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# Head injury: Importance of the deep brain nuclei in force transmission to the brain

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## ABSTRACT

Finite element modeling provides a digital representation of the human body. It is currently the most pertinent method to study the mechanisms of head injury, and is becoming a scientific reference in forensic expert reports. Improved biofidelity is a recurrent aim of research studies in biomechanics in order to improve earlier models whose mechanical properties conformed to simplified elastic behavior and mechanic laws. We aimed to study force transmission to the brain following impacts to the head, using a finite element head model with increased biofidelity. To the model developed by the Laboratory of Applied Biomechanics of Marseille, we added new brain structures (thalamus, central gray nuclei and ventricular systems) as well as three tracts involved in the symptoms of head injury: the corpus callosum, uncinate tracts and corticospinal tracts. Three head impact scenarios were simulated: an uppercut with the prior model and an uppercut with the improved model in order to compare the two models, and a lateral impact with an impact velocity of 6.5 m/s in the improved model. In these conditions, in uppercuts the maximum stress values did not exceed the injury risk threshold. On the other hand, the deep gray matter (thalamus and central gray nuclei) was the region of highest risk of injury during lateral impacts. Even if injury to the deep gray matter is not immediately life-threatening, it could explain the chronic disabling symptoms of even low-intensity head injury.

## 1. Introduction

Traumatic brain injury is a major cause of death and disability in worldwide. In France, there are about 150 000 head injuries a year, resulting in 8000 deaths [1]. The understanding of the injury mechanisms involved is sometimes limited when the lesions involved are not hemorrhagic. Traumatic brain lesions are consecutive to acceleration [2] with development of shear and tension forces within the nervous system. Some primary effects are immediate and symptoms appear in the hours following the head injury, whereas secondary effects develop more slowly over time [3]. In some cases, the onset of initial symptoms is delayed by several hours or even several days [4].

Numerical simulation study of the mechanisms of injury may require models to be validated using cadavers donated to science. However, post-mortem brain lesions are not comparable with those observed in a vascularized brain. Changes in consistency occurring after death affect

the mechanical response of the structure and the dynamics of the forces transmitted through it [5,6]. Finite element modeling, giving detailed biofidelic representation of the human body, is currently the most pertinent method for study of the mechanisms of head injury and is currently becoming a scientific reference in forensic expertise [7–9]. Use of the model after validation makes it possible to correlate the kinematics of the impact, the stresses and tissue responses with the resulting brain lesions [10]. The distribution of the stresses reflects the propagation of the forces in the structure in response to the impacts [11].

Biofidelity of the model is a recurring aim of biomechanical research in order to improve earlier models whose mechanical properties conformed to simplified elastic behavior and mechanical laws [12]. Studies have been carried out to improve the modeling of certain parts of the cephalic segment, such as cerebrospinal fluid and its interface with the skull and the brain [13,14]. Other works have incorporated into existing models brain structures such as the corpus callosum, the gray nuclei, the

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thalami, and the ventricular system [15–17] and differentiation of white and gray matter. Anisotropy of white matter, based on diffusion tensor imaging (DTI) data, has been increasingly integrated in most of the recent models [10,15,18–20]. Severe head injury is principally characterized by widespread involvement of white matter. Some injury locations immediately appear to be indicators of severe lesions, such as involvement of the internal capsule, corpus callosum, brainstem (midbrain and pons) and temporal lobes [21,22]. Involvement of other areas predicts long-lasting post-injury cognitive sequelae (uncinate tracts and chronic headache, memory disturbances, post-traumatic stress disorder [23,24] or motor disorder) [25,26]. In addition, loss of volume of the deep gray nuclear structures has been described in patients monitored after mild or more severe head injury [27,28].

The aim of this work was to improve the detection of injuries caused by cranial impact such as uppercut and lateral impact. To respond, we started from our previous model [29], which we refined by the addition of the deep gray nuclear structure, the ventricular system and certain tracts involved in head injury as well as their mechanical properties.

