Human Brain Deformation During Controlled Dynamic Rotation of the Head

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I. INTRODUCTION

Finite element models of the human brain are the state-of-the-art technique for simulating real-world head impacts to assess brain injury risk, investigate potential neurotrauma mechanisms, and develop injury countermeasures. However, these models must be validated to human brain deformation. Recently, a technique was developed using sonomicrometry to record 3D brain motion data in a human cadaver model subjected to injurious conditions generated using a controlled dynamic rotation of the head [1]. Leveraging this technique, the objective of this study was to generate a dataset of dynamic brain deformation collected from multiple specimens under various kinematic conditions to investigate the relationship between brain deformation magnitude and the characteristics of the applied head loading.

II. METHODS

All tissue donation, testing, and handling procedures for this study were approved by the University of Virginia Institutional Review Board – Human Surrogate Use Committee. Intact head-neck specimens transected at the C7T1 junction were harvested from six fresh post-mortem human surrogates (PMHS). Magnetic Resonance Imaging (MRI) was collected for each PMHS prior to transection. The skull was denuded and secured to fixture plates that were attached to the superior, lateral, and posterior surfaces using a custom-built jig (Figure 1, left). All instrumentation and fixtures were installed relative to the head center of gravity (CG) which was estimated based on anatomical landmarks [2]. Artificial cerebrospinal fluid was used to provide constant perfusion throughout preparation and testing, with a hydrostatic pressure of approximately 78 mmHg.

An array of 30 neutrally-dense sonomicrometry crystals were implanted into the brain tissue via a stereotactic cannula system, and six crystals were affixed to the inner surface of the skull (Figure 1, right). Following the installation of the sonomicrometry sensors, computed tomography (CT) images were acquired at a resolution of 0.625 mm to determine the initial coordinates of each receiver and transmitter relative to the head CG. The specimen was then installed onto a custom-built test device designed to apply controlled and repeatable rotations in the sagittal, coronal, and axial directions through the head CG. In all rotation directions, the head was inverted at the initiation of every test to allow for consistent perfusion and brain geometry, and the specimen was returned to its initial position after every test.

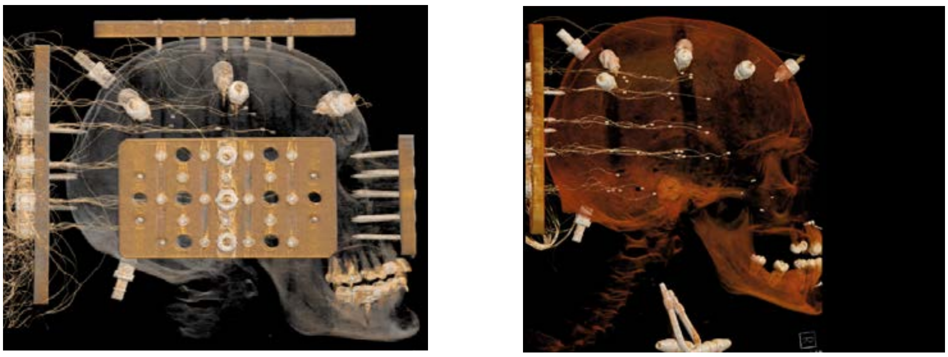

Figure 1: Representative CT images following the specimen preparation and crystal insertion with (left) and without (right) mounting fixtures. Note that slack in the wires during insertion, and the perfusion ports.

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Somomicrometry data was sampled at 600 Hz which is sufficient for brain tissue displacement response. Position time-history data for brain motion was calculated from sonomicrometry measurements using an Extended Kalman Filtering trilateration algorithm [3], and reported as 3D brain tissue displacement relative to the skull. Four nominal severities of rotation ranging from a peak angular velocity of 20 – 40 rad/s with a duration of 30 – 60 ms were applied about three orthogonal anatomical for a total of 12 test conditions per specimen. All kinematics data was collected using a six degree-of-freedom sensor package recorded at 10 kHz. All tests were completed within 72-hours post-mortem.

