Non-Uniform Effects of Cerebral Volume on Subject-Specific Brain Strain Across Multiple Head Impacts

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I. INTRODUCTION

Brain anatomy influences brain strain estimated by finite element (FE) models, a biomechanical measure commonly used to assess traumatic brain injury risk [1-3]. Total cerebral volume (TCV) has been identified as one of the strongest anatomical determinants of predicted brain strain [1-5]. However, previous studies have typically examined this relationship using only one or a small number of impacts, limiting insight into how consistently it holds across different loading conditions. Studies incorporating slightly larger sets of simulated impacts have suggested that the relationship may not be uniform [5-6]. Therefore, we aimed to evaluate how subject-specific strain differs from generic-model strain across a broader representative set of head impacts, explicitly capturing multiple impacts per subject. This design enables assessment of not only overall trends with TCV, but also the consistency of subject-specific effects across varying loading conditions, which has not been systematically examined in previous studies.

II. METHODS

A Bayesian sampling algorithm [6] was applied separately to the subject pool and the impact dataset to identify representative samples for analysis. First, 21 subjects were selected with TCVs spanning a broad range representative of natural human anatomical variation [7], and subject-specific brain FE models were generated from their magnetic resonance images. Secondly, 70 head impacts spanning a representative range of severities were selected from validated instrumented mouthguard recordings obtained in boxing, mixed martial arts, and rugby. Recorded impact kinematics underwent video verification and signal filtering as part of the data-processing pipeline to improve quality and reduce noise. Impact severity was defined as the 90th percentile peak maximum principal strain (hereafter called MPS) in the corpus callosum, estimated using the validated Imperial College FE brain model based on a 50th percentile anatomy (hereafter called the generic model) [8]. For each simulation, MPS was extracted for the whole brain, corpus callosum, and brainstem.

Subject-specific strain was compared with the corresponding generic-model estimate for each subject–impact pair, and the relative difference was expressed as percentage MPS change. Associations of percentage strain change with TCV and impact severity were assessed using Pearson correlation on subject-level and impact-level median percentage MPS change, respectively. Percentage MPS changes in the whole brain, corpus callosum, and brainstem were also summarised across all simulations.

III. INITIAL FINDINGS

Percentage MPS change showed a strong positive linear association with TCV in the whole brain (r = 0.866) and similarly for the brainstem (r = 0.767), and fair association with corpus callosum (r = 0.588) (Fig. 1). In contrast, no significant association was observed between percentage MPS change and impact severity for the whole brain (r = 0.196), corpus callosum (r = −0.031), or brainstem (r = −0.259).

Table I summarises regional differences in percentage MPS change relative to the generic model. Median change was negative in the whole brain (-4.2%) and brainstem (-4.2%), but positive in the corpus callosum (3.1%). The corpus callosum also showed the largest mean absolute change (9.7%), compared with the whole brain (6.8%) and brainstem (8.0%). Positive changes were observed in 63.2% of corpus callosum simulations, versus 23.6% in the whole brain and 30.2% in the brainstem. Absolute changes greater than 10% were also most frequent in the corpus callosum (37.9%), compared with the brainstem (29.0%) and whole brain (23.6%).

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TABLE I
SUMMARY STATISTICS OF PERCENTAGE MPS CHANGE ACROSS BRAIN REGIONS

Brain region	*Median change (%)*	*IQR (%)*	*Mean absolute change (%)*	*Positive changes (%)*	*Absolute change > 10% (%)*
Whole brain	-4.2	-8.7 to -0.3	6.8	23.6	23.6
Corpus callosum	3.1	-3.1 to 11.4	9.7	63.2	37.9
Brainstem	-4.2	-9.5 to 1.5	8.0	30.2	29.0

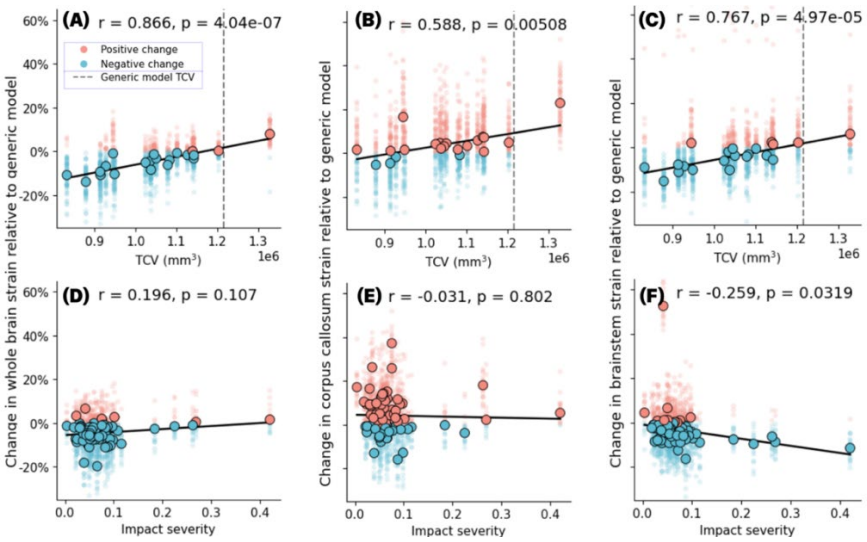

Fig. 1. Percentage MPS in subject-specific strain relative to the generic model, shown for the whole brain (A, D), the corpus callosum (B, E), and the brainstem (C, F). Strain change is plotted against TCV (A–C) and impact severity (D–F). Faint points show individual subject–impact simulations, coloured by positive (salmon) or negative (blue) change relative to the generic model. Larger points show grouped medians used for Pearson correlation. Solid black lines show the fitted linear trends. Vertical dashed lines in A–C indicate the TCV of the generic model.

IV. DISCUSSION

The present findings indicate that subject-specific variation in MPS is influenced more clearly by anatomy than by impact severity. While previous studies have established that anatomical factors such as TCV influence brain strain estimates, these have largely been based on a limited number of impacts per subject [1-3]. By evaluating a larger and more representative set of impacts, the present study extends this understanding by demonstrating that the relationship between TCV and strain is not consistent at the level of individual impacts.

Specifically, simulating multiple impacts per subject reveals substantial within-subject variability in MPS change that is not captured in studies using single or few loading conditions. Although subjects with smaller TCV than the generic model tended overall to show lower MPS, this was not true for every impact; positive MPS changes were still observed in a substantial number of cases. This shows that TCV influences the overall tendency of strain response but does not determine the direction of MPS change in a deterministic manner for a given subject and impact. Consequently, subject-specific strain cannot be fully accounted for by a single uniform scaling factor based only on TCV relative to the generic model.

This work extends that of [4] by evaluating subject-specific effects over a larger number of impacts with a broader severity range. We showed that these effects are not adequately captured by a simple TCV-based scaling approach. One limitation is that percentage MPS change was analysed in relation to TCV and impact severity separately, without assessing potential interaction effects between TCV and impact severity. Future analyses should account for the substantial impact-dependent variability observed within the same subject, and subject-specific strain prediction should move beyond simple scaling approaches and model the nonlinear relationships between brain anatomy, impact severity, and brain strain.

V. REFERENCES

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