## 2. Methods

### 2.1. Finite element model of the head

#### 2.1.1. The LBA model

The finite element model of the head developed by the Laboratoire de Biomécanique Appliquée de Marseille was produced in several stages.

In the first stage, the model was developed as part of the study by Hamel et al [30]. Skull geometry was obtained from computed tomodensitometry scans of a 30-year-old man, using 1 mm sections. The subarachnoid space and brain were created by meshing using Hypermesh software (Altair Engineering Inc., Detroit, MI, USA). The skull was composed of the inner and outer table (three-node shell elements) and the diploë (tetrahedral elements). The brain was modeled with tetrahedral volume elements and the subarachnoid space, which simulates the cerebrospinal fluid, was modeled with a layer of tetrahedral elements. The scalp was modeled with two layers of hexahedral volume elements.

In a second stage, this model was significantly improved [8] and then combined with a model of the neck developed in collaboration with the international laboratory iLab-Spine, which is formed by two laboratories in Marseille (the Laboratoire de Biomécanique Appliquée, LBA, and the Centre de Résonance Magnétique Biologique et Médicale, CRMBM) and two universities in Montreal (the École de Technologie Supérieure (ETS) and the École Polytechnique Montréal) [29]. All the facial bones were modeled separately, using a parametric approach to define the thickness of cortical bone. The inner and outer tables were modeled with tetrahedral volume elements. The junction of the brainstem and the spinal cord were modeled in continuation of the elements of the brainstem. For greater conformity with the anatomy of the brain, meninges and neck, new elements such as the pia mater, dura mater, falx cerebri, cerebellum, tentorium cerebelli, the hemispheres, brainstem, cervical spinal cord, cervical vertebrae and ligaments were modeled by continuous meshing. The model was validated by reproducing the studies of Nahum et al. [31], Trosseille et al [32]. and Viano et al. [33], and an experimental studies of mandibular impacts [29].

#### 2.1.2. Improvement of the biofidelity of the brain model

New brain structures (thalamus, central gray nuclei and ventricular system) as well as three tracts involved in the symptoms of head injuries (corpus callosum, uncinat tracts and corticospinal tracts) were modeled in three dimensions on 3D Slicer software [34]. This stage enabled us to obtain precise geometry of each new anatomic structure.

The brain structures were obtained from the mni-icbm152-nlin 2009c model of the human brain, available as open-source data. This multicontrast atlas, that includes T1w, T2w and PDw sequences, was constructed from magnetic resonance imaging of 152 young adults at

1.5 T (resolution  $1 \times 1 \times 1$  mm). The resulting model is an averaged anatomy of the population and is not biased, unlike models of a single subject. It was created by the Institut Neurologique de Montréal (INM) based on anatomical data of the International Consortium for Brain Mapping (ICBM) (35). The tracts were taken from tractographs from the HCP1065 atlas (36).

All the three-dimensional (3D) elements were exported in STL format and imported using Hypermesh software (Altair Engineering Inc., Detroit, MI, USA) in order to integrate these new structures into the existing finite element model of the head. Each new segment was placed in its anatomic position in the brain within the existing meshing. For each of the new elements of the brain to be integrated, a new component was created on Hypermesh (Altair Engineering Inc., Detroit, MI, USA). The behavior of the improved brain model at impact was also compared to cadaveric head impacts (Annex 1).

#### 2.1.3. Biomechanical properties

In order to use a finite element model of the head, the specific mechanical properties of each component must be integrated in the model so as to simulate the mechanical behavior of the targeted area. Numerous studies have shown a significant difference in mechanical behavior between the white matter and the gray matter of the brain [35, 36]. Most models described in the literature apply a viscoelastic material law to the brain [33,35,37,38]. White matter and gray matter are differentiated by their viscoelastic parameters.

The mechanical properties used were taken from the study by Ji et al [37].

