Examination of Brain Injury Thresholds in terms of the Severity of Head Motion and the Brain Stresses

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Introduction

Human head injuries occur due to many causes including falls, car accidents, sports, and physical assaults. According to the Center for Disease Control and Prevention (CDCP), each year in the United States (US), as many as 300,000 mild traumatic brain injuries (mTBI) occur due to sports.[1] Although clinical data from such incidents is usually considered to be the prime source of information regarding the injury, biomechanical simulations for such incidents can reproduce data for injury protection. The brain injury thresholds in a biomechanical analysis are set in terms of the severity index (SI), or head impact criteria (HIC), which, in turn, are measured in terms of the linear accelerations of the head under an assault. The severity of the motion, including its acceleration, can be a good indicator of the cause of any failure or injury. The size of the inflicted stresses/strains is, however, a step further in the detection of any failure or injury. Thresholds, in terms of intracranial pressure (ICP) and shear stresses (the external force that acts on an object parallel to the plane in which it lies) and strains (over twisting and stretching), have also been documented in the literature.[2-4] Although such criteria cannot be tested, or set at a unique value due to many uncompromised parameters, the severity of each threshold can be challenged in biomedical simulations of a human head model.

Researchers have carried out various experiments of simulating assaults on surrogated heads to relate the injury to head kinematics (movement analysis) of the motion. While such efforts are always valuable, more concentration needs to be placed on brain stresses and strains as primary causes of injury. Nahum et al.[5], Hardy et al.[6], Troseille et al.[7] carried out several impact scenarios on human cadaver heads to measured ICP of the brain, as well as acceleration of the head. Numerical methods and, in particular, finite element (FE) simulations, have been successful techniques for biomechanical analysis of the brain under various types of loading and they give remarkable insight into what happens to the brain in those situations. Several studies that have determined the mechanical responses of brain tissue under impact and blast loading conditions can be referenced.[8-10]

Injury criterion is necessary for safety, training, protection, and design of safety equipment. The definition of various injury criteria, highlighting the injury thresholds, has had positive effects on reducing the severity of injuries and mortalities. The Wayne State Tolerance Curve (WSTC) was introduced by Gurdjian et al.[11] as a human head tolerance limit indicator. The WSTC assumes that the fracture tolerance of the skull is equivalent to the tolerance of the brain injury. Gadd[12] introduced the Severity Index (SI), based on the WSTC, by integrating the linear acceleration raised to the power of 2.5. The HIC was then introduced by the US National Highway Traffic Safety Administration (NHTSA) as an alternative formulation of the SI.[13] The HIC is often used in the diagnoses of traumatic brain injuries (TBIs). The major limitation of both the HIC and the SI is that they do not take the rotational acceleration/angular acceleration (quantitative expression of the angular velocity change that occurs to a spinning object per unit time) into account. The Abbreviated Injury Scale (AIS) was introduced by the Association for the Advancement of Automotive Medicine (AAAM) as an anatomically-based coding system to classify, and describe, the severity of specific individual injuries. AIS codes range from 0 (no injury) to 6 (fatal injury).[11] There are also a number of criteria that include the effect of rotational/angular accelerations.[14-16] The injury thresholds, in terms of stresses/strains and ICPs, have not been employed extensively. ICP causes volume change while shear stress distorts and deforms the brain tissue. Some suggested values for brain injury threshold strains and stresses are given as: ICP > 235 kPa = severe or fatal injury and ICP < 173 kPa = minor or no injury[2]; strain > 0.2 injury[3]; and shear stress 11 to 16.6 kPa = injury.[4] In this paper, comparisons have been made between SI, the resultant head acceleration, brain ICP, and shear stresses when a human head falls and strikes with a rigid wall from the occipital side at different speeds. It is concluded that these thresholds are correlated.

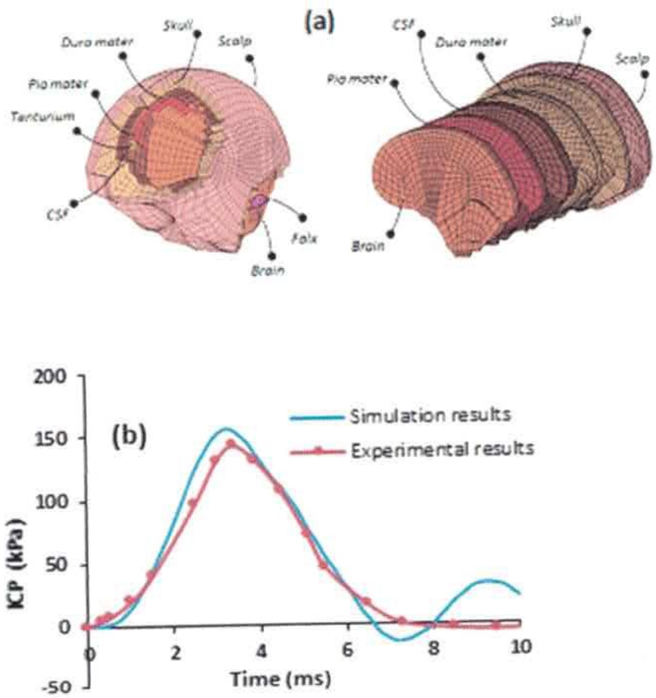
Table 1. Correlations between accelerations and AIS levels[16]

