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REVIEW ARTICLE

Finite-element models of the human head and their applications in forensic practice

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Abstract Since the 1960s, predictive human head impact indices have been developed to help the investigation of causation of human head injury. Finite-element models (FEM) can provide interesting tools for the forensic scientists when various human head injury mechanisms need to be evaluated. Human head FEMs are mainly used for car crash evaluations and are not in common use in forensic science. Recent technological progress has resulted in creating more simple tools, which will certainly help to consider the use of FEM in routine forensic practice in the coming years. This paper reviews the main FEMs developed and focuses on the models which can be used as predictive tools. Their possible applications in forensic medicine are discussed.

Keywords Finite element models · Forensic science · Head injury · Ballistics

Introduction

It can be a fundamental problem in forensic investigations to establish whether a head injury is the consequence of an accident or an assault. Close examination of the wounds may help to understand the mechanism of injury, but sometimes doubt remains and it may be particularly difficult to differentiate the consequence of a fall from the consequence of a blow. During the second half of the twentieth century, engineers have tried to develop mathematical models using fundamental Newtonian principles and experimental observations to predict the mechanisms of head injury for a given scenario. An overview of these models has been given by Cory et al. in 2001 [1]. Yet, inaccuracies can arise from these models in which tolerance to impact originates from various sources including experiments on animals, human cadavers, anthropomorphic dummies, and human volunteers. A proposed alternative method for assessing the consequence of a given head impact scenario is the use of finite-element models (FEM) of the human head. In this paper, we shall review the main FEM of the human head developed to date and discuss the possible use of FEM in forensic cases.

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Finite-element models

Computer models are increasingly proving to be an alternative to complicated, practically unfeasible or unethical (human or animal) experiments. The finite-element method, which is a mathematical method for solving complex physical problems on domains with complicated geometries, is commonly used in constructing such computer models. The finite-element modelling technique offers the advantage of being able to model structures with intricate shapes and indirectly quantify their complex mechanical behaviour at any theoretical point. Because the finite-element method uses the theories of elasticity and static equilibrium, the effects of multiple external forces acting on a system can be assessed as physical events in terms of deformations, stresses or strains.

Creating a FEM starts by creating a topological description of the structure's geometric features, which can be in either 1D, 2D or 3D form, modelled by line, shape, or surface representation, respectively, although nowadays, 3D models are predominantly used. The primary objective of the model is to realistically replicate the important parameters and features of the real model. Once the finite-element geometric model has been created, a meshing procedure is used to define and break up the model into small elements. In general, a FEM is defined by a mesh network, which is made up of the geometric arrangement of elements and nodes. Nodes represent points at which features such as displacements are calculated. Elements are bounded by sets of nodes and define localised mass and stiffness properties of the model. Elements are also defined by mesh numbers, which allow references to be made to corresponding deflections or stresses at specific model locations.

One of the first 3D models was developed by Ward and Thompson in 1975 to reproduce the experimental tests carried out on cadaver heads [2]. In this model, the brain was modelled by means of 189 eight-node brick elements while dura mater, falx and tentorium membranes were modelled by means of 80 four-node shell elements. The main features of this model are a rigid skull, a cerebro-spinal fluid with linear elastic properties and an elastic brain. The membranes and the foramen magnum were also modelled.

In 1977, Shugar and Kahona developed a 3D model based on a previous 2D model developed by his team in 1975 [3]. A thin layer is modelled between the skull and the brain in order to represent the subarachnoid space. In 1980, Hosey and Liu developed a FEM with 637 brick elements and 149 shell elements [4]. The aim was to show the cavitation phenomenon in the contrecoup area.

In 1991, Dimasi et al. created a 3D FEM in order to simulate damped and undamped impacts with accelerations varying from 165 to 302 g [5]. This model, made of 500 elements, was a first step in the comprehension of brain injuries in car crashes. In 1992, Mendis [6] developed two FEMs in order to analyse brain stress and strain during a rotational acceleration of the head and to correlate the axonal injury intensity observed experimentally on primates by Gennarelli and Thibault in 1982 with strains predicted in the brain [7]. With the rapid advances in computer technology, more sophisticated FEMs of the head could be created. Ruan et al. in 1992 illustrated the typical contrecoup phenomenon with a new FEM based on Shugar and Kahona's model [8].