Gray matter includes the thalamus and the central gray nuclei, whereas white matter is made up, among other components, of the uncinat tracts and the corticospinal tracts. Data on response to shear stress reveal differences between hemispheric white matter and the corpus callosum, so different parameters were retained. The cerebrospinal fluid, within the subarachnoid space and the ventricular system was model with tetrahedral elements and fluid-like elastic mechanical properties (Supplementary Table S1). Fig 1.

#### 2.1.4. Modeling of the uppercut

In order to compare and to understand the influence of conditions of impact on the development of head injury, two scenarios of head impacts were digitally simulated using Radioss 2019 software (Altair Engineering Inc., Detroit, MI, USA). Fig 2 and Fig 3.

The LBA model has been the subject of previous studies on uppercut [8]. But we also want to evaluate the conditions of lateral impact in order to study the lesions induced during the phenomena of rotation of the brain. All the simulated impacts were delivered by a model of a hand boxing glove with an impact mass of 1.5 kg. Two types of scenario and impact locations were selected (Fig. 4): an uppercut with submandibular impact and a lateral impact at the anterior part of the left temporal bone in contact with part of the sphenoid bone. The uppercut impact was simulated on the prior model and on the improved model. The lateral impact was simulated only on the improved model. The characteristics of each impact are summarized in Table 1.

The literature shows that neurological symptoms develop at relatively consistent intracerebral von Mises stresses. According to

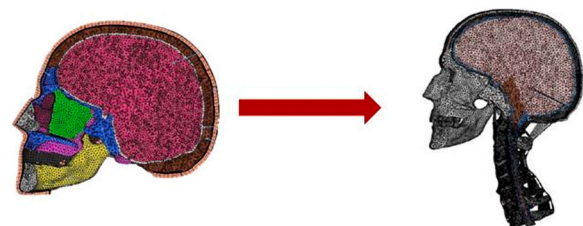


Fig. 1. First finite element model of the head (left) and second finite element model of the head and neck (right) (Tuchtan, 2019).

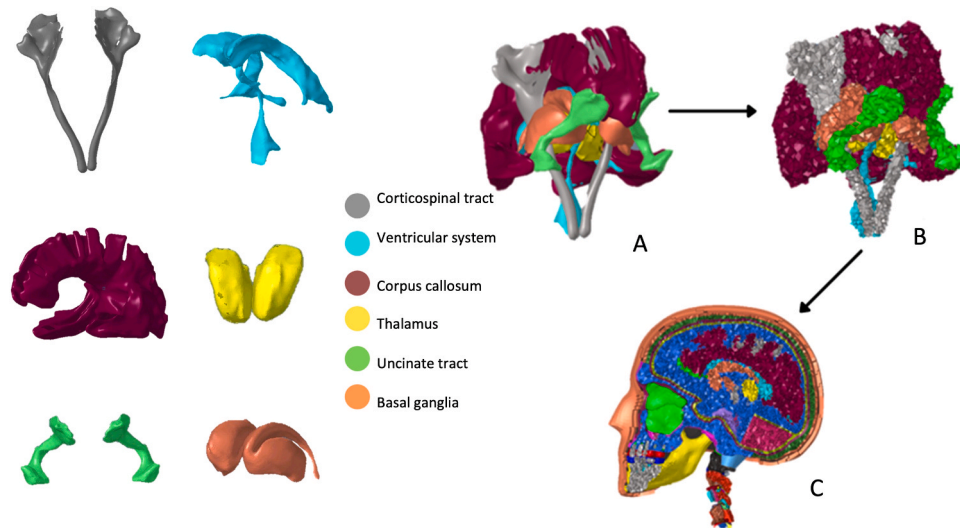


Fig. 2. 3D model of the new components in anatomical position. A, distribution of the existing elements and B, the new components; C, new finite element model of the head.

