Added Value of Tissue Level Brain Injury Criteria
- Towards Injury Criteria for Elderlies -

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ABSTRACT: Traumatic brain injury (TBI) is the leading cause of death and permanent impairment over the last decades. In both the severe and mild TBI, diffuse axonal injury (DAI) is the most common pathology. Computation of axon elongation by using finite element (FE) head model in numerical simulation can enlighten the DAI mechanism and help to establish advanced head injury criteria. The main objective of this study is to propose a brain injury criterion per age-class based on multiscale computation of axonal elongation of real world head trauma. The implementation of advanced skull mechanical properties and new medical imaging data such as fractional anisotropy and axonal fiber orientation from Diffuse Tensor Imaging (DTI) into the FE brain model was performed to improve the brain constitutive material law with more efficient heterogeneous anisotropic visco-hyper-elastic material law and enables it to compute axon elongation at the time of impact. Further, well-documented head trauma cases were simulated by using this finite element head model in order to derive head injury criteria for different injury mechanisms. Coming to brain injury, the head trauma database was divided into three different groups depending on victims’ age: under 30 years old, between 30 to 50 years old and over 50 years old. An extensive real-world head trauma simulation exercise including age-class analysis was performed on an advanced head FE model including the computation of axonal elongation. Based on the statistical analysis, axonal strain was the most relevant candidate parameter to predict moderate DAI. It was showed that the threshold value in terms of axonal strain for a 50% risk of moderate DAI decrease with the increase of victim’s age. Senior people seem to be more sensitive to moderate DAI than the other age-classes.

KEYWORDS: Safety, Head FE modelling, Axonal strain, Injury Criteria, Elderlies [C1]

1. Introduction

Biomechanical response of the human head during vehicular crashes, falls, and sports related events can lead to mechanically induced trauma. About 1.35 million people die each year as a result of road traffic crashes (3). Skull fracture accounts for 32% of all head injuries, sustained by pedestrians, motorcyclists, vehicle occupants and sportsmen (2). Fractures occur when dynamic input to the cranium exceeds the tolerance limit of skull material, but this bone tissue level injury criteria has rarely been implemented into head FE models.

On the other hand traumatic brain injury (TBI) is the leading cause of death and permanent impairment over the last decades (3-4). In both the severe and mild TBI, diffuse axonal injury (DAI) is the most common pathology. (5). DAI has been characterized by dynamic tensile elongation of axonal fibers and consequential fiber rupture (6). Several widely recognized FE head models were developed to study the specific aspects of head trauma biomechanics. Based on these models and head-trauma simulations, brain stress and strain were proposed as possible criteria to predict DAI (7-9). Further studies emphasized that the tensile axonal elongation was the most realistic mechanism of DAI (10-11). Multiscale computation of axon elongation by using finite element head model in numerical simulation can enlighten the DAI mechanism and help to establish advanced head injury criteria. In the present study, a composite material model for the skull, taking into account damage, was implemented in the Strasbourg University Finite Element Head Model (SUFEHM) in order to enhance the existing skull mechanical constitutive law. Further, 15 experiments and 70 real-world head trauma cases were combined to derive injury risk curves for skull fracture. For this same head model enhanced brain material laws including main axon bundles were implemented and the model was used for numerical simulation of 109 real world head traumas including the computation of an axon elongation in order to derive brain injury tolerance curve. Finally the head trauma database was organized in terms of age classes in order to progress towards brain injury criteria as a function of age.

2. Human Head FE Modelling

An existing validated FE head Model developed in Strasbourg University by Deck et al. (9) was used as a base for further improvements in the current study to develop model-
3. Head Trauma Database

3.1. Head trauma involving critical skull loading

A total of 86 drop tests were conducted on 17 Post Mortem Subject’s (PMHS) skulls, isolated at the level of the occipital condyles and reported by Yoganandan et al. (23). The PMHS specimens were impacted using drop techniques with successive increasing drop heights until fracture. The first drop height or the velocity was estimated to provide baseline data without fracture so that all specimens had a non-fracture data point for impact velocity ranging from 2.4 to 6.5 m/s. Acceleration- and force-time signals were collected during the experiment and peak resultant forces and center of gravity linear and angular accelerations were considered. Resultant force-time histories from each specimen at each velocity for each target were used to develop the biomechanical corridors, expressed as mean and plus or minus one standard deviation.

