SIMon: A SIMULATED INJURY MONITOR; APPLICATION TO HEAD INJURY ASSESSMENT

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ABSTRACT

Advancements in computational techniques used to simulate human impact injury response, coupled with those in computer hardware, bring the idea of detailed injury assessment closer to reality. Consequently, next-generation (G2) injury assessment processes are being explored to potentially augment or replace methods using dummy-based, empirically-derived, gross injury risk relationships. These processes use computational models that give more detailed injury response resulting from dummy-measured loading. This paper discusses the development of an initial version of such a next-generation injury assessment tool called *SIMon*: *A Simulated Injury Monitor*, as it is applied to the assessment of brain injury.

INTRODUCTION

SIMon is a result of a program to develop a G2 injury assessment tool. *SIMon* is used as a research tool to evaluate injury potential by directly imposing measured crash dummy responses on a finite element model of the body region, and analyzing its detailed structural response. *SIMon* is dependent on the development of accurate, computationally-based injury measures. Figure 1 is a schematic of the general concept of *SIMon* where injury measures are developed using combined experimental injury data with animal and human finite element models. These measures are then used to assess injury potential resulting from dummy loading applied to a human model.

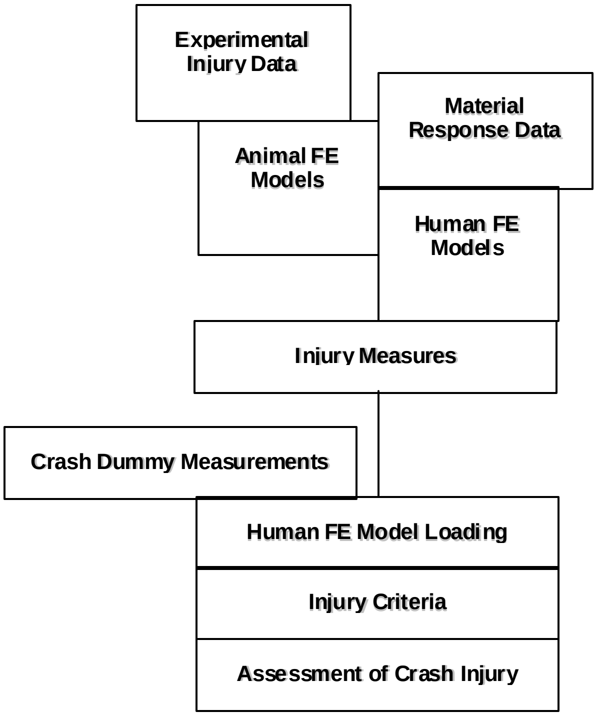

Figure 1: A schematic of SIMon concept.

The *SIMon* tool was developed as a PC Windows application to make a complex operation simple and easy to use. It enables a user to retrieve measured data from crash dummy tests, manipulate and transform and analyze the data, display results, and make injury assessments. It utilizes an intuitive graphical user interface combining, in a single package, several previously developed analysis modules [1,2]. The user simply clicks on a pictured crash dummy of interest from among the existing NHTSA dummy family. The individual picture of the dummy selected then appears with markers on each body region. A click on a body region marker brings out an appropriate dialog for analysis. When a body region is selected, for example the head, the applet that processes raw nine-accelerometer dummy data into solution compatible head loading for one *SIMon*'s core finite element models appears. The source of the data can be either an existing test in a NHTSA supplied database, or new traces and descriptor fields to be added to a separate user database, created, maintained and displayed automatically by *SIMon.* In this paper, the *SIMon* version for the assessment of injuries to the head will be presented. Similar presentations will be made at a later date for the assessment of thoracic, neck, and lower extremity injuries.

DEVELOPMENT OF COMPUTATIONALLY-BASED HEAD INJURY MEASURES

Three computationally-based measures representing the general types of brain injuries experienced in car crash environments have been developed [1,3]. Descriptions of these measures are given below.

