Head injury prediction tool for protective systems optimisation

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Summary:

This paper presents an original numerical human head FE models followed by its modal and temporal validation against human head vibration analysis in vivo and cadaver impact tests from the literature. The human head FE model developed presents two particularities : one at the brain-skull interface level were fluid-structure interaction is taken into account, the other at the skull modelling level by integrating the bone fracture simulation. Validation shows that the model correlated well with a number of experimental cadaver tests including skull deformation and rupture, intra-cranial pressure and brain deformation. This improved numerical human head surrogates has then been used for numerical real world accident simulation. Helmet damage from eleven motorcycle accidents was replicated in drop tests in order to define the head's loading conditions. A total of twenty well documented American football head trauma have been reconstructed as well as twenty eight pedestrian head impacts. By correlating head injury type and location with intra-cerebral mechanical field parameters, it was possible to derive new injury risk curves for injuries as different as subdural haematoma and neurological injuries. Illustration of how this new head injury prediction tool can participate to the head protection system optimisation is also provided.

Keywords:

Finite Element Head Model, Head Trauma Database, Head Injury Criteria, Tolerance Limits

1 Introduction

THE HEAD and more specifically the brain is among the most vital organs of the human body. From a mechanical point of view, the biological evolution of the head has lead to a number of integrated protection devices. The scalp and the skull but also to a certain extent the pressurized sub arachnoidal space and the dura matter are natural protections for the brain. However, these are not adapted to the dynamical loading conditions involved in modern accidents such as road and sport accidents. The consequences of these extreme loadings are often moderate to severe injuries. Preventing these head injuries is therefore a high priority.
Over the past forty years, a slant has been put by the biomechanical research on the understanding of the head injury mechanisms. One of the main difficulties of this research field is that a functional deficiency is not necessarily directly linked to a damaged tissue. Nevertheless, an injury is always a consequence of an exceeded tissue tolerance to a specific loading. Even if local tissue tolerance has very early been investigated, the global acceleration of the impacted head and the impact duration are usually being used as impact severity descriptors. The *Wayne State University Tolerance Curve* has therefore been proposed since the early Sixties thanks to several works by Lissner *et al*. (1960) [1] and Gurdjian *et al*. (1958) [2]. This curve shows the link between the impact of the head described by the head acceleration and the impact duration and, on the other hand the head injury risk. Hence, after the work of Gadd (1966) [3], the *National Highway Traffic Safety Administration* (NHTSA) proposed the *Head Injury Criterion* (HIC) in 1972. This is the tool used nowadays in safety standards for the head protection systems using headforms. Since it is based solely on the global linear resultant acceleration of a one mass head model, some limitations of this empiric criterion are well-known, such as the fact that it is not specific to direction of impact and that it neglects the angular accelerations.
A proposed alternative method for assessing head injury risk is to use a human head Finite Element Model (FEM), which can enable the investigation of the intra-cranial response under real world head impact conditions. This method is well known since 1975 when one of the first three dimensional model was developed by Ward et al [4]. This method thereby leads to added useful mechanical observables which should be closer to the description of known injury mechanisms. Hence, new injury criteria can be proposed. In the last decades, more than ten different three dimensional finite element head models (FEHM) have been reported in the literature by Ward *et al.* (1980) [4], Shugar *et al.* (1977) [5], Hosey *et al.* (1980) [6], Di Masi *et al.* (1991) [7], Mendis *et al.* (1992) [8], Ruan *et al.* (1991) [9], Bandak *et al.* (1994) [10], Zhou *et al.* (1995) [11], Al-Bsharat *et al.* (1999) [12], Willinger *et al*. (1999) [13,] Zhang *et al.* (2001) [14]. Fully documented head impact cases can be simulated in order to compute the mechanical loadings sustained by the head tissues and to compare it to the real injuries described in the medical reports. It has for example been shown in Zhou *et al.* (1996) [15], Kang *et al.* (1997) [16] and more recently in King *et al.* (2003) [17], Kleiven et al. (2007) [18] and Deck et al. (2008) [19] that the brain shear stress and strain rates predicted by their FEHM agree approximately with the location and the severity of the axonal injuries described in the medical report.Since these finite element head models exist, new injury prediction tools based on the computed intracranial loadings should become available.
In order to undertake a statistical approach to injury mechanisms, more accident cases including footballers, motorcyclists and pedestrians were introduced in Marjoux *et al. (*2007) [20] and Deck et al. (2008) [19] and a first attempt of injury criteria to specific mechanisms was proposed. Another FEHM presented in Takhounts *et al* (2003) [21] is very suitable for this kind of study due to the very short computing duration: the *Simulated Injury Monitor* or SIMon. A number of scaled animal model loading conditions lead the authors to propose as well injury mechanisms and related injury criteria based on animal experiments
In this context, the objective of the present study is therefore to transfer an available (under Radios code) FEM to Ls-Dyna software and to investigate on a same set of real world accidents the injury prediction capability of the injury mechanisms related criteria provided by the Strasbourg University Finite Element Head Model (SUFEHM) under Ls-Dyna software in order to illustrate of how this new head injury prediction tool (SUFEHM) can participate to the head protection system optimisation.

