A NEW BIOMECHANICAL PREDICTOR FOR MILD TRAUMATIC BRAIN INJURY – A PRELIMINARY FINDING

Liying Zhang (1), King H. Yang (1), Albert I. King (1), David C. Viano (2)

(1) Bioengineering Center
Wayne State University
Detroit, MI

(2) MTBI Subcommittee
National Football League
New York, NY

BACKGROUND

Traumatic brain injury (TBI) continues to be a serious societal problem. Even with the advent of the airbag in automobiles and the use of advanced protective devices in sport, the incidence of head injury does not appear to be decreasing rapidly. Currently, the head injury criterion (HIC), Severity Index (SI) or simply the acceleration of the dummy head, measured at its center of gravity are used as safety standards for the assessments of head protective devices. These injury indices are based on linear acceleration input to the head. They appear to have some validity because automobile and sports related head injuries have been kept in check over the last 30 years. On the other hand, research on the effects of angular acceleration was pursued more vigorously than that on the effects of linear acceleration in an attempt to find a tolerance limit for angular acceleration. Based on research conducted over the past four decades, the current belief is that angular acceleration is more damaging than linear acceleration, even though in any head impact, both forms of acceleration are usually present.

Much research has been conducted to find the causes of brain injury. One unfortunate consequence among researchers is their focus on injury due to two types of accelerations and the failure to consider other parameters that may be a more direct cause of brain injury. Recent Wayne State University (WSU) head impact tests, using a mini-sled, revealed that a helmeted head sustained the same degree of angular acceleration as the unhelmeted head for the same impact, but its linear acceleration was decreased significantly. In a separate experiment conducted at WSU, data on brain motion experiments confirm that there is a ±5 mm of relative displacement of the brain with respect to the skull during angular acceleration and that this displacement is minimal for purely linear motion. Even at accelerations in excess of 10,000 rad/s^2 the displacement remains at ±5 mm. So, if angular acceleration is the cause of brain injury, then how is the brain protected by the helmet?

This paper proposes a new hypothesis on brain injury mechanisms and suggests that the traditional thinking regarding linear and angular acceleration should be abolished in favor of considering response variables instead of input variables. The proposed variables to be studied are the strain rate and the product of strain and strain rate.

Football-related mild traumatic brain injury (MTBI) incident data were obtained from the NFL. The incidents involving both injury and non-injury were replicated using the 2001 version of the Wayne State University Head Injury Model (WSUHIM). This finite element (FE) model simulates all essential anatomical features of a human head and has been rigorously validated against cadaveric data [1]. It can predict intracranial pressure distribution, local stress, and strains throughout the brain due to any blunt impact. Statistical analyses were conducted to determine the more promising injury predictors and to estimate the injury probability.

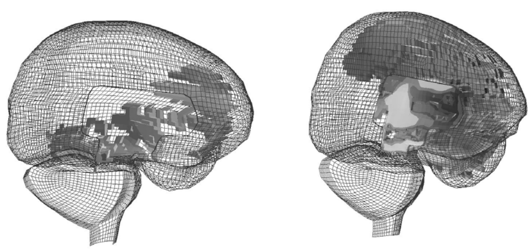
METHODS

A total of 53 cases, including those with and without injury, were reconstructed at Biokinetics (Ottawa, Ontario) by Newman et al [2], using game films. They then used helmeted Hybrid III dummy head and neck complexes to obtain head acceleration data, simulating the actual field impacts. Histories of the three translational and three rotational acceleration components at the center of the gravity of the head were used as input into the WSUHIM to simulate the actual incident. For the injury cases, the peak resultant linear and angular head acceleration varied from 48 to 138 g and 2,615 to 9,678 rad/s^2 with an average value of 94 g and 6,398 rad/s^2, respectively. For the non-injury cases, the peak value of head acceleration varied from 19 to 102 g and 1,170 to 6,613 rad/s^2 with an average value of 55 g and 3,938 rad/s^2, respectively. The primary duration of impact for cases associated with injury and non-injury were about 20 and 15 ms respectively. The resulting brain response in terms of the intracranial pressure, maximum principal strain, and shear stress was analyzed to assess the linkage between model predictions and injury outcome associated with a particular event.

RESULTS AND DISCUSSION

Brain Response

Figure 1 highlights those elements which have a maximum principal strain of 10% or higher for a typical non-injury case and a typical injury case. The strain response limit was set as 10% to show regions of the brain that experienced strains above 10%. As demonstrated in the figures, high strains were located in the midbrain and the posterior portion of the corpus callosum for a non-injury case. The proportion of the elements experiencing maximum principal strains of over 10% was larger for the injury case. The high maximum principal strains were concentrated at the central core region of the brain, more specifically, located in the midbrain, upper brain stem and most of the diencephalon. The white matter of the frontal lobe sustained high strains as well. The corpus callosum region, where diffuse injury is commonly reported, did not experience significantly high strains.