Over the last few years, several versions of the Wayne State University brain injury model (WSUBIM) were developed. WSUBIM version I (1993–1997) simulated essential anatomical compartments of the head [9, 10]. This model represents a 50th percentile male human head and has 32,898 nodes and 41,354 elements, with a total mass of 4.3 kg. By differentiating the material properties of grey matter from white matter, the model was capable of predicting the location of diffuse axonal injury (DAI) in the brain. It was used to predict the directional sensitivity of the brain to impacts from varying directions. Later, the model was revised and upgraded to WSUBIM version II (1998–1999) by introducing a sliding interface between the skull and brain surface. Recently, the model was used to study minor traumatic brain injury sustained by American football players. This study by Zhang et al. suggests that the intra-cranial pressure is largely a function of the translational acceleration of the head, while the maximum shear stress is more sensitive to rotational acceleration [11]. The aim of Zhang et al. was to develop a FEM capable of simulating direct and indirect impacts over a wide range of impact severities. The goal was to enable the model to yield robust results for a combination of angular accelerations in excess of 8,000 rad/s^2 and linear accelerations in excess of 200 g. For this, the previous version of the WSUBIM was completely revised using a much finer mesh to construct a new 3D FEM (Fig. 1). The totally revised model simulated all essential anatomical features of a 50th percentile male head, including the scalp, skull with an outer table, diploe, and inner table, dura, falx cerebri, tentorium, pia, sagittal sinus, transverse sinus, cerebrospinal fluid (CSF), hemispheres of the cerebrum with distinct white and grey matter, cerebellum, brainstem, lateral ventricles, third

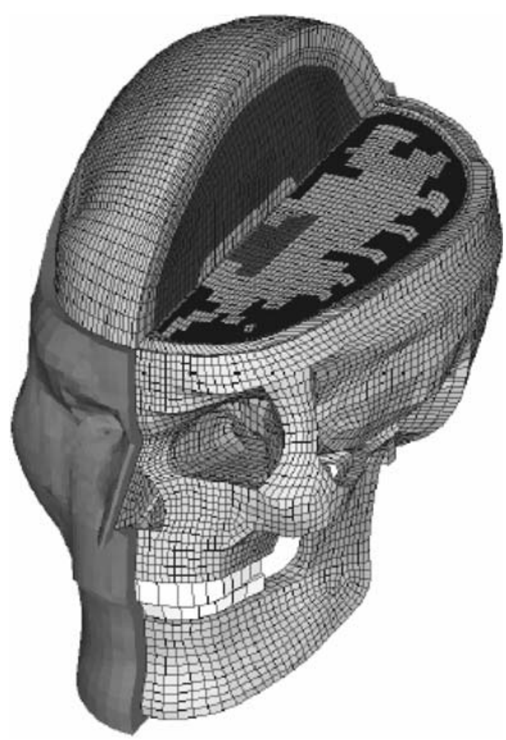

Fig. 1 An overall view of the WSUBIM [11]

ventricles and bridging veins. Moreover, this model included a facial model simulating all essential anatomical features of the human face (14 facial bones). This model consisted of a total of over 281,800 nodes and 314,500 elements, with a mass of 4.5 kg. Concerning the mechanical properties of this model, the brain behaviour was characterised as viscoelastic, and an elastic–plastic material model was used for cortical and cancellous bones of the face. This FEM was used to reconstruct 53 cases of sport accidents of which there were 22 cases of concussion. King et al. showed that strain rate and the product of strain and strain rate in the midbrain region appeared to be the best injury predictors for concussion [12].

In 1997, Claessens et al. developed a head model using the Visible Human Project [13]. In 2002, the model was completely transformed by Brands et al. [14, 15]. The anatomical structures included in the current Eindhoven model are grouped into three components: the cranium, the meningeal layers and CSF and the brain tissue. All structures were assumed to be rigidly connected to each other. The objective of this new model was to study the effect on non-linear material behaviour on the predicted brain response. Their conclusions were that the pressure response remained unaffected by application of non-linear behaviour; the pressure gradient being completely determined by the equilibrium of momentum and, thus, independent of the choice of the brain constitutive properties.

