Evaluating the Biofidelity of Human Brain Finite Element Models Using Sonomicrometry Data

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I. INTRODUCTION

Traumatic brain injury (TBI) presents an urgent public health concern with both short and long-term consequences. It is estimated that 1.5–3.6 million concussions occur annually in the USA from impacts sustained during falls, motor vehicle accidents, and competitive sport [1]. Finite element (FE) models of the brain are the state-of-the-art technique for predicting injury severity and the effectiveness of safety gear in mitigating injury. Injury is correlated to strain-based metrics calculated from the deformation response of the brain resulting from an impact to the head. The accuracy of these models is therefore dependent on how well they compare to experimentally obtained brain motion validation data. However, these models have been developed using limited validation data for relative brain-skull motion [2] The objective of this study is to evaluate the biofidelity of two human brain FE models to *in situ* 3D human brain motion data collected using sonomicrometry.

II. METHODS

In a previous study, validation data for brain motion was obtained using an array of tiny (2–3 mm), neutrally dense sonomicrometry crystals that were implanted throughout the brain tissue of a fresh cadaveric head specimen (sex: male, age: 53 years, mass: 116 kg, height: 173 cm) that was subjected to prescribed rotational skull motions. Eight crystals were affixed to the inner skull to serve as transmitters, and 24 crystals were implanted in the brain to serve as receivers, for a total of 32 crystals. Dynamic 3D displacement time-history data for each crystal was calculated using trilateration and reported as brain tissue motion relative to the skull. Four rotational impact conditions, ranging from a peak angular velocity of 20–40 rad/s with a positive-phase duration of 30–60 ms, were applied to the same cadaveric head/brain specimen in the three anatomic planes.

Two brain FE models – the GHBMC detailed M50 (v4.3) [3], and SIMon [4] – were evaluated to assess the biofidelity of brain deformation. All test cases were simulated by prescribing the experimental head centre of gravity (CG) kinematics to the FE model through a rigidised dura. The response of the brain models was assessed by comparing the motion of the crystals to the motion of the corresponding model nodes. The x, y and z motion of all functional implanted brain crystals were compared for each test for a total of 800 validation comparisons. Given the anatomical differences between the models and the cadaveric specimen (Table I), three methods for model evaluation were considered in this study: (1) using absolute coordinates of the initial crystal position relative to the head CG to identify the corresponding model node; (2) using relative coordinates based on the maximum length, width and height of the head to identify the corresponding node; and (3) scaling the dimensions of the FE models to those of the cadaveric head and using the initial crystal positions to identify the corresponding model node. The Correlation and Analysis tool (CORA) [5], using only the cross-correlation rating, was used to evaluate the displacement time-histories of the nodes. An average score of all crystals for all rotation severities in each plane was used to assess the general performance of the model.

TABLE I
ANTHROPOMETRIC MEASUREMENTS OF BRAIN

Brain	Length (x)	Width (y)	Height (z)
Specimen	150.8 mm	129.4 mm	139.2 mm
GHBMC	161.7 mm	130.2 mm	133.4 mm

III. RESULTS

There were no substantial differences between the three analysis methods, partially because of how close the models matched the specimen anthropometry. The results using the relative coordinate method (method 2) are presented because of slightly higher CORA score. The models matched the transient response of the experimental data reasonably well, resulting in responses lasting 100–200 ms (Fig. 1). The largest differences between the model responses and the experimental data were observed in magnitude and, in some cases, direction of motion. Both models performed similarly in response to all loading conditions. On average, the CORA scores ranged from 0.50–0.59 for GHBMC and 0.50–0.53 for SIMon (Fig. 2). The overall trajectory for the models matched the experimental response (Fig. 2). While SIMon performed equally in all loading directions, the GHBMC model performed best in the sagittal tests. The models also showed the same axis-dependence as the experiments, with rotations in the axial direction causing higher displacements than the sagittal and coronal rotations.

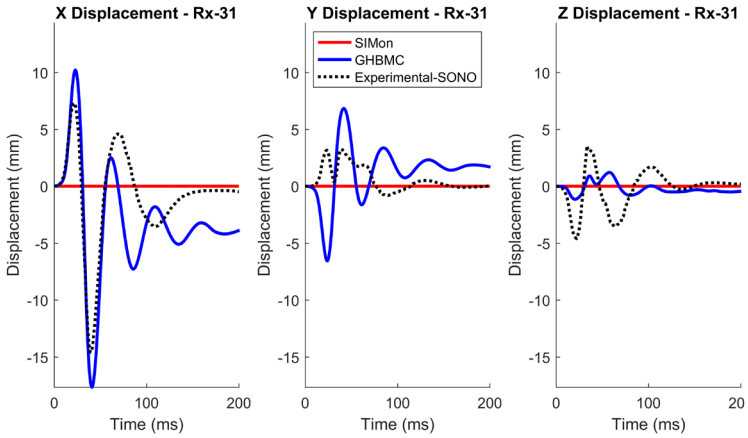

Fig. 1. Displacement time history for the x, y, z motion of receiver 31 and corresponding model nodes for the axial 40 rad/s–30 ms case.