Cumulative Strain Damage Measure

The first mechanical measure was developed [1] to evaluate the strain-related damage within the brain. This mechanical measure is referred to as the *Cumulative Strain Damage Measure* (CSDM). It has been shown to be useful in the evaluation of deformation-related brain injuries resulting from head impact [1]. The *CSDM* is based on the hypothesis that Diffuse Axonal Injury (DAI) is associated with the cumulative volume of the brain matter experiencing tensile strains over a critical level. The CSDM monitors the accumulation of strain damage by calculating the volume fractions of the brain experiencing strain levels greater than various specified levels. It is based on the maximum principal strain calculated from a strain tensor obtained by integration of the rate of deformation tensor [1]. At each time increment, the volume of all the elements that have experienced a strain above prescribed threshold values is calculated. The affected brain volume monotonically increases in time during conditions where the brain is undergoing tensile stretching deformations and remains constant (does not decrease) for all other conditions (i.e. compression, unloading, etc.). The cumulative nature of the *CSDM* means that the end state of a calculation represents the strain damage that may be related to DAI associated with a particular loading regime up to that point in time.

Dilatation Damage Measure

The second mechanical measure proposed [3] is for the evaluation of brain injury that occurs as a result of dilatational stress states. It is referred to as the *Dilatation Damage Measure* or DDM. It involves localized regions where stress states in the brain result in mechanical pressures exceeding negative values that are large enough to produce tissue damage. Dilatational stress modes are postulated to be involved in the damage processes of the biphasic brain with fluid (cerebrospinal, blood, and water) permeating nearly all of its solid soft tissue. Although no direct observational evidence has been reported on the relationship between pressure mechanisms and the production of axonal, vascular, dendritic, or other soft tissue injury, the proposed measure presumes that, on a mechanics basis, such mechanisms can cause these injuries. The DDM monitors the cumulative volume fraction of the brain experiencing specified negative pressure levels. Similar to the CSDM calculation, at each time step, the volume of all the elements experiencing a negative pressure level exceeding prescribed threshold values is calculated. This pressure threshold is, for the purposes here, set at –14.7 psi, the vapor pressure of water. The spatial distribution of affected volumes of brain matter reaching this negative pressure value indicates a higher possibility of lesions.

Relative Motion Damage Measure

The third mechanical measure proposed [3] is for the evaluation of injury related to brain movements relative to the interior surface of the cranium. It is referred to as the *Relative Motion Damage Measure* (RMDM). This measure monitors the tangential motion of the brain surface resulting from combined rotational and translational accelerations of the head. Such motions are a suspected cause of subdural hematomas associated with large-stretch ruptures of the parasagittal bridging veins. The RMDM does not require the explicit representation of the bridging veins but rather monitors the relative displacement of several node pairs. Each pair represents a bridging vein tethered between the skull and brain near the parasagittal sinus. The measure accounts for the large-stretch modes of rupture while leaving open the possibility of using other micro or macro rupture-modes associated with more complex vascular tethering states. The RMDM also incorporates the dependence of bridging vein stretching rupture on strain rate.

DUMMY-BASED MEASUREMENT OF HEAD LOADING

A technique to obtain the body-fixed translational and rotational acceleration of a rigid body by processing dummy-measured nine accelerometer head data was developed by Padgaonkar et al. [4]. The technique uses a unique 3-2-2-2 configuration of nine accelerometers where three accelerometers are at the head CG aligned along each principal body axis, and two on each principal arm, with sense axes oriented normal to the arm (Figure 2). A procedure that allows these body fixed head accelerations to be transformed into an inertial reference frame suitable as a loading input for existing finite element codes has been developed [2]. This is done by computing the six degree-of-freedom angular and translational velocities relative to inertial coordinates and using a simple direction cosine matrix to transform incremental changes in vector quantities from quantities in the body fixed frame. This transformation can be expressed as the summed transformation of the vector time-rate of change in the body coordinate system plus the cross product of the body angular velocity vector and the vector quantity in the body coordinate system. The orientation of the body coordinate system is computed and continually updated relative to fixed coordinates based on incremental changes in the body angular velocity vector. Typical NHTSA crash test head acceleration data is digitized at 8,000-10,000 samples/sec assuring small incremental head angular displacements making this updated coordinate tracking algorithm suitable for this data. A single output file containing the three translational and three angular velocities at the head CG is generated for direct use in *SIMon*.