2 Strasbourg University Finite Element Head Model (SUFEHM) presentation

2.1 Meshing presentation

Kang et al., in 1997 [16], has developed the Strasbourg University Finite Element Head Model (SUFEHM) under Radioss software. The geometry of inner and outer surfaces of the skull was digitised from a human adult male skull. The main anatomical features modelled were the skull, falx, tentorium, subarachnoid space, scalp, cerebrum, cerebellum, and the brainstem. The finite element mesh is continuous and represents an adult human head. Globally, SUFEHM model consists of 13208 elements. Its total mass is 4.7 kg, a representation is given in Figure 1. This SUFEHM has been transferred under Ls-Dyna software in a nastran format.

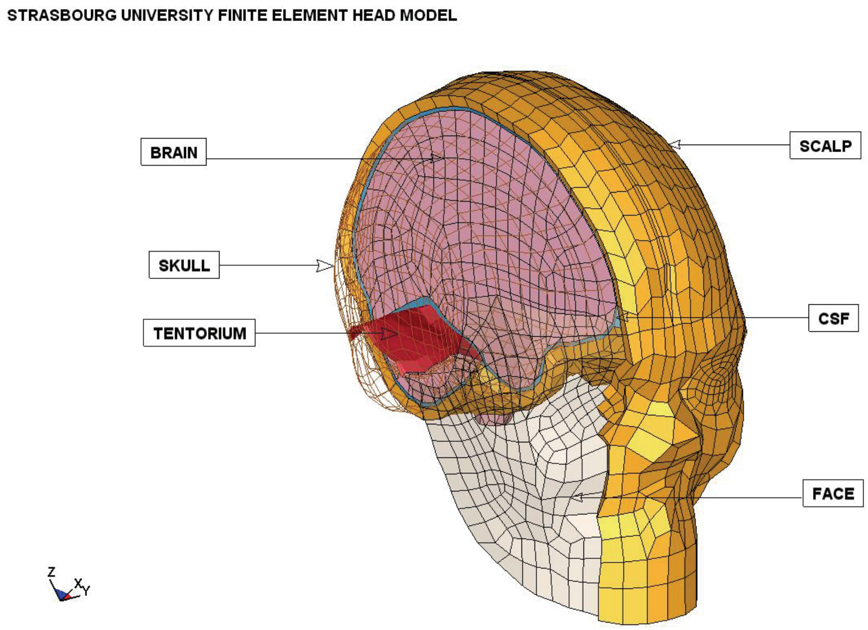


Figure 1. Section through the Strasbourg University Finite Element Head Model (SUFEHM).

2.2 Mechanical properties under Ls-Dyna software

2.2.1 Introduction

The source model is available under Radioss code; the aim here is to implement mechanical properties under Ls-Dyna code before SUFEHM's validation. Material properties of the cerebral spinal fluid, scalp, facial bones, tentorium and falx are all isotropic, homogenous and elastic, with mechanical properties similar than those used under Radioss code (*MAT_ELASTIC law) (Willinger et al., 1995 [22]). Table 1 summarizes mechanical properties and element characteristics used for the SUFEHM.

