INFLUENCE OF TIME CONSTANTS AND DIRECTIONAL INTERACTION OF A KINEMATICS-BASED BRAIN INJURY METRIC ON ITS PREDICTIVE CAPABILITY OF BRAIN STRAIN RESPONSE IN CAR CRASHES

Toshiyuki, Yanaoka
Honda R&D Co. Ltd.
Japan

Paper Number 23-0183

ABSTRACT

Among the studies focusing on criteria for brain injuries induced by the rotational motion of the head, one of the recent studies has compared the predictive capability of various injury criteria proposed by different studies, with the results showing that the best predictor depends upon specific impact configurations. This suggests the need for a more robust injury criterion across a variety of impact configurations with different duration of an impact event. The aim of this study is to investigate the effect of incorporating additional time constants and modifying directional interactions on the predicting accuracy of the physical model-based criterion called CIBIC (Convolution of Impulse Response for Brain Injury Criterion) proposed by the author's group.

A Maxwell model was parallelly added to the simplified physical model (standard linear solid) of the CIBIC criterion to improve the time-dependent responses. One simplest candidate formulation of the cross-terms was tried to replace the originally used root sum square to combine the three components of the strain. The Global Human Body Models Consortium (GHBMC) head/brain model was used to obtain the target response of the maximum principal strain (MPS). A step function with the magnitude of 10,000 rad/s^2 was used to optimize the spring and damping coefficients. The spring and damping coefficients were optimized by maximizing the CORA (CORrelation and Analysis) score. The modified CIBIC was further validated against the GHBMC model using a total of 256 time histories of the head rotational acceleration representing those of the four groups of load cases (occupants in full-frontal, oblique-frontal and side impacts as well as pedestrian impacts). The coefficient of determination calculated from the correlation of peak MPS and the average value of the CORA score were compared between the original and the modified CIBIC.

The modified CIBIC with the modified time constants was found to improve both assessment metrics for all of the four groups of the load cases, while both assessment metrics predicted by the modified CIBIC with the directional interaction was not improved.

The effect of the modifications shown by the modified CIBIC suggest that further consideration of the directional interaction is needed to develop a robust criterion, requiring thorough investigations on the method to combine the responses of the three axes.

INTRODUCTION

According to the Japanese accident statistics [1], the percentage of number of the fatalities sustaining the head injury as the major part of physical damage is 21.7% for motor vehicle occupants, 41.7% for 2-wheeled vehicle occupants, 58.2% for pedal cyclists and 53.3% for pedestrians. Since the respiratory and cardiovascular center is located in the brain [2], the traumatic brain injury (TBI) is the main causation of the death due to the head injury. Therefore, preventing the TBI is crucial to reduce the number of the fatalities in traffic accident.

The analysis on National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) from 2010 to 2014 and Pedestrian Crash Data Study (PCDS) from 1994 to 1998 conducted by Takahashi et al. [3] showed that brain injury accounts for 78% and 81% of the head injuries sustaining Maximum Abbreviated Injury Scale (MAIS) in fatal occupant and pedestrian accidents, respectively. They classified the TBIs into three major categories based on the tissue failure and anticipated mechanisms; pressure and/or skull fracture (brain contusion, epidural hematoma), brain strain (subarachnoid hemorrhage, intracranial hemorrhage and diffuse axonal injury) and displacement relative to the skull (subdural hematoma). Category of the brain injuries primarily induced by the strain are the most frequent in all of the categories for both vehicle occupants (81%) and pedestrians (78%). When considering the incompressible nature of the brain and the fact that the brain is surrounded by the closed skull, brain parenchyma can be deformed largely in rotational motion of the head compared to the translational motion of the head [4].