Further a total of 70 head trauma cases collected from different pedestrian accident databases are used as accident data. Fifteen well-documented accident cases were selected from in-depth investigations of the Vehicle Accidents in Changsha database (24). A total of 28 cases were collected from the German In-depth Accident Study database (9, 24). Pedestrian accident cases were collected by the Centre for Automotive Safety research from crash sites in Adelaide, South Australia (24). Seven pedestrian cases were selected from this database (25). Similarly, 12 pedestrian cases were selected from the Tsinghua accident database and eight cases from the Virginia accident database. In the accident database, 24% of cases were with skull fracture and 76% cases are without skull fracture. The 70 pedestrian accident cases were reconstructed in previous studies by using MADYMO software. From this multi-body replication of the pedestrian kinematics, the information about the velocity of the head just before the impact, impact location and orientation of the skull was used to develop critical skull loading parameter values.

Table 1. Skull and brain mechanical parameters implemented in the Head FE Model

| Parameters                      | Cortical | Diploe         |
|---------------------------------|----------|----------------|
| Mass density (Kg/m³)            | 1900     | 1500           |
| Young’s Modulus (MPa)           | 15000    | 4665           |
| Poisson’s ratio                 | 0.21     | 0.05           |
| Long. and trans. Comp. strength (MPa) | 132    | 24.8           |
| Long. and trans. Tensile strength (MPa) | 90     | 34.8           |

Matrix

| C10 | -1.034 kPa |
|-----|------------|
| C3  | 13.646 kPa |
| C4  | 4.64*FA    |
| C01 | 7.809 kPa  |

Fibers

| S1  | 4.5 kPa    |
| S2  | 9.11 kPa   |
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BRAIN MECHANICAL PARAMETERS

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Viscoelasticity

| T1  | 1x109 s⁻¹ |
| T2  | 6.8966 s⁻¹|

Fig. 1 Illustration of the different parts of Strasbourg University Finite Element Head Model (SUFEHM) including main axon bundles.

SKULL MECHANICAL PARAMETERS

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the head were obtained. The methodology of these pedestrian kinematic reconstructions are reported in Sahoo et al. (26).

3.2. Head trauma involving critical brain loading

For the derivation of brain injury criteria, the accident database used consists of 109 cases collected from different accident databases and involving pedestrian, motorsport, American football player and motorcycle accidents. In each database, the accident report consists of the final position of the pedestrian and vehicle after the accident, skid marks on the road and vehicle, type of vehicle, vehicle speed, impact position of the pedestrian on the vehicle and the condition of the road at the scene. The medical report includes the victim’s age, gender, height, weight and details of injuries sustained by the victims. For each of these accidents the head impact conditions were investigated in partnership with a number of institutions as briefly exposed here after:

- Six motor sport accidents were collected from Formula 1 accidents (FIA) as reported in (9, 27).
- A total of 11 well-documented motorcycle accident cases were collected from European cooperation in science and technology (COST327) accident databases (28).
- Twenty-two American football impact events were collected from the reconstruction study reported by (29-30).
- Seventy pedestrian accident cases as described in the previous section and involving also critical skull loading

Concerning motorcyclist accidents, American football player impacts and FIA cases, the 3D head acceleration fields were recorded during experimentation which have been done in the COST project (28) for motorcyclists cases, by (29, 30) for American football player accident cases and FIA cases respectively. For all these experimental accident reconstructions (39 cases), the 6 accelerations versus time curves (3 linear and 3 rotational accelerations), recorded at the center of gravity of the dummy were transferred to Strasbourg University and considered as input for the numerical simulation of the head trauma.

For the pedestrian accident cases direct impacts against a validated finite element windscreen model were done with the SUFEHM (all the victims impacted the head against the windscreen) by using the information about velocity of the head just before the impact, impact location and orientation of the head obtained from previous multibody study.

Finally the 109 head trauma cases were divided into two groups i.e. with (27%) and without diffuse axonal injury (DAI) (73%). DAI is characterized in this study as loss of consciousness (AIS2+).

4. Head Injury Criteria

4.1. Skull fracture criteria

The 15 experimental PMHS head drop tests cases along with 70 pedestrian accident cases were combined and mechanical parameters like peak interaction forces, skull internal energies and head kinematics-based parameters HIC and SFC were extracted for each simulation.

Figure 2 illustrates the peak contact force, skull internal energy, HIC and SFC for all cases reconstructed with the advanced FEHM. The white columns represent the cases without skull fracture and black columns represent the cases suffering skull fracture.

The ranges of contact force, skull internal energy, HIC and SFC were 1326-14418 N, 36-1476 mJ, 26-8540, and 22-311, respectively. It was observed that the skull internal energy presents a smooth histogram with smallest discontinuity from non-injured to injured cases than other potential parameters.

Fig. 2 Maximum parameters computed for all head trauma simulations and displayed for non-injured (no skull fracture in white column) and injured (skull fracture in black column) victims in terms of peak contact force, internal energy of skull, HIC and SFC.

