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Mild Brain Injury Predictors Derived From Dummy 6DOF Motions

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ABSTRACT

BRIC (BRain Injury Criterion) and RIC (Rotational Injury Criterion) have been proposed as Mild Traumatic Brain Injury (MTBI) predictors. Both predictors had been verified with football players' head impact data. This study employed two human brain Finite Element (FE) models of THUMS ver.3 and SIMon ver.4 to find out correlations between the MTBI predictors and FE-based brain injury predictors such as Cumulative Strain Damage Measure (CSDM). The CSDM is defined as the percent volume of the brain FE model that exceeds a specified first principal strain threshold, which is proposed to predict Diffuse Axonal Injury (DAI) as one of Traumatic Brain Injury. Four vehicular crash test data obtained from NHTSA database of "Query Vehicle Crash Test Database on select test parameters" were applied to calculate MTBI predictors and the FE-based brain injury predictors. Very small number of crash test data demonstrated that the RIC showed strong correlations with CSDMs predicted by the two human brain FE models. Since BRIC and RIC are different in definitions of brain injury mechanisms, further studies are needed to investigate brain injury mechanisms from the medical point of view and verify the effectiveness of the MTBI predictors using more crash test data.

INTRODUCTION

HIC (Head Injury Criterion) is an effective criterion for head injuries correlated with linear acceleration, such as skull fractures. However, no injury criterion involving head rotational kinematics is fully accepted as effective so far. Recently, BRIC (BRain Injury Criterion) and RIC (Rotational Injury Criterion) have been proposed by Takhounts et al. (2011), and Kimpara and Iwamoto (2012) as MTBI (Mild Traumatic Brain Injury) predictors, respectively. The BRIC is calculated from a summation of normalized maximum angular acceleration and normalized maximum angular velocity. The RIC is defined by integrating angular acceleration during a pre-determined time duration. Since both predictors stand on the rotational kinematics of the head, it is not clear how comparable or different are the MTBI predictors.

In previous study, we evaluated the predictive capabilities of the RIC using only football players' head impact data and a human brain Finite Element (FE) model that we developed previously. However, it is not guaranteed whether the RIC is still effective for severe head impacts during automotive crashes and whether it is still effective for other human brain FE models due to differences in their geometry, material properties, and boundary conditions. In this study, we employed another brain FE model in addition to the brain FE model we used previously, and applied a series of vehicular crash test data to correlation analyses between the two promising MTBI predictors and outcomes from the brain FE models in order to investigate the effectiveness of the MTBI predictors in severe head impacts.

METHODS

The purpose of this study is to investigate the effectiveness of two MTBI predictors for football player's head impact data and vehicular crash test data by correlation analyses between the MTBI predictors and outcomes from two human brain FE models. This section describes definitions of the two MTBI predictors and characteristic features of the two human brain FE models as well as two types of head impact data and procedure of correlation analyses.

MTBI predictors

The BRIC is defined as below:

$$BRIC = \frac{\omega_{\max}}{\omega_{cr}} + \frac{\alpha_{\max}}{\alpha_{cr}} \tag{1}$$

where $\omega_{\max}$ and $\alpha_{\max}$ are the maximum angular velocity and the maximum angular acceleration for each test, and ω_{cr} and α_{cr} are critical values of angular velocity and angular acceleration, respectively. The critical values are determined as BRIC is equal to 1.0 at 30% probability of DAI with AIS 4+.

The equation of RIC is defined as below:

$$RIC_{36} = \left[(t_2 - t_1) \left\{ \int_{t_1}^{t_2} \alpha(t)\, dt \Big/ (t_2 - t_1) \right\}^{2.5} \right]_{\max} \Big/ C_{RIC} \tag{2}$$

where $\alpha(t)$ is resultant angular acceleration, and t_1 and t_2 represent the initial and final integral times which RIC_{36} is calculated over (t_1 and t_2 are selected to maximize RIC_{36}). The maximum integral time duration for RIC_{36} is set to 36 msec. The symbol of C_{RIC} is a constant value (= $1.0e^4$).

