Finite element modelling of the human head and application to forensic medicine

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Résumé :
Un modèle par éléments finis de la tête humaine développé antérieurement ainsi que les mécanismes de lésions de cette dernière et les limites de tolérance des tissus peuvent constituer de précieux outils d'investigation dans le domaine de la médecine légale. En effet, ces modèles numériques, à condition qu'ils soient bio fidèles, permettent de valider ou d'infirmer un scenario d'accident où une victime a subi un ensemble de lésions à la tête et constituent ainsi des atouts supplémentaires d'aide à la décision d'un organisme judiciaire.

Abstract:
A finite element model of the human head that was developed previously, as well as human head injury mechanisms and tolerance limits are powerful investigation tools for the legal medicine applications. In fact, these numerical models allow confirming or canceling an accident scenario in which a victim suffered under head injuries if they can be considered as bio fidelic. Thus, these tools constitute precious decision making aid in the forensic medicine field.

Mots clés : human head trauma, finite element modelling, forensic medicine, biomechanics of impact.

1 Introduction
Until recently, the legal system relied on the testimony of medical experts to determine whether the force imparted to the human head in a given scenario was consistent with the resulting human head injury. Since the 1960s, predictive human head impact indices have been developed to aid the investigation of causation of human head injury. Finite element models (FEM) can provide interesting tools for the forensic scientists when different human head injury mechanisms need to be evaluated. Human head FEM are mainly used for car crash evaluations and are not in common use for forensic science. Recent technological progress has resulted in creating tools which can be used in forensic cases. To illustrate this purpose and to show some of the possibilities of human head FEM, a reconstruction of two well documented falls was performed as well as a comparison of the obtained results to clinical data.

2 Material and methods

2.1 Accident case
A 63 year old male alcoholic was slightly pushed by a young adult after annoying the girlfriend of the latter during a party in France. Being drunk, he took two steps backward, stopped, and fell backwards like a stick sustaining a parieto-occipital head impact on the wooden floor. This fall was witnessed by ten people who all gave the same version of the fall. The victim showed immediate loss of consciousness. The nearest hospital was called and three firemen arrived ten minutes later and put the victim on a cart. While lifting the cart to about 30 cm, the victim fell on his right side sustaining a parietal head impact. After arriving in the emergency room, the victim was taken to a critical care unit. A CT-scan was performed showing right and left frontal, temporal and occipital contusion, an occipital subdural hematoma, a diffuse subarachnoidal...
hematoma and a parieto-occipital skull fracture. In spite of one month of intensive care, the victim finally died and an autopsy was performed. The skull fracture was still visible at autopsy and the basal part of the temporal and frontal lobes of the brain showed necrotic evolution of the contusions seen on the CT-scan.

2.2 FEM of both head impacts

The FEM of the human head used in this study (called UDS FEM of the human head) is the one developed by [1] at the University of Strasbourg (UDS). It is assumed to be homogenous and isotropic. It is continuously meshed in 11939 nodes and 13208 elements which are subdivided in 10395 brick elements and 2813 shell elements. Its geometrical characteristics and the mechanical behaviour of its anatomical components are as follows:

- A viscous elastic brain and cerebellum meshed in 5508 brick elements. Density = 1040 kg/m³, bulk modulus = 1125 MPa, short time shear modulus = 0.049 MPa, long time shear modulus = 0.0167 MPa, decay constant = 145 s⁻¹.
- An elastic brain skull interface meshed in 2591 brick elements. Density = 1040 kg/m³, Young modulus = 0.012 MPa, Poisson ratio = 0.49.
- An elastic falx of the brain and an elastic tentorium of the cerebellum meshed in 471 shell elements. Density = 1140 kg/m³, Young modulus = 31.5 MPa, Poisson ration = 0.23.
- An elastic plastic brittle skull and an elastic plastic brittle face meshed in 1813 three layered composite shell elements (cortical bone – trabecular bone – cortical bone). Cortical bone: density = 1800 kg/m³, Young modulus = 15 GPa, Poisson ration = 0.21, ultimate tensile stress = 90 MPa, ultimate compression stress = 145 MPa. Trabecular bone: density = 1500 kg/m³, Young modulus = 4.5 GPa, Poisson ration = 0, ultimate tensile stress = 35 MPa, ultimate compression stress = 28 MPa.
- An elastic scalp meshed in 2296 brick elements. Density = 1200 kg/m³, Young modulus = 16.7 MPa, Poisson ratio = 0.42.