Table 1. Mechanical properties and element characteristics of the SUFEHM.

Part	Material property	Material parameter	Value	Element type	Shell thickness [mm]
Face	Elastic	Density Young modulus Poisson's ratio	2500 $Kg.m^{-3}$ 5.0E+03 MPa 0.23	Shell	10.0
Scalp	Elastic	Density Young modulus Poisson's ratio	1.0E+03 $Kg.m^{-3}$ 1.67E+01 MPa 0.42	Solid	/
CSF	Elastic	Density Young modulus Poisson's ratio	1040 $Kg.m^{-3}$ 0.12E-01 MPa 0.49	Solid	/
Falx	Elastic	Density Young modulus Poisson's ratio	1140 $Kg.m^{-3}$ 3.15E+01 MPa 0.45	Shell	1.0
Tentorium	Elastic	Density Young modulus Poisson's ratio	1140 $Kg.m^{-3}$ 3.15E+01 MPa 0.45	Shell	2.0

2.2.2 Brain material law choice

The brain is assumed to be visco-elastic. The visco-elastic law used under Ls-Dyna code is Material Type 6 (MAT_VISCOELASTIC). This model allows the modelling of visco-elastic behaviour for beams, shells and solids. The shear relaxation behaviour is described by:

$$G(t) = G_\infty + (G_0 - G_\infty)Exp(-\beta t) \qquad [1]$$

With G_0 short-time shear modulus, G_∞ Long-time shear modulus and β Decay constant. Values of the parameters are the same than for Radioss code i.e. G_0=4.9E^{-02} MPa, G_∞=1.62E^{-02} MPa and β=145s^{-1}.

2.2.3 Skull material law choice

The skull was modelled by a three layered composite shell representing the inner table, the diplöe and the external table of human cranial bone. For this an INTEGRATION_SHELL card has been implemented in order to define the three skull layers (cortical bone and diploe) as layers' thicknesses (2mm for cortical layers and 3mm for diploe layer).
The material model 55, which is available under a single label "*mat_enhanced composite_damage*", in LS-DYNA was used to represent the mechanical behaviour of the skull bones The material model 55 has three failure criteria expressions for four different types of in-plane damage mechanisms. Each of them predicts failure of one or more plies in a laminate. The expressions accommodate four in-plane failure modes: matrix cracking, matrix compression, fiber–matrix shearing and fiber breakage. Skull mechanical parameters are presented in Table 2.

Table 2. Skull mechanical parameters under Ls-Dyna code for the SUFEHM.

	Cortical bone	Diploe bone
Mass density [Kg/m3]	1900	1500
Young modulus [MPa]	15000	4665
Poisson's ratio	0.21	0.05
Shear stress parameter	-0.5	-0.5
Longitudinal and transverse compressive strength [MPa]	145	24.8
Longitudinal and transverse tensile strength [MPa]	90	34.8

3 Strasbourg University Finite Element Head Model (SUFEHM) validation

3.1 Introduction

After Strasbourg University Head FE meshing transfer under Ls-Dyna code and after the identification of the material laws, the SUFEHM's validation under this code for Nahum's impact (in order to validate brain response) and for Yoganandan's impact (in order to validate the skull behaviour and bones failure) is proposed.

3.2 Brain behaviour validation

3.2.1 Nahum's experiment presentation

The experimental data used in order to validate brain behaviour were published by Nahum et al.(1977) [23] for a frontal blow to the head of a seated human cadaver. For this impact configuration, a 5.6 kg rigid cylindrical impactor launched freely with an initial velocity of 6.3 ms-1 generates an interaction force and a head acceleration characterised by their peak values which are respectively 6900 N and 1900 ms-2 over a duration of 6 10-3 s. Intracranial pressures were also recorded in this test, at five well defined locations : behind the frontal bone, adjacent to the impact area, immediately posterior and superior to the coronal and squamosal suture, respectively in the parietal area, inferior to the lambdoidal suture in the occipital bone (one in each side), and at the posterior fossa in the occipital area.
Since the neck was not included in this model, a free boundary condition was used to simulate Nahum's impact. This hypothesis is based on the justification that the time duration of the impact is too short (6 ms) for the neck to influence the kinematics head response during pulse duration.
In order to reproduce the experimental impact conditions, the anatomical plane of the SUFEHM was inclined about 45°, as shown in Figure 2, like in the Nahum's experiment. For modelling a direct head

impact, the model was frontally impacted by a 5.6 kg rigid cylindrical impactor (with an elastic padding, E= 13.6MPa, Poisson's ration=0.16) launched freely with an initial velocity of 6.3 m/s.

