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Development of Improved Brain Injury Predictors for Diverse Impacts

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ABSTRACT – Tissue-level deformation is the mechanism for brain injury, and rotational head motion is the mechanism for brain deformation. While numerous rotational metrics have been proposed, many do not represent the mechanics principles that govern brain deformation rendering them ineffective for application over a broad range of head impacts. This study highlights the development of two new brain injury metrics based on deformation response from a second order mechanical system, which are proposed as predictors of a strain-based brain injury metric: maximum principal strain (MPS) from finite element (FE) models. Efficacy of the proposed metrics was verified computationally by comparing kinematics-based predictions of MPS to those obtained from FE simulation of nearly 1600 head impacts. Relative to existing criteria, the new metrics correlated better with MPS across various impact modes, and may provide a more reliable tool for brain injury assessment in a broad range of head impacts.

INTRODUCTION

Although mandatory and voluntary requirements for automobile countermeasures and head protective equipment have had led to a significant reduction in the number fatal injuries and skull fractures, the number of survivable brain injuries spanning mild to severe are believed to be rising (Takhounts et al., 2013). One explanation is that the existing standards used in helmet and crash testing are based solely on translational head kinematics. However, brain strain is believed to be the primary mechanism for brain injuries including concussion and diffuse axonal injury (DAI), and rotational head motion is the primary cause of brain strain (Holbourn 1943).

To address the disconnect between hypothesized brain injury mechanism and risk assessment model, numerous rotational metrics have been proposed: Ommaya & Hirsch 1971, Takhounts et al., 2011, 2013, and Kimpara et al., 2012. While these metrics have demonstrated efficacy as brain injury predictors, they are based on fits to limited datasets using empirically derived formulations. Although empirically derived metrics are favored given their simplicity, they do not represent brain deformation mechanics for a broad range of impacts, thus limiting their effectiveness as a brain injury criterion (Gabler et al., 2016b).

Given that brain deformation is a mechanical response to head kinematics, the metric that establishes the severity of a head impact should be formulated based on the mechanics principles that govern this relationship. Second-order mechanical systems have been used extensively in biomechanical research; however, they have not been leveraged for brain injury criterion development until more recently (Gabler et al., 2016a, Takahashi et al., 2017). Thus, the focus of this study is to demonstrate that brain injury criterion metrics formulated based on second-order mechanical systems, which account for the mechanical properties of the brain, can improve prediction of deformation responses over a broader range of head impacts.

METHODS

Two metrics are proposed for predicting deformation-based brain injury indicators from finite element (FE) brain models using head kinematics. These metrics are developed on the assumption that brain deformation to rotational head motion is analogous to deformation from a second-order system under applied excitation.

Development of a Kinematics-based Metric

In previous work, a single-degree-of-freedom (sDOF) mechanical analogue was used to show that brain deformation in one dimension is governed by three general categories of rotational head motion, each distinguished by the pulse duration (Δt) relative to the natural period (Δt_n) of the brain-skull system (Gabler et al., 2016a): for short-duration pulses, maximum brain strain depended primarily on the magnitude of angular velocity (Fig. 1, $\Delta t \to \Delta t_1$), for long-duration pulses, maximum brain strain depended primarily on the magnitude of angular acceleration (Fig. 1, $\Delta t \to \Delta t_2$), and for pulses near the natural period of the brain, maximum strain depended on the velocity and

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acceleration magnitudes (Fig. 1, $\Delta t \rightarrow \Delta t_n$). To generalize the transition between velocity and acceleration dependent brain deformations, a pair of exponential functions were used (Fig. 1, right).