In 1997, Kang et al. developed the Université Louis Pasteur (ULP) human head FEM shown in Fig. 2 [16]. The geometry of the inner and outer surfaces of the skull was

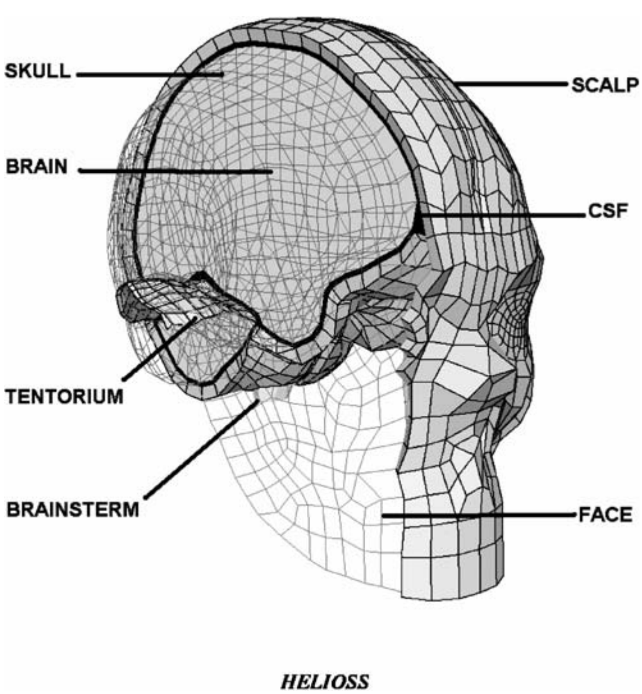

Fig. 2 Section through the ULP human head model

digitised from a human adult male skull. The main anatomical features modelled were the skull, falx, tentorium, subarachnoid space, scalp, cerebrum, cerebellum and brainstem. For the CSF, a Lagrangian formulation was selected and the brain–skull interface was modelled by an elastic material validated against the in-vivo vibration analysis. The scalp was modelled by a layer of brick elements and surrounds the skull and facial bone. Globally, the ULP model consists of 13,208 elements. Its total mass is 4.7 kg. Material properties of the CSF, scalp, facial bones, tentorium and falx are all isotropic and homogenous. The brain was assigned viscoelastic properties from Khalil and Viano [17]. Moreover, tolerance limits were identified by Willinger and Baumgartner in 2003 and Marjoux et al. in 2008 with respect to a given lesion [18, 19]. Their study established human head tolerance limits relative to DAI, subdural haematoma and skull fracture with a risk of occurrence of 50%. This model was used for the first time in forensic science by Raul et al. in 2005 [20]. In 2004, Deck et al. proposed a new 3D FEM, which describes in detail the complex geometry of the skull, including the evolution of the skull thickness throughout the skull and, for the first time, the reinforced beams which play an important role in its dynamical response to impact [21]. Concerning the brain mechanical properties, the authors improved two new laws based on original experimental tests by Nicolle et al., in 2003, focusing on high strain rates and non-linear behaviour in order to investigate the brain material properties' influence in the head model validation procedure against existing experimental brain deformation [22].

In 2002, Kleiven and Hardy proposed a detailed and parameterised FEM of the adult human head including the scalp, skull, brain, meninges, CSF and 11 pairs of parasagittal bridging veins, namely the Kungliga Tekniska Högskolan (KTH) human head FEM (Fig. 3) [23]. A simplified neck, including the extension of the brain stem to the spinal cord, dura mater, spine and muscle and skin, was also modelled. This model consists of 18,400 elements. This homogeneous, isotropic, non-linear and viscoelastic constitutive model was based on the work by Mendis et al. [24]. In addition, dissipative effects are taken into account through linear viscoelasticity by introducing viscous stress that is linearly related to the elastic stress. This model has been validated against experimental pressure data, as well as relative motion magnitude data [23, 25]. In 2007, Kleiven compared various predictors for mild traumatic brain injuries. The model was imposed on the kinematics of 58 National Football League accidents. Eight tissue injury predictors were evaluated for six different regions, covering the entire cerebrum, as well as the maximum for the whole brain [26]. For the maximal principal strain, a 50% probability of concussion was found by the author for a level of 0.21 in the corpus callosum or 0.26 in the grey matter.