Human brain FE models

Two human brain FE models were employed to obtain FE-based injury predictors describing outputs of brain responses during head impacts. One model was an isolated human brain FE model segmented out from a commercially available human FE model, THUMS ver.3 (Total HUman Model for Safety; Toyota Central R&D Labs., Inc. and Toyota Motor Corporation; Kimpara et al., 2006). Another was

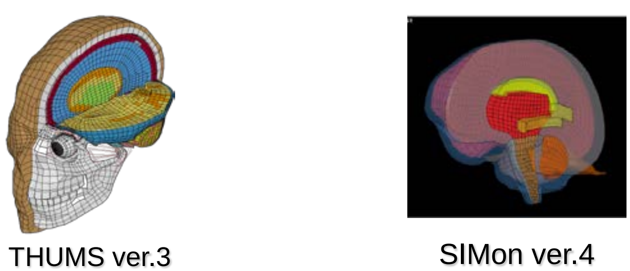


Figure 1: Human brain FE models.

SIMon (SIMulated Injury Monitor; the National Highway Traffic Safety Administration (NHTSA); Takhounts et al., 2008) Finite Element Head Model ver.4. The same isotropic linear viscoelastic material model is used to represent material properties of brain tissue in both models while the two models are different in geometry of brain tissue and interfaces between the skull and the brain.

Both brain FE models of THUMS and SIMon can predict the first principal strain on elements of brain tissue and the Cumulative Strain Damage Measure (CSDM) during head impacts. The CSDM is defined as the percent volume of the brain FE model that exceeds a specified first principal strain threshold. When the threshold of the first principal strain is set to 10%, the variable term is expressed as “CSDM 10%”.

Head impact data

*Football head impact data***.** Two datasets on football players' head impacts were used; one football dataset being non-concussive head acceleration data (Rowson et al., 2009 and 2011) collected directly from living human subjects (referred to as 6DOF device data), another football data being concussive head acceleration data (Newman et al., 2000) from the National Football League (NFL) head impacts reconstructed using Hybrid III dummies. Both the 6DOF device data and NFL data were utilized for correlation analyses between the MTBI predictors and CSDMs predicted by the THUMS brain model.

A logistic regression analysis was conducted for only NFL data to obtain injury risk curves of the MTBI predictors. Modified Maximum Likelihood Method (MMLM) proposed by Nakahira et al. (2000), which is one of methods for the logistic regression analyses, was carried out using MS-Excel in order to determine degree of precision for injury predictors. This study presumes injury risk probability as logistic curves determined by MMLM method. The goodness of curve fit predicted by MMLM was evaluated using the Combined Evaluation Method (CEM). In this method, the greater EB indicates better goodness of curve fit.

*Vehicular crash test data***.** Vehicular crash test data conducted by NHTSA were utilized in this study. Four cases of small overlap frontal crash test data were obtained from NHTSA database of “Query Vehicle Crash Test Database on select test parameters”. Linear and angular head acceleration data were obtained from 3-2-2-2 acceleration data of THOR dummy.

Procedure of correlation analyses using vehicular crash test data

Figure 2 shows the procedure of correlation analyses using vehicular crash test data. Head acceleration data obtained from vehicular crash test data were directly inputted to human brain FE models as boundary conditions of the head through the skull, and then the FE-based brain injury predictors such as the first principal strain and CSDMs were predicted by the FE models. On the other hand, the head acceleration data were used to calculate the MTBI predictors of BRIC and RIC_{36} directly. Finally, correlation analyses were conducted between the FE-based brain injury predictors and the MTBI predictors.

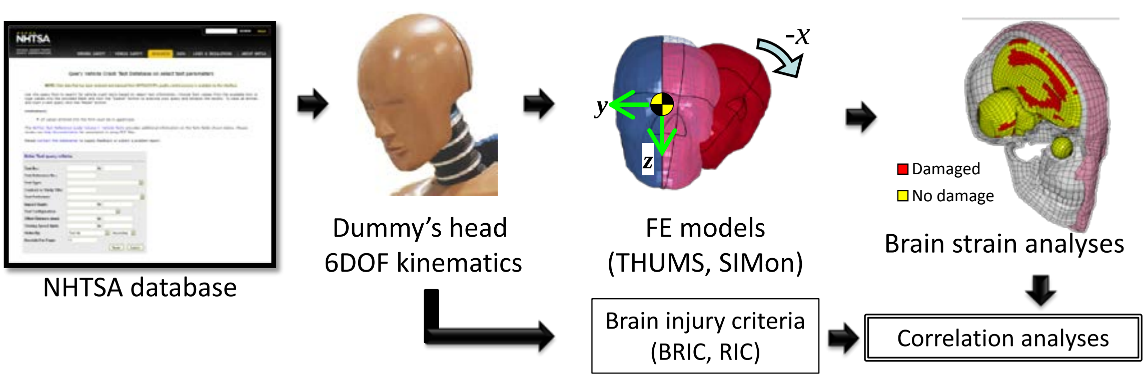


Figure 2: Procedure of correlation analyses using human brain FE models.

