Inter-subject Variability in Brain Regional Peak Strains

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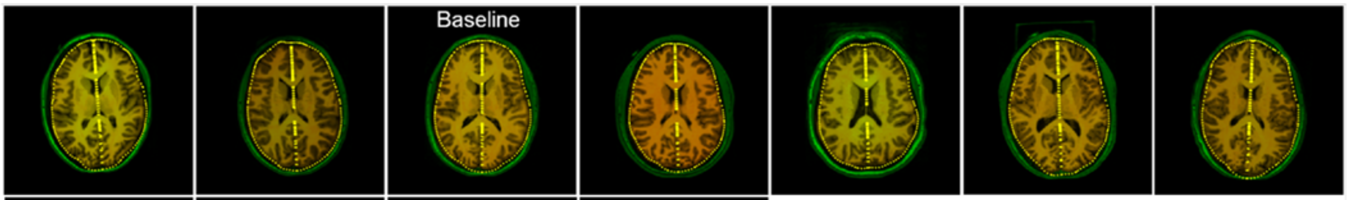
I. INTRODUCTION

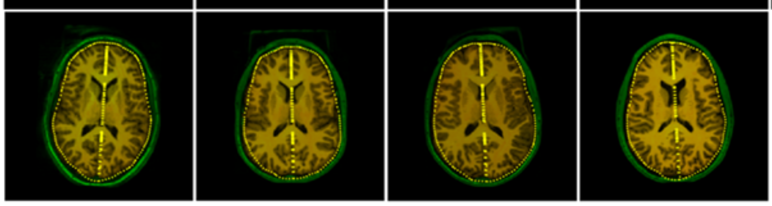
Finite element (FE) models of the human head are important tools to investigate the mechanisms behind traumatic brain injury (TBI). Over the last several decades, numerous models have been developed with varying anatomical complexity and tissue material properties, especially of the brain. They have been used extensively to estimate impact-induced intracranial mechanical responses.

Most of the models represent a 50th percentile adult head, suitable for population-based investigations. However, individual variability in head morphology exists and is well recognised [1]. There is a need to investigate how well the generic models could perform in individualised injury studies, especially given that accurate head morphological measures are becoming more accessible with the deployment of advanced neuroimaging. Previous studies along this line of research were limited. They either parametrically varied the size of a baseline adult model [2-3] or focused primarily on paediatric head models [4-5] due to the substantial head growth in this particular population. In this study, we investigate inter-subject variabilities based on actual neuroimages for a defined, given population participating in contact sports. This is an important extension to prior efforts and could lead to important implications for improving injury metrics in order to account for individual variability [6].

II. METHODS

We used the baseline Worcester Head Injury Model (WHIM) to generate 10 additional, subject-specific models via image registration and warping that account for changes in internal anatomical shapes, using a previously developed technique [7]. All of the 11 subjects participated in either high school (age 15–16 years) American football or college (age 18–23 years) football or ice hockey. The accuracy of the brain models is qualitatively illustrated by the alignment between outer brain mesh intersections and the corresponding axial images for each athlete (Fig. 1, ordered by the increase in brain volume, along with summary of morphological measures). Prior to impact simulations, these models were transformed into the baseline model coordinate system following a rigid-body registration, in order to ensure that the impact kinematics were prescribed in a coordinate system consistent with a natural head orientation [7]. Impact kinematics of a reconstructed NFL head injury case (struck athlete in Case 157; oblique impact with peak linear/rotation acceleration of 103 g and 6750 rad/s^2) [8] was employed as input. For each model/simulation, cumulative peak maximum principal strains, regardless of their time of occurrence (ε), were obtained for each element. Peak ε in the whole-brain, cerebrum, cerebellum, brainstem and corpus callosum were compared. Mesh quality of all of the individualised models was verified. In addition, all regional peak ε measures were evaluated at the 95th percentile level to further mitigate any potential numerical issues with degraded mesh quality due to non-rigid B-spline registration in mesh morphing [7].





	Brain length (mm)	Brain width (mm)
Mean±SD	171.5±5.6	127.8±2.9
Range	164. 9–180.9	123.9–132.6
	Brain Circumference (mm)	Brain volume (L)
Mean±SD	468.4±12.7	1.6±0.1
Range	452.3–495.3	1.4–1.8

Fig. 1. Brain mesh outer boundary intersections overlaid on a representative axial MRI for each athlete, along with the summary of brain (not head) morphological measures.