Head/brain FE models representing detailed structure of the brain and material properties were developed to investigate the brain injury mechanism and the predict the tissue level predictor (e.g. strain of the brain) [5 to 7]. Some studies focused on the brain injury criterion predicting the strain in the brain induced by the rotational motion of the head by using head/brain FE models [3, 8, 9 and 10]. In addition, these head/brain FE models allowed to compare the predicting capability of the brain injury criterion for the strain in the brain. Östh et al., [11] investigated the predicting capability of six injury criteria for the brain strain by using a head/brain FE model in such crash configurations as frontal impact, near-side impact, far-side impact and accident reconstruction using human body model. They found that the best criterion predicting the strain in the brain was different in each of the crash configurations. This result suggests that an injury criterion which can accurately predict the strain in the brain is needed regardless of the crash configurations.

The difference of the crash configuration makes the difference of the duration of the rotational acceleration to the head and the difference of the dominant input direction to the head. The time-dependent response predicted by the criterion is deemed important to predict the strain in the brain to cover a wider range of the duration of the rotational acceleration to the head. Therefore, in order to develop an injury criterion whose predicting accuracy of the strain in the brain is independent to the crash configuration, it may be needed to consider the time dependent response of the strain in the brain and directional interaction of the rotational input to the head. The physical model-based criterion called CIBIC (Convolution of Impulse Response for Brain Injury Criterion) proposed by the author’s group [3] was developed by using one single standard linear solid model with one single time constant represented. Representation of an additional time constant may improve the prediction capability of the CIBIC. In addition, a highly three-dimensional shape and structure of the brain may require representation of a cross-term between the responses in different axes, which is not represented by the CIBIC. The aim of this study is to provide a preliminary insight into the effect of incorporating additional time constants and modifying directional interactions on the predicting accuracy of the CIBIC criterion.

METHODS

A Maxwell model was parallelly added to the simplified physical model (standard linear solid) of the CIBIC criterion to improve the time-dependent responses. The spring and damping coefficients of the modified physical model were determined to match the response calculated from the modified physical model with the strain response of the brain calculated using the 3D head/brain FE model when a step function was applied. Same as the development of the CIBIC criterion, the strain response for each axis calculated from the modified CIBIC criterion was represented by the form of convolution integral of the response of each axis when the step function was applied to the modified physical model. In order to investigate the effect of the directional interaction, one simplest candidate formulation of the cross-terms was tested to replace the originally used root sum square to combine the three components of the strain as the attempt for the first step. The effect of candidate modifications on the predicting accuracy was evaluated by comparing the correlation of the peak value between the strain response in the brain calculated from the criteria (CIBIC criterion and modified CIBIC criterion) and the strain response in the brain calculated using 3D head/brain FE model. Total 256 load cases including full-frontal, oblique-frontal, moving deformable barrier (MDB) side and pedestrian impact were used for the input to the criteria and the 3D head/brain FE model.

Identification of the coefficients of the modified physical model

Figure 1 shows the comparison of the physical model used in the CIBIC criterion and the modified CIBIC criterion. In order to match the condition in the development of the CIBIC criterion, the following use same thought as the CIBIC criterion; 1) representation of the displacement of the mass of the physical model, 2) applied acceleration to the physical model, 3) the mass of the physical model and 4) determination of the coefficients and scaling factor of the physical model. By considering the analogy, the displacement of the mass of the modified physical model represents the strain of the brain, while acceleration applied to the bottom of the modified physical model represents the rotational acceleration applied to the head. The mass of the physical model was set to 1 kg for simplification. The coefficients K0, K1, K2, C1 and C2 were determined to match the strain response in the brain of the 3D head/brain FE model when applying a step function. Since the CIBIC criterion was developed by using the assumption that the rotational response of the 3D head/brain FE model was represented by an analogous linear viscoelastic model (generalized linear solid), there was difference in the dimension between the response calculated from the 3D head/brain FE model and the response calculated from the analogous linear viscoelastic model. The scaling factor was determined for each axis to compensate the difference of the dimension by dividing the peak value of the strain form the 3D head/brain FE model by the peak value of the displacement from the analogous linear viscoelastic model.