RESULTS AND DISCUSSION

Results

*Football head impact data***.** Figure 3 shows data plots on the relation of MTBI predictors and CSDM 10% predicted by the THUMS brain model. Estimated linear regression lines for the NFL data and 6DOF device data were depicted on the plots of circle and triangle, respectively. Coefficients of determination (R^2) of BRIC with CSDM 10% were 0.66 and 0.43 in datasets of NFL and 6DOF, respectively. The RIC_{36} had significant correlation with CSDM 10% ($R^2 \geq 0.84$) in both the NFL data and 6DOF device data.

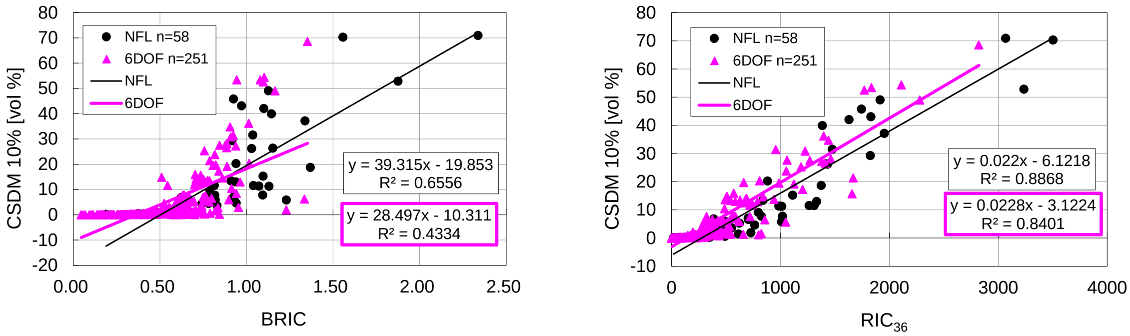


Figure 3: Correlations of BRIC and RIC_{36} with CSDM 10%.

Figure 4 shows injury risk curves (red colored lines) for BRIC and RIC_{36}, which were obtained from logistic regression analyses. Injured and non-injured data were plotted as 100% and 0% probability data, respectively. These graphs indicate that thresholds of BRIC and RIC_{36} for 50% probability of concussion are 0.901 and 1030, respectively. Injury severity of concussion is ranged from AIS 1 to 3 based on the AIS 2005. When loss of consciousness is observed, the injury severity is raised to AIS 2+. The EB values were similar

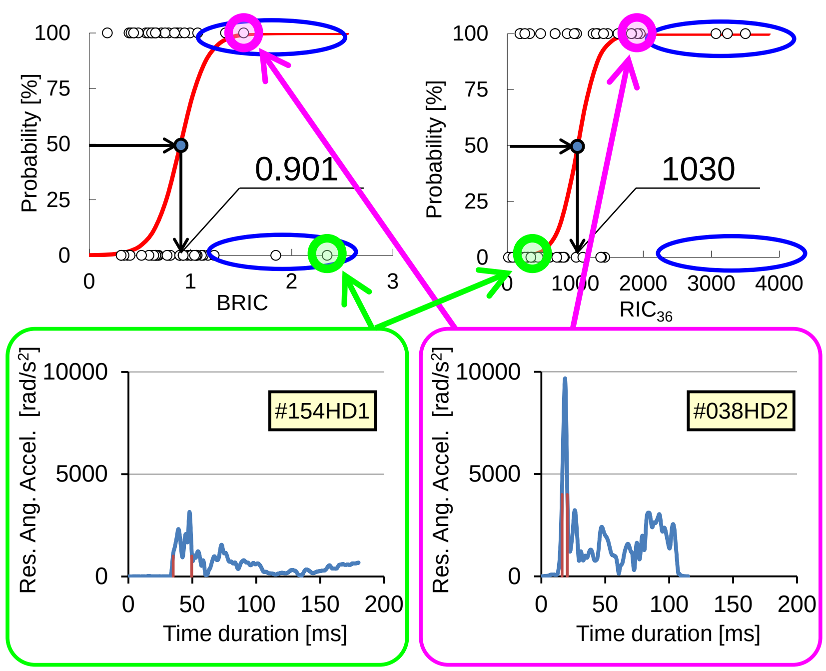


Figure 4: MTBI risk probabilities for rotational head motion based injury predictors determined by MMLM.

