Finite Elements Models of the Head in Craniocerebral Trauma – Review

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Abstract: *Head injuries are a major health and socio-economic problem. To better protect the head against various crash, sport, or fall events, the underlying mechanisms and tolerances need to be investigated. Many investigations have been conducted using cadaver heads, animal heads, physical head models, and in vitro models throughout the world. These experiments, together with the development of computational techniques, have subsequently led to the development of numerical head models, especially finite element (FE) models, to allow more in-depth biomechanical studies. A large number of FE head models have been developed during the years and authors are trying to find the best solutions for a correct explanation of the lesional mechanisms. The finite element method (FEM) is based on the energy formulation of the mechanics of the structures and on approximation methods. It consists of approximating the actual structure through a model consisting of finite elements interconnected in points called nodes. By nodes, each item is under compatibility and balance conditions with adjacent elements. The present paper is a literature review, underlying some of the finite element models, which allowed a good explanation of the head trauma mechanisms.*

Keywords: *finite element models; head trauma; forensic applications.*

Introduction

Forensic activity frequently includes the evaluation of the lesions underlying the lesions found in either adults or children.

The anatomical segment most affected in the event of accidents or voluntary violent acts is the cervicocephalic extremity. Trauma to the cervicocephalic extremity is the mechanical consequence of an overload of the head and its component parts. Whatever the nature of the external mechanical agent, by contact or by inertia, the mechanical response of the anatomical elements involved translates into deformation and contraction phenomena. If the tolerance limit of an anatomical element is exceeded, then the lesion occurs.

Until recent years, the forensic analysis of traumas of the cervicocephalic extremity was based on expert opinions, some empirical, others based on biomechanical studies. The development of digital structural models, first in aeronautics, then in mechanical and civil engineering gradually evolved towards the development of digital models of human anatomical structures (Chera-Ferrario et al., 2019), mainly due to the impossibility of using human beings as subjects for research in the field of trauma to the cervicocephalic extremity (Jackson, 2019; Wichsova & Horakova, 2018).

The finite element method is based on the energy formulation of the mechanics of the structures and on approximation methods. It consists of approximating the actual structure through a model consisting of finite elements interconnected in points called nodes. By nodes, each item is under compatibility and balance conditions with adjacent elements. This concept allows for a simplified treatment of problems of continuous environments, because this way we can trace the points using their coordinates and belonging to a continuous environment.

At the same time, the digital simulation for a given force allows a realistic estimate of displacement, contractions and deformity energy to any component of a model. The results of these simulations can therefore be compared with the tolerance limits resulting from tissue research or the reconstruction of accidents, the ultimate purpose being the prediction of the main lesions. For this very reason, models of finished elements have started to be widely used in different areas in order to optimize protection systems and establish rules in industries (e.g., automobiles).

Objective

The present paper is a literature review on the models of finite elements of the craniocerebral extremity of the adult from a forensic point of view, with the aim of enriching the analysis and interpretation of forensic trauma of the adult.

The objective is to review the literature on various models of finite elements of the head and possible tolerance limits, ultimately proving the interest of the use and development of models of finite elements in forensic practice and reasoning.

Material and method

This paper is a literature review that includes the presentation of models of finite elements in craniocerebral trauma and their usefulness in forensic practice.

The articles selected were found and accessed through the PubMed and ResearchGate scientific databases using as tools keywords such as "models of finite elements", "craniocerebral trauma", "practical applications of finite elements".

Results

The authors have identified approximately 40 recent studies focusing on the presentation of finite element models of craniocerebral trauma in different situations encountered in forensic practice.

The most important aspects discussed are the creation of models of complex finite elements, including as many parameters as are involved in the production of craniocerebral trauma, and providing an interpretation of high accuracy of the production mechanism and formation of lesions.

Given the difficulty of experimenting on living animals, corpses or subjects (Costeniuc, 2019), various digital models were used in the research to better understand the dynamics of the head in a shock situation. The approach consisted in determining the mechanisms based on comparing the results of simulations with tolerance limits. Indeed, finite element models of different structures were created first, but also the finite element models (FEM) of the head date as back as the 1970s.