(A) (B)

Figure 1. The highlighted elements are those experiencing maximum principal strains of over 10% from (A) non-injury case (B) injury case, as predicted by the WSUHIM.

Strain rate was hypothesized to be a key biomechanical parameter to explain the cause of brain injury and concussion. It is being introduced for the first time as a measure of human brain injury. Strain rate ($d\varepsilon/dt$) was manually calculated by differentiating the maximum principal strain vs. time curves for those elements that have the highest values of strain. The rate varied from 23 to 140 s^{-1} with an average value of 84 s^{-1} for injury cases and from 11 to 67 s^{-1} with an average value of 38 s^{-1} for non-injury cases. The product of strain and strain rate is another local tissue response measure that could be a mechanical parameter for neural injury. This product was computed by taking the product of the instantaneous strain and strain rate. For injury cases, the average $\varepsilon \bullet d\varepsilon/dt$ was around 36 s^{-1} while, for non-injury cases, the average $\varepsilon \bullet d\varepsilon/dt$ was as low as 10 s^{-1} in the midbrain region. Typically, the peak $\varepsilon \bullet d\varepsilon/dt$ occurred at least 5 ms after the linear and angular accelerations have peaked, due to viscous nature of the brain material.

Logistic Regression

Logistic regression was carried out to determine effective injury predictors and to estimate the probability of injury. To form the regression model, the dependent or outcome variable was the occurrence of concussion (MTBI). The independent or predictor variables were divided into two groups. One group consisted of input variables and head injury assessment functions, such as the Head Injury Criterion (HIC), Head Impact Power (HIP), and Head Impact Jerk (HIJ). Group two contained all predicted brain response parameters. Significance tests of –2 Log Likelihood ratio, Score and Wald Chi-Squared were performed to determine statistical significance between injury outcome and the predictor variables, using SPSS Version 8.0 (SPSS Inc. Chicago, Illinois).

Based on values of p and chi-squared from all three significance tests, the product of strain and strain rate ($\varepsilon \bullet d\varepsilon/dt_{max}$) at the midbrain region provided the strongest correlation with the occurrence of MTBI ($p<0.0000$, $\chi^2=34$). Strain rate was also a good injury predictor, based on the magnitudes of the three test statistics. A multivariate analysis revealed that no other multivariate model was significantly better than the univariate models because one of the p values for the multivariate variables in the model was not statically significant. A Logist plot of the probability of sustaining an MTBI versus the product of strain and strain rate is presented in Figure 2.

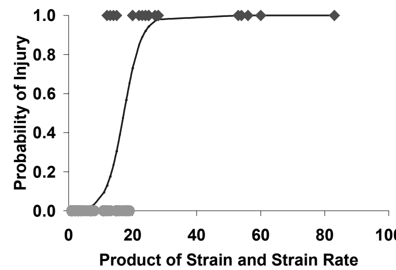


Figure 2. The probability of MTBI as predicted by the product of strain and strain rate in the midbrain region.

MTBI thresholds were determined from Logist plots for a number of probability values. The estimated concussive strain levels at the midbrain were 0.25, 0.37, and 0.49 for a 25%, 50%, and 75% probability of MTBI, respectively. The estimates of tolerance levels with 25%, 50%, and 75% probability of injury for strain rate were 46, 60, and 80 s^{-1}, and the threshold for the product of strain and strain rate was estimated to be 14, 19, and 24 s^{-1}, respectively.

CONCLUSIONS

A combined study using field impact data and our validated FE model yielded preliminary findings which highlight a new direction for the study of brain injury mechanisms. Based upon these results, the following conclusions can be reached:

- Strain rate and product of $\varepsilon \bullet d\varepsilon/dt$ in the midbrain region appeared to be the best injury predictor for concussion
- Strain rate was proposed as a cause of brain injury in order to challenge researchers to move away from their focus on either linear or angular acceleration.
- To study injury mechanisms, it is best to focus on brain reaction to complex inputs of translational and rotational acceleration
- The inevitable conclusion is that, if we are to define tolerance in terms of brain response, we will need a computer model to describe this response. Intelligent helmet design will also need such a computer model for omni-directional protection

REFERENCES

1. Zhang, L., Yang, K.H., Dwarampudi, R., Omori, K., Li, T., Chang, K., Hardy, W.N., Khalil, T.B., and King, A.I., 2001, "Recent advances in brain injury research: A new human head model development and validation," Stapp Car Crash Journal, 45, pp. 369-393.
2. Newman, J.A., Beusenberg, M., Fournier, E., Shewchenko, N., Withnall, C., King, A.I., Yang, K.H., Zhang, L., 1999, "A new biomechanical assessment of mild traumatic brain injury Part I – Methodology," Proceedings, the ICORBI conference, Barcelona, Spain.

ACKNOWLEDGMENTS

This research was supported in part by a grant from National Football League Charities and by the National Center for Injury Prevention and Control, CDC Grant No. R49/CCR503534-12.