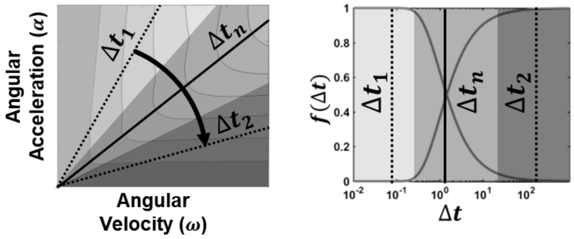


Figure 1. Contours of maximum sDOF model deformation (left), which shared remarkable similarity to maximum strain contours from the FE brain model (Gabler et al., 2016a). Exponential functions that were used to generalize the deformation behavior of the mechanical models (right).

Adding these exponentials results in a function that switches between velocity and acceleration dependent deformations in a smooth and continuous manner:

$$f(\Delta t) = \omega\left(1 - e^{-\frac{1}{\Delta t}}\right) + \alpha e^{-\frac{1}{\Delta t}}. \tag{1}$$

Assuming the duration of an arbitrary impact is related to the magnitudes of angular velocity and acceleration, ($\Delta t = \omega/\alpha$) and that the one dimensional deformation patterns can be generalized for each direction of the head, the kinematics-based metric the Universal Brain Injury Criterion (UBrIC) was proposed:

$$UBrIC = \left\{\sum_i \left[\omega_i^* + (\alpha_i^* - \omega_i^*)e^{-\frac{\alpha_i^*}{\omega_i^*}}\right]^2\right\}^{\frac{1}{2}}, \tag{2}$$

where ω_i^* and α_i^* are the directionally dependent (i) maximum magnitudes of angular velocity and angular acceleration, respectively, each normalized by a critical value (cr); $\omega_i^* = \omega_i/\omega_{icr}$ and $\alpha_i^* = \alpha_i/\alpha_{icr}$.

Development of a Multibody (MB) Model

While a kinematics-based metric can provide quick feedback on brain deformation, it may not be adequate for use in more complicated head impacts, e.g., highly irregular pulse shapes with multiple peaks. Multibody (MB) models are alternative tools that can be used to improve prediction of brain deformation under more complex loadings by taking into account the impact time history and the mechanical properties of the brain. Given the similarity between the sDOF and FE models deformations in one dimension (Gabler et al., 2016a), the concept was expanded for application in three dimensions using three, uncoupled sDOF models as analogues for brain deformation due to rotational head motion about each axis of the head (Fig. 2).

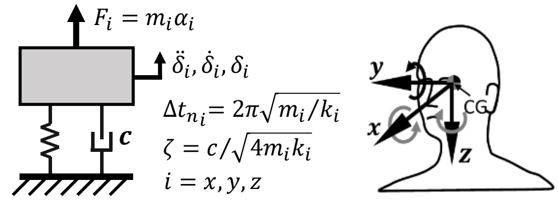


Figure 2. MB model analogue for brain deformation (left). Local head anatomical coordinate system (right). The linear MB system shown is ananlogous to a rotational lumped-parameter system.

The equations of motion for a 3DOF, uncoupled system with stiffness proportional damping are:

$$\ddot{\delta}_i + 4\pi^2 \Delta t_{n_i}^{-2}\left(a_o\dot{\delta}_i + \delta_i\right) = \alpha_i, \tag{3}$$

where $a_o = c_i/k_i$ is a stiffness proportional damping constant, and the maximum magnitude of the solution to equation (3) is assumed to be correlated with maximum brain deformation; $\max_t\{|\vec{\delta}(t)|\}$.