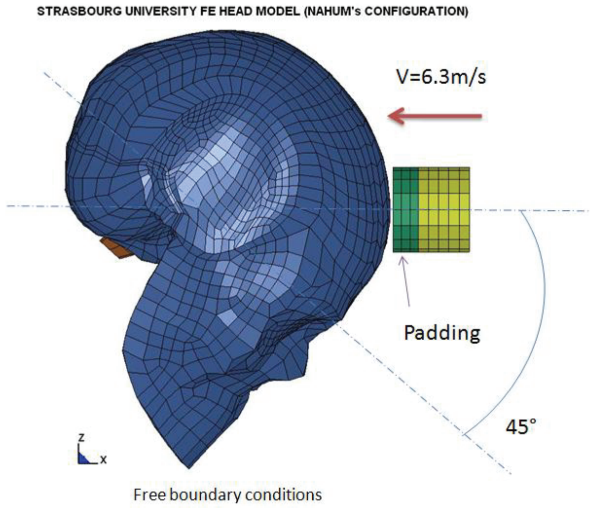


Figure 2. Nahum's configuration

3.2.2 SUFEHM results for a Nahum's experiment replication

In order to validate brain mechanical properties under Ls-Dyna code, a Nahum's experiment has been numerically replicated. The comparison of numerical and experimental forces is shown in Figure 3a for the Nahum's impact. A good agreement for the impact force was found as the time duration of impact and the amplitudes were well respected. The comparison of pressure time histories between numerical and experimental data is presented in Figure 3b, c, d, e for the Nahum's impact simulation. As shown in these figures, five intracranial pressures from the model matched the experimental data very well. The maximum difference of pressure peak is under 10 %. An illustration of the brain pressure field and brain Von Mises stress field obtained during Nahum's impact is proposed in Figure 4.