The literature mentions various models of finite elements of craniocerebral trauma in different situations. Most focus on identifying the mechanisms of the injury in road accidents, especially the driver's. This proves helpful both in forensic practice, to provide a logical chain and a

correct mechanism to produce injuries, but also in the practice of automotive engineering for the safety features of motor vehicles.

Also, beginning with the first finite element model, researchers have tried to create all the components of the cephalic extremity, ranging from a simple model of hollow skull to simulating the cerebrospinal fluid and subarachnoid spaces, subdural and extradural.

The first three-dimensional finite element model presented in the literature is that of Ward, composed of 300 elements and validated by static crushing tests of the brain stem, measured by X-rays (Ward et al., 1980). It puts the condition of a lack of slipping between the brain and the skull, due to the very low values of relative displacement between the brain and the skull, measured with X-rays on human subjects. In 1977, Shugar developed a three-dimensional model based on a two-dimensional model created by his team two years earlier. It introduces a fine layer between the brain and the skull, with the aim of reproducing the sub-arachnoid space. The validation of this model is done by comparing the pressures calculated with those recorded on a physical model, made up of a human skull filled with water. Shugar thus notes that, in impact situation, the calculated pressure values are 3 to 10 times higher than those experimentally measured for a given impact configuration (Shugar, 1977).

In 1980, Hosey created a model with 637 three-dimensional elements and 149 two-dimensional elements, with the aim of highlighting the cavitation phenomenon at the level of the area that supports the blow. The model validation is based on the frontal impact tests carried out by Nahum et all on anatomical subjects and refers to a digital experimental comparison of intracranial pressures (Ward et al., 1908; Ono et al., 1980).

In 1991, Dimasi developed a three-dimensional model to simulate the attenuated, i.e. unattenuated impact for a range of accelerations between 165g and 302g. This model was a useful tool in investigating brain damage related to car accidents. Here during the application of static forces. In order to analyze intracerebral contractions and deformations in the case of angular acceleration of the head, and to establish a correlation between the intensity of the axonal lesions observed in generally et all's primate experiments and the distribution of the calculated encephaloma deformities, in 1992 Mendis developed two models of finite elements (Gennarelli et al., 1972; Gennarelli & Thibault, 1982). The first is a simplified model of a baboon head, used for validation after Margulies et all's experiments (Margulies & Thibault, 1989). The results obtained on primates are then extrapolated to humans. The second is a model of the human head, whose brain is shaped by a hyperplastic law. In 1991, Ruan illustrated a typical counterblow

phenomenon for intracranial pressures with the help of a new FEM, based on Shugar's, and made up of a 3-layer skull and cerebrospinal fluid (Ruan et al., 1991; Ruan et al., 1993). The brain is characterized by a linear elastic law, and the validation of the model was carried out from the frontal impact tests carried out by Nahum et all on anatomical subjects. Their results were compared with the model's digital response, in terms of pressure in the impact zone and the counter-blow zone (Ward et al., 1980; Kang, 1998).

Then, in 1993, Ruan improves his previous model, using this time a visco-elastic brain and visco-elastic skin. All components, except the skin and the brain, have linear elastic behavior (Ruan et al, 1993).

Discussions

The literature mentions a wide variety of finite models for adults, which have been proposed in recent years trying to provide with most accuracy craniocerebral trauma under certain conditions and established parameters.

The Wayne State University Model

In recent years, several versions of finite element models of Wayne State University (WSU) have been proposed (Ruan et al., 1993; Zhou et al., 1996; Al-Bsharat et al., 1999; Zhang et al., 2001). The first version dates from 1993-1997 and represents a male skull containing 32,898 knots and 41,354 elements, reaching a total mass of 4.3 kilograms. The model was partially validated using a set of intracranial precise dates defined based on experiments on corpses reported by Nahum et all (Ward et al., 1980). Distinguishing the material properties of the gray substance from the white one, the model could predict the location of diffuse axonal lesions (DAI) in the brain. This first version was used to predict cerebral sensitivity to the impact in variable directions. Thus, a lateral impact produces a local deformation of the skull, an intracranial pressure and a more important shear force in the basal nuclei region than in the case of a frontal shock. The results therefore suggest the location and direction of impact (Zhang et al., 2001).