in both BRIC and RIC_{36}. This means that goodness of curve fit was comparable between BRIC and RIC_{36}. However, BRIC and RIC_{36} presented different injury predictions in a few data plots. For example, in non-injured case of #154HD1 in NFL dataset, BRIC predicted the greatest value over 2.0 while RIC_{36} predicted very small values. This difference is due to a difference in definitions between RIC_{36} and BRIC, because angular velocity has about 80% contribution in BRIC so that whole time history of angular acceleration data would affect BRIC significantly while RIC_{36} includes effect of integral time duration in its definition. Further study is necessary to investigate effects of time duration using more brain injury data.

*Automotive crash data***.** Table 1 summarizes MTBI predictors and FE-based brain injury predictors calculated for four vehicular crash test data. This table includes crash conditions, crash speed, resultant angular acceleration of the head with notation of integral time duration, values of HIC, BRIC, and RIC_{36}, and FE outputs of the first principal strain and CSDMs obtained from THUMS and SIMon models. Injury thresholds of HIC, BRIC, and RIC_{36} are determined as 700, 1.0, and 1030, respectively. When the values of injury predictors were over the thresholds, the values were indicated with bold characters.

In all datasets, HIC did not exceed the threshold. In case of Data C, all injury predictors were smaller than their corresponding thresholds. In Data D, BRIC and RIC_{36} were greater than those thresholds. On the other hand, BRIC and RIC_{36} presented different injury predictions between Data A and Data B. In Data A, RIC_{36} of 4245 was extremely greater than the threshold while BRIC of 0.99 fell short of the threshold by a narrow margin. On the contrary, in Data B, BRIC of 1.04 exceeded the threshold while RIC_{36} of 973 was less than the threshold.

Table 1. Summary of MTBI predictors and FE-based brain injury predictors calculated for four vehicular crash test data.

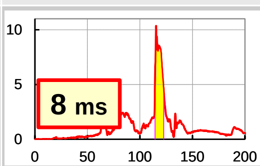
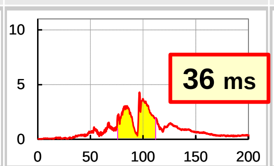
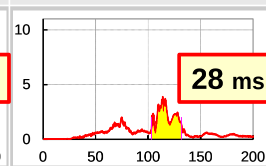
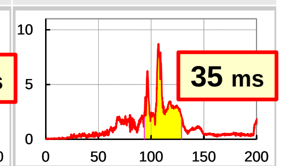
	Data A	Data B	Data C	Data D
	Vehicle vs. vehiclle	Vehicle vs. barrier	Vehicle vs. vehiclle	Vehicle vs. barrier
Speed	113 km/h	126 km/h	112 km/h	115 km/h
Angular acceleration [x10^3 rad/s^2]				
HIC (700)	595	234	362	578
BRIC (1.0)	0.99	1.04	0.82	1.06
RIC (1030)	4245	973	637	2348
First princ. strain [%] / CSDM 25% [vol.%]				
THUMS	52.5% / 1.22 vol.%	46.5% / 0.17 vol.%	46.4% / 0.09 vol.%	70.2% / 0.41 vol.%
SIMon	106.4% / 72.1 vol.%	86.8% / 41.8 vol.%	56.6% / 26.6 vol.%	79.7% / 49.1 vol.%

Figure 5 shows correlations between MTBI predictors and CSDM 25% predicted by THUMS and SIMon. Each plot is tagged expression. Although this study used a small number of vehicular crash test data, it is found that BRIC had relatively week correlation with CSDM 25% ($R^2 < 0.3$), while RIC_{36} had significant correlation with CSDM 25% ($R^2 > 0.9$). In three cases of Data A, B, and D, BRIC was equivalent to 1.0, while RIC_{36} ranged from 973 to 4245.