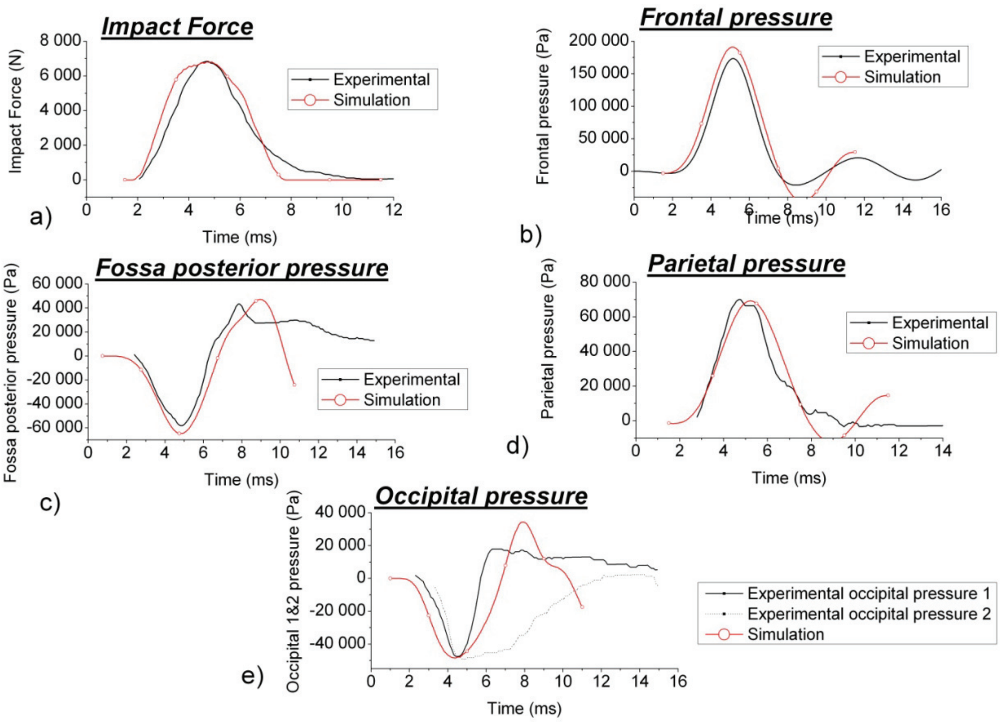


Figure 3. Experimental and numerical results comparison obtained for a Nahum's impact in terms of interaction force (a), frontal pressure (b), Fossa posterior pressure (c), parietal pressure (d) and occipital pressure (e) under Ls-Dyna code.

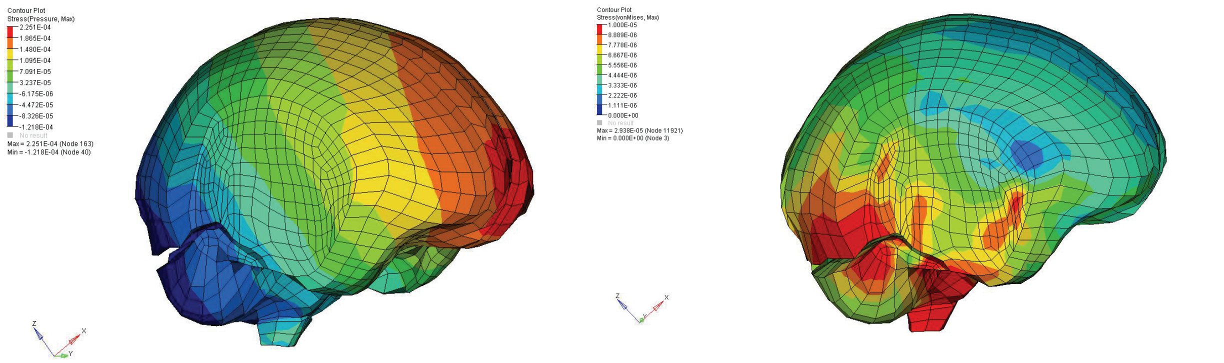


Figure 4. Pressure field (left) and Von Mises stress field (right) obtained with SUFEHM during Nahum's impact.

3.3 Skull behaviour validation

3.3.1 Yoganandan's experiment presentation

Experimental tests carried out by Yoganandan et al. in 1994 has been used in order to validate the ability of the human head finite element model to predict a skull fracture. The impact configuration is shown in Figure 5. The surface of the impactor was modelled by a 96mm diameter rigid sphere. Initial conditions were similar to the experimental ones i.e. a mass of 1.213kg with an initial speed of 7.1 m/s. The base of the skull was embedded as in the experiment. For the model validation, the contact force and the deflection of the skull at the impact site, were calculated.

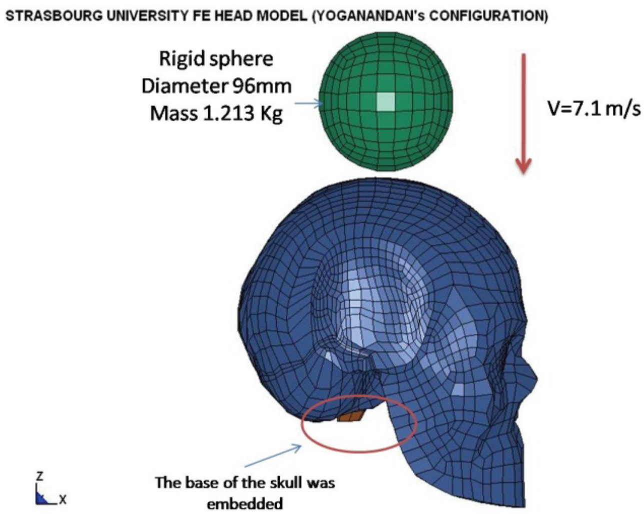


Figure 5. Yoganandan's configuration

3.3.2 SUFEHM results for a Yoganandan's experiment replication

In order to validate material and section definition of the skull under Ls-Dyna software, Yoganandan's experiment was simulated. The numerical force-deflection curves are compared to the average dynamical response of experimental data (Figure 7). The dynamical model responses agree well with the experimental results, both the fracture force and the stiffness level.