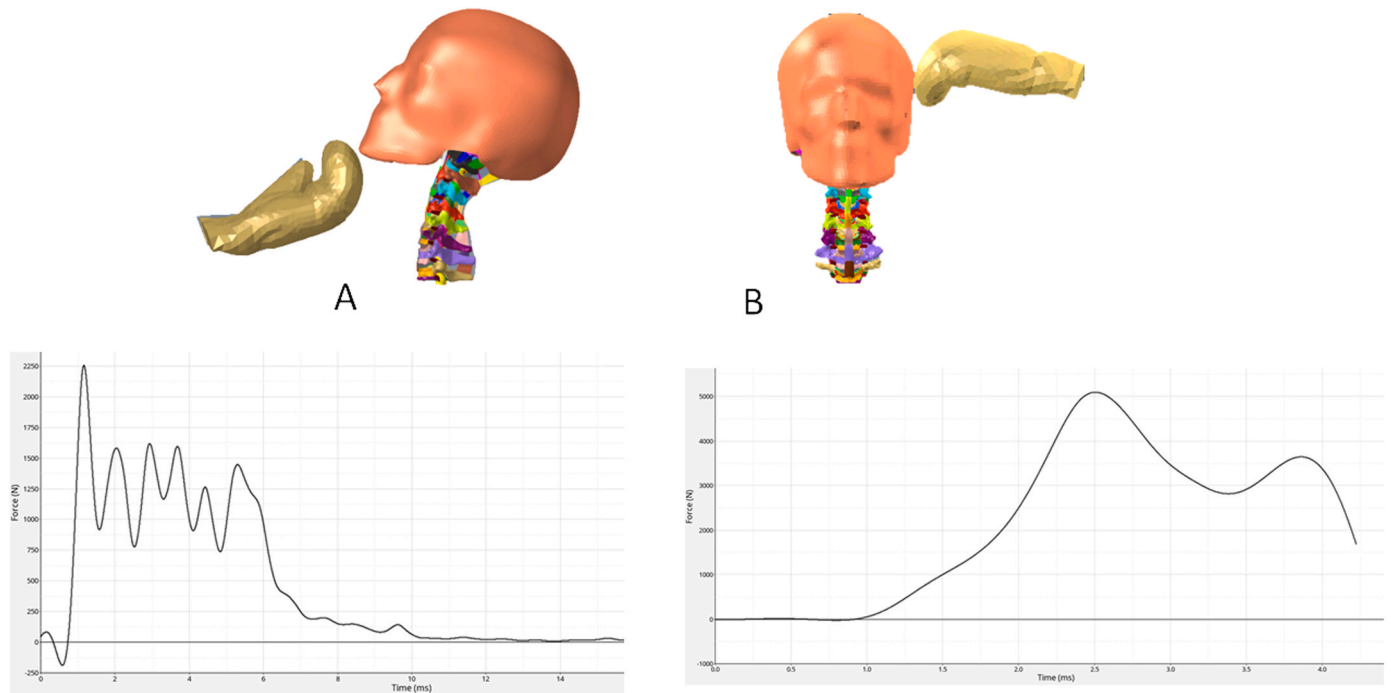


Fig. 3. A, scenario of an uppercut impact; B, scenario of a lateral impact and time-contact force graphs for uppercut and lateral impact.

Baumgartner, moderate neurological lesions begin to be generated at stresses of 18 kPa onwards [39]. According to Sahoo et al. [40], there is a 50% risk of developing moderate neurological lesions at stresses of 16.8 kPa, while the risk is 95% at stresses of 20.8 kPa.

### 3. Results

#### 3.1. Uppercut, prior model

After the uppercut impact on the prior model, the stresses show that forces are transmitted in brain tissue in two stages. In the first stage, up to about 13.6 ms, forces are propagated from the anterior region to the posterior region, passing through all the brain structures. From the beginning of the impact (2.4 ms), stresses can be observed in the

medulla oblongata (on the corticospinal tracts), the prefrontal lobe (on the uncinate tracts) and the genu of the corpus callosum. Next, stresses are propagated to the median regions of the brain (central gray nuclei, passing through the thalamus). They continue to be propagated along the corpus callosum in a fairly homogeneous manner up to the splenium. In the second stage (13.6 ms onwards), during the backlash, stresses appear first of all in the corpus callosum and spread quite rapidly throughout the entire brain tissue.