SIMon COMPUTATIONAL CORE

The computational core of the current *SIMon* consists of a finite element model of the skull and intracranial contents that include the dura mater and the falx cerebri [1]. The tentorium and the region underneath the brain are approximated as a continuation of the dura mater and the cerebellum, midbrain, and brain stem, which exits the cranial cavity through the foramen magnum were not modelled. The model admits the imposition of variable traction boundary conditions on the surface of the brain. The surface of the brain was taken to be the outside of the subarachnoidal layer and to be coincident with the inner surface of the dura mater. The two surfaces are connected through a contact prescription developed and implemented in the finite element code [1] to release under pre-specified tensile and shear loading levels. Upon release and thereafter, the specified level of normal traction on the two separated surfaces is maintained. The skull is modelled as a rigid structure for the purposes of *SIMon*.

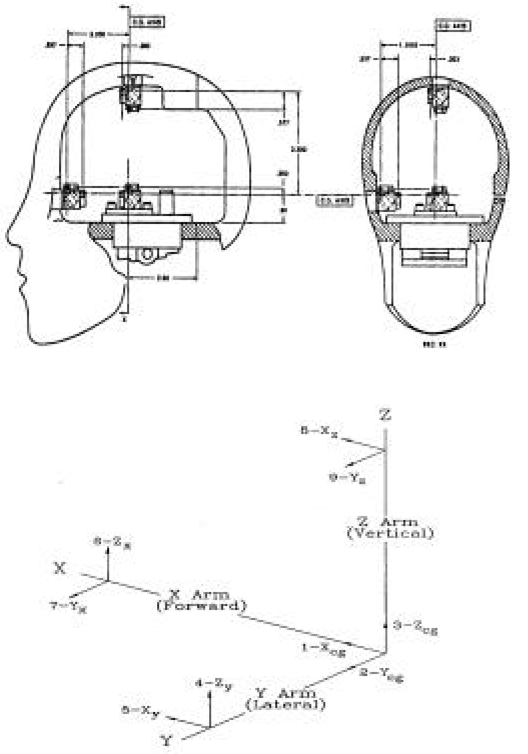

Figure 2: Accelerometer locations in dummy head with an ideal 3-2-2-2 configuration

DAMAGE MEASURES VS. EXPERIMENT

The three computationally-based damage measures described earlier were checked against existing experimental injury data. This was accomplished using finite element models to directly simulate experiments that are well enough described mechanically.

CSDM vs. Experiment

A two-dimensional finite element model of the midcoronal plane of the miniature pig was developed to simulate brain responses in existing experimental data [3]. The model was loaded by applying hypothetical but experimentally similar angular acceleration pulses to the rigid skull of the model. The loading range was chosen to cover the range of experimental data as shown in Figure 3 by the square symbols. The CSDM level, that is, the volume fraction of the total brain volume exceeding 15% strain, was calculated for each simulation. Figure 3 shows these results and the available experimental data plotted in maximum rotational velocity/maximum angular acceleration space. The triangles represent the experimental tests while the squares represent the model calculations. The labels next to the square symbols are the calculated CSDM levels ranging from 0-100, with 100 meaning 100% of the brain volume experiencing strain in excess of the prescribed strain threshold of 15%. Comparing calculated CSDM levels with reported DAI severity level, it can be seen that a CSDM level of 5 corresponds to mild DAI injury while a CSDM level of 22 corresponds to moderate or greater DAI severity levels.