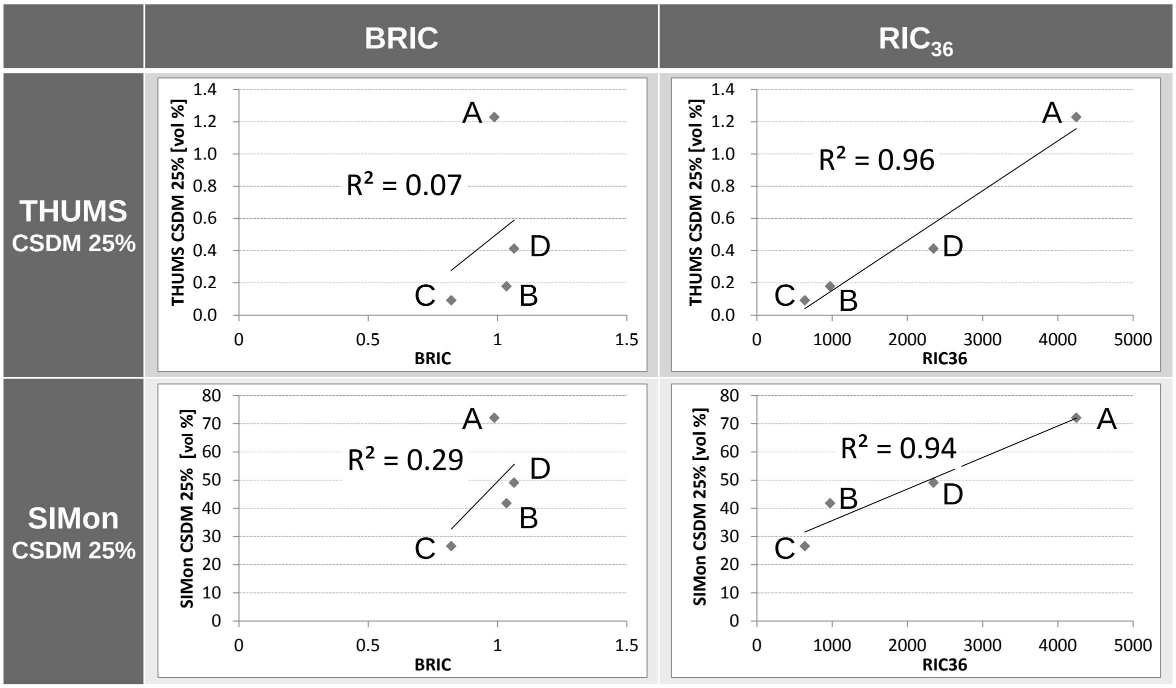


Figure 5: Correlations between MTBI predictors and CSDM 25%.

Discussion

It could be important to consider the time duration of angular acceleration for discussion of the traumatic brain injuries. Since time duration for RIC_{36} was determined to obtain the maximum value of RIC_{36}, it could be possible to have great value of RIC_{36} from strong peak pulse with short time duration, as shown in Data A. However, angular velocity is integrated variable of angular acceleration. Therefore, even if head angular acceleration does not have great magnitude of peaks, it is possible to have a great maximum angular velocity due to long time duration, as shown in Data B. Since angular velocity has about 80% contribution in BRIC, whole time history of angular acceleration data would affect the BRIC significantly. Therefore, the reason why BRIC and RIC_{36} presented different injury predictions between Data A and Data B, is due to a difference in definitions between RIC_{36} and BRIC, that is, RIC_{36} includes effect of time duration while BRIC does not include effect of time duration. Further studies are needed to investigate effect of time durations for brain injury mechanisms from the medical point of view.

Limitations

The utilized data were only four cases of small overlap crash test data. More data are needed to verify effectiveness of the MTBI predictors in automotive crashes. Another limitation is less biofidelity of dummy's head kinematics necessary to obtain the MTBI predictors, because the spine of dummy tends to be stiffer than that of real human body.

Human brain FE models used in this study have some biofidelity to represent brain responses during head impacts. However, the brain models do not have enough biofidelity to predict MTBI under head rotational accelerations. Therefore, further studies are needed to represent more realistic material properties of brain tissues in the FE models.

CONCLUSIONS

Effectiveness of two MTBI (Mild Traumatic Brain Injury) predictors as BRIC and RIC based on rotational head kinematics were investigated using football player's head impact data and vehicular crash test data by correlation analyses between the MTBI predictors and outcomes from two human brain FE models of THUMS ver.3 and SIMon ver.4. The very limited number of vehicular crash test data demonstrated that the RIC showed significant correlations with CSDMs, which is proposed to predict Diffuse Axonal Injury (DAI) as one of TBI, predicted by the two human brain FE models. Since BRIC and RIC are different in definitions of brain injury mechanisms, further studies are needed to investigate brain injury mechanisms from the medical point of view and verify the effectiveness of the MTBI predictors using more crash test data.

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