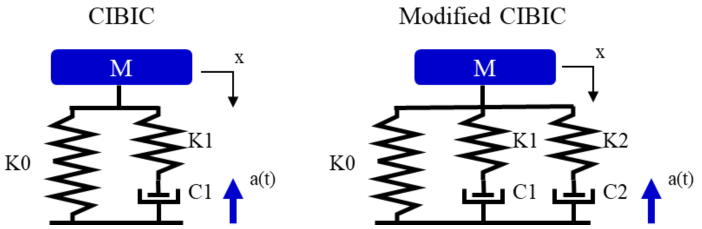

Figure 1. Comparison of the Physical model used for the CIBIC and modified CIBIC criterion

Global Human Body Model Consortium (GHBMC) head/brain FE model developed by Mao et al. [7] and shown in Figure 2 was used to obtain the target response of the strain in the brain for the determination of the coefficients and scaling factor and for the confirmation of predicting capability of the modified CIBIC criterion since this model is one of the most enhanced model. The skull, mandible and skin of the original GHBMC model was changed from deformable to rigid-body to obtain the strain response in the brain when the rigid body motion of the head was represented by the GHBMC model. Time histories of maximum principal strain (MPS) of all of the brain elements were obtained by applying time history data of the head rotational accelerations to the skull of the GHBMC head/brain FE model. Time history of the MPS in the brain (MPS_{brain}) for each load case was obtained from the time history of the MPS of the element indicating maximum of MPS in all of the brain elements over time.

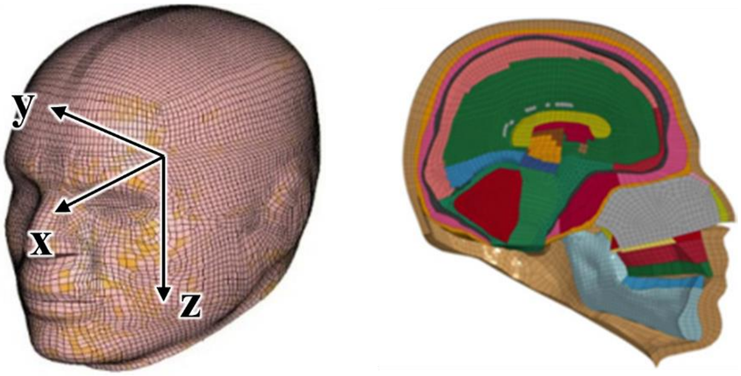

Figure 2. GHBMC head/brain model (left: local coordinate system used in this study, right: mid-sagittal section)

The coefficients and scaling factor of the modified physical model was determined for each of three axes separately. The input pulse to identify the coefficients and scaling factor of the modified physical model was a step function with 10,000 rad/s2 and with 1ms duration, referring to the development of the CIBIC criterion. The coefficients of the modified physical model for each axis were optimized by maximizing the CORA (CORrelation and Analysis) score which evaluates the agreement of the time history defined by ISO/TS18571 [12]. In calculation of the CORA score, the MPS_{brain} time histories calculated from the modified physical model and the GHBMC head/brain model were normalized by their peak value to compensate the dimension difference since the rotational response of the

GHBMC model was represented by the translational response calculated from the analogous physical model. The response of the modified physical model when applying the step function input was calculated by using model-based simulation software, MATLAB/Simulink [13]. An optimization software (modeFRONTIER [14]) was used for the optimization of the coefficients by controlling the MATLAB/Simulink model on the optimization platform. The MOGA-II algorithm in the modeFRONTIER was used for the optimization of the coefficients. The scaling factor was determined such that the peak value of the MPS_{brain} time history calculated from the modified physical model is equal to that obtained from the GHBMC model.