When a layer fails, a parameter, called damage parameter, which is zero by default is set to one. Figure 6 illustrates damaged layer(s) in the simulation. The blue colour indicates that at least one layer of the element failed. The model indicates fracture located around the impact point which complies with pathological observations.

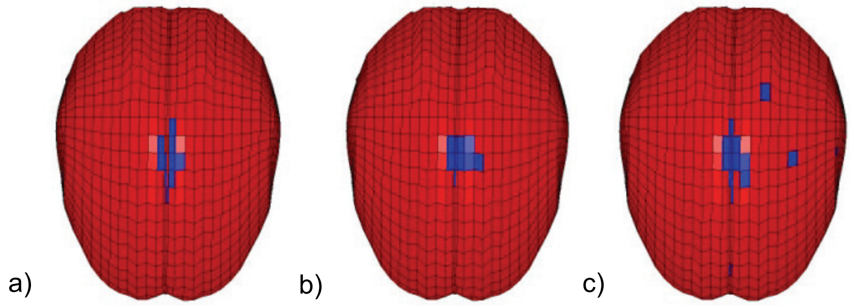


Figure 6. Skull failure description in terms of a) tensile fiber break, b) compressive fiber break and c) compressive matrix break

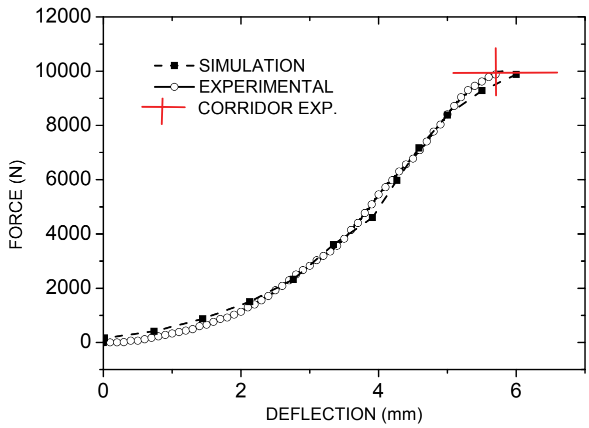


Figure 7. Experimental versus simulated force deflection curves until fracture (+ gives the corridor of Yoganandan's experimental results).

4 Strasbourg University Finite Element Head Model (SUFEHM) criteria

4.1.1 Methodology

SUFEHM tolerance limits to specific injury mechanisms are available under Radioss code and published by Deck et al. (2008) [19]. The objective here is to propose tolerance limits under Ls-dyna code. For this, 59 head impact conditions that occurred in motorcyclist, American football and pedestrian accidents were reconstructed with the SUFEHM under Ls-Dyna code. A summary of the type and number of accident reconstructions is given through Table 3.
The reconstructions involved applying the motion of the head from the accidents to the rigid skull of the SUFEHM. Same methodology (statistical analysis) than methodology used by Deck et al. (2008) [19] has been undertaken.

For the statistical analysis the injuries for the accident data were categorised into the following types and levels based on the details of the medical report from each accident case:

- Diffuse axonal injuries (DAI): DAI cases covered all incidences in which neurological injuries occurred and covered concussion, unconsciousness and coma. Incidences of DAI were broken down into mild and severe levels according to coma duration (<24H for moderate DAI and >24H for severe DAI)

- Subdural Haematomas (SDH): This category of injuries covered all incidences in which vascular injuries with bleeding were observed between the brain and the skull of which there were six cases.

