Intracranial strain measurements within a polymeric head surrogate

Jennifer Rovt, Sheng Xu, Scott Dutrisac, Simon Ouellet, Oren E. Petel

I. INTRODUCTION

Contemporary sports helmet testing standards have successfully reduced the prevalence of focal injuries, such as skull fracture and severe brain trauma, among athletes [1], although concussion prevalence remains high [2]. These standards have traditionally focused on monitoring the kinematic response of a rigid head surrogate (headform) subjected to a drop test or linear impact loading event. Acceptable acceleration thresholds and kinematic-based impact severity indices have been used to correlate impact kinematic characteristics and the associated brain injury risk [3-4]. Despite the correlation between head kinematics and injury outcomes, kinematics-based metrics remain an indirect predictor of injury, which might lose accuracy when used outside of its range of validation or for protected impact scenarios. Tissue strain is thought to be the primary mechanism of injury [5] and finite element (FE) models are commonly used to link head kinematics to tissue strain [6]. Alternatively, a properly calibrated anthropomorphic surrogate, consisting of a deformable polymeric skull and elastomeric brain that provides a direct measurement of intracranial strain, would be an invaluable tool for helmet performance evaluation. In this study, we demonstrate the use of a deformable headform to measure full-field displacements and strains taken within an elastomeric brain surrogate using an X-ray Digital Image Correlation (XDIC) technique. Using a direct tissue-level metric, such as the Maximum Principal Strain (MPS) within tissue-simulants, may provide a more robust basis for helmet performance comparisons.

II. METHODS

The BIPED headform [7], which has a urethane rubber skin and skull and Sylgard 527 brain, was used in the present study. The brain simulant was constrained within the skull by a falx membrane simulant and was floated within water to simulate cerebrospinal fluid. The speckles used in the XDIC calculations were obtained by the insertion of approximately 500 radiopaque markers, placed along a parasagittal plane (15 mm from midsagittal) during the casting process. These markers were designed based on the results of a parametric study of embedded marker interference on the natural deformation of a tissue simulant [8] and shown to have minimal interference in the strains measured in their surrounding matrix [9]. The markers were prepared from a mixture of thermoplastic gel (Humimic gel #4) and barium sulphate powder (60% by mass), having a cylindrical shape with a 2 mm diameter and length. Once sealed, the headform was fully perfused with water prior to testing. It was agitated to remove any trapped air and maintained under a static pressure of 1 m of H_20 during testing.

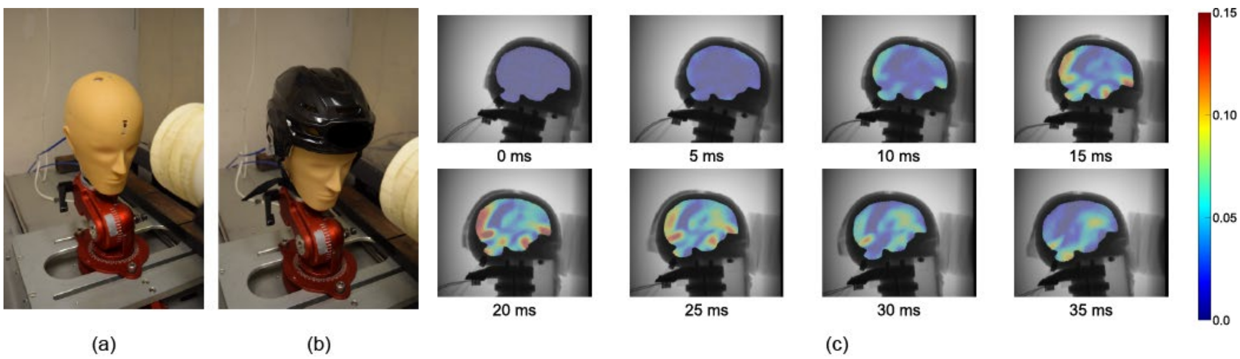

Fig. 1. Photographs of (a) the bare headform and (b) the helmeted headform prior to testing. (c) A sequence of X-ray images and the associated shear strain response in the headform surrogate for a 3.1 m/s impact at 5 ms intervals.