Prediction of time history of MPS_{brain} by the modified physical model

In the CIBIC criterion, time histories of the MPS_{brain} for each axis were represented by the form of the convolution integral of the response of the physical model when applying the step function with 1ms duration. Same as the CIBIC criterion, the time histories of MPS_{brain} predicted by the modified physical model for x, y, and z axis input are represented by Equation 1, 2 and 3, respectively.

$$S_X = \int_0^t X(t-\tau)\alpha_y(\tau)d\tau \quad \text{(Equation 1)}$$

$$S_Y = \int_0^t Y(t-\tau)\alpha_y(\tau)d\tau \quad \text{(Equation 2)}$$

$$S_Z = \int_0^t Z(t-\tau)\alpha_z(\tau)d\tau \quad \text{(Equation 3)}$$

Where S_X, S_Y and S_Z are the time histories of the MPS_{brain} predicted by the modified physical model for x, y, and z axis, respectively. And, $X(t)$, $Y(t)$ and $Z(t)$ are the response of the modified physical model when applying the step function for x, y and z axis, respectively. Furthermore, $\alpha_x(\tau)$, $\alpha_y(\tau)$ and $\alpha_z(\tau)$ are the input rotational acceleration for x, y and z axis, respectively.

Combining the strain responses of three axes calculated from the modified physical model

In order to investigate the effect of the directional interaction, in addition to the originally used root sum square to combine the three components of the strain shown in Equation 4, one formulation combining the responses for each axis was investigated as the first attempt. The additional formulation was expressed in the summation of the square of each axis and cross-terms between two axes to investigate the effect of consideration of cross-term in the simplest formulation (Equation 5).

$$MPS_{brain}1 = \sqrt{{S_X}^2 + {S_Y}^2 + {S_Z}^2} \quad \text{(Equation 4)}$$

$$MPS_{brain}2 = \sqrt{{S_X}^2 + {S_Y}^2 + {S_Z}^2 + aS_XS_Y + bS_YS_Z + cS_XS_Z} \quad \text{(Equation 5)}$$

Where $MPS_{brain}1$ and $MPS_{brain}2$ are the MPS_{brain} calculated from the modified CIBIC (here after called the MPS_{brain} calculated from modified CIBIC-1 and 2, respectively). a, b and c are the coefficients for each cross-term. The coefficients for Equation 5 were optimized to maximize the CORA score of the MPS_{brain} response calculated from the modified CIBIC-2 against that calculated using GHBMC model when the step function with the magnitude of 10,000rad/s^2 and with the duration of 1 ms was applied to x, y and z axes simultaneously. The optimization was performed by using modeFRONTIER with MOGA-II optimization algorithm.

Evaluation of the improvement of the predicting accuracy

The effect of the modification on the predicting accuracy was evaluated in terms of the coefficient of determination (R^2) and the agreement of the time histories of MPS_{brain}.

ISO/TR19222 [15] evaluated the various brain injury criteria in terms of correlation of peak value of the MPS_{brain} using approximately 1,600 load cases including vehicle crash tests, vehicle sled tests and pendulum impact tests with various impact configurations. Of those load cases, the datasets of the time history of head rotational acceleration currently available in NHTSA crash test database [16] were used as the load cases for full-frontal (71 cases), oblique-frontal (49 cases) and MDB side (64 cases) impact configurations. The 72 results of the MADYMO car-to-pedestrian impact simulations used in Takahashi et al. [3] were used as the loading condition for the pedestrian impact configuration due to the lack of the available head rotational acceleration data used in ISO/TR19222 [15]. Total 256 load cases were used for evaluation. The time duration after the main impact and rebound phase was excluded to eliminate the secondary head impact irrelevant to the crash configurations.

The correlation analysis of peak value of MPS_{brain} was performed between the GHBMC and each of the CIBIC criterion and the modified CIBIC criteria in all of the load cases along with each of four crash configurations. The CORA score of the each of CIBIC criterion and the modified CIBIC criteria against the GHBMC model was calculated for all of 256 load cases. The average values of the CORA score in all of the load cases along with each of four crash configurations were compared between the original and the modified CIBICs.

RESULTS

Identification of the coefficients of the modified physical model

Table 1 shows the five model parameters and scaling factor for each axis.