The UDS FEM of the human head is validated in terms of brain pressure and brain acceleration [2,3] and in terms of bone rupture [4]. That FEM of the human head was developed using the ALTAIR HYPERWORKS software. This code allows achieving dynamic simulations in which the geometrical deformation is taken into account at each time step. The elements used have one integration point and a dynamic Lagrange formulation was used since each modelled part is assumed to have a homogenous and isotropic solid mechanical behaviour. The meshing was built in a regular way in terms of element dimension, angle and warpage. The average dimension of the ridge of an element amounts to 5 mm. The meshing is continuous between the different anatomical components which were modelled. Therefore no interface was used in the human head FEM.

A numerical reconstruction of the two falls was performed using the UDS FEM of the human head to assess the consequences of each fall. The mechanical properties of the wooden floor were taken into account for the simulation as follows. A flat surface was regularly meshed in shell elements with a thickness of 10 mm. A density of 0.9 kg.m⁻³, a Young modulus of 11 GPa and a Poisson ratio of 0.49 were used for the elastic behaviour of the wooden floor. The wooden floor was also assumed to be stuck to a non deformable surface representing the base floor. The initial velocity for the human head was of 6 m.s⁻¹ for the first fall and 1.5 m.s⁻¹ for the second fall. That initial velocity was inferred from an analytical analysis of both falls of the victim, using mechanics general equations. Both velocities were applied to the FEM of the head of the victim. After those initial conditions, the head of the victim is left free in its six degrees of freedom shall it be in translation or in rotation. It is important to underline that it was hypothesised that the neck and the complete body do not influence the dynamical response of the human head in the first 30 ms after the impact. Both impacts under study last no more than 15 ms. Therefore the human head will be considered as free of motion just after each impact on the floor. Nevertheless, this statement is still under study in our laboratory. The locations of the human head impact were also taken into account for the reconstruction. The first impact of the head of the victim was a right occipito-parietal impact; the second was a right parietal impact. Mechanical field parameters sustained by the different tissues of the head of the victim during the impact were obtained after simulation, such as the brain pressure and the brain Von Mises stress, the global strain energy of the skull and the number of deleted elements, and the global strain energy of the brain skull interface.
2.3 Human head injury mechanisms and tolerance limits
The human head injury mechanisms and tolerance limits used in the present study were derived from a numerical real world accidents reconstruction [5]:

- A brain pressure reaching 200 kPa is an indicator for brain contusions, oedema and hematoma.
- A brain Von Mises stress reaching 18 kPa is an indicator for moderate neurological injuries.
- A brain Von Mises stress reaching 38 kPa is an indicator for severe neurological injuries.
- A global strain energy of the brain skull interface reaching 5.4 J is an indicator for subdural hematoma and subarachnoidal bleeding.
- A global strain energy of the skull reaching 2.2 J is an indicator for skull fractures.

3 Results
The 15 first milliseconds of each head impact are simulated. The average time step rises with $10^{-3}$ ms which is compatible with the wave propagation time in the modelled materials. This time step is calculated by the code at each new time increment. This time step calculation rests on the size of the smallest elements and on the sound’s velocity in the different modelled materials.

For the first impact configuration under study, the brain pressure reached values of 574 kPa predicting brain contusion. The human head model also predicted the location of the bleeding and showed a classical coup and contrecoup injury located in the occipital (for the coup) and fronto-temporal (for the contrecoup) lobes. As seen in FIG. 1 and FIG. 2, the distribution of brain pressures correlated with the images obtained from the CT-scan performed when the victim was admitted to hospital. For the second impact configuration, the brain pressure remained below the tolerance limit. Therefore, brain contusion should not be observed after this impact.

The first impact configuration, predicted a coma with a calculated Von Mises stress of 66 kPa. This immediate loss of consciousness had been witnessed by the surrounding observers. For the second impact configuration under study, the brain Von Mises stress remained below the proposed tissue tolerance limit (12 kPa). Therefore, moderate neurological injuries should not be observed in this case.

For the first impact configuration, the calculated global strain energy of the skull reached a value of 27.5 J and bone fracture was predicted by the model through the destruction of 40 of the three layered composite shell elements of the skull, as shown in FIG. 3. The anatomical distribution of the deleted elements is close to the fracture seen at autopsy, yet it is not very accurate. The reason is that the skull of the UDS FEM of the human head has the same thickness everywhere. For the second impact configuration, the calculated global strain energy of the skull was of 0.6 J and no three layered composite shell elements of the skull were destroyed.

For the first impact configuration, the global strain energy of the brain skull interface reached values up to 14.7 J, twenty times higher than for the second impact configuration. Subdural hematoma and subarachnoidal bleeding are therefore very likely to occur in the first impact configuration.
FIG. 1 – Occipital brain contusions: correlation between CT-scan and simulation.

FIG. 2 – Frontal brain bleeding: correlation between CT-scan and simulation.

FIG. 3 – Anatomical distribution of the skull deleted elements and correlation with the observed skull fracture.

