BIOMECHANICAL DIFFERENCES BETWEEN CONTACT AND NON-CONTACT HEAD IMPACTS IN VEHICLE CRASH TESTS

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ABSTRACT

The purpose of this research is to study brain biomechanics between contact and non-contact head impact during vehicle crash tests in head kinematics, global brain injury metrics, and region brain strain. Nine array accelerometer package data from dummy head were extracted from 13 lateral and 14 rigid pole crash tests conducted by the National Highway Traffic Safety Administration (NHTSA). Head accelerations, HIC values and their duration were computed. Cumulative strain damage measure 15% (CSDM), dilatational damage measure (DDM), and relative motion damage measure (RMDM) were studied using SIMon finite element head model (FEHM). Averaged regional brain strains were conducted by grouping brain element in SIMon FEHM into frontal, parietal, occipital, cerebellum, fronix and brain stem region. Head contact occurred in two lateral and six rigid pole tests. Head contact durations were less than one millisecond in rigid pole tests and ranged from 3-7 ms in lateral impact tests. The ratio of biomechanical measurements between contact and non-contact cases in lateral tests were: translational acceleration 4x, rotational acceleration 3.5x, HIC 12x, and CSDM 5x, regional brain 1.5x. The ratios were higher for rigid pole tests: translational acceleration 14x, rotational acceleration 25.7x, HIC 29.5x, CSDM 12x, regional brain strain 1.5-3x. Head accelerations, HIC values, DDM and RMDM increased with increasing rotational accelerations. They were the lowest in non-head contact rigid pole tests, followed by non-contact lateral impact tests, contact lateral impact tests, and the highest in head contact rigid pole tests. However, CSDM values were higher in lateral tests than rigid pole tests for head contact cases, indicating a higher chance of diffused axonal injury in head contact lateral impact tests. On the other hand, averaged brain strain in cerebellum increased 3x for contact cases, indicating high probability of injury to this region during this model of impact.

INTRODUCTION

Motor vehicle crashes are one of the major causes of traumatic brain injury in the United States [1]. High-rate head accelerations during crashes were contributed to the injury and associated with excessive strains to the brain tissue [2-10]. In particular, side crashes often result in direct head impact with the vehicle interior component or exterior object, resulting in severe head/brain injury. However, the difference in head injury biomechanics between crashes with head contact and no head contact are yet to be clearly delineated.

NHTSA conducts lateral impact and rigid pole side impact tests to obtain biomechanical data, including head accelerations. Finite element modeling is a powerful tool to study tissue level brain strain under global head acceleration [11-13]. The objective of the current study is to investigate biomechanical differences between head contact and non-head contact side impacts using vehicle crash test data and parameterized finite element modeling approach.

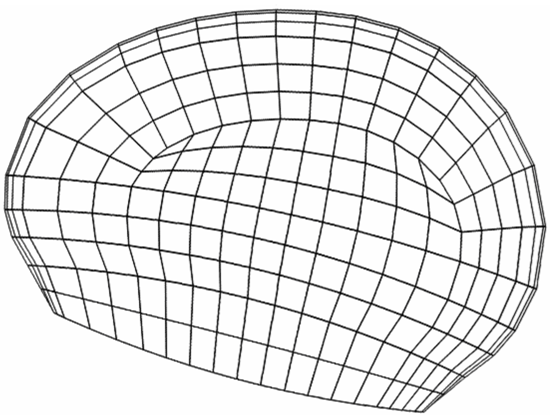
METHODS

Lateral impact test and rigid pole side impact test results from the US New Car Assessment Program (NCAP) were obtained from NHTSA vehicle crash test database. Nine accelerometer package (NAP) data from the head of the test dummy in the driver seat were extracted from the results and imported into customized software to obtain head kinematics. The acceleration data were filtered with SAE Class 1000 and translational and rotational head accelerations were computed. Peak head accelerations, HIC value, and their durations were obtained.

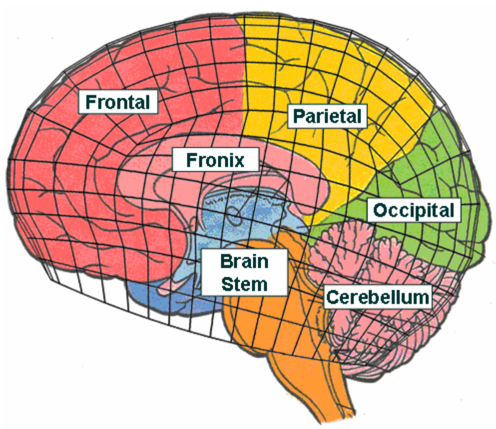
Injury metrics from head acceleration were analyzed by using the FEHM included in the SIMon software package (Simulated Injury Monitor, developed by NHTSA). Head accelerations were applied to the model as an inertial loading, and injury measurement metrics: CSDM, DDM and RMDM were the major outputs from the model.