Table 1.
Five model parameters and scaling factor for each axis

Axis	K0 (N/m)	K1 (N/m)	C1 (Ns/m)	K2 (N/m)	C2 (Ns/m)	Scaling Factor for
X	2.09E+04	1.92E+04	3.35E+01	4.80E+04	8.33E+01	4.17
Y	1.43E+04	6.14E+04	2.89E+01	9.63E+04	7.02E+01	3.41
Z	1.68E+04	3.17E+04	4.57E+01	7.17E+04	2.71E+01	4.67

Combining the strain responses of three axes calculated from the modified physical model

Table 2 shows the optimized cross-term coefficients for Equation 5.

Table 2.
Three coefficients for the cross-term

Coefficients	a	b	c
$MPS_{brain}2$	0.132	0.034	0.629

Evaluation of the improvement of the predicting accuracy

Figure 3 through 7 show the correlation between the peak value of the MPS_{brain} from the GHBMC model and the criteria considered in this study (CIBIC, modified CIBIC-1 and 2) for the all of the load cases, full-frontal, oblique-frontal, MDB side and pedestrian impact configurations, respectively. Table 3 summarizes the coefficient of determination (R^2) for all of the correlation plots shown in Figure 3 through 7.

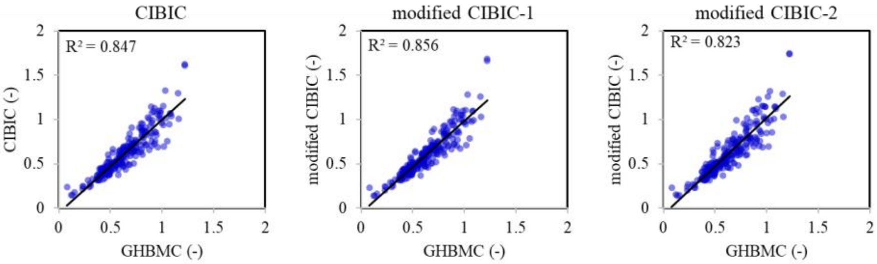

Figure 3. Correlation of the MPS_{brain} between the GHBMC and CIBIC/modified CIBIC (all of load cases)

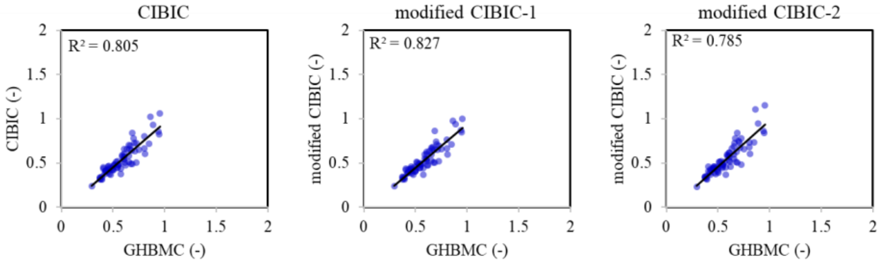

Figure 4. Correlation of the $\text{MPS}_{\text{brain}}$ between the GHBMC and CIBIC/modified CIBIC (full-frontal)

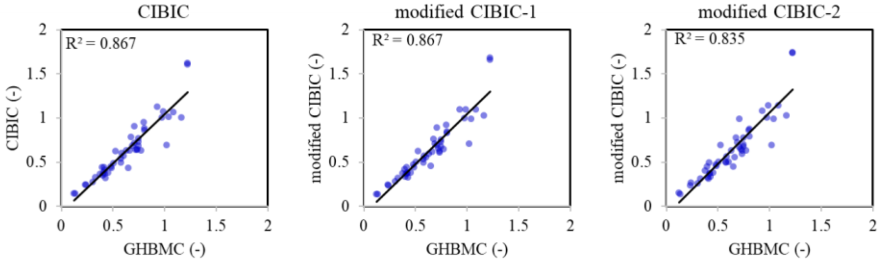

Figure 5. Correlation of the $\text{MPS}_{\text{brain}}$ between the GHBMC and CIBIC/modified CIBIC (oblique-frontal)