Analysis of stresses in the brainstem shows a concentration in the marrow, which is elongated from the start of the impact (4.4 ms). Stresses are then propagated throughout the brainstem. At the cerebellum, from the start of the impact stresses are observed in its lower part (tonsil) and in the posterior lobes.

Fig. 4 shows that the cerebellum and brainstem are the structures

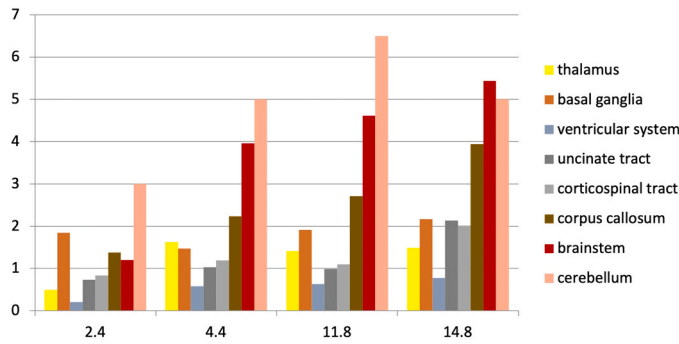


Fig. 4. Distribution over time (ms) of maximum von Mises stresses (in kPa) in brain structures.

most affected by the impact, with von Mises stresses constantly increasing over time. However, the values reached do not exceed the injury risk threshold.

### 3.2. Uppercut, improved model

During this impact, forces are first propagated anteriorly to posteriorly from the corticospinal and uncinete tracts to the splenium of the corpus callosum, followed by delayed transmission in the opposite direction at the end of simulation. However, propagation is seen to be quite heterogeneous depending on the brain tissue. Stresses are distributed in a more localized manner in each brain tissue and in a much less diffuse manner in the central gray nuclei and the thalami in particular. Stress transmission to the corpus callosum is more delayed, starting between 5 and 19 ms at the splenium, and is then propagated quite rapidly. From 18.8 ms until the end of simulation at 20 ms, there is a second anteroposterior propagation (backlash) throughout the brain, notably the anterior part of the thalamus, in the internal capsule of the central gray nuclei and in particular in the genu of the corpus callosum.

In the brainstem, stresses are present from the beginning of the simulation at the medulla oblongata and persist throughout the simulation. At the end of the simulation, stresses accumulate at the anterior aspect of the pons and the upper part of the cerebellum.

Fig. 5 shows the progression of maximum von Mises stresses in each brain tissue during the second uppercut. The brainstem and cerebellum throughout the simulation and the central gray nuclei during the backlash are the structures that undergo the greatest stresses. Here again, the values reached did not exceed the injury risk threshold.

### 3.3. Lateral punch simulated

Analysis of von Mises stresses in this simulated scenario shows that forces cross the brain from right to left. The frontal region is less affected than the parietal and occipital regions. Stresses first appear in the upper part of the left corticospinal tract and in its pontic part, while stresses

appear in the contralateral corticospinal tract 10 ms after the impact. In the central gray nuclei, stresses appear bilaterally in the internal part at 10 ms. Stresses are propagated fairly rapidly in the internal part of the thalamus. After 10 ms, stresses appear in the body and the splenium of the corpus callosum until the end of simulation. Stresses are observed at the posterior lobes of the cerebellum. At the end of simulation at around 13 ms, stress loading is also observed at the brainstem. During simulation, the change over time of the maximum value of von Mises stresses in each brain tissue (Fig. 3) shows that the tissues most affected are the thalamus and the central gray nuclei, where stresses exceed 16 kPa, the injury risk threshold (Fig. 6). The brainstem is also affected, with stress levels close to the injury risk threshold (14–15 kPa). Fig 7.