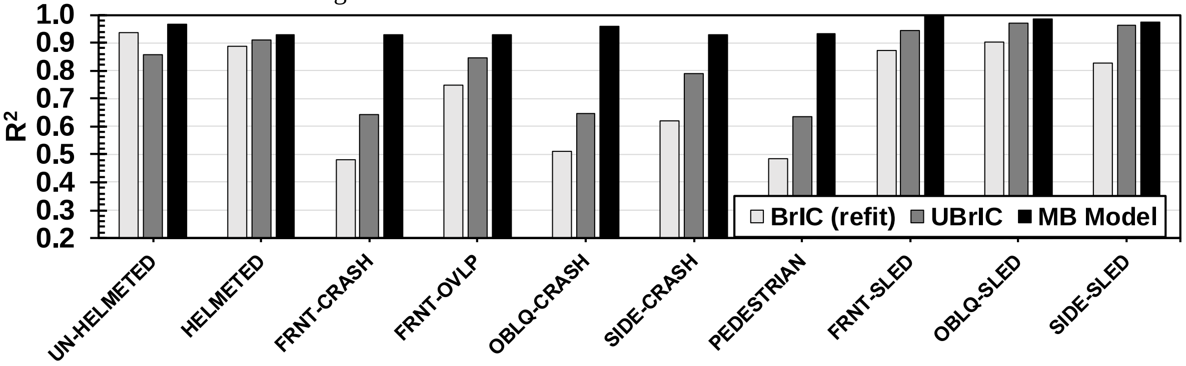
FE model Head Impact Simulations

Six-DOF head kinematics for 1,595 head impacts were used to fit the critical values of UBrIC and system parameters of the MB model. Head impacts include helmeted (Viano et al., 2012) and un-helmeted dummy impactor tests (Takhounts et al., 2013), automotive sled and crash tests (Gabler et al., 2016), and human volunteer response to sub-injurious sled tests (Sanchez et al., 2017). Each impact was simulated in the Global Human Body Models Consortium-owned (GHBMC) 50th percentile human male head model (Mao et al., 2013) to obtain Maximum Principal Strain (MPS). Model fits were performed using a nonlinear, least-squares solver, and the coefficient of determination (R^2) was used to assess correlations with MPS. To benchmark improvements, the critical values of BrIC (one of the best kinematic correlates to MPS, Gabler et al., 2016b) were refit to the dataset, and correlations were assessed relative to UBrIC and the MB model.

RESULTS

Relative to BrIC (refit), UBrIC and the MB model had better correlation with MPS using all 1,595 head impacts; $R^2 = 0.93$ and 0.96 for UBrIC and the MB model, respectively compared to 0.88 for BrIC (refit). When assessed by impact mode UBrIC outperformed BrIC in nearly every condition; however, correlations with maximum deformation magnitude from the MB model were higher in every impact mode (Fig. 3). The natural periods for the MB model were 32.0, 37.5, and 43.6 ms, for the x, y, and z directions, respectively.

Figure 3. Correlations with MPS based on GHBMC



DISCUSSION

Tissue-level deformation is believed to be the primary mechanism for brain injury; however existing metrics used in brain injury assessment do not represent brain deformation over a broad range of head impacts. This study proposes two metrics that are formulated based on mechanics principles that govern the relationship between rotational motion of the head and brain deformation. Compared to BrIC, UBrIC has similar computation time, and requires three additional parameters to compute. While the MB requires the full impact time history and slightly more time to solve, it correlates best with MPS. The proposed metrics calculate MPS and not injury risk. Until existing injury risk functions can be verified or new risk functions developed for the GHBMC, these metrics should only be used to assess relate head impact severity.

Although GHBMC has been validated for brain deformation, it is likely that head impacts used in the development of the proposed metrics fall those used to validate the model. Thus, future studies should focus on verifying the accuracy of FE brain deformations over a broader range of head impacts. Furthermore, the proposed metrics only predict global MPS. Although maximum brain strain is primarily used as an indicator of brain injury (Takhounts et al., 2013), recent evidence points toward the use other tissue-level predictors, e.g., regional MPS, tract oriented strains, and strain rate. Thus, future studies should focus on developing brain injury criteria based on these metrics.

CONCLUSION

This study proposes two new metrics for predicting brain deformation using head impact kinematics. Both were shown to be better predictors of a common strain-based brain injury indicator relative to existing metrics for brain injury criteria. This work highlights the efficacy of a mechanics based-approach using second order mechanical systems to develop more effective metrics for brain injury assessment across a broad range of head impact conditions.

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