Binary output results from the SIMon FEHM were further analyzed by grouping the brain elements into six anatomical regions (frontal lobe, parietal lobe, occipital lobe, cerebellum, fronix and brain stem) by mapping the FEHM mesh to an anatomical illustration (Figure 1). Regional averaged brain strains were computed by averaging strain histories of all the elements in these regions, and peak of the regional averaged strain were obtained.

Head accelerations, HIC value, CSDM, DDM, RMDM, and regional averaged brain strains were compared between tests with head contact and tests without head contact to determine biomechanical differences.



SIMon FEHM brain mesh



Regional differentiation of SIMon FEHM

Figure 1. Region mapping of SIMon Finite Element Head Model.

RESULTS AND DISCUSSION

The study used vehicle crash test data from NHTSA database with the focus on inertial loading-induced head/brain injury. The major inclusion criteria is the dummy must have an NAP in the head so that full head kinetics, both translation and rotation, can be obtained. A query of the database resulted in 27 cases, 13 lateral impact tests and 14 rigid pole tests. Out of the selected tests, six rigid pole tests and two lateral impact tests had head contact. Vehicle in these tests were all passenger cars although there are variations in vehicle maker and model. There were 20 4Dr Sedans (10 in lateral tests and 10 in pole tests). Other vehicles include SUV, MV and 2Dr Sedan.

Three levels of biomechanical analysis were conducted: head kinematics, global brain injury metric analysis, and regional brain strain analysis.

On the head kinematics, head accelerations and HIC value were obtained from NAP data using an in-house developed software package. The software package was designed for generic head kinetic analysis using internal or external NAP data [14]. The accelerometer data from NAP and the output head accelerations were filtered with SAE Class 1000 filter.

A comparison of averaged peak head accelerations are shown in figure 2 and 3. Head accelerations in cases with head contact are considerably higher than no head contact cases. The ratio of head accelerations and HIC values between contact and non-contact cases in lateral tests were: translational acceleration 4x, rotational acceleration 3.5x, HIC 12x. The ratios were higher for rigid pole tests: translational acceleration 14x, rotational acceleration 25.7x, HIC 29.5x. Considerably higher head acceleration in contact cases indicates a high probability of severe injury in these cases.

Comparing contact cases between the two crash modes, rigid pole tests had the highest head accelerations and HIC value. Translational accelerations were 4x higher and rotational accelerations were more than 5x higher than lateral impact tests. This was due to the fact that head directly impacted the rigid pole in pole tests, whereas head impacted the vehicle interior or the incoming barrier in lateral crash tests. The higher rigidity of the pole may be attributed to the difference.

The durations of head acceleration were also obtained in addition to peak acceleration values. However, there were no significant differences between contact and no contact cases. The duration of translational accelerations ranged from 46.8 to 60.6 ms and the duration of rotational accelerations were relatively shorter, ranging from 26.3 to 45.2 ms.

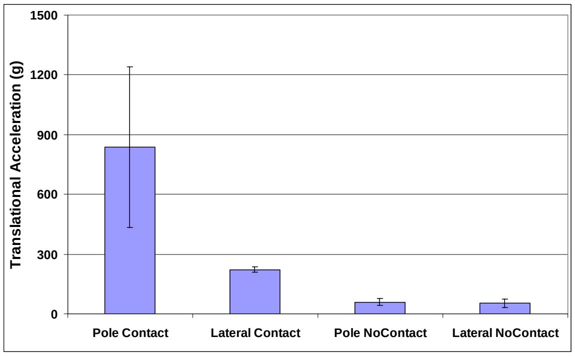


Figure 2. Comparison of average translational acceleration.

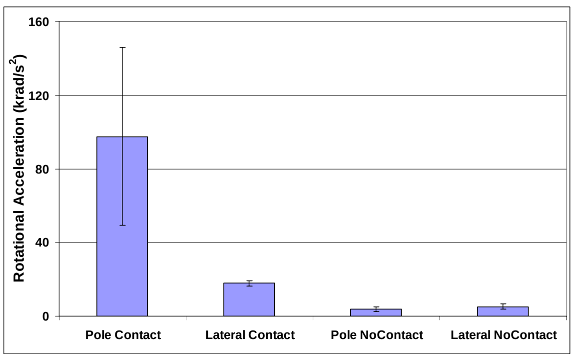


Figure 3. Comparison of average rotational acceleration.