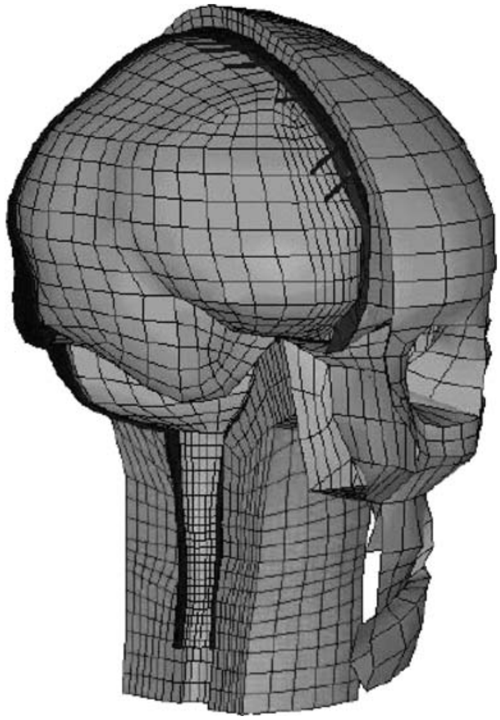

Fig. 3 Finite-element mesh of the KTH human head model [25]

Takhounts and Eppinger in 2003 proposed the simulated injury monitor (SIMon) FEM based on the model originally developed by DiMasi et al. in 1995 and later improved by Bandak and Eppinger in 1994 and Bandak et al. in 2001 [27–30]. It consists of the rigid skull, the dura-CSF layer, the brain, the falx cerebri and the bridging veins (Fig. 4). The brain has been simplified in order to generalise the model and to meet the run-time constraint of 2 h. The region under the brain and the tentorium was modelled as a continuation of the dura-CSF layer and did not account for either the cerebellum or the midbrain. This model represents the head of a 50th percentile male and has a total mass of 4.7 kg. The skull was assumed to be rigid, whereas the rest of the structures were considered as deformable, linear viscoelastic, isotropic, and homogeneous. The brain was characterised as viscoelastic. Data from animal experiments were used to determine critical values for each injury metric. In order to apply these data, the linear and angular kinematics recorded for the animal's head were scaled in magnitude and time to what a human would experience. These responses were then applied to the rigid skull of the SIMon FEM. The injury metrics were computed from each test and logistic regression was used to establish the critical values. Three intra-cerebral injury mechanisms are available:

- Cumulative strain damage measure (CSDM) as a correlate for diffuse axonal injuries. CSDM is based on the hypothesis that DAI is associated with the cumulative volume of brain tissue experiencing tensile strains over a predefined critical level.
- Dilatation damage measure (DDM) as a correlate for contusions. The second computational injury metric proposed is for the evaluation of brain injury that occurs as a result of dilatational stress states.
- Relative motion damage measure (RMDM) as a correlate for acute subdural haematoma. The third computational injury metric proposed, RMDM, is used for the evaluation of injuries related to brain motion relative to the interior surface of the cranium. This includes injuries due to acute subdural haematoma.

In 2003, the University College Dublin Brain Trauma Model was created by Horgan and Gilchrist and improved