Table 3. Summary of the type and number of accident reconstructions

Accident Type	Number of cases
Motorcycle accidents	11
American football accidents	20
Pedestrian accidents	28

4.1.2 SUFEHM tolerance limits to specific injury mechanisms

Results computed with the SUFEHM under Ls-Dyna code are reported in terms of correlation coefficients (Nagelkerke R-Squared values) in order to express their injury prediction capability.
Based on SPSS method it appears that DAI are well correlated with intra-cerebral Von Mises stress. Maximal principal strain as well as Von Mises strain presents also an acceptable correlation.
Coming to maximum R^2 values, the maximum Von Mises stress conducts to 0.6 and 0.39 for respectively moderate and severe neurological injury.
The threshold for this parameter are of the order of 28 and 53 kPa respectively for moderate and severe neurological injuries as it appears in the injury risk curves reported in Table 5.

Concerning the SDH injuries two mechanical parameters, i.e. CSF minimum pressure and CSF strain energy were considered.
With the SUFEHM it was shown (Table 4) that the best correlation with SDH was the maximum strain energy within the CSF, with a R^2 value of 0.465 and a threshold value of about 4950 mJ.

After the analysis of regression correlation method Table 5 and Table 6 report the tolerance limits and the injury risk curves obtained with the SUFEHM for each of the injury types with an injury risk of 50%.

Table 4. Nagelkerke R-Squared value for the logistical regressions between the injury predictors computed with SUFEHM and the injury data.

Injury Predictors	Mild DAI	Severe DAI	SDH
CSF minimum pressure			0.367
CSF strain energy			**0.465**
Peak brain Von Mises stress	**0.6**	**0.39**	
Peak brain first principal strain	0.43	0.355	
Peak brain Von Mises strain	0.43	0.35	

Table 5. Tolerance limits calculated for DAI injuries (mild and severe) with the SUFE head model under LS-DYNA software and Best fit regression models for DAI injury investigated for the SUFEHM considering brain Von Mises stress.

	Mild DAI	Severe DAI
Brain Von Mises stress [kPa]	**28**	**53**
Brain Von Mises strain [%]	**30**	**57**
Brain First principal strain [%]	**33**	**67**

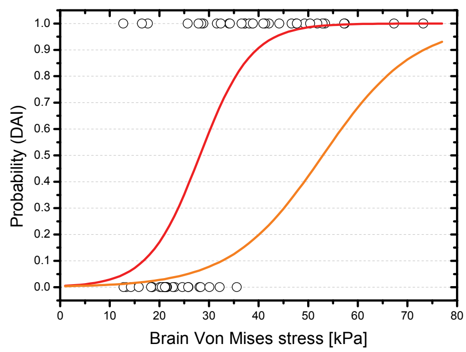
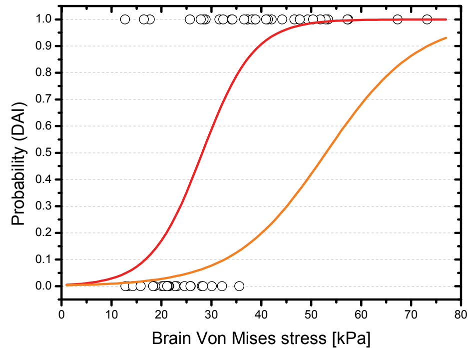


Table 6. Tolerance limits calculated SDH injury with the SUFE head model and LS-DYNA software and best fit regression models for SDH/SAH injury investigated for the SUFE head model considering CSF strain energy.

	SDH
Minimum of CSF pressure [kPa]	290
CSF strain energy [mJ]	4950



CONCLUSIONS AND PERSPECTIVES

In this study the Strasbourg University Finite Element Head Model (SUFEHM) has been transferred under LS-DYNA code, and mechanical properties have been implemented. Two experimental impacts have been replicated numerically, a Nahum's impact in order to validate the brain behaviour and a Yoganandan's shock to validate the skull stiffness and fracture.
In an attempt to develop improved head injury criteria under Ls-Dyna code, 59 real world head trauma that occurred in motorcyclist, American football and pedestrian accidents were reconstructed with SUFEHM. Statistical analysis was then carried out on intra cerebral parameters computed in order to determine which of the investigated metrics provided the most accurate predictor of the head injuries sustained in the accidents.