4 Discussion
The last forty years have seen biomechanical studies emerging in forensic research. Many of these aimed to establish whether a head injury of an infant was the result of accident or abuse, and if it was abuse, what
were the possible mechanisms leading to certain injuries such as subdural hematomas [6,7]. These studies have been recently criticised [8,9]. Other works such as multi body dynamics reconstruction of adult head injury accidents, and biomechanical studies of falls, have recently been published [10,11,12,13]. FEM are considered as good and the power full tools to investigate the dynamic response of the human head under impact conditions even if a great amount of progress is still needed to increase their bio fidelity. Nevertheless, no work has yet been published using FEM for the evaluation of human head injuries in forensic cases.

Thus, it can be stated that brain Von Mises stress is a good indicator for brain neurological lesions, whether they are moderate or severe. Moreover, this mechanical parameter allows distinguishing these lesions into two categories: moderate or severe. Global strain energy in the brain skull interface and in the skull is a reasonable indicator for subdural hematoma and skull fracture respectively. These tolerance limits used for the UDS FEM of the human head have been detailed in previous papers [1,5]. Brain pressure has been shown to be correlated with brain haemorrhages resulting in brain contusions, oedema and hematoma when reaching values above 200 kPa. The tolerance limits predicting neurological injuries resulting in unconsciousness, contusion and coma are correlated to the calculated brain Von Mises stress. The tolerance limits for neurological moderate or severe injuries are established for brain Von Mises stress of 18 kPa and 38 kPa, respectively. The global strain energy of the brain skull interface has been shown to be correlated with haemorrhages resulting in subdural and subarachnoid hematoma when reaching values above 5.5 J. In other studies this injury is evaluated by the parasagittal elongation of bridging veins or their elongation rate computed with the FEM. For the UDS FEM of the human head used here a tolerance limit for skull fracture was established numerically at 2.2 J in terms of global strain energy of the skull.

Two impacts were studied here which happened to the same individual, the medical examination being performed after the second impact. This could have caused a problem in separating the effects of each impact. In fact, it has been assumed, in the present study, that there is no interaction between both impacts. Nevertheless, it is not excluded that such an interaction exist and that the second impact increased the severity of the first one which would have been less injurious if the second would not have occurred. In the case under study, both velocities at the time of impact were four times different (6 m.s\(^{-1}\) for the first impact and 1.5 m.s\(^{-1}\) for the second impact) and the location of the first impact was occipital but the second parietal corresponding to a side impact. The location of the skull fracture seen on the victim was more likely explained by the first fall. Also, there was a witnessed immediate loss of consciousness following the first fall. The results of the simulation of the first fall predicted all of these findings. The results of the simulation of the second fall showed brain pressures ten times lower than for the first fall and four times lower than the tolerance limits, and global strain energies of the brain skull interface thirty times lower than for the first fall and ten times lower than the tolerance limits. The first fall was therefore very much more likely to create the contusions seen on the CT-scan. Moreover, the simulation of the first fall showed an anatomical distribution of predicted brain contusions comparable to the contusions seen on the CT-scan. The point was to compare two falls and it can be concluded that the second fall alone was very unlikely to have created any injury seen on the first CT-scan of the victim. But it is of course difficult to discuss the consequences of the second fall on an injured human head, even if the predicted levels of the mechanical field parameters are in majority very much lower than the tolerance limits values. Conclusions can of course only be drawn for this particular case.

The UDS FEM of the human head can also be used with its injury mechanisms and tolerance limits, completing clinical data to compare the biomechanical consequences of a fall to blows when a victim is found unconscious or dead and these two scenarios are being discussed. The UDS FEM of the human head is a head model. Therefore only impacts to the human head can be discussed with minor uncertainty. The possible effects of impacts to the trunk or to the arms and legs preceding the impact to the human head can be taken into account but may raise many questions concerning the energy of the impact to the human head. Therefore, the biomechanical study can be completed by the use of multi body dynamics. A biomechanical approach can be very helpful to investigate forensic cases and there is a need for collaboration between forensic sciences and biomechanics to objectively and scientifically evaluate adult and infant head injuries using well documented cases.

5 Conclusion

The UDS FEM of the human head was developed in the late 1990s and has been validated towards experimental impacts on cadavers. The present study shows the relevance of numerical methods, and
especially FEM, for reconstructing and predicting human head injuries. For the case studied, two falls were compared and their consequences were shown to be very different. Moreover, the injuries predicted by the human head UDS FEM were very similar to the injuries sustained by the victim. Numerical tools have to be accurately defined in terms of geometry and mechanical behaviour. The FEM may then become invaluable tools in the future for injury prediction and may therefore contribute to objectively and scientifically evaluate adult and infant head injuries in forensic cases. Nevertheless, some great efforts must be achieved to increase the bio fidelity of such numerical tools.

References