A preliminary series of impacts was conducted to test the bare and helmeted headform response using a linear impactor (13.13 kg ram). Photographs of the test configuration are shown in Fig. 1a and 1b, respectively. The headform was subjected to frontal impacts at speeds of 3.1 m/s and 5.0 m/s. The end cap of the impacting ram was an 85 mm-thick vinyl nitrile foam pad to ensure that the bare skull of the headform did not risk fracture during testing. The headform was supported on a neck that was pre-tensioned to 10 in-lb and was designed to

J. Rovt is an MASc student, S. Xu and S. Dutrisac are PhD students, and O.E. Petel (e-mail: oren.petel@carleton.ca) is an Associate Professor in Mechanical & Aerospace Engineering at Carleton University, Ottawa, ON, Canada. S. Ouellet is a Defence Scientist at Defence Research and Development Canada Valcartier in Quebec City, Canada.

exhibit no directional bias [10]. The kinematic response of the headform was recorded on a rigidly attached neck extension using a 6DX Pro accelerometer (DTS) and then translated to the centre of gravity of the headform. Data were captured at 20 MHz and filtered using a low pass CFC180 filter at 300 Hz. Marker motion paths were captured using a custom high-speed X-ray (HSXR) system at a frame rate of 5,000 fps. These images were corrected for distortion. XDIC calculations were carried out using NCorr [11], providing measures of internal displacement and strain within the brain simulant. All reported strains are Green-Lagrangian strain.

III. INITIAL FINDINGS

A sequence of images showing the X-ray images and associated two-dimensional MPS distribution within the bare headform, impacted at a speed of 3.1 m/s, are shown in Fig. 1c. A summary of the kinematic response of the headform for the four impact conditions described in the present work is provided in Table I. The 95th percentile MPS values associated with these impacts are shown over the first 35 ms following impact in Fig. 2, capturing the initial strain peak, prior to the influence of the neck form.

TABLE I: SUMMARY OF THE KINEMATIC RESULTS FOR THE SINGLE IMPACT TESTS.

Impact #	Headform	Impact Speed (m/s)	a^p (g)	ω^p (rad/s)	α^p (rad/s^2)
1	Bare	3.1	45.3	17.9	2085
2	Helmeted	3.1	38.3	16.5	2297
3	Bare	5.0	62.1	29.9	2841
4	Helmeted	5.0	52.1	25.4	3319

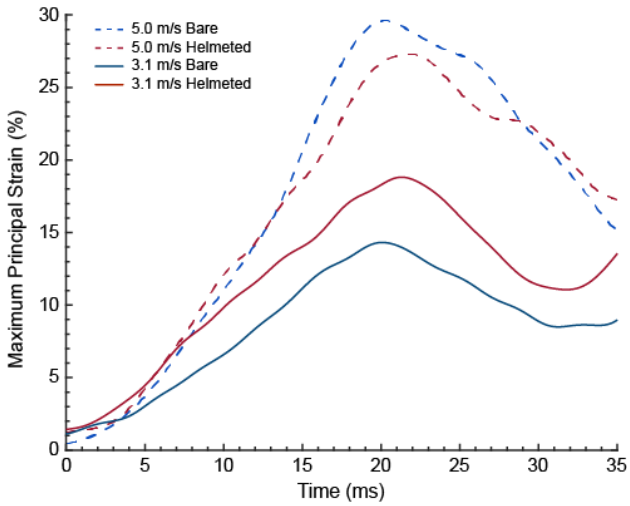

Fig. 2. Comparison plot of the 95th percentile MPS in the headform for two sets of impacts described in Table I.

IV. DISCUSSION

A comparison of the results in both Fig. 2 and the kinematic response of the headform in Table I demonstrates that no single peak kinematic response value can be used to predict strain outcomes. At the lower speed impact condition, although impact severity was reduced by the addition of the helmet, the peak rotational acceleration was increased, as was the measured MPS within the brain surrogate. At the higher impact speeds, similar trends in the head kinematics were observed, however the strain for the helmeted headform was reduced in comparison to the bare headform. This technique opens the door to using intracranial strain within tissue-simulants to evaluate helmet performance in addition to its kinematic response, providing a tool that can be more directly translated to represent mTBI injury mechanisms. Efforts to validate and calibrate the response of this headform against cadaveric datasets using the identical HSXR and linear impactor setup to ensure biofidelity are ongoing.

V. REFERENCES

[1] Biasca, N., *et al., Br J Sports Med*, 2002.
[2] Rao, D. P., *et al., CMAJ Open*, 2017.
[3] Pellman, E. J., *et al., Neurosurgery*, 2003.
[4] Rowson, S., *et al., Ann Biomed Eng*, 2012.
[5] Margulies, S. S., Thibault, L. E., *J Biomech*, 1992.
[6] Patton, D. A., *et al., J Appl Biomech*, 2013.
[7] Ouellet, S., Philippens, M., *Shock Waves*, 2018.
[8] Dutrisac, S., *et al., EngrXiv ksq7p*, 2021.
[9] Dutrisac, S., *et al., EngrXiv 7jtvw*, 2021.
[10] Walsh, E. S., *et al., Sport Eng,* 2018.
[11] Blaber, J. *et al., Exp Mech*, 2015.