Two tolerance limits to specific injury (for a 50% risk of injuries) have been computed:
- A maximum Von Mises stress value: 28 kPa for moderate DAI and 53 kPa for severe DAI.
- A maximum CSF strain energy: 4950 mJ for SDH

It is concluded, based on the results of this work, that there is evidence to support the use of alternative parameters to predict head injury risk over HIC. It is determined that additional work is needed, beyond that carried out here, to consolidate the proposed improved criteria for predicting head injury risk especially when SDH are concerned. To achieve this goal better documented head trauma is needed that is truly representative of what happened in the accident.

Finally, we can say that this new head injury predictive tool, which is SUFEHM model, can participate to the head protection system evaluation and optimization. The use of the proposed head injury prediction tool is illustrated in Figure 8 which shows a coupled experimental versus numerical approach. It is a matter of recording the linear and rotational 3D acceleration of the headform under impact and to consider these experimental data as the input for the driving of the head FE model, which in turn will derive the injury risk for DAI, SDH and skull fracture. Such an approach is possible with Hybrid III head, with the pedestrian headform or with the helmet standard test headform and is ready for transfer to end users.

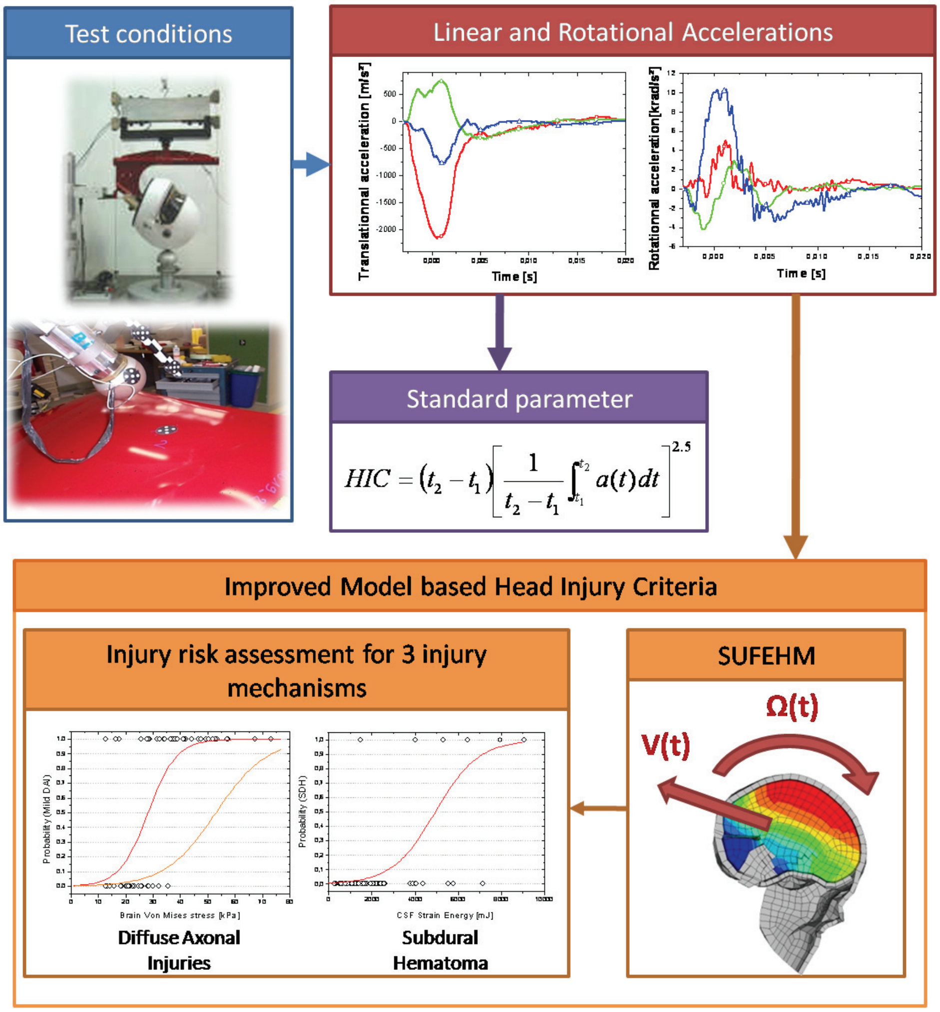


Figure 8. Strasbourg University Finite Element Head Injury Prediction Tool

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