Regional Brain Injury Vulnerability in Football from Two Finite Element Models of the Human Head

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I. INTRODUCTION

Finite element (FE) models of the human head provide unparalleled rich information about brain mechanical responses upon head impact. The most frequently used injury metrics derived from FE models are either the peak magnitude of maximum principal strain or cumulative strain damage measure (CSDM). However, they do not inform how brain strains are distributed. Strain measures in specific regions of the brain have been proposed to predict injury [1-2]. Most recently, this included the use of a co-registered neuroimage atlas to analyse strains in the 50 deep white matter (WM) regions of interest (ROIs)[2]. Using the Worcester head injury model (WHIM) [3], the relative injury vulnerabilities of the deep WM ROIs were evaluated in terms of nine strain-based injury metrics [2]. Of note, the reconstructed National Football League (NFL) head impacts [4] used in that study were found to be associated with errors [5], which necessitate re-evaluations. In addition, as head injury models could have significant disparities [6], it is also necessary to investigate whether relative brain regional vulnerability depends on the head injury model used. Therefore, the purpose of this study is to reanalyse brain regional vulnerabilities using two versions of the WHIM based on a large impact dataset measured in American high school football. We also extend the evaluation of regional vulnerabilities to both the WM and gray matter (GM) ROIs.

II. METHODS

The isotropic [3] and anisotropic [7] WHIMs were used to simulate 314 head impacts measured from high school football using an Impact Monitoring Mouthguard (IMM) [8]. All of the head impacts were verified by time-synchronised video recordings. Any events collected when the athlete was not being impacted in the head were identified as false positives and were discarded. The remaining true positive events were further scrutinised based on published methods to confirm a head impact occurred in the video and that the computed motion was physically realistic and matched with the video [9]. The impacts were not necessarily associated with a diagnosed concussion, as the purpose of our study was to identify ROIs with the highest likelihood of experiencing largest strains, regardless of whether a concussion actually occurred. This may be important to provide insight in developing a cumulative injury metric based on localised tissue responses to predict concussion in the future.

For each simulated head impact, the 50 deep WM and 54 cerebral GM ROIs were localised *via* a co-registered WM atlas [10] and a separate GM atlas [11], using techniques described previously [2]. For each head impact, peak magnitude of maximum principle strain (ε_1) was obtained for each WM and GM ROI. For each ROI, tied rank values were assigned to score ε_1 in the order of their magnitudes. ROI-wise average rank values across all impact cases were then calculated to evaluate their overall relative vulnerabilities. For both WM and GM, their respective top five most vulnerable ROIs were identified that would indicate the ranks experiencing the highest strains.

To further evaluate the robustness of the ranking, a repeated random subsampling technique was adopted to generate 100k random samples by halving the sample size to 157 impacts. For each random sample, the same ranking analysis was repeated to identify the top five most vulnerable WM and GM ROIs experiencing the highest strains, respectively. From all of the random subsamples, we evaluated the consistency in ranking.

III. RESULTS

Using the isotropic WHIM, the genu (GCC) and main body (BCC) of corpus callosum, and cingulum

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(hippocampus) left (CGH-L) were consistently ranked among the top five most vulnerable WM ROIs in >99.91% of the 100k random trials. For GM, the top five most vulnerable ROIs were consistently found in >99.96% of the random trials, including right inferior frontal gyrus (IFG-R), left and right precentral gyrus (PreCG-L and PreCG-R, respectively), and left and right postcentral gyrus (PoCG-L and PoCG-R, respectively).

Using the anisotropic WHIM, BCC, CGH-L and CGH-R were consistently ranked among the top five WM ROIs (in >99.97% of the random trials). For GM ROIs, the same five most vulnerable ROIs were found (IFG-R, PreCG-L, PreCG-R, and PoCG-R were ranked among the top five in 100% random trials, while >96.16% for ProCG_L).

For illustration, tied rank values averaged from the entire impact dataset are reported in Fig. 1 for the isotropic WHIM. The identified top five WM and GM ROIs are also shown for the two versions of the WHIM (Fig. 2).

