Preliminary investigation of sex-specific geometries and head kinematics on brain response using finite element brain models in automotive crash loading conditions

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I. INTRODUCTION

Approximately 2.5 million US emergency department visits are linked to traumatic brain injuries (TBI), with causes of injury including automotive vehicle crashes [1]. Within frontal automotive crashes, females have a significantly greater risk for moderate brain injury compared to males, including an increased risk of sustaining a concussion [2-3]. Several biomechanical factors, including neuroanatomy, material properties, head kinematics, or injury tolerance, could contribute to differences between male and female brain deformation responses and resulting TBI risk. To study the effects of these biomechanical factors, finite element (FE) brain models are used to predict brain response under loading conditions that may result in injury [4]. Using a set of subject-specific FE brain models based on various male and female brain neuroanatomies, the objective of this study was to determine the effect of total intracranial volume (ICV) and head kinematics on strain-based deformation metrics, using a range of head kinematics seen in automotive crashes and sex-specific head kinematics from sled tests.

II. METHODS

In this study, six subject-specific brain models were developed to represent the 5th, 50th and 95th percentile intracranial volumes (ICV) of the healthy male (M) and female (F) adult (21–65 years) brains within the Enhanced Nathan Kline Institute – Rockland Sample (N=391) [5]. These models were generated using registration-based morphing (RBM), which leverages medical image registration transformations to morph a calibrated and extensively verified template model to the anatomy of a target subject. Developed specifically for automatically generating subject-specific brain models, this nonlinear morphing technique accurately captures the size, shape and local anatomy of the subject's brain [4]. Across the six models, material parameters, boundary conditions, and numerical implementations were consistent, and the geometry for each model was subject-specific [6].

TABLE I
AGE AND INTRACRANIAL VOLUME FOR EACH SUBJECT-SPECIFIC MODEL

Model	Age (yr.)	ICV (cm^3)	Model	Age (yr.)	ICV (cm^3)
F05	36	1177.1	M05	30	1274.2
F50	40	1337.9	M50	36	1494.6
F95	44	1530.6	M95	45	1701.9

The first set of head kinematics was selected to represent a range of severity levels seen in automotive crashes. The Diffuse Axonal Multi-Axis General Evaluation (DAMAGE) metric was calculated for all automotive loading conditions within the Gabler *et al.* head impact database, which includes kinematics from anthropometric test devices (ATDs), post mortem human surrogates (PMHS), and volunteers in sled and crash tests [7-8]. Three loading conditions, associated with the 5th, 50th and 95th percentile DAMAGE values from a 50th percentile male PMHS in oblique impacts, were selected and simulated with each subject-specific model, for a total of 18 simulations.

Sex-specific head kinematics were selected from multiple Gold Standard 2 (GS2) sled test series using ATDs and PMHS. The GS2 test conditions approximate an occupant's response to a 30 km/h frontal crash using a rigid planar seat, bilateral rigid knee bolsters, pelvic blocks and a force-limited 3-point shoulder and lap belt (shoulder belt force limiter: 3 kN for males and 2 kN for females) [9-12]. The selected GS2 sled tests included multiple surrogates (M50 PMHS (n=4), F05 PMHS (n=10), Hybrid III M50 (n=5) and F05 (n=5) ATDs, and THOR M50 (n=3) and F05 (n=3) ATDs). Each set of sex-specific 6-DOF head kinematics was run with the corresponding FE brain model, matching both sex and percentile (e.g. F05 head kinematics simulated with F05 model).

All loading cases were simulated by prescribing the experimental 6-DOF head kinematics to the brain model through a rigid dura part. The 95th percentile maximum principal strain across all brain elements (MPS-95) was used to compare brain response between each of the models and loading. All simulations were performed using the LS-DYNA explicit solver (mpp971R9.1.0, double precision, LSTC, Livermore, CA, USA), and run on 40 CPUs.

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III. INITIAL FINDINGS

The first set of simulations was based on the head kinematics selected to represent a range of severity within automotive impacts. For the 5th, 50th and 95th percentile DAMAGE-based head kinematics, MPS-95 increased linearly with increasing intracranial volume with high correlation (Fig. 1). As loading severity increased, the correlation between MPS-95 and intracranial volume increased. The 12% increase of MPS-95 between the M95 and F05 models was the largest for the most severe kinematics, with MPS-95 values of 0.44 and 0.39, respectively.