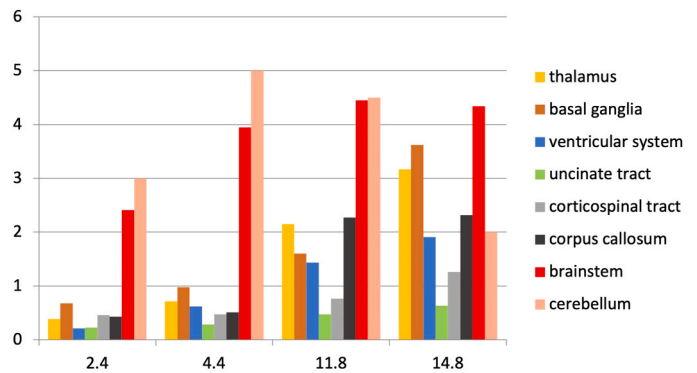


Fig. 5. Distribution over time (ms) of maximum von Mises stresses (kPa) in brain organs during the second uppercut.

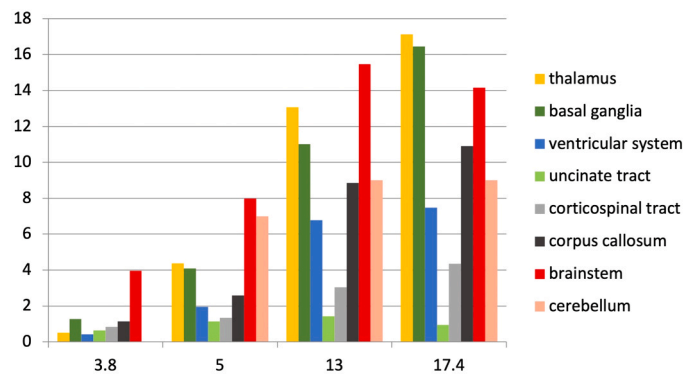


Fig. 6. Distribution over time (ms) of maximum von Mises stresses (kPa) in brain structures during a lateral impact.

Table 1  
Characteristics of the different impact scenarios.

Scenarios	Mechanical properties of the brain						Impact mass	Impact speed
Uppercut 1	Supplementary data						1.5 kg	6.7 m/s
Uppercut 2	GM	1020	2.00	0.012	LTSM	0.002	1.5 kg	6.7 m/s
	WM	1060	2.00	0.010	DF	0.1		
	CC	1060	2.00	0.007	0.0007	0.1		
Lateral 1	D		BM	STSM	LTSM	DF	1.5 kg	6.7 m/s
	GM	1020	2.00	0.012	0.002	0.1		
	WM	1060	2.00	0.010	0.001	0.1		
	CC	1060	2.00	0.007	0.0007	0.1		

Abbreviations: Density (kg/m<sup>3</sup>) (D), Bulk modulus (MPa) (BM), Short-term shear modulus (MPa) (STSM), Long-term shear modulus (kPa) (LTSM), Decomposition factor (ms<sup>-1</sup>) (DF) Gray matter (GM), White matter (WM), Corpus Callosum (CC).