Max linear acceleration	AIS level	Injury description
<50g	0	No injury
50-100g	1	Minor
100-150g	2	Moderate
150-200g	3	Serious
200-250g	4	Severe
250-300	5	Critical
>300g	6	Non-survivable

FE Modeling of the Human Head

The size and geometry of a 50th percentile deformable finite element head model (FEHM) (a FEHM is a model being discretized into several simple-shaped elements so that their related mathematical equations can be easily and accurately solved and implemented for the whole complex structure). The FEHM is derived from a Magnetic Resonance Tomography (MRT) method adapted from Horgan and Gilchrist.[17] While the FEHM is clinically simplistic, it consists of the essential parts of the head anatomy including the scalp, skull, pia mater, dura mater, cerebral spinal fluid (CSF), tentorium, falx, and brain that can all act, mechanically, as a real human brain (Figure 1(a)). Materially, the brain of the FEHM is assumed to be a viscoelastic substance—a substance that displays elasticity and viscosity, or resistance of the fluid to flow, and that resists applied forces in a time-dependent manner—and its constants have been obtained by Ruan et al.[6] The mechanical properties for CSF of the FEHM is derived from the research of Kleiven and Hardy.[18] The rest of the components are assumed to have linear elastic response.[18,19] To properly, and accurately, model the interactions of the different parts, when the head experiences different types of loading conditions, or kinematical motions, appropriate contact conditions are defined between different elements of the head and brain.

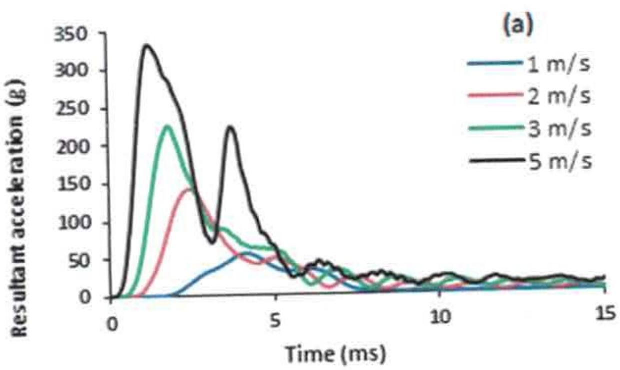
Figure 1. (a) Human head model and its components; (b) computational ICP which is justified by the experimental data

