Measuring 3D Brain Deformation During Dynamic Head Motion Using Sonomicrometry

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I. INTRODUCTION

Mild traumatic brain injury (mTBI) presents an urgent public health concern. 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]. Although the exact mechanism of mTBI is unknown, studies have suggested that rotational loading of the head, and ensuing brain deformation, is the primary cause of the diffuse injuries associated with mTBI [2-4]. Previously, human brain deformation has been studied through the use of neutrally dense, radiopaque targets implanted in the brain tissue of cadaveric specimens and their 3D motion tracked using bi-planar X-ray during head impact [5-6]. Although these experiments provide insight on how the brain deforms, they include several limitations associated with line-of-sight constraints. The objective of this study is to develop a novel methodology to quantify 3D whole brain deformation *in situ* for multi-directional dynamic head rotation. This method will provide a framework for acquiring accurate and repeatable brain deformation data using sonomicrometry that can be used to generate biofidelity targets for finite element (FE) model development, validation, and improvement. Considering the widespread use of these models for injury prediction, it is essential that they are validated using comprehensive experimental data with well-defined boundary conditions.

II. METHODS

A fresh cadaveric specimen (sex: male, age: 53 years, mass: 116 kg, height: 173 cm) was obtained 14 hours post mortem, and the head and cervical spine were dissected at the T1-T2 joint. An array of neutrally-dense targets was implanted into the brain tissue of the specimen using a minimally invasive cannula technique. These targets are piezoelectric sonomicrometry crystals (2–3 mm diameter) that are each capable of transmitting and receiving ultrasound pulses. Once implanted into tissue, the distance between each pair of sonomicrometry crystals can be determined by the time of flight of the ultrasound pulse travelling from one crystal to another [7]. In this study, the sonomicrometry crystal array geometry was designed to maximise the volume over which the brain deformation was captured, while avoiding the periphery of the brain and the ventricles. Twenty-four receiving crystals were implanted into the brain tissue, and eight transmitting crystals were rigidly fixed to the inner surface of the skull to act as a fixed reference frame. Initial placement of all 32 crystals was documented using computed-tomography (CT) images acquired after the head was instrumented. During each test, point-to-point distances between transmitting and receiving crystals were recorded at 500 to 700 Hz, and trilateration was used to calculate the 3D coordinate-time histories for each crystal within the skull reference frame. The head/brain specimen was actively perfused with artificial cerebrospinal fluid to maintain the desired state of the brain, and to eliminate the presence of any air pockets that would interfere with the transmission of ultrasound [5-6].

Tests were performed with a rotational test device (RTD) designed to deliver controllable and repeatable pure-rotational pulses to the head about all three anatomical axes of rotation through the head centre of gravity (CG). The RTD was powered by a pneumatically driven, PID-controlled servohydraulic linear drive system. A cable transmission system translated the linear output of the drive cylinder into a rotational pulse. A gearbox was used to allow rotation of the head in three orthogonal axes, while maintaining a consistent initial position of the head (inverted). Fifteen dynamic rotation tests were performed on the specimen, with four different rotation pulses (ranging from 20 rad/s to 40 rad/s peak angular velocity, with positive-phase velocity durations of 30–60 ms), three different rotation directions (sagittal, coronal, and axial), and three repeated tests at the highest severity levels. Head kinematics were acquired using an array of three linear accelerometers and three angular rate sensors. All data, including sonomicrometry displacements, were transformed to the head CG. All testing was performed on the specimen less than 60 hours post mortem.

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III. RESULTS

Preliminary results show that sonomicrometry provided good quality and highly repeatable 3D deformation data for the brain. Following the load, the crystals consistently returned to their initial positions, indicating that they did not move relative to its surrounding tissue, and that these test conditions did not result in gross structural damage of the brain (as expected). Peak-to-peak crystal displacements as large as 8.5 mm, 9 mm, and 15 mm were measured in the sagittal, coronal, and axial rotation tests, respectively, for the 40 rad/s, 60 ms condition. Brain deformations were larger in axial rotation for a given loading condition than in the sagittal and coronal directions. The transient response of the brain was observed to last between 100 and 200 ms after the initiation of rotation (Fig. 1), and the first mode natural frequency of the marker motion was found to be approximately 12 Hz. The repeated test condition (40 rad/s, 30 ms) indicated that the observed deformation time histories were highly repeatable (Fig. 1).