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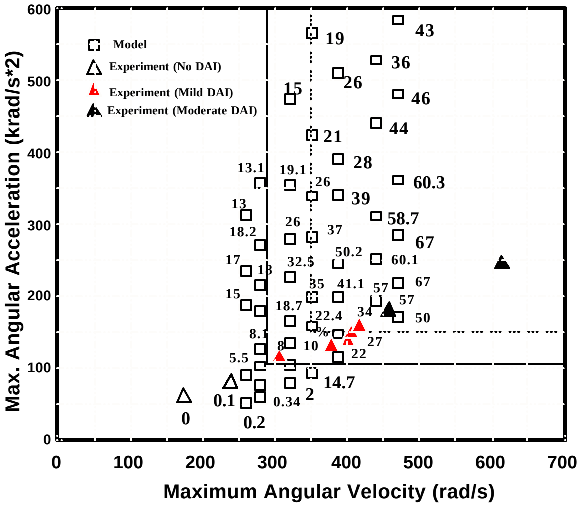

Figure 3: CSDM comparison with pig injury experimental data.

There are several implications of these results. The first is that once the CSDM relation to experiments is firmly established, a brain model of any shape and size (corresponding to a particular species and age) can be used to evaluate the risk of DAI. In other words, the individual sized finite element models account explicitly for shape and size and scaling is not needed to assess the potential for DAI. Similarly, mass scaling is also addressed by the FEM process enabling the CSDM to be used for any size brain including the various human sizes such as females, children, etc. In addition, properties of brain matter enable the use of cross-species data in human models

The CSDM, calibrated against the pig experiments, was implemented in the human model. The loading range covers the range of loading applied in the primate experiments [6] but scaled for the human head mass. Results of the comparison are shown in Figure 4 where solid triangles represent loading conditions where DAI occurs in the experiment and the solid circles represent loading conditions under which *SIMon* indicates DAI. Open circles represent the loading conditions for which *SIMon* indicates that no DAI occurs. The figure shows that the experimental DAI injuries fall within the loading region where *SIMon* predicts the potential for DAI.

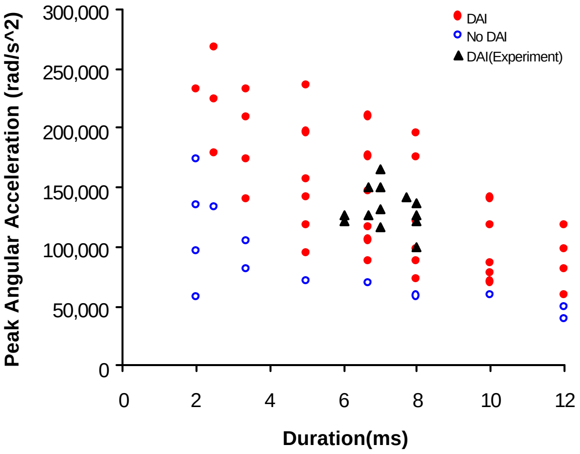

Figure 4: CSDM comparison with primate injury experimental data.

DDM vs. Experiment

The DDM was compared to available experimental data [7,8] using the human head model. A translational acceleration pulse in the anterior-posterior direction was applied to the head model to evaluate the critical level that may cause injury. The pulse was derived from experiments conducted on simple models of the human head that estimated surface pressure acting on the brain under impact loading [7, 8]. The pulse has a peak acceleration of 150g with a 4ms duration. This loading resulted in a DDM value of 5 which indicates that 5% of the brain experienced negative pressure of –14.7 psi. Therefore, this DDM value was chosen as the injury threshold. The DDM was compared against animal experiments [9]. The results suggest that the DDM value of 5 is proportional to the experimental results but may need additional modification to represent actual injury thresholds.

