Multimodal Experimental Acquisition of Brain Motion in a 3D Headform Phantom

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I. INTRODUCTION

Computational models of the brain are a useful predictive tool to investigate risk of brain injury and the effectiveness of safety devices. The strain output of these models is often used to correlate head kinematics to injury risk within automotive, military and sports environments. The biofidelity of the strain is essential to the predictive capability of these models. Recently, several studies have been able to measure the displacement and deformation time-history of the *in vivo* brain under non-injurious loading scenarios using tagged magnetic resonance imaging (tMRI) [1][2], and the *in situ* brain under injurious loading scenarios using sonomicrometry [3]. The data generated from these experimental approaches provide extensive validation data, but are still disparate in providing comprehensive model evaluation. The tagged MRI (tMRI) data are collected in living humans with high spatial resolution (1.5 mm), but it is limited to low rates of loading (3–4 rad/s) and low temporal resolution (50 Hz) [2]. The sonomicrometry method generates data at injurious loading conditions (20–40 rad/s) at high temporal resolution (600 Hz) but is limited in spatial resolution to 24 discrete markers within the brain [1]. The objective of this study was to investigate the complementary attributes and results of tMRI and sonomicrometry for measuring deformation response of the brain. Here, a physical headform was developed with an instrumented, deformable brain to be used for a wide range of test conditions with both measurement techniques.

II. METHODS

The external geometry of the headform was matched to the standard National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform [4]. The geometry of the internal brain cavity was obtained from an anatomical brain template constructed from scans obtained from 20 young, healthy male subjects [5]. The brain template had an intracranial volume of 1440 cm^3. The headform was designed in four quadrants to permit filling the headform with a brain simulant material and to precisely place brain surrogate instrumentation. A cylindrical void representing the brain stem was left to allow the cavity to be filled with brain simulant, and to allow instrumentation cables to exit the cavity. The headform was 3D printed using Onyx on a Markforged Mark Two printer. Sylgard 527 (with a 1:1 ratio of A:B) was selected as the brain simulant material based on a prior investigation of seven different materials that measured deformation amplitude, frequency response, speed of sound and rheometry-derived shear response compared to published human brain tissue data [6]. Two headforms were created: one with embedded sonomicrometry sensors to be used in the high-rate loading test environment; and one without sonomicrometry sensors to be used in a MRI scanner. Measurements of displacement and strain within the brain surrogate were obtained using both tMRI and sonomicrometry in response to a mild head rotation (4 rad/s) in the axial direction.

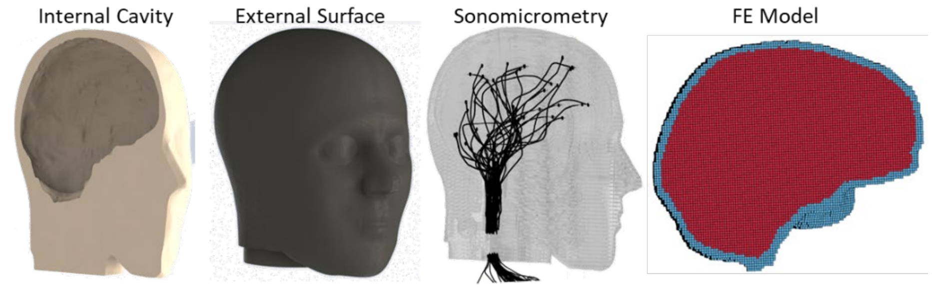

Fig. 1. The headform internal and external geometry are shown in addition to one headform with sonomicrometry sensors and its FE model.

A finite element (FE) model of the headform was also created that represents the deformable simulant in

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the cavity and the rigid external layer. The simulant was modelled using a linear viscoelastic material with two time constants, which were calibrated using rheometry tests of Sylgard 527 gel. Loading conditions measured from the experimental mild head impact were applied to the model to investigate its correlation to the experimental displacements.