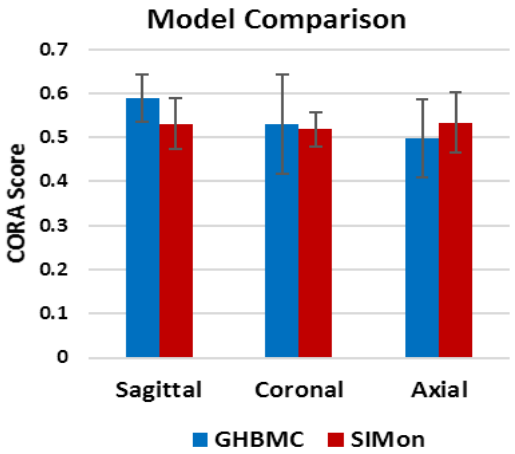

Fig. 2. CORA scores and standard deviation for all tests for each rotation axis for GHBMC and SIMon.

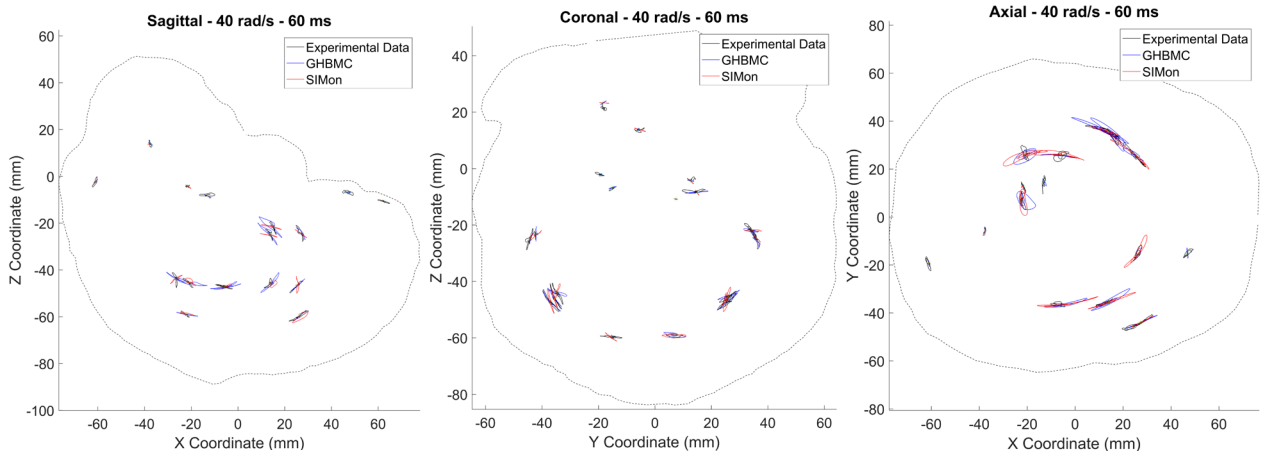

Fig. 3. Motion trajectory plots for all crystals and corresponding nodes for the 40 rad/s–60 ms case in all rotation axes.

IV. DISCUSSION

The sonomicrometry technique for dynamic brain deformation measurement represents a major opportunity to advance the field of FE brain modelling for injury analysis. This is the first study to compare the response of human brain FE models to 3D whole brain motion data acquired from a single specimen with a range of head motions in all three anatomical planes. These preliminary results suggest that the biofidelity of these models could be improved. The analysis of these models to previous datasets (Hardy 2007), showed similar CORA scores ranging from 0.15 to 0.5 for both GHBMC and SIMon [6]. While the FE responses did not correlate well to this experimental data set, these data were obtained from a single specimen, and the experimental data is specific to the anthropometry of the tested specimen. With additional specimens, it is possible model responses will fall within the response corridors. This limitation was considered by using three analysis methods, by choosing nodes relative to the dimensions of the models and by scaling the model geometry. These approaches may not, however, be appropriate for model assessment. Additional details, such as regional skull and brain anatomical differences, were not considered. This study also suggests the need to re-evaluate brain tissue material properties and/or to develop more sophisticated scaling techniques specific to brain deformation.

IV. REFERENCES

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