III. INITIAL FINDINGS

There were a total of 72 tests conducted across six specimens, corresponding to approximately 5000 response curves for brain motion in the local head coordinate system. Brain deformation response was dependent on peak angular velocity, duration, and loading direction – axial rotation resulted in the greatest deformation. Peak-to-peak displacement amplitudes reached as high as 23 mm in the most severe loading case (the 40 rad/s, 30 ms case in axial rotation). The brain motion in the plane of rotation follows an arcing trajectory about a point independent of the head CG, and the transient duration of the brain response lasted for 100-150 ms after head motion stopped.

The maximum peak-to-peak brain displacement for every test was used in a multiple linear regression (with interaction terms) to determine the dependence of brain deformation magnitude on peak head kinematics (Figure 2). The regressions showed a statistically significant ($p<0.05$) increase of brain deformation, with increasing angular velocity and decreased duration. All three directions of loading had similar characteristic response, with sagittal and coronal rotation having similar magnitudes of peak-to-peak deformation, while the axial direction resulted in higher deformation for the same input kinematics.

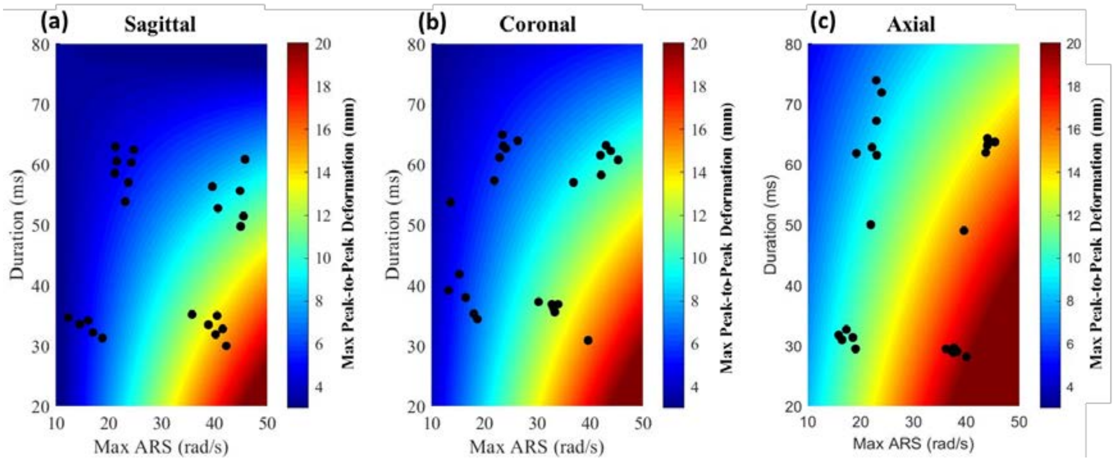

Figure 2: Contour plots depicting the results of the linear regression using the maximum angular velocity (ARS) and duration for the sagittal (a), coronal (b), and axial (c) tests. The sagittal regression model had an R^2 of 0.691, the coronal regression model had an R^2 of 0.693, and the axial regression model had an R^2 of 0.795.

IV. DISCUSSION

This is the first study to quantify 3D brain deformation in multiple human specimens in response to a range of rotational motions in all three anatomical planes. Sonomicrometry was a successful method that provided highly repeatable 3D displacement data of the *in situ* dynamic motion of the brain. The empirical evidence that brain deformation was dependent on the angular velocity amplitude, duration, and direction of the head loading. This suggests that prediction of brain injury risk with kinematic metrics may require consideration for duration or acceleration in addition to angular velocity, such as UBRIC [4] and DAMAGE [5], in contrast to predicting injury risk based on angular velocity magnitude alone, such as BrIC [6].

V. REFERENCES

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