HIC value has been widely used to evaluate head injury during vehicle crashes, although it does not include rotational accelerations. A comparison of HIC values is shown in figure 4. HIC values in all no head contact cases were well below 1000, indicating low probability of head injury. However, averaged HIC values in contact cases were approximately 10,000 for rigid pole crashes and 2,300 in lateral impact cases. The high value indicates the severity of head injury in head contact cases. HIC duration is a good indicator of the duration of major acceleration (figure 5). Average HIC duration was 3.2 ms for rigid pole tests with head contact (shortest), and 5.1 ms for lateral impact with head contact, whereas, the cases without head contact had an averaged HIC duration of approximately 22 ms, which was approximately 4x to 7x longer. This result indicates that stopping the head with a smooth continuous deceleration can significantly reduce the probability of head injury.

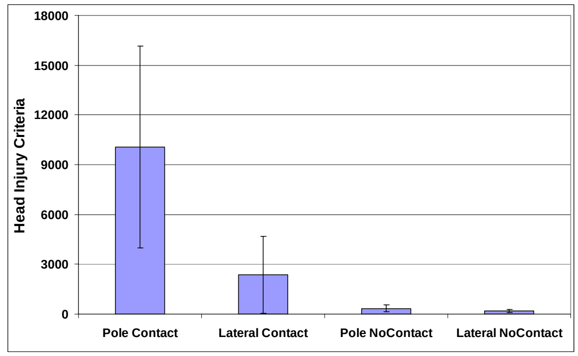


Figure 4. Comparison of Head Injury Criteria.

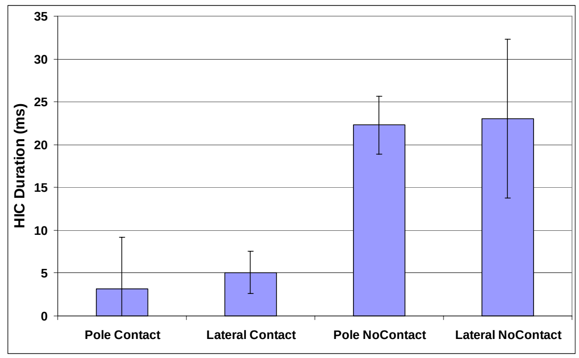


Figure 5. Comparison of HIC duration.

Head accelerations, HIC value and HIC duration give the kinematics of head motion. Specific types of brain injuries may be controlled by one or a combination of these biomechanical variables.

To study the probability of brain injury during the four modse of vehicle crash, SIMon FEHM was chosen for the global brain injury metric analysis in the current study. The model was originally developed by DiMasi et al. and enhanced by Bandak et al., and Takhounts et al. [15-18]. The model is comprised of a rigid skull, dura-CSF layer, brain, falx cerebri and bridging veins, with a total of 8,290 nodes and 5,900 elements. The model takes the head acceleration as input and computes stress-strain distribution in the brain tissue under inertial loading. The model has been validated with cadaver and animal experimental data [15, 17, 18]. It takes approximately 2 hours for the model to run a 220 ms acceleration pulse. The model was selected because of its small size, suitability for parametric studies [19], and its unique output of CSDM, DDM, and RMDM metrics for potential brain injury assessments.

CSDM in SIMon FEHM is defined as the percentage of total brain volume experiencing strains exceeding a threshold. The metric was introduced in an attempt to quantify the overall severity of injury to the whole brain, and its probability of diffuse axonal injury.

Rotational acceleration is the major contributor to this injury metric [20, 21]. It is found that a 50% probability of diffuse axonal injury is best correlated to a CSDM value of 55% at a threshold strain level of 0.15. Therefore, a CSDM value at 0.15 strain threshold was used in the current study. A comparison of CSDM value is shown in figure 6. Averaged CSDM were highest in lateral tests with head contact (CSDM 57%), although head accelerations and HIC value were highest in rigid pole tests with head contact (CSDM 47.0%), indicating higher probability of diffuse axonal injury in lateral impacts. This may be due to the fact that HIC durations were shorter in rigid pole tests. The finding also correlated well with the results in literature that higher accelerations are needed to produce equivalent injury at shorter pulse durations [22, 23].