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III. INITIAL FINDINGS

A large variation was observed in brain morphological measures among the group (Fig. 1). For example, the volumes of the smallest and the largest brains differed by 20.7% relative to the group average (3.3% below and 19.0% above the baseline WHIM). Figure 2 illustrates the element-wise minimum, average and maximum ε, along with that of the baseline WHIM, for the 11 individualised models (resampled and presented on the baseline WHIM). A significant and positive correlation existed between regional ε and brain volume (except for the corpus callosum; Fig. 3). The differences between the minimum and the maximum ε relative to the corresponding group average ranged from 9.5% (whole brain and corpus callosum) to 25.4% (brainstem). However, strain patterns remained similar, with Pearson correlation coefficients between pair-wise ε ranging from 0.93 to 0.97.

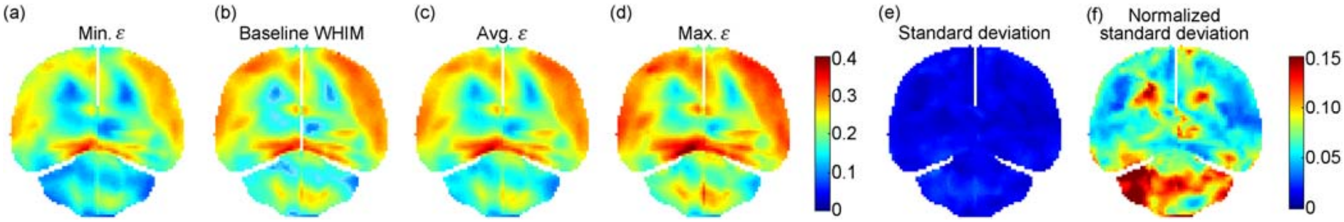

Fig. 2. Element-wise (a) minimum, (b) baseline, (c) average and (d) maximum ε along with the standard deviation (e) (further normalised by the corresponding average ε (f)). All resampled on a coronal plane.

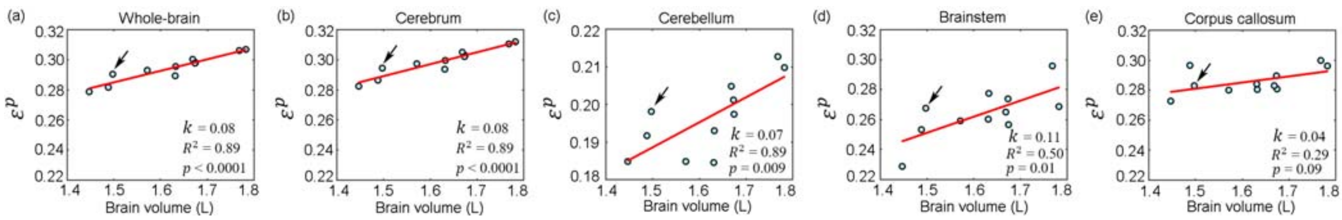

Fig. 3. Regional peak ε from individualised models as a function of brain volume: (a) whole-brain; (b) cerebrum; (c) cerebellum; (d) brainstem; (e) corpus callosum. Baseline ε from WHIM identified by arrows.

IV. DISCUSSION AND CONCLUSION

Injury diagnosis is an individualised decision-making process. Although a generic model is important for population-based studies, individual variability in mechanical responses and subsequent injury risks must also be investigated. Using subject-specific models of a group of high-school/collegiate athletes participating in contact sports, we found a large inter-subject variability in regional peak strains. The variability was largely due to differences in brain size, but can also likely be attributed to variations in brain anatomical shapes because the former did not completely account for the observed differences (maximum R^2 of 0.89; Fig. 3). This finding suggests limitations in the scaling law [9] that only considers brain size to compensate for strain/stress difference.

Our current study was limited to simple morphological and strain measures. As high-level brain functions rely on a network of grey matter regions and white matter neural tracts, further investigation into the response variability in more targeted regions/tracts and other mechanical response variables such as white matter fiber strains is warranted. This would provide critical insight into the use of a generic head injury model for studying a general population where neoroimages may not be available to generate subject-specific models.

V. REFERENCES

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