comparison of brain regions' volume fraction in the FeFEHM and YEAHM. (A) Volume fraction of brain regions with MPS value over 0.2. (B) Cumulative curves of 95th percentile volume fraction of the brain regions over the 0.2 threshold.

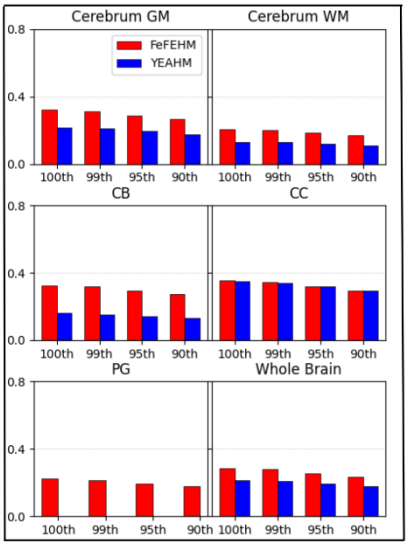

Figure 2 – Comparison of strain peak results of 100th, 99th, 95th, and 90th percentiles for both models.

IV. DISCUSSION

This study highlights the significance of material characterisation of biological tissues. The presented models diverge firstly in the head anthropometry of the subjects, which may result in different outcomes for the same simulation input. Secondly, the mesh density was established for each model as the ideal optimization for biofidelity versus computational performance. The YEAHM was validated against pressure values [5], while the FeFEHM was validated against brain receivers' displacement [6]. However, both models were characterised using the same material formulations, with only some parameters being adjusted with recent viscoelastic parameters provided by the work of Alshareef *et al* [7]. The results obtained demonstrate the importance of such choices. The FeFEHM was more susceptible to strain. These findings were investigated as volume fraction, where the cumulative distribution curves revealed that more tissue experiences higher strain regimes. Also, the gap from the 100th percentile to the 90th percentile does not decrease, suggesting that it is not some numerical instability. The CC demonstrated similar curves in both models and equivalent strain values, explained by the same material characterisation in this region. Therefore, from geometrical to material characterisation, a multitude of variables may be responsible for the observed strain differences. The density and hyperelastic formulation and parameters are consistent across all regions within both models, differentiating only the viscoelastic parameters. The observed disparities may serve as catalysts for the stiffer behaviour of the FeFEHM, allowing more deformation in these regions. These underline the importance of calibrating the constitutive model parameters. Since the FeFEHM produces higher strain volumes of tissue, it would predict higher likelihood of injury for established thresholds, and given that the selected case study was non-injurious in practice, the YEAHM model's lower predicted strain volumes may better reflect the real-world outcome, suggesting potential overestimation in the FeFEHM under the current conditions.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

[1] Gupte, R., *et al.*, J Neurotrauma, 2019.
[2] Munivenkatappa, A., *et al.*, Inj Science, 2016.
[3] Zhang, C., *et al.*, J Neurotrauma, 2023.
[4] Wahlquist, V., *et al.*, Sports Med, 2021.
[5] Fernandes, F., *et al.*, Eng Computations, 2018.
[6] Carmo, G., *et al.*, Comp Meth & Prog Biomed, 2023.
[7] Alshareef, A., Annals Biomed Eng, 2025
[8] Gilchrist, M., Key Eng Materials, 2003.