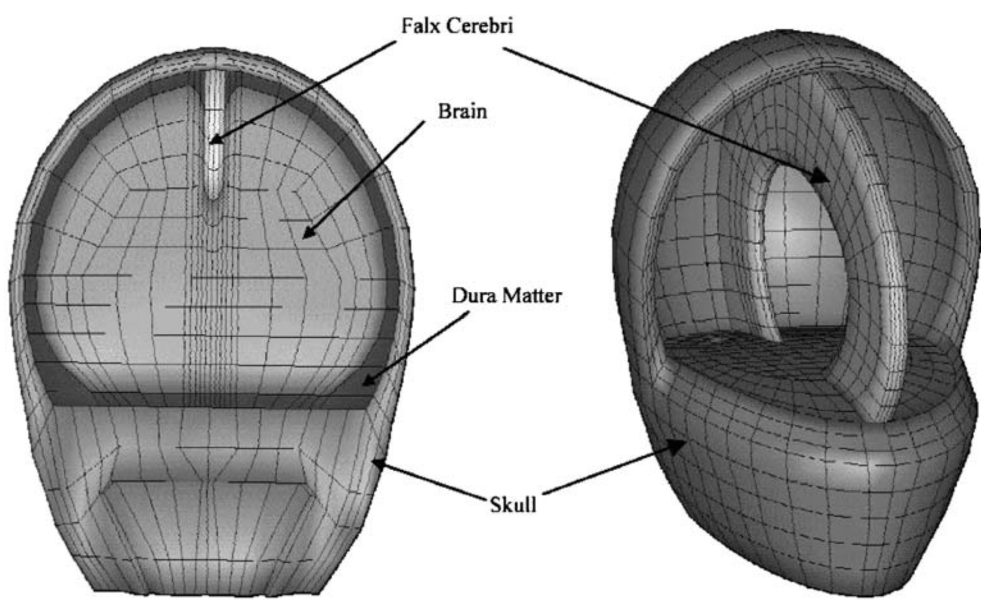

Fig. 4 SIMon finite-element head model [30]

in 2004 by the same authors [31, 32]. This new 3D FEM of the human head complex has been built for simulating the transient occurrences of simple pedestrian accidents. A parametric study was performed to investigate the effect of different mesh densities on response of the models as well as the use of a composite shell element skull and the influence of material properties. By considering some values, it was found that the short-term shear modulus of the neural tissue had the biggest effect on intra-cranial frontal pressure and on the model's Von Mises response. The bulk modulus of the fluid had a significant effect on the contrecoup pressure when the CSF was modelled using a coupled node definition. A comparison between different mesh densities showed that a coarsely meshed model is adequate for investigating the pressure response of the model, while a finer mesh is more appropriate for detailed investigations [31].

In 2006, a 3D FEM of the head–neck complex has been developed by Kimpara et al. with a detailed description of the brain and the spinal cord. The proposed model can be used to simulate the biomechanical behaviour of the entire central nervous system at the same time. For the authors, the brain–spinal cord model was useful to investigate the relationship between the restraint conditions and the central nervous system injuries [33].

Applications

In forensic investigations, head injury is a particular topic for which the mechanism of injury may be particularly difficult to appreciate. It may therefore be useful, based on biomechanical studies, to compare different head impact scenarios. The main features are represented by head impacts with different objects (e.g. stones, bottles, wood) and falls from different heights. The question is often whether the fall was the consequence of an impact or if the head injury may be explained by the sole consequence of a fall. Computed tomography; magnetic resonance imaging; clinical examination and, for fatal cases, autopsy findings bring to light injuries which need to be put into balance with the different possible scenarios given by the witnesses or suspected by the forensic specialist. FEM may help to evaluate different scenarios giving the possibility to exclude some of them. As an example, when different objects may have been used, the consequence of a blow given by each object on the head may be studied. Each object can be modelled as a FEM with mechanical properties depending on its constitution. It may be possible to predict that the object may be destroyed by the impact and that the head will not be particularly injured or that the impact will not lead to a loss of consciousness or a skull fracture.

This evaluation is based on tolerance limits which have been proposed for some FEMs. Only four FEMs are predictive for head injury evaluation and can therefore be used in forensic practice. These models are the WSUBIM, the SIMon, the KTH and the ULP models. Table 1 shows the main tolerance limits for each of these models.

In a former paper, we have presented the use of an adult FEM of the head, namely, the ULP model, to study the consequence of two fall scenarios [34]. A new model of an adult head taking into account the different thickness of the skull has since been developed and has been previously presented in this paper and shown Fig. 5. This new model gives the possibility to study the consequence of head impacts and tends to predict skull fractures with a better accuracy.

Another application of the finite-element method is its use in the study of gunshot injury cases where the

Table 1 Tolerance limit with a 50% risk of injury of each predictive FEM

FEMs	Injuries							
	DAI		Contusion		SDH		Skull fracture	
	Criteria	Tolerance limit	Criteria	Tolerance limit	Criteria	Tolerance limit	Criteria	Tolerance limit
SIMon	CSDM	55%	DDM	7.2%	RMDM	1		
WSUBIM	Strain rate	19s-1						
	Strain rate*Strain	60s-1						
KTH	Brain first principal strain	0.21 (corpus callosum) 0.26 (grey matter)						
ULP	Brain Von Mises stress	27 kPa (moderate) 39 kPa (severe)			CSF strain energy	4,211 mJ	Skull strain energy	833 mJ