The second version of the FEM (1998-1999) of the WSU features a sliding interface between the skull and the brain surface. With such a representation of the craniocerebral interface, the model can correlate most of the pressure data of Nahum et all (Ward et al., 1980) with relative brain/cranial displacement measured from experiments on corpses carried out at WSU (Al-Bsharat et al., 1999).

Recently, this model was used to study minor traumatic brain injuries of American football players. The results suggest that intracranial pressure depends largely on the acceleration of the translation of the head, while the maximum shear force is more sensitive to rotational acceleration (Zhang et al., 2001).

In 2001, Zhang initiated a new version of WSUBIM (Wayne State University Brain Injury Model), which would be able to simulate a direct or indirect impact of different severities. Thus, this new, finer network allowed more detailed and precise modelling of the anatomical elements of the head. At the same time, for the first time, the distinction was made between the brain stem and the cerebellum, by detailing the structural characteristics (Zhang et al., 2001).

In addition to the finished network of the cranial box and intracranial elements, a full and detailed face was also shaped. The geometry of the face was obtained based on the MRI sections of the "visible human" project. The facial model includes the 14 facial bones. Due to the irregularities and complexity of facial bone structures, the geometry of some of them was simplified and flattened, but the structure of the face was preserved. The facial part of the model consists of approximately 36,400 elements, with a mass of 0.78 kilograms and is fully integrated into the cranial part of the model. An elastic-plastic pattern was implemented so that it could better restore the behavior of the cortical and trabecular bones of the face.

Within the model, the maxillary sinuses and ethmoid cells were also taken into account, which can affect the distribution of forces in the bones of the face. Nasal cartilage forms the external and internal frame of the nose; septal, lateral and alar cartilage of the nose were also included in the model, directly joined and fixed by the adjacent bones.

At the time of impact, soft tissues like muscles, skin and adipose tissue of the face contribute mainly to the distribution of forces applied to the bone structure. These soft tissues were shaped as a single element, covering the entire face and attached directly to the external surface of the face bones. Their thickness varies between 3 mm at the nose, 8 mm to the zygomatic bone, 8.75 mm at the upper jaw and 10 mm in the mandibular region. The temporo-mandibular joint, stabilized by ligaments, was included.

Two campaigns of experiments on corpses were used to validate model responses (WSUNIM) in terms of intracranial and ventricular pressure. Similarly, the model was subjected to intracranial pressure and ventricular validation of various pressures, using cadaveric data reported by Trosseille et all (Trosseille et al., 1992).

Following data obtained more recently by Hardy et all (Al-Bsharat et al., 1999) in a frontal, lateral and occipital shock situation, this model was revalidated, referring it to them. At the same time, it was also validated in terms of digital behavior towards the experiments of Nyquist et all and those of Allsop et all (Nyquist et al., 1986; Allsop et al., 1991).

This FEM was also used in the digital reconstruction of 53 sports accidents, 22 of which were contusions. A first limit has been set on accelerations between injured and non-injured players. Thus, the average linear acceleration is 94.27g for injured players, respectively 55.21g for non-injured, while the average angular acceleration for these two groups of players is 6398-1978 and 3938-1406 rad/s2. We can therefore say that the rate of deformation is a good indicator for predicting injuries (King et al., 2003).

The Stockholm model

The Stockholm model, developed by Kleiven in 2002, is based on CT and MRI images obtained from the visible human database and consists of 11454 three-dimensional elements, 6940 two-dimensional elements and 22 resort elements (Kleiven & Hardy, 2002).

This FEM comprises the scalp, three layers of cranial bones, encephalic, meningeal, cerebrospinal fluid and 11 pairs of venous veins. As shown in Fig. 3, a simplified neck has been added to the FEM in order to prolong the brain stem, dura mater, pia mater and thus be able to change the conditions to the model limits. In order to better simulate the distribution of forces and intracerebral contractions, the gray and white substances were differentiated, and ventricles were included (Kleiven & Hardy, 2002).