This qualitative observation was objectively confirmed by the statistical analysis leading to the highest Nagelkerke parameter ($R^2$=0.633) for skull internal strain energy when this regression parameter was 0298, 0341 and 0.268 respectively for HIC, Force and SFC.

The derived injury risk curve for the best candidate parameter (skull internal energy calculated with SUFEHM) is reported in figure 3 and shows that a 50% injury risk is obtained for skull internal energy of 453 mJ.

More details about the development of skull fracture criterion using Strasbourg University Finite Element Head Model is available in (26).
4.2. Brain injury Criteria

The statistical analysis for the 109 simulated head traumas involving critical brain loading is carried out by using binary logistical regression and the metric for predicting injuries (DAI) along with their Nagelkerke $R^2$ value were calculated. It appeared that axonal strain presented the highest Nagelkerke- $R^2$ value with a value of 0.876 whereas for Von Mises stress, Von Mises strain and HIC the $R^2$ values were 0.502, 0.446 and 0.055 respectively. Hence, axonal strain is the most suitable parameter to predict DAI.

Based on this statistical analysis, the injury risk curve for predicting DAI is plotted as shown in figure 4.

The solid black circles represent the cases for which injury occurred and the white circles are representative of non-injured cases.

From this injury risk curve, the critical axon elongation for a 50% risk of DAI is obtained and corresponds to an axons strain of 0.1465.

4.3. Towards brain injury criteria for elderlies

In order to progress towards brain injury criteria as a function of age, the 109 well-documented head trauma cases reported in section 3.2 have been divided into three different groups depending on the age of the victims, according to following criteria.

- Under 30 years old (45 cases),
- Between 30 to 50 years old (34 cases),
- Over 50 years old (27 senior cases).

For each head trauma simulation, maximum axon elongation was computed to derive brain injury tolerance curve per age-class. Statistical analyses of these intra-cerebral parameters were conducted to obtain the most suitable parameter to predict moderate DAI and to derive brain injury tolerance limits for each of the three age-classes as illustrated in figure 5.

The proposed brain tolerance limit in terms of axon elongation for a 50% risk of moderate DAI has been established per age group as follows:

- 15.2% for age-class under 30 years old associated with a Nagelkerke’s parameter of 0.94
- 14.5% for age-class 30 to 50 years old associated with a Nagelkerke’s parameter of 0.76,
- 14.1% for elderly people associated with a Nagelkerke’s parameter of 1.

5. Conclusion

A Head Finite Elements Model with enhanced brain and skull material laws which enable it to compute axon elongation was used for numerical simulation of real world head trauma to
develop a robust head injury criterion for specific head injury mechanisms.

A total of 70 real world pedestrian accidents and 86 experimental PMHS head drop tests were gathered and simulated in order to establish skull fracture criteria.

Further 109 well-documented TBI cases were simulated and axon elongations were computed to derive a brain injury tolerance curve. Based on statistical analysis, it was shown that axonal strain was the appropriate candidate parameter to predict DAI.

The proposed brain injury tolerance limit for a 50% risk of moderate DAI has been established at 14.65% of axonal strain. The proposed threshold in terms of axonal strain is in accordance with studies reported in literature. Head kinematics based other metrics have also been computed for all head trauma cases to compare its capability to predict skull fracture and brain injury. Results showed very poor correlation of HIC with injury compared to skull strain energy and axon strain. It is therefore concluded that the present study provides realistic methods and tools for advanced model based head injury risk assessment and mitigations.

The extensive real-world head trauma simulation exercise also included age-class analysis in order to compute axonal elongation for different age groups showed that the threshold value in terms of axonal strain for a 50% risk of moderate DAI decrease with the increase of victim’s age, which demonstrate that elderly people seem to be more sensitive to moderate DAI than the other age-classes.

The proposed results is a first attempt to propose brain injury tolerance limit for senior and more cases involving elderly people are needed to confirm this trend.

The developed head injury prediction tool can be applied in a “full FE approach” when a FE model of the protective system exists.

In this case the head-structure interaction can be simulated and it is possible to assess the head injury risk in terms of skull fracture and brain injury directly for this simulation. For protected head impacts, when the skull fracture is unlikely to appear it is possible also to implement a “coupled experimental versus numerical approach”.

In this case the head 6D kinematic is recorded from the experience and considered as the initial condition of the head impact simulation with a rigid skull assumption as illustrated in figure 6. This coupled experimental versus numerical method permitted also to propose novel helmet test methods which consider oblique impacts with the recording of the 6D headform kinematic and followed by the numerical assessment of the brain injury risk.

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![Fig. 6 Illustration of the experimental versus numerical brain injury risk assessment.](image)

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