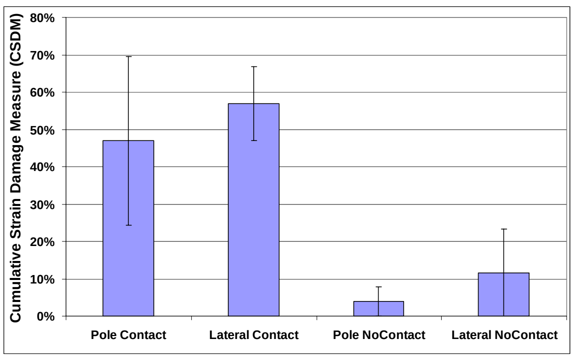


Figure 6. Comparison of CSDM.

DDM was introduced in SIMon to quantify negative pressure-induced brain contusion. It accounts for the ratio of the total volume of brain that experiences a negative pressure of 100 kPa. Physical model experiments have indicated that impacts above 150 g may cause vaporization, and impacts above 350 g can result in violent cavity collapse [24, 25]. Logistic regression based on animal and physical models have reported that 50% probability of contusion corresponds to 7.2% of brain tissue volume experiencing a pressure of -100 kPa, i.e., DDM of 7.2%. Other research indicates this injury metric to be closely associated with translation head acceleration [20, 21]. DDM value in all the non-head contact cases were well below the threshold value (Figure 7). However, rigid pole head contact cases had a DDM value of 14.8%, approximately 2x of the 7.2% threshold, indicating a high probability of brain contusion. In contrast, DDM value in lateral impact tests with head contact was only 2.2%. Brain contusion is less likely to happen in head contact lateral impacts.

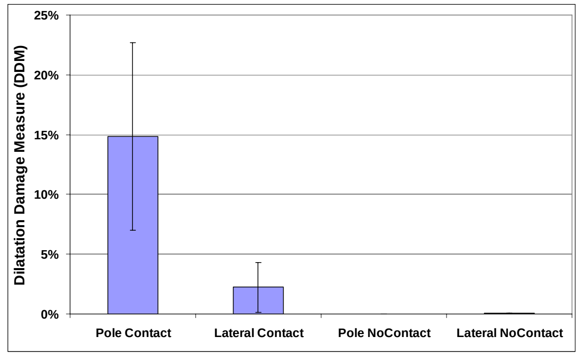


Figure 7. Comparison of DDM.

RMDM metric is introduced to evaluate the probability of acute subdural hematoma resulting from relative brain motion to the interior surface of cranium causing bridging vein rupture. RMDM is defined by calculating the ratio of a vein's current strain to the Lowenhielm threshold at the vein's current strain rate [26]. RMDM value of 1.0 is associated with 50% probability of vein failure. RMDM value in most of the cases in current study exceeded the threshold value of 1.0 (figure 8). As indicated by the authors of SIMon FEHM, there are possible sources of error in this injury metric, including its sensitivity to model geometry and selection of node pair for RMDM computation, and the justification of RMDM threshold [18]. Despite these drawbacks, RMDM value in contact cases were approximately 4x (rigid pole) and 2x (lateral impact) higher than non-head contact cases, indicating the severity of injury in head contact cases.

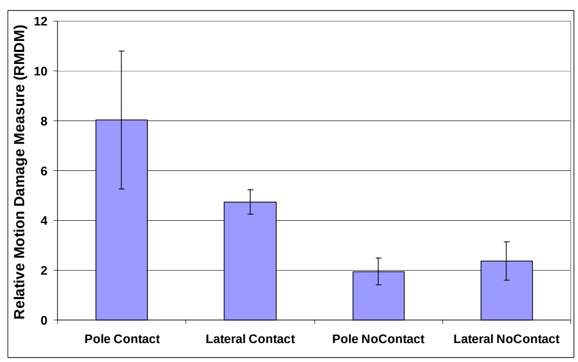


Figure 8. Comparison of RMDM.

The CSDM, DDM, and RMDM injury metrics from SIMon FEHM model treats the whole volume as one unit and does not differentiate between anatomical regions. Region-specific analysis may reveal the injury risk imposed to a local brain region and lead to a better understanding of the injury mechanism. Excessive brain strain may induce local brain tissue injury [27]. Maximum principal strain histories for all elements in an anatomical region were averaged as an indicator of brain tissue distortion of the region. Averaged regional brain are compared between contact and non-contact cases for lateral and rigid pole crash tests in figure 9 and figure 10. Contact cases systematically had higher regional strain through all regions. For lateral impact tests without head contact, most regions had averaged brain strain less than 10%. Brain strains for contact cases were approximately 1.5x of non-contact cases, except the difference between contact and non-contact case for left occipital and partial lobe were not significant. For rigid pole crash tests, regional brain strains were around 8% for non-contact cases, and about 2x higher for head contact cases. For the right cerebellum region, averaged brain strain was 21.6%, approximately 3x higher than non-contact cases, indicating high probability of injury in this region. Because SIMon FEHM does not differential material property in different anatomical regions, the differences in regional brain strains were attributed to the geometry of the model and the crash mode.