The University of Eindhoven Model

The Eindhoven model was developed by Claessens in 1997 and is based on CT sections and MRI data available in the visible human database. The basic model consists of a skull, a brain and a simplified face, consisting of 1756 hexaedric elements and having a mass of 3.1 kg. The skull and brain are considered linear, homogeneous and isotropic (Claessens et al., 1997).

The model validation was based on the experiments of Ward and collab. (Ward et all., 1980) for a frontal shock and a modal digital analysis of its component parts. Then his complexity increased, including cerebri falx (brain scythe), cerebelli tentorium, cerebellum and brain stem, thus reaching 12,126 elements. The FEM was validated in the situation of a Nahum type frontal shock (Ward et all., 1980) following a study of Young's brain module and the influence of the brain-skull interface on the model's response.

In 2002, Brands resumed this model in order to complete the existing network and include a layer of elements between the brain and skull, which represents the CRL. The new variant of FEM consists of 14092 elements, distributed as follows: 3212 for skull and face, 3188 for meninges and 7692 for encephalic. Brands' objective was to study the effect of a non-linear law on brain response to shear, contractions and pressures. Its conclusion was that non-linear behavior influences the value of shear forces (+20%), contractions (-11%), but that the brain's response to pressure is independent of the non-linear behavior of the material.

The United States National Highway Traffic Safety Administration (NHTSA – SIMon) Model

The SIMon (Simulated Injury Monitor) software was created by NHTSA (National Highway Traffic Safety Administration) in order to progress in interpreting the injury mechanisms based on cinematic and kinetic data resulting from experiments on anthropomorphic mannequins, the response was measured on the mannequin, and was then applied to the human mathematical model SIMon. The SIMon finite element model is based on the original model developed by Dimasi et all and later improved by Bandak in 1994 and 2001 (Bandak et al., 1995).

It comprises a rigid skull, layers of meninges, CSF, encephalic, scythe and venous network. Representing a medium head with a total mass of 4.7 kg, of which 1.36 kg is the mass of the brain, and 2.91 kg is the mass of the skull, the model consists of 10475 knots and 7852 elements (49% belong to the rigid, non-deformable skull, 16% of the mater/CrL, 35% of the brain, and the 76 grind elements represent the venous network).

The lower face of the hemispheres has been rounded and there is no differentiation between the brain, the cerebellum and the brain stem. This anatomical simplicity has certain advantages: it reduces the complexity of the problem from the outset (both the number of equations to be solved and the required calculation time) and, because it does not contain any encephalic structure, can be generalized for other cases and can be resized independently in any of the three axes. Within the model, the skull is considered rigid and the rest of the intracranial components, especially the venous network, are considered deformable, linear, isotropic and homogeneous.

The SIMon model also has three criteria that allow the occurrence of subdural hematomas, brain contusions and neurological lesions (diffuse axonal lesions).

1. For diffuse axonal lesions, CSDM (cumulative strain damage measure) is based on maximum main deformation by integrating the deformer tensor. The maximum deformation of each element of the FEM is compared to a threshold value and CSDM is the percentage of volume of the brain whose main deformation exceeds this threshold. Then, by performing a regression, the probability of injury is obtained, depending on the amount of CSDM. Thus, there is a 50% chance of developing diffuse axonal lesions when 55% of the brain suffers a main deformation of more than 15%.

2. For brain contusions, DDM (dilatational damage measure) is based on negative pressure values. DDM is the percentage of volume of the brain whose pressure is below the threshold value of -100kPa (water vapors pressure).

3. For subdural hematomas, the relative motion damage measure (RMDM) is based on the deformation of the venous network at impact.

4. These three criteria are added a predictive criterion for skull fractures: AHIC, calculated numerically and compared to a risk curve for frontal and linear skull fractures. For 50% fracture risk, the authors propose the AHIC value = 165g.