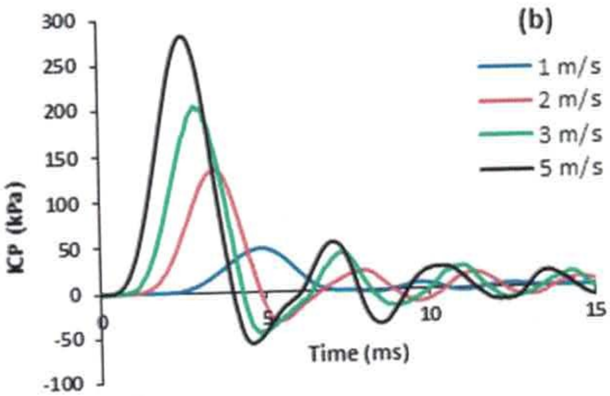


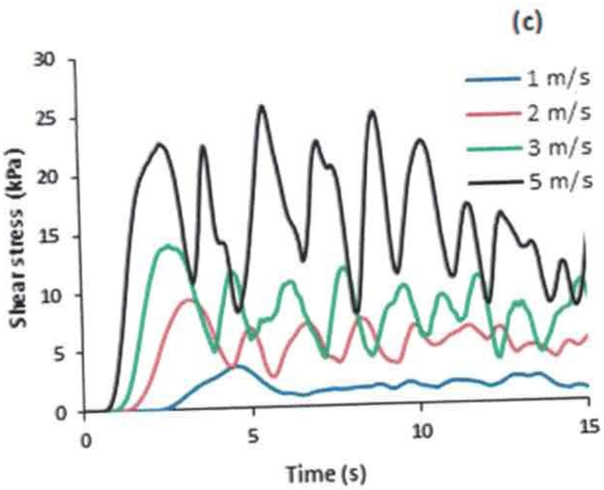
Validation of Human Head Impact

In all computational simulations, validation is of great importance because it indicates the credibility of the results. The FEHM in this study has been validated, several times, under impact loads. Originally Horgan and Gilchrist[17] verified it against different commonly referenced cadaveric experiments.[2-4] In the modeling process, the authors of this paper examined and validated the FEHM with an experiment of Nahum et al.[2] In the experiment, a cylindrical mass, with a weight of 5.59 kg and a speed of 9.94 m/s, impacted the head which was inclined 45 degrees from the brain Frankfort plane. The results of computational replication of the impact scenario that monitor ICP are shown in Figure 1(b). The close agreement of the results against the cadaver experiment meets the requirements for the simulation.

Figure 2. (a) Resultant accelerations of the head; (b) Variation of ICPs; and (c) Shear stress on the brain, at four impact speeds







Biomechanical Data due to Impact

In the study presented here, the head was assumed to hit the wall with the velocities of 1, 2, 3 and 5 m/s. In Figure 2(a), the accelerations of the head were monitored and illustrated for different impact scenarios. When the speed was increased, the acceleration increased dramatically. At the speed of 1 m/s, the acceleration of the head was less than 50g. Table 1 shows the comparisons and correlations of the linear acceleration with AIS levels.[11] When the speed increased to 2 m/s, the head was under an acceleration of about 140g which is the vicinity of moderate injury. This can also be supported by previous studies that have found the acceleration of 98g is the risk of mild concussion in football players.[1] At the speed of 3 m/s, the acceleration went beyond 220g, causing severe head injury (AIS 4+). HIC values can be better representatives of the injury than acceleration as they include the size, as well as the duration of acceleration. The corresponding HIC_{15} values for the three scenarios were calculated as 196.4, 363.8, 705.3, and 1939, all in terms of g, respectively. As indicated, the impact at 3 m/s created HIC of more than 700 which is in the region of high risk and severe brain injury.[20] At 5 m/s, the maximum acceleration and the corresponding HIC value confirmed that fatal injury would occur.

At the tissue level, ICP rapidly changes over time due to the relative motion of the brain, with respect to the skull. This relative motion creates positive and negative pressures in the coup and contrecoup sites of the brain. In this study, the variations of ICPs were collected from an area of the occipital lobe and are demonstrated in Figure 2(b). Likewise, the acceleration changed and the value of the ICP increased as the velocity of the head increased. The duration of the ICP elevation, however, became shorter. For these specific case studies, the ICPs changed from 47 to 276 kPa when the impact velocity of the head varied from 1 to 5 m/s. This correlation indicates that when the ICP goes up to about 191 kPa, the HIC is almost 700, which is the threshold of brain injury. The value of 191 kPa is in between the ICP range proposed by Ward et al.[12] and this verifies the accuracy of the computational studies. At the maximum speed of 5 m/s, the ICP threshold clearly indicated a non-survivable injury. The collected results of accelerations, ICPs, and HICs are shown in Table 2 and can be compared, and correlated, to each other.

Table 2. Correlation of ICP and acceleration of the head with HIC scores

Speed of impact (m/s)	Acceleration (g)	ICP (kPa)	Shear stress (kPa)	HIC
1	62.1	47.4	3.71	196.1
2	140.3	137.3	9.31	363.8
3	222.3	191.1	14.05	705.3
5	317.07	276.14	25.64	1939

A similar response and correlation can be seen in the behavior of brain tissue shear stress as depicted in Figure 2(c); At 1 m/s no injury is expected. Based on the thresholds proposed by Kang et al.[4], at speeds of 2 and 3 m/s, however, the shear stresses are 9.3 and 14.05 kPa, respectively, estimating the probabilities of mild and severe injuries. At speed of 5 m/s, the shear stress is considerably larger than 16 kPa (brain tolerance) and fatal injury occurs. The data of shear stress can clearly predict the occurrence of injury.

Conclusion

In this paper, a computational study of a head impact with a rigid surface has been presented. Kinematical and biomechanical data from a validated head model were collected for several head impact scenarios. With the velocity of impact ranging from 1 to 5 m/s, the acceleration of the head changed from 62g to 317g, respectively. The HIC scores of the impact indicated the risk of severe injury for velocities higher than 3 m/s. ICP variations were also measured as important injury-related parameters and were compared and correlated with acceleration and HICs. The ICP varied from 47 to 276 kPa and, acceptably, explained the level of injuries. The response of the brain in terms of shear stress also showed similar correlations. The study showed correlations of the injury thresholds.

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