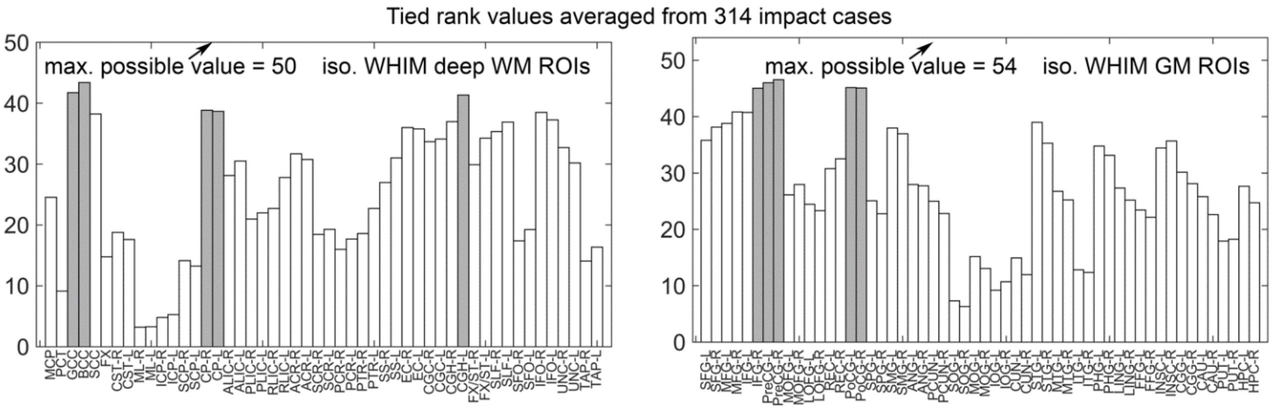

Fig. 1. Tied rank values averaged from 314 impact cases for the deep WM (left) and GM (right) ROIs with their respective top five most vulnerable ROIs highlighted using the isotropic WHIM. Abbreviated ROI labels can be found in [10-11].

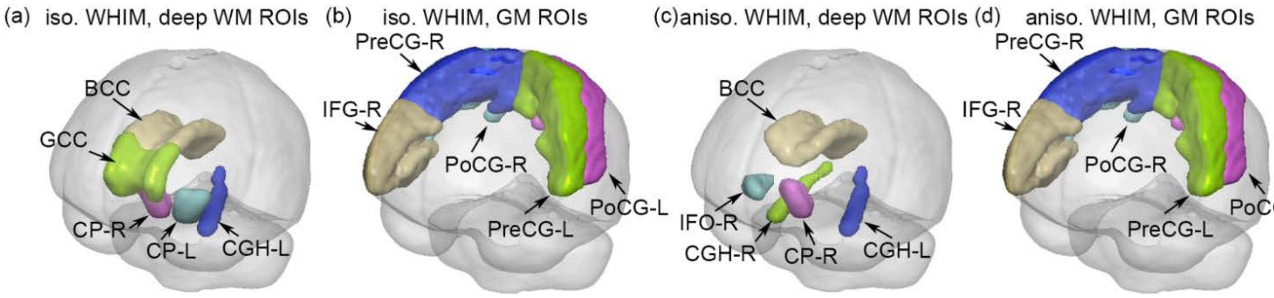

Fig. 2. The top five most vulnerable deep WM (a and c) and GM (b and d) ROIs identified using the isotropic (a and b) and anisotropic (c and d) WHIMs, respectively. For WM ROIs, three regions (BCC, CP-R and CGH-L) were identical between the two WHIMs. For GM ROIs, all of the five regions were identical between the two WHIMs.

IV. DISCUSSION

Identifying the most vulnerable regions may have important implications in understanding the mechanisms of traumatic brain injury (TBI) and in its mitigation. Applying a previously developed technique to a large impact kinematic dataset measured in American high school football using two versions of the WHIM, we found significant consistency in the brain ROIs most frequently experiencing the highest maximum principal strains. Both WHIMs identified the same top five most vulnerable GM ROIs. For deep WM ROIs, BCC, CP-R, and CGH-L were consistently ranked among the top five most vulnerable ROIs. It was interesting to note that two of them, BCC and CP-R, were also found to rank among the top five in an earlier study even though it employed errorneous reconstructed NFL impacts [2]. Further, when using the isotropic WHIM (Fig. 1), the distribution of the relative vulnerability rankings of the WM ROIs was also highly similar to the previous study based on maximum principal strain (with four identical ROIs ranked among the top five: GCC, BCC, CP-R and CP-L [2]). In general, our finding also agreed well with another study that identified the corpus callosum and midbrain regions to sustain the largest strains [12]. These results from independent datasets and head injury models may suggest certain underlying mechanisms in TBI biomechanics. Further investigation is necessary to evaluate other ROI-wise injury metrics such as fiber strain [2], and to incorporate region-dependent material properties and injury tolerances to better assess brain regional vulnerability.

V. References

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