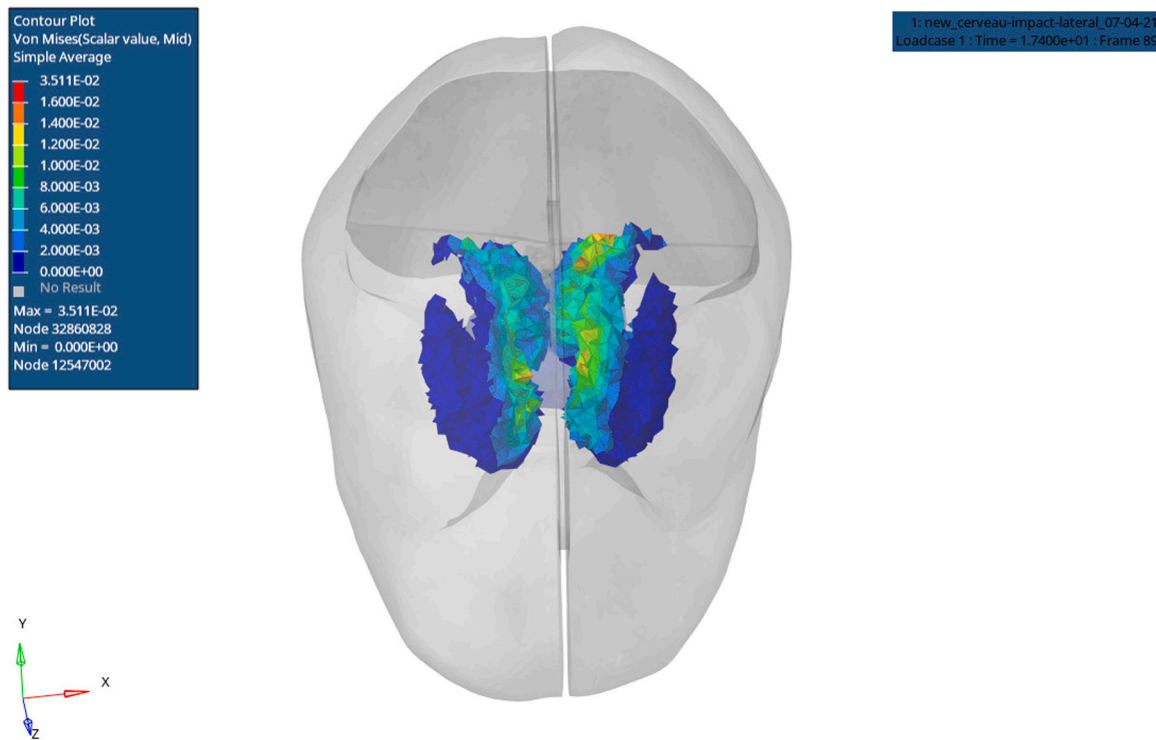


Fig. 7. Von Mises stresses exceeding the injury threshold in the central gray nuclei and thalami.

## 4. Discussion

### 4.1. Biofidelity of the finite element head model and mechanical variation

This new finite element model of the head integrates the complex anatomy of the brain through differentiation of brain tissues. The model includes six new components: the thalamus, central gray nuclei, ventricular system, uncinate tracts, corticospinal tracts and corpus callosum. Some biomechanical studies have examined the mechanisms involved during injury by adding to the meshing of their models anatomic components of the brain such as the corpus callosum [17,41] ventricular system [37] or thalamus [17], but our model is one of the rare models to include such a large number of different brain tissues. This greatly improves the biofidelity of the model with regard to the anatomy of the human head.

This finite element model of the head is interesting because the mechanism of injury in each brain structure at the time of injury can be observed independently and precisely. The older model of the head and neck used in previous studies [29] showed that forces were transmitted in an anterior to posterior direction, with strong stresses at the base of the brain and the brainstem due to cervical hyperextension during an uppercut impact. This transmission of forces was observed but with a lower level of precision concerning the distribution of von Mises stresses. These stresses begin at the uncinate tracts (prefrontal and anterior temporal lobe) towards the anterior part of the brainstem (via the corticospinal tracts), the cerebellum and the splenium of the corpus callosum. Our study does not demonstrate, under these conditions, values of von Mises stresses sufficient to cause lesions.

When we integrate the parameters of the literature for the various new components added, stresses are seen to be redistributed, with decreased von Mises stresses in the corpus callosum and increased stresses during the backlash in deep gray matter structures: the central gray nuclei and the thalamus. However, these stresses still remain below the injury risk threshold. This difference is related to differentiation of the mechanical parameters of the brain tissues, and demonstrates the importance of these parameters when using the finite element model of

the head. These findings are in line with those of Zhang and Gennarelli [42].