The University of Strasbourg (ULP Model) Model

This three-dimensional finite element model of the human head was created in the laboratories of Louis Pasteur University in Strasbourg, by Kang [21, 22]. Building on an empty human skull, whose external and internal surfaces have been digitized using a three-dimensional measuring device, the semi-automatic creation of the network of elements is carried out in Hypermesh software. Then the intracerebral membranes were installed, and the brain was designed to fill the intracranial space up to 2 mm of the cranial box. The network of elements shall be continuous through all component parts of the model. In order to simulate the cerebrospinal fluid, the sub-arachnoid space is represented between the brain and the skull, while the tent separates the cerebellum from the brain, and the scythe is interspersed between the two cerebral hemispheres, in sagittal. Overall, the model consists of 11939 knots and 13208 two-dimensional and three-dimensional elements.

The cranial bones consist of an external headboard and an internal cortical bone that limits a spongy structure: diploe. The connection between the brain and the skull is represented on the model by a layer of elements of small elasticity, which simulates the sub-arachnoid space. The supposedly homogeneous and isotropic structure of the brain is modelled according to a

law of visco-elastic behavior, which is provided by a Boltzmann rheological model, whose mechanical parameters are optimized to have a response that overlaps tests Shuck (1972). The elements that constitute the scalp, scythe and tent are elastic.

Willinger's validation of the model was made (Willinger et al., 1999; Willinger et al., 1995; Willinger & Césari, 1990), which confronted the dynamic response of models with experiments conducted by:

- Nahum, on the contact force between the frontal bone and the foreign body that strikes it, the acceleration of the skull and intracranial pressures in the frontal, occipital, parietal and posterior regions (Ward et all., 1980);

- Trosseille, with regard to intracerebral acceleration in the frontal, occipital, lenticular nucleus and intracranial pressures in the frontal, occipital, temporal and lateral ventricle and 3rd ventricle regions (Trosseille et al., 1992);

- Yogonandan (1994), on the forces of interaction between the bullet and the cranial bones and the observation of the characteristics of the fractures during the simulation.

In order to determine the mechanisms of the injury and tolerance limits of the tissues of the finite element model, Baumgartner carried out 66 digital reconstructions of real accidents (Baumgartner, 2001).

The accidents considered are in the field of transport, sport, ballistic impact and have four different origins:

- motorcycle accidents (helmet-protected head)

- shocks between the windscreen and the head of pedestrians overturned by automobiles

- shocks between the heads of American football players in sports competitions

- ballistic impact on protected or unprotected head.

The correlation between the calculated mechanical parameters and the observed lesions allowed the tolerance limits to be quantified, which correspond to a 50% probability of lesions.

- for subdural or subarachnoid hematomas, a total 5.4 J subarachnoid space deformation energy

- for moderate neurological lesions, a Von Mises intracerebral contraction of 18 kPa

- for severe neurological lesions, a Von Mises intracerebral contraction of 38 kPa

- for fractures of the cranial bones, an energy of deformation of the skull of 2.2 J. (Baumgartner, 2001).

By experimental reconstruction of 13 motorcycle accidents, mechanical criteria of injuries were established, based on the following experimental mechanical parameters: linear and angular acceleration of the skull, brain and relative skull and brain. Therefore, for a 50% probability, the mechanical criteria of cranio-cephalic tissue lesions and their thresholds are:

- for subdural or subarachnoid hematomas, a linear brain acceleration of 273 g

- for moderate or severe neurological lesions, an angular acceleration of the brain of 25970 rad/s2 and a relative linear acceleration between the brain and skull of 78 g (Hodgson et al., 1970; Thali et al., 2002; Newman et al., 1999; Chitescu et al., 2018; Perju-Dumbrava et al., 2010).

Conclusions

These reconstructions are experimental (in the case of American bikers and football players) and analytical replicas (for pedestrian) of the accident. Although the absolute validity of the results obtained must be modulated according to an unvalued time uncertainty interval, the thresholds set are reasonable in view of the model used. The analysis leads to the identification of the lesions in the form of a scale of severity of the injuries produced, considered as a whole. Therefore, this type of criterion underlines the effectiveness of finite element models as instruments for predicting lesions.

The application of such methods may be supported by creating a *Biomechanical platform,* where the tools and skills are made available for forensic scientists. Different applications of the finite element method can help in forensic sciences and increase the correct interpretation of trauma mechanisms.

Their importance is highly obvious in forensic practice; these models of finite elements could represent a future research in forensic science for approximately all lesion mechanisms.

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