RMDM vs. Experiment

The RMDM was checked against bridging vein rupture experiments [10]. These experiments investigated the mechanical properties of cadaveric bridging veins and the rupture tolerance levels in terms of strain and strain rate. The rupture strain versus the strain rate for human bridging veins is reproduced in Figure 5.

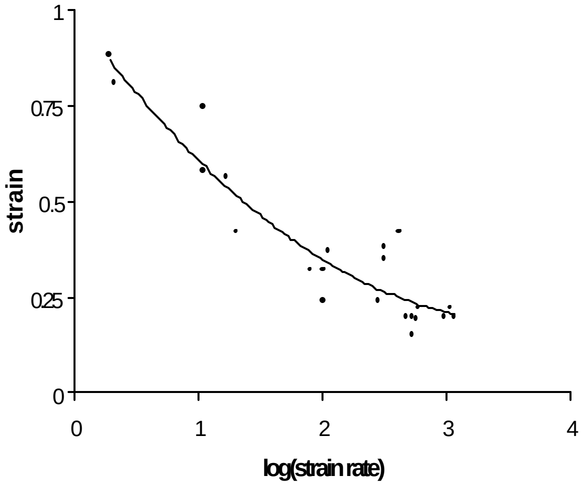

Figure 5: Bridging veins failure criterion based on strain and strain rate.

This failure description was implemented in the RMDM and evaluated against Acute Sub-Dural Hematoma (ASDH) experiments in the primate [11]. Figure 6 shows solid triangles indicating ASDH from experiment. Simulation cases are indicated by the circle symbols. Open circles represent cases where maximum strain/strain rate does not exceed failure limit and thus, ASDH is not expected to occur. Solid circles represent cases where ASDH is expected to occur. The results indicate the experimental data agree well with the ASDH predicted by *SIMon*.

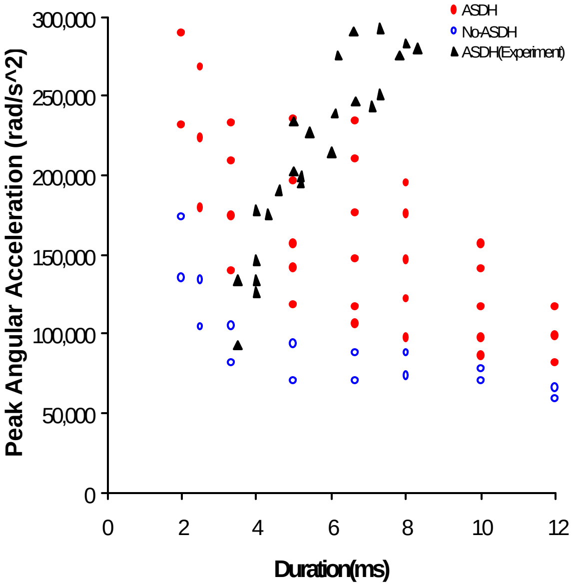

Figure 6: RMDM comparison with primate injury experimental data.

Application of SIMon to Crash Data

A total of fourteen crash tests found in the NHTSA crash database were used to provide an initial evaluation of the operation and performance of *SIMon*. These tests involved a 50th percentile dummy that had the acceleration time-histories obtained from a nine-accelerometer array in the dummy's head. These acceleration time-histories were used both as input to standard HIC algorithms as well as to *SIMon*. Table 1 lists the individual crash conditions for each test. This includes variables such as impact angle, closing speed and restraint type, as well as values of HIC 15, HIC36, and the component and cumulative pass/fail results provided by *SIMon*. The table shows that with HIC15, five of the fourteen tests exceeded the limit of 700, while for HIC36, with a limit of 1000, four tests failed.

Even though the individual measures of *SIMon* registered different failure rates than HIC15 or HIC36 (CSDM has five, RMDM none, and DDM four), *SIMon's* cumulative or overall evaluation of the set of crashes turned out to be more stringent. Additionally, the *SIMon* output indicates, that even with the limited number of test types examined, a number of brain injury mechanism are active and that two cases, tests 3 and 6, are situations where *SIMon* detects high *CSDM* conditions where the HIC values are low.

