Computational Brain Injury Responses of Helmeted Side Impacts Using Data from ATDs versus PMHS

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I. INTRODUCTION

In previous studies, investigators have examined the brain response to helmeted head impacts by performing standard laboratory tests and driving computational finite element (FE) models with kinematics data collected from the head centre-of-gravity (CG) [1-3]. Anthropomorphic test devices (ATDs) are often used to assess helmet performance and risk of skull fracture. However, post-mortem human subjects (PMHS) may be advantageous for assessing risk of brain injury due to the presence of a brain and a decoupled head-neck motion compared to ATDs. Depending on the ATD model chosen, FE simulations may be influenced by the somewhat decreased head-neck kinematic biofidelity observed in ATDs [4]. The objective of this study is to compare brain strains derived from FE simulations of PMHS and ATDs subjected to similar pendulum impacts.

II. METHODS

A custom-built rigid arm pendulum system (Fig. 1(A)) was used to conduct lateral-impact tests with American Football helmets mounted on ATDs and PMHS. ATD tests included a medium National Operating Committee on Standards for Athletic Equipment (NOCSAE) head, which is representative of a 50th percentile male and was attached to a EuroSID-2 (ES-2) neck via custom adapters (Fig. 1(B)) [5]. The NOCSAE head was instrumented with a nine-accelerometer package and was chosen for its shape features that facilitate a realistic helmet fit [6]. The ES-2 neck was chosen because it was designed for lateral-impact tests [7].

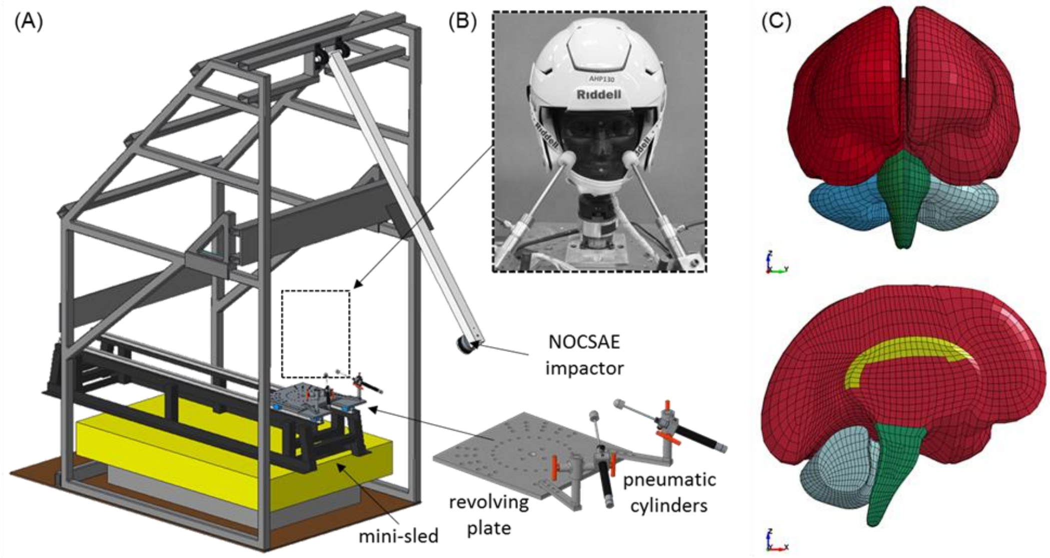

Fig. 1. (A) 3-D drawing of rigid arm pendulum system. The impact site was adjusted with the mini-sled and revolving plate. (B) Pneumatic cylinders balanced the head to prevent neck buckling due to gravity. (C) Coronal and mid-sagittal views of the SIMon model with the cerebrum (red), cerebellum (blue), brainstem (green), and ventricles (yellow) shown.

For PMHS tests, the specimen was isolated from the head to T2, potted in polymethyl methacrylate (PMMA) at T1, and instrumented with an internally mounted six degree-of-freedom reference sensor near the head CG. The helmet impact site for ATD tests was located 60 mm above the basic plane of the NOCSAE head, in accordance with NOCSAE test protocols. The helmet impact site for PMHS tests was consistent with the location specified for ATD tests. The specimen was oriented with the Frankfort plane horizontal and the occipital condyles positioned

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directly superior to T1 [8]. Instrumentation measurements accounted for the reference sensor orientation relative to the Frankfort plane and the reference sensor location relative to the centre of the auditory meatus. Only lateral impacts were considered, based on previous analyses of on-field data and diagnosed concussions.

The Simulated Injury Monitor (SIMon) (Fig. 1(C)) FE model was based on a 50th percentile male and selected due to its validation with animal and PMHS data [9]. Compared to the geometry of the medium NOCSAE head (i.e., 50th percentile male), the PMHS head geometry differed by 17% in length, 2% in width, and 6% in circumference. Experimental data obtained from the head CG was applied to the rigid skull of SIMon. The extent of brain injury was assessed with the Cumulative Strain Damage Measure (CSDM), which relates to the maximum principal strain and represents the brain volume that exceeds a predefined strain threshold. The CSDM was calculated at a strain threshold of 10%, which was denoted as CSDM(10), and was chosen for this work because it has been correlated previously with head impact data collected from American Football players [10].

III. INITIAL FINDINGS

Average peak head kinematics matched well between ATD and PMHS tests (Table I), with lateral linear accelerations within 6% and coronal angular velocities within 1%. Average times-to-peak (TTP) were 27% higher for linear accelerations in ATD tests but 51% higher for coronal angular velocities in PMHS tests. Average peak CSDM(10) values were 15% higher with the SIMon model driven by ATD versus PMHS data.

TABLE I
COMPARISON OF EXPERIMENTAL AND FE SIMULATION RESULTS.

Test ID	Peak a_y (G)	Peak ω_x (rad/s)	TTP a_y (ms)	TTP ω_x (ms)	CSDM(10) (%)
ATD-1	24.5	16.8	9.2	30.4	8.4
ATD-2	26.2	16.0	8.4	33.9	7.3
PMHS-1	25.1	15.4	7.2	45.7	6.1
PMHS-2	26.9	16.4	7.5	46.2	6.3
PMHS-3	28.7	17.3	6.0	54.5	8.0

IV. DISCUSSION

Computational models are vital tools for assessing the risk/extent of brain injuries attributed to helmeted head impacts. Despite the technical challenges, PMHS test data may be advantageous for use in FE brain models due to the more realistic helmet-head coupling and decoupled head-neck response of PMHS compared to ATDs. Variations in CSDM were attributed to angular velocity differences between ATDs and PMHS. This observation is based on previous work which showed that CSDM had a stronger correlation to angular velocity compared to angular or linear acceleration [11]. Another study showed that change in angular velocity was a strong predictor of CSDM regardless of impact location [12]. Although a larger sample size is needed, these initial findings showed that the NOCSAE head/EuroSID-2 neck configuration generated a similar lateral-impact ATD response as PMHS.

V. ACKNOWLEDGMENTS

This publication was supported by the National Center for Advancing Translational Sciences, National Institutes of Health, through Grant Number 8UL1TR000055, the US Army Medical Research and Materiel Command under Award No. W81XWH-12-1-0004 and by the Defense Health Program under the Department of Defense Broad Agency Announcement for Extramural Medical Research through Award No. W81XWH-14-1-0561. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the Department of Defense or NIH.

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