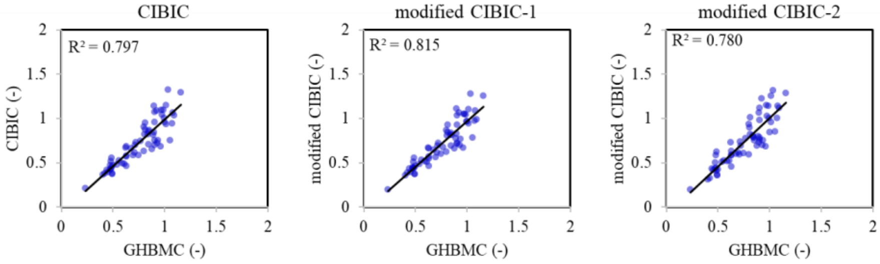

Figure 6. Correlation of the $\text{MPS}_{\text{brain}}$ between the GHBMC and CIBIC/modified CIBIC (MDB side)

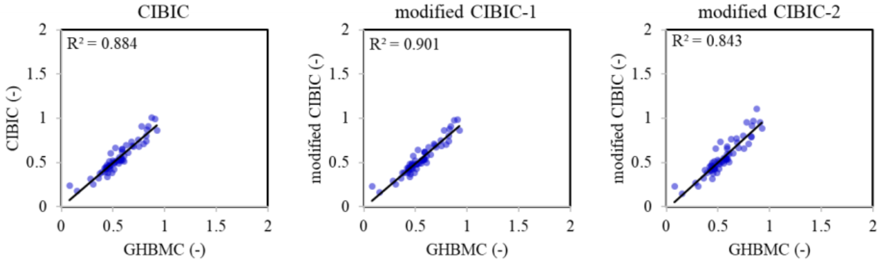

Figure 7. Correlation of the $\text{MPS}_{\text{brain}}$ between the GHBMC and CIBIC/modified CIBIC (pedestrian)

Table 3.
Summary of coefficient of determination (R^2)

Load case	GHBMC v.s. CIBIC	GHBMC v.s. modified CIBIC-1	GHBMC v.s. modified CIBIC-2
All load cases	0.847	0.856	0.823
Full-Frontal	0.805	0.827	0.785
Oblique-frontal	0.867	0.867	0.835
MDB side	0.797	0.815	0.780
Pedestrian	0.884	0.901	0.843

Figure 8 compares the time history of the MPS_{brain} between calculated from GHBMC, calculated from the CIBIC criterion, calculated from modified CIBIC-1 and calculated from modified CIBIC-2. For the comparison of the time history, an exemplar load case was chosen for the each of full-frontal, oblique-frontal, MDB side and pedestrian impact configurations. For these three criteria, Table 4 shows the summary of the average value of the CORA score for all of the load cases along with each of the four crash configurations.