The head model's behavior has been compared to the results of several cadaveric head impact studies [8,31–33,38]. However, the in-vivo brain may exhibit different behavior, and it would also be interesting to include in-vivo data, such as data from diffusion tensor imaging after a traumatic brain injury (TBI), to enhance the validation of the current model. The white matter of the brain was modeled using isotropic material properties, despite its microstructure being highly anisotropic. In the literature, some finite element (FE) models of the brain have incorporated white matter anisotropy and demonstrated its significant influence on local brain motion [43]. However, the extent of mechanical anisotropies in the white matter is still a topic of debate. According to Eskandari et al [44], and Feng et al [45], the white matter appears to be mechanically anisotropic when tested in shear, indentation, and tension. In contrast, Budday et al [46], argued that the heterogeneous microstructure leads to regional but not directional dependence of the mechanical properties when tested in simple shear in two orthogonal directions, compression, and tension. Further research is necessary to enhance our understanding of brain anisotropy and to refine the FE models accordingly.

### 4.2. Variation of impact location

We have shown that von Mises stresses increased and reached the injury risk threshold in lateral punch simulated as soon as an impact speed of 6.5 m/s was attained. Lesions may then be concentrated in the thalamus and the central gray nuclei.

The influence of impact location on injury severity may be explained by the anatomy of the human head. Lee et al [47], demonstrated the impact-absorbing effect of the facial bones in anteriorly-directed traumas such as uppercuts.

It has been shown that frontal impacts cause greater axonal damage than other impacts (lateral, occipital) for a given force [48]. Other studies found that, due to brain rotation, a lateral punch simulated was more likely to result in injury than an impact in the sagittal plane

[49–52].

In a study of simulated sagittal rotation, Zhang et al [38]. demonstrated strong stresses in the deep gray matter of the brain. Our findings appear to be in agreement with theirs. As we observed, the falx cerebri and the tentorium cerebelli, because of their rigidity, cause considerable tensions in the adjacent brain tissues, in particular the corpus callosum [53], brainstem and cerebellum [54].

In addition to the presence of the falx cerebri, the stresses observed in our study of a finite element model of the head may be explained by the biomechanical properties of the cerebrospinal fluid and by the presence in our model of the lateral ventricles. Wu et al [13]. modeled the cerebrospinal fluid, considered as an elastic and incompressible medium, using membrane elements. These authors demonstrated that the cerebrospinal fluid absorbs the dynamic energy transmitted to the brain by an impact. Ivarsson et al [55]. observed that the cerebrospinal fluid reduced deformity in the regions around the ventricular system and may have a protective role on the structures internal to the impact. However, during our simulations we demonstrated von Mises stresses in the thalami and the central gray nuclei, nevertheless very close to the ventricular system, as recently described by Zhou et al [56]. Neuropathological studies of patients who had received fatal head injuries have shown that the thalamus frequently sustained traumatic lesions in this setting [3,57,58]. In lateral punch simulated, we indeed observed stresses that reached the injury threshold in the thalami and the central gray nuclei.

Although the central gray nuclei and the thalami have been little described in the literature as giving rise to acute symptoms, nevertheless involvement of these structures has been observed in patients with post-traumatic stress disorder [59] including sleep disorders, fatigue, memory disturbances or post-traumatic headache [60,61]. These structures play a central role in the brain, as they project into the entire cerebral cortex and are involved in processing and transmitting information between the sensory, motor and association areas of the brain [62].

## 5. Conclusion

The improved finite element model of the head developed by the Laboratoire de Biomécanique Appliquée de Marseille can predict much more precisely the regions where brain injury develops.

We found that the deep gray matter (thalamus and central gray nuclei) is the region with the greatest risk of injury in lateral punch simulated. Although its involvement is not immediately life-threatening, it could explain the chronic disabling symptoms of even low-intensity head injury. These results should be compared to in vivo studies in which data from diffusion tensor imaging are available.

## CRedit authorship contribution statement

Study conception and design: C. Delteil, Y. Godio, L. Thollon; O. Marle; data collection: C. Delteil. Author; analysis and interpretation of results: C. Delteil, L. Thollon; draft manuscript preparation: Y. Godio, L. Tuchtan, C. Delteil, O. Marle, N. Bailly; reviewer L. Tuchtan, N. Bailly MD Piercecchi. All authors reviewed the results and approved the final version of the manuscript.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2024.111952.

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