Within the sex-specific head kinematics, the spread of the female MPS-95 values was larger than the spread of the male MPS-95 values. This is likely at least partially attributable to the spread of the female head kinematics in the GS2 test series, where the small females exhibited larger variation than the mid-sized males [9-12]. For the kinematics simulated, the average MPS-95 from the M50 Hybrid-III and THOR head kinematics were larger than the average MPS-95 from the PMHS head kinematics. Conversely, the average MPS-95 from the F05 Hybrid-III and THOR head kinematics were smaller than the average MPS-95 from the PMHS head kinematics.

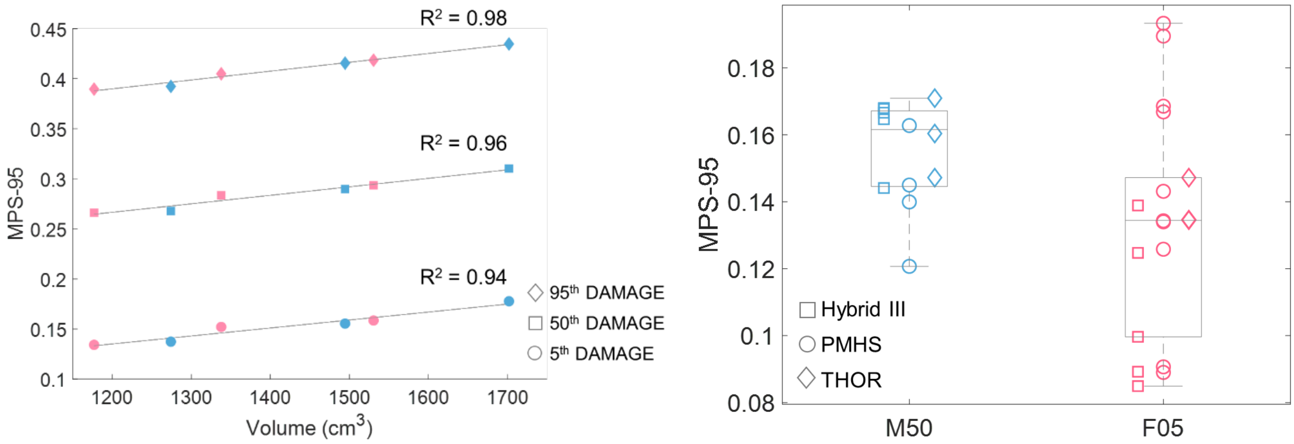

Fig. 1. (Left) The MPS-95 value for each of the six models (female models in pink, male models in blue) from the three different DAMAGE-based kinematics (shapes indicate DAMAGE severity). (Right) The MPS-95 value from the sex-specific head kinematics for the M50 and F05 models for all surrogates (shapes indicate surrogate kinematics simulated).

IV. DISCUSSION

There is a pressing need for a better understanding of female TBI biomechanics to reduce the incidence and severity of TBI in females. Currently the majority of TBI biomechanics research and strain-based brain injury metrics are derived using 50th percentile male FE brain models. For the same input head kinematics, there is a positive linear correlation between intracranial volume and MPS-95. Additional work should be done to improve the understanding of this relationship across a wider range of head kinematics and potentially establish injury risk metrics that consider intracranial brain volume. Furthermore, additional matched sex-specific head kinematics are needed to draw further conclusions about the effect of sex-specific head kinematics on brain deformation response. While sled kinematics were similar for the male and female surrogates in the GS2 sled test series, differences in shoulder belt force limiters, 3 kN for males and only 2 kN for females, result in the inability to discern sex-specific differences in brain response. The importance of comparable male and female data cannot be overstated to improve sex-specific injury research.

In addition to the sex differences in neuroanatomies and head kinematics, the effect of regional material property differences and localized strain distributions needs further research. While the relative effect different neuroanatomies, material properties, head kinematics, and injury tolerances have on brain response and TBI risk are a topic of current investigation, advancements in understanding the effects of these biomechanical factors may reduce injury severity and risk for all occupants.

V. REFERENCES

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