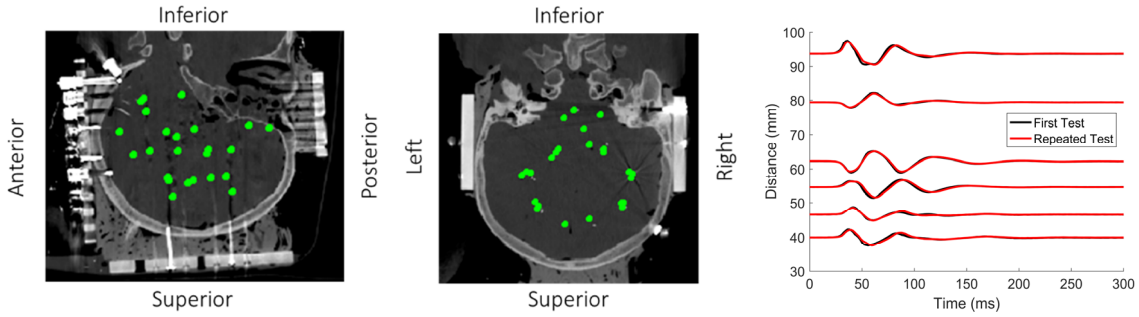

Fig. 1. Left and centre: projected CT images illustrating the location of each of the sonomicrometry crystals implanted in the brain (not shown: an additional eight crystals were rigidly fixed to the inner surface of the skull). Right: select point-to-point distance traces from the raw sonomicrometry data for the repeated coronal rotations, 40 rad/s, 30 m/s tests.

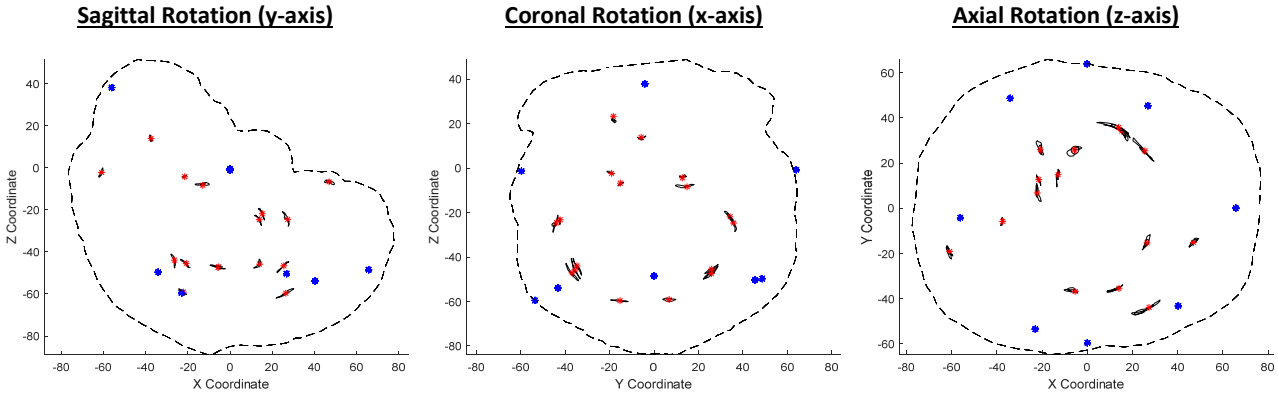

Fig. 2. Trilaterated trajectories of the crystals implanted in the brain from select tests (all 40 rad/s, 60 ms) in the skull reference frame. The three plots show the results of three different tests: one test with rotation in the sagittal plane (left); one with rotation in the coronal plane (centre); and one with rotation in the axial plane (right). The red dots indicate the initial positions of the crystals implanted into the brain tissue, with trajectory traces shown projected in the plane of rotation. The blue dots indicate the positions of the eight crystals affixed to the skull.

IV. DISCUSSION

The results presented in this study suggest that sonomicrometry is an effective tool for measuring 3D *in situ* brain deformation during dynamic head rotation. Compared to other approaches, such as bi-planar X-ray [5-6], sonomicrometry allowed for a single instrumented specimen to be tested in a range of impact severities, without line-of-sight or test volume constraints. Both the sonomicrometry and the mechanical test device proved to be highly repeatable, which will be crucial for developing biomechanical response targets for brain FE model validation. Future investigation will include increasing the sample size with additional cadaveric specimens to create brain deformation response corridors for FE model validation. This methodology may also be extended in the future to other potential brain injury environments, including direct head impact and other types of loading.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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