CONCLUSIONS

Using parametric analyses and controlled motor vehicle crash test data, this study compared biomechanical head injury metrics between tests with and without head contact. Overall, all cases with head contact appear to have more severe brain injury than non-contact cases. Therefore, the ultimate goal of preventing head injury in vehicle crashes appears to be to implement safety devices that prevent/limit direct head contact.

Both head translational and rotational accelerations and HIC value indicated high potential of head injury in head contact cases, with head contact in rigid pole crash tests being the most severe. CSDM indicated highest probability of diffuse axonal injury in head contact lateral crashes. DDM indicated the highest probability of brain contusion for head contact cases in rigid pole tests. High regional strain in the right cerebellum for head contact cases in rigid pole tests indicated high probability of injury to this region. These biomechanical results may help in a better understanding of the head injury mechanism and improve therapeutic treatments.

ACKNOWLEDGMENTS

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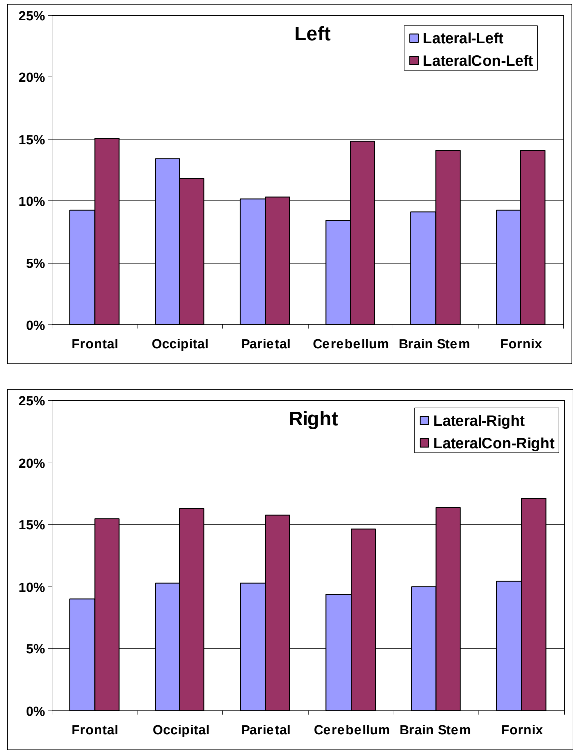

Figure 9. Comparison of regional averaged brain strain between contact and non-contact lateral crash tests

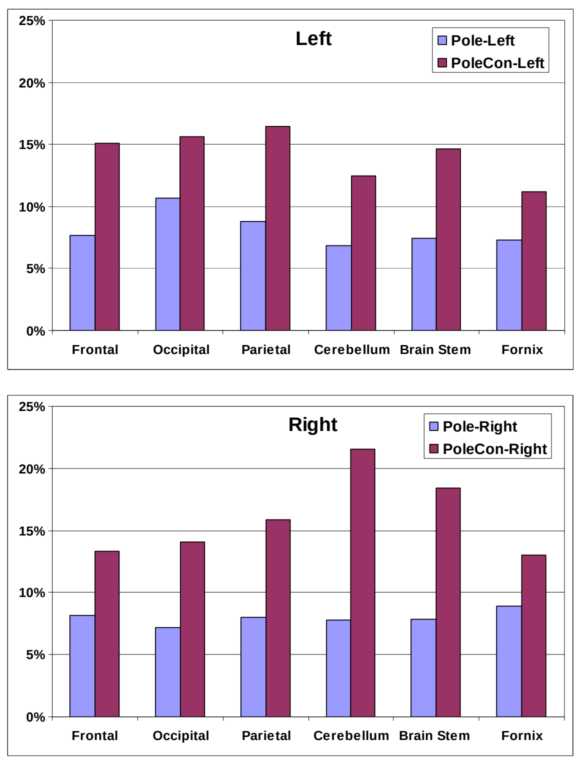

Figure 10. Comparison of regional averaged brain strain between contact and non-contact rigid pole crash tests

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