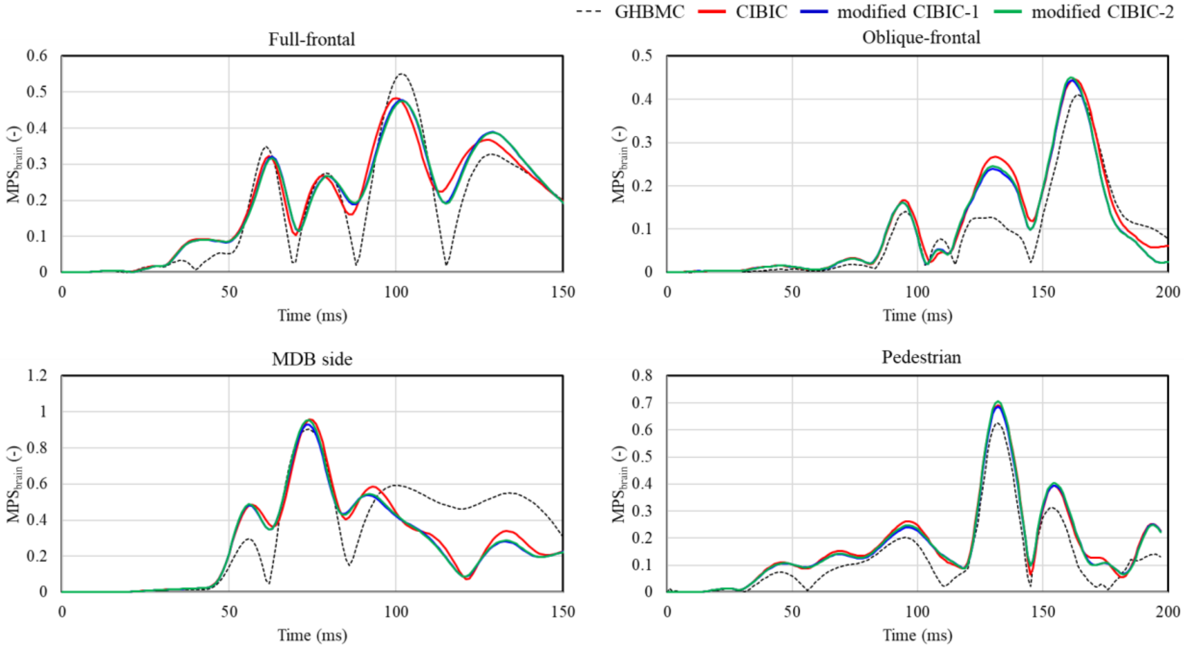

Figure 8. Comparison of the time history of the MPS_{brain} between GHBMC, CIBIC, modified CIBIC-1 and modified CIBIC-2

Table 4.
Summary of average value of the CORA score

Load case	GHBMC v.s. CIBIC	GHBMC v.s. modified CIBIC-1	GHBMC v.s. modified CIBIC-2
All load cases	0.736	0.739	0.730
Full-Frontal	0.741	0.743	0.741
Oblique-frontal	0.728	0.734	0.715
MDB side	0.657	0.658	0.645
Pedestrian	0.819	0.826	0.821

DISCUSSION

This study investigated the effect of the modification of the CIBIC criterion on the improvement of the predicting accuracy of the $\mathrm{MPS}_{\mathrm{brain}}$ by changing the physical model of the CIBIC criterion and the formulation combining the response of the three axes. A Maxwell model was parallelly added to the physical model to improve the time-dependent responses. One exemplar formulation for combining the response of the three axes was used to clarify potential improvement in the directional interaction. As summarized in Table 3 and 4 for the coefficient of determination of peak value of the $\mathrm{MPS}_{\mathrm{brain}}$ and the average value of the CORA score of the $\mathrm{MPS}_{\mathrm{brain}}$ time history, respectively, the result of this study showed that the addition of the time constant tended to improve the predicting accuracy of the $\mathrm{MPS}_{\mathrm{brain}}$ while consideration of the directional interaction by changing the combining formulation did not.

The improvement in the prediction capability by adding one time constant was 1.1% and 0.4% for the coefficient of determination of peak value of the $\mathrm{MPS}_{\mathrm{brain}}$ and the average value of the CORA score of the $\mathrm{MPS}_{\mathrm{brain}}$ time history in all of load cases. The small amount of improvements in the prediction capability and the high prediction capability of the original CIBIC criterion may suggest that the original CIBIC is already accurate enough, with such a simplified modeling, not to enhance its prediction capability significantly. The prediction capability was not improved with the introduction of the cross-term investigated in this study. Since only one formulation was investigated in this study, a future study needs to further investigate the influence of the formulation of combining responses in different axes.