III. INITIAL FINDINGS

Measurements of displacement and strain within the brain headform were obtained using tMRI in response to a mild head impact. Preliminary results show that the magnitude of maximum resultant displacement (MRD) and strains in the headform were larger than what has been measured in healthy volunteers under the same loading conditions [2], likely due to the fixed boundary condition of the gel to the external casing. Displacement measured using the two experimental techniques with the same loading conditions show that maximum resultant displacements (0.23–3.75 mm) were roughly 1.5 times larger with the sonomicrometry experiments than tMRI (0.23–2.5 mm) (Fig. 2A), likely due to the higher sampling rate of sonomicrometry (i.e. missing the peak displacement in the tMRI data). The vector of maximum displacement for each sensor location (Fig. 2A) is consistent between the two experiments and with the FE model. The resultant displacement time-history (Fig. 2B) shows the effect of temporal resolution in tMRI in missing the peak, as well as noise at the end of the trace due to tag fading. The effect of spatial resolution is shown in Fig. 2C, with limited coverage of the sonomicrometry crystals in comparison to tMRI and the FE model.

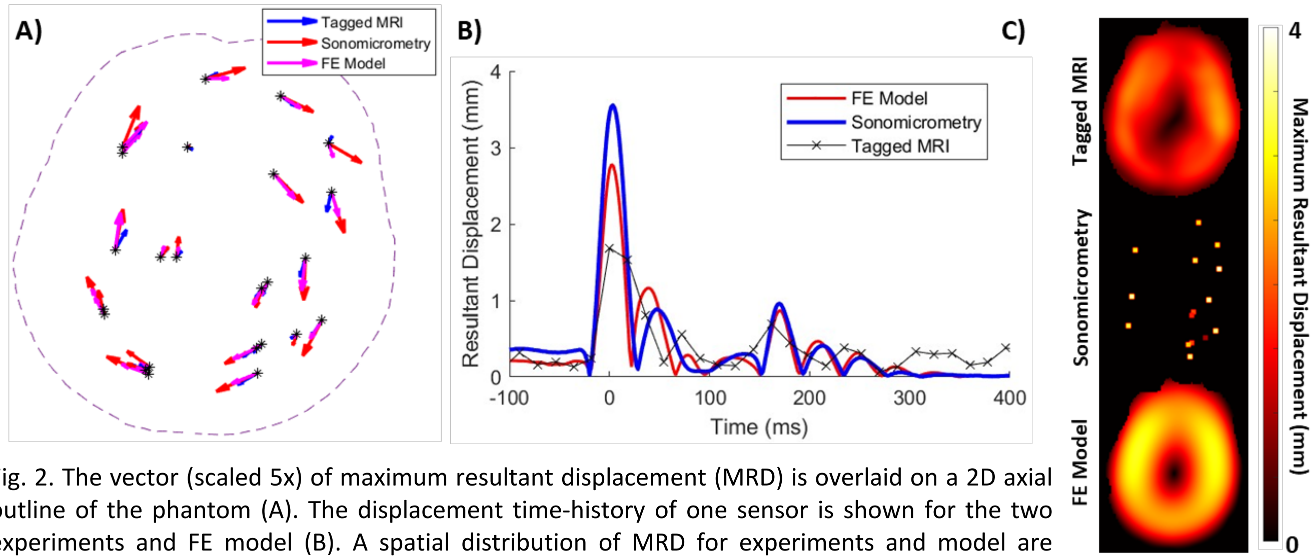

Fig. 2. The vector (scaled 5x) of maximum resultant displacement (MRD) is overlaid on a 2D axial outline of the phantom (A). The displacement time-history of one sensor is shown for the two experiments and FE model (B). A spatial distribution of MRD for experiments and model are shown for one axial slice.

IV. DISCUSSION

Overall, the two experimental methods show consistent measurements in direction, magnitude and spatial distribution of motion, providing preliminary data for multimodal interpolation of the 3D dynamic displacement field. Once fully validated using the two experimental techniques, this headform will provide a platform for investigating dynamic brain deformation under a wide range of experimental loading conditions. The use of sonomicrometry and tMRI will allow for investigations of interpolation algorithms in space and time to alleviate the disadvantages in resolution of either technique. To date, the biofidelity of the headform has only been assessed under low-energy loading conditions. Future work will be performed to assess the brain deformation response under injurious loading conditions, compared to those obtained from post-mortem human surrogate tissue [3]. Additionally, a spatial interpolation scheme informed by tMRI data would allow for the calculation of strain from the sparse sonomicrometry markers at higher loading conditions.

V. REFERENCES

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