SDH subdural haematoma

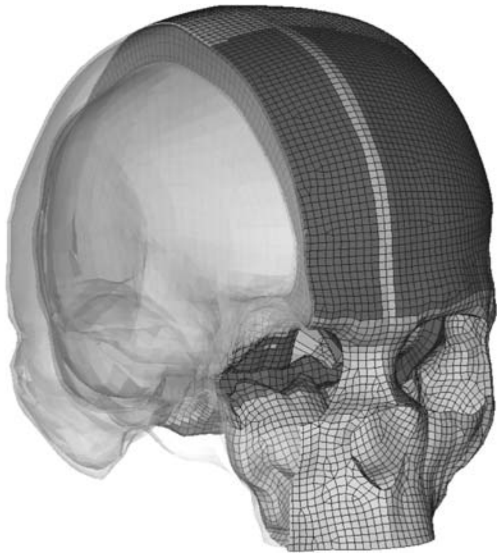

Fig. 5 2004 ULP head model, side view showing the sagittal reinforcement beam and the varying thickness of the skull

consequence of the impact of a ballistic projectile needs to be studied. One possible application has been shown in a previous paper where we studied the effect of a gunshot between the eyes in a multiple-gunshot-wound-to-the-head case [20]. Until recently, only the effect of the impact of the projectile on the head or the head response to ballistic helmet impacts could be studied using FEM. It was not possible to study the effect of the bullet passing through the brain. A first step was made by Pintar et al. in 2001 [35]. Recently, a non-linear dynamic solver LS-DYNA (LSTC, Livermore, CA, USA), which was used in the car industry to simulate the opening of airbags, has been shown by Zhang et al. to be particularly interesting when there is a need to study a penetrating traumatic brain injury [36].

Most firearm wounding studies are performed using large gelatine blocks with unconstrained boundaries to capture the entire projectile path. Blocks are then cut open along the projectile path post testing to measure permanent cavity and penetration distance. These studies focus on quantifying projectile wounding potential. Compared to these models, the human head is smaller and the brain is enclosed in the cranium; therefore, results from these studies may not be directly applicable to penetrating traumatic brain injuries. In a series of recent papers, Thali et al. used a spherical head model to reproduce gunshot wounds to the head [37]. Various projectiles were used to study the creation of external gunshot wounds with high-speed photography. In a follow-up study, more human-like skull geometry was used [38]. These studies focused on the external wounding morphology for forensic purposes. Injuries can occur from pressure changes accompanying passage of a projectile [39]. Quantification of pressures from multiple locations is necessary to better understand injury dynamics. Correlation of pressures with temporary cavity in the time domain may also assist in characterising projectile dynamics. The research performed by Zhang et al., using a brain stimulant (Dow Corning Sylgard 527 A&B, Midland, MI, USA), a silicone dielectric gel, used as brain surrogate in blunt impact studies, the mechanical properties of which are similar to brain tissues, also demonstrating rate-sensitive properties, was designed to quantify temporary cavity dynamics with high-speed digital video images and dynamic pressure changes at various locations and correlate gel disruption with pressure change due to projectile penetration in geometrically appropriate models [40–43]. Experimental data were used to develop a validated FEM to further investigate penetrating traumatic brain injury biomechanics. Their results open the way to further studies in the field of gunshot injuries to the head using FEM.

FEM have been used for the development of ballistic helmets and to study the rear effect of a gunshot impact on protection helmets [44–46]. It appears possible to study the effect of an intermediate target on gunshot injuries, but to date, no study has been made to study the feasibility of this technique.

In recent years, only particular cases for which sufficient information has been recorded have been studied with promising results. The use of FEM relies on the available information concerning the element impacting the head, such as the type of ground or the size and mechanical properties of a stick, a bottle or any element which may be used during an assault. These elements are sometimes unknown or lacking and therefore may limit the use of the finite-element method. This point needs to be outlined because this method is of recent use in forensic practice and, therefore, is not used in routine; therefore, important information may not be recorded by the crime scene investigators. Good information concerning this technique and its needs will help developing its use in forensic cases. Another drawback may be the calculation time to study a single case. However, the evolution of the computer's capability to perform faster calculations will certainly help to consider the use of FEM in routine forensic practice in the next few years.

Conclusion

Finite-element methods appear to be a promising tool for assessing the consequence of a given head impact scenario and for future ballistic studies. Good comprehension of this technique and evolution of computer capability will help developing its use in forensic routine practice. Research and regular practice in this field will help develop the accuracy of this method.

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