CONCLUSIONS

The effect of one additional time constant in the simplified physical model and consideration of one exemplar cross-term on the predicting accuracy of the $\mathrm{MPS}_{\mathrm{brain}}$ was investigated relative to the CIBIC criterion developed by the author's group. As a result, following were found:

- The improvements of the predicting accuracy by the modified CIBIC with one additional time constant considered in this study were 1.1% and 0.4% for the coefficient of determination of peak value of the $\mathrm{MPS}_{\mathrm{brain}}$ and the average value of the CORA score of the $\mathrm{MPS}_{\mathrm{brain}}$ time history in all of the load cases.
- An exemplar formulation to combine responses in different axes by introducing the cross-terms investigated in this study did not improve the predicting accuracy, requiring a more comprehensive study on the method to combine the response in three axes.

REFERENCES

[1] National Police Agency. (2022, March 3). Table Number 2-4-2, Casualties by major part of physical damage and road user type. Traffic Accident Statistics, Annual Report 2021 (Serious accidents). https://www.npa.go.jp/publications/statistics/koutsuu/toukeihyo_e.html

[2] Felten, D.L., O'Banion, M.K., Maida, M.S. 2016. "Netter's Atlas of Neuroscience (Third Edition)." https://doi.org/10.1016/B978-0-323-26511-9.00011-4.

[3] Takahashi, Y. and Yanaoka, T. 2017. "A study of injury criteria for brain injuries in traffic accidents." In proceedings of the 25th ESV conference (Detroit, MI, USA, June 5-8), paper number 17-0040

[4] Holbourn, A.H.S. 1943. "Mechanics of head injuries." Lancet 2. October 9: 438–41

[5] Kleiven, S. 2007. "Predictors for Traumatic Brain Injuries Evaluated through Accident Reconstructions." Stapp Car Crash J. 51: 81-114

[6] Takhounts, E.G., Ridella, S.A., Hasija, V., Tannous, R.E., Campbell, J.Q., Malone, D., Danelson, K., Stitzel, J., Rowson, S. and Duma. S. 2008. "Investigation of Traumatic Brain Injuries Using the Next Generation of Simulated Injury Monitor (SIMon) Finite Element Head Model." Stapp Car Crash J. 52: 1-31

[7] Mao, H., Zhang, L., Jiang, B., Genthikatti, V.V., Jin, X., Zhu, F., Makwana, R., Gill, A., Jandir, G., Singh, A., Yang, K.H. 2013. “Development of a finite element human head model partially validated with thirty five experimental cases.” J Biomech Eng., 135(11): 111002

[8] Takhounts, E.G., Craig, M.J., Moorhouse, K., McFadden, J. and Hasija, V. 2013 “Development of Brain Injury Criteria (BrIC).” Stapp Car Crash J. 57: 243-266

[9] Yanaoka, T., Dokko, Y., Takahashi, Y. 2015. “Investigation on an injury criterion related to traumatic brain injury primarily induced by head rotation.” SAE International Technical Paper, 2015-01-1439.

[10] Gabler, L., Crandall, J. and Panzer, M.. 2019. “Development of a Second-Order System for Rapid Estimation of Maximum Brain Strain.” Ann Biomed Eng. 2019 Sep; 47(9):1971-1981

[11] Östh, J., Bohman, K. and Jakobsson, L. 2022. “Assessment of Brain Injury Criteria using Head Kinematics Data from Crash Tests and Accident Reconstructions.” In proceedings of the IRCOBI conference 2022. paper number IRC-22-16

[12] ISO. 2014. “ISO/TS 18571:2014 Road vehicles - Objective rating metric for non-ambiguous signals”

[13] MathWorks. 2019. “MATLAB/Simulink.” https://jp.mathworks.com/products/simulink.html

[14] ESTECO SpA. 2022. “modeFRONTIER.” https://engineering.esteco.com/modefrontier/

[15] ISO. 2021. “ISO/TR 19222:2021 Road vehicles - Injury risk curves for the THOR dummy”

[16] National Highway Traffic Safety Administration. “Vehicle Crash Test Database.” https://www.nhtsa.gov/research-data/research-testing-databases#/vehicle