DISCUSSION AND CONCLUSIONS

A new injury assessment tool called *SIMon* (Simulated Injury Monitor) has been developed. It is an automated, PC based, tool for evaluation of injury potential from dummy-measured crash data. *SIMon* represents a substantial refinement over conventional methods that employ empirically derived relationships to predict only a gross probability of injury. *SIMon* accomplishes this by interpreting detailed structural response of a particular body region model. *SIMon* was presented here for the case of head injury, where it utilizes a computationally efficient finite element head model that can be loaded directly by acceleration-time histories from crash test dummy tests. It, then evaluates the detailed structural response of the brain over the entire crash event and assesses potential of injury using three previously developed damage/injury measures that account for different categories of brain injury. These three individual measures have been checked and calibrated against existing experimental data from animal, cadaver, and physical model tests.

SIMon was operationally tested with real crash test acceleration data from the NHTSA archives demonstrating its operational robustness at processing real crash data. This analysis also demonstrated that *SIMon*'s three structurally-based failure criteria, *CSDM*, *DDM*, and *RMDM* collectively detect the conditions that the current HIC detects as well as detecting other injurious conditions that have low HIC levels. In these low HIC cases, *SIMon* indicated potentially injuries because of high CSDM levels associated with a high probability for DAI. In particular, case 3 vs. case 4 with nearly identical HIC36 values one fails and one passes SIMon. This is due to the higher level of angular acceleration in test 3 contributing to a higher CSDM but not affecting the HIC values.

The *SIMon* tool demonstrated a balance between complexity, robustness, and utility in injury evaluation. It was designed to be totally resident and operational on a current high end PC and capable of providing results in a reasonable time. The operational efficiency of *SIMon* is certain to benefit from the rapidly increasing capabilities in computer hardware and computational speed.

Table 1. Test data and HIC values for adult hybrid III dummy, along with head injury assessment according to the various measures implemented in SIMon.

Test Number	Test Config.	Impact Angle (deg)	Closing Speed (kmh)	Restraint Type	HIC Clip (ms)	HIC36	HIC15	SIMon	CSDM	DDM	RMDM
1	VTV	30	93	3PT/ABG	35.9	102	61	P	0.30	0.00	0.0
2	VTB	0	64.7	3PT/ABG	35.9	174	79	P	3.00	0.00	0.0
3	VTV	30	105.6	3PT/ABG	36.0	195	98	**F**	**5.01**	0.00	0.0
4	VTV	30	105.9	3PT/ABG	31.0	208	160	P	0.50	0.00	0.0
5	VTV	30	119	3PT/ABG	35.9	405	280	P	3.30	0.00	0.0
6	VTV	30	111.4	3PT/ABG	26.6	489	417	**F**	**8.50**	0.00	0.0
7	VTV	0	112	3PT/ABG	34.9	530	364	P	0.10	0.60	0.0
8	VTV	30	113	3PT/ABG	27.8	614	412	P	0.60	0.50	0.0
9	SLB	0	59.5	3PT	36.0	750	393	P	3.60	0.60	0.0
10	VTV	30	122.6	3PT/ABG	21.2	893	**777**	**F**	**12.00**	1.00	0.0
11	VTV	30	124.4	3PT/ABG	35.9	**1222**	**971**	**F**	**9.80**	**5.00**	0.0
12	SLB	0	61.2	3PT	12.8	**1330**	**1330**	**F**	1.20	**9.00**	0.0
13	SLB	0	52.6	3PT	11.5	**1568**	**1568**	**F**	2.40	**7.20**	0.0
14	SLB	45	40.7	None	3.6	**2301**	**2301**	**F**	**28.00**	**8.25**	0.0

VTV: Vehicle to Vehicle; SLB: Sled with Vehicle Body; VTB: Vehicle into Barrier;

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