Adv. Theor. Appl. Mech., Vol. 1, 2008, no. 5, 225 - 240

Recent Progress in Application of FEM in Study of Non-penetrating Brain Injuries

Yunhua Luo

Department of Mechanical & Manufacturing Engineering
Faculty of Engineering, University of Manitoba, Winnipeg, Canada R3T 5V6
luoy@cc.umanitoba.ca

Qiang Zhang

Department of Biosystems Engineering, Faculty of Engineering
University of Manitoba, Winnipeg, Canada R3T 5V6

Marc Del Bigio

Department of Pathology, Faculty of Medicine
University of Manitoba, Winnipeg, Manitoba Canada R3E 3P5

Abstract

In this paper, recent progress on application of the Finite Element Method (FEM) in the study of non-penetrating human brain injuries is reviewed and classified under a framework. Unresolved issues and possible solutions are discussed.

Keywords: Finite Element Method, Non-penetrating Brain Injury, Coup-Contrecoup Injury

1 Introduction

Brain injury is a major cause of death in many accidents, especially in traffic accidents. According to a survey done in 2001 by Injury Surveillance, Health Canada and Road Safety, Transport Canada, based on data from ten industrial countries, the average deaths per billion vehicle kilometres travelled is 8.6. That means nearly every one minute one person is killed by traffic accident in this world. This number is still rising despite increased use of protective devices such as seat belts, airbags, safety helmets, etc. Approximately 70% of the death was due to brain injury. Brain injuries can be roughly classified into penetrating (or fractured) [40] and non-penetrating (or non-fractured) [17]. As pointed out by Goldsmith [13] and confirmed by clinical findings, skull fracture may occur with or without brain damage, and brain damage may ensue without any damage to the skull. This may explain why the death rate is still high even with the use of protective device. Protective device such as a helmet may provide an effective protection from penetrating injury, but it may have much less effect on non-penetrating injury.

The mechanism of non-penetrating injury is much more complicated than that of penetrating injury. It is determined by the complexity and the fine anatomical structure of human brain, Fig. 1. Roughly speaking, human brain consists of a hard skull, brain tissue and cerebrospinal fluid. The brain tissue contains vasculature and nerve net. Brain tissue is much more fragile than the skull and it is loosely connected and coupled to the skull. From the point view of mechanics, the hard skull may provide effective protection against static forces; The skull and the cerebrospinal fluid may act as damping materials and absorb a certain amount of kinetic energy induced by an impact. Nevertheless, a portion of the kinetic energy may still transmit into brain tissue through the skull and the cerebrospinal fluid. For the difference in mechanical properties of the skull and the brain tissue, the motion of brain issue will lag behind that of the skull. It is generally believed that it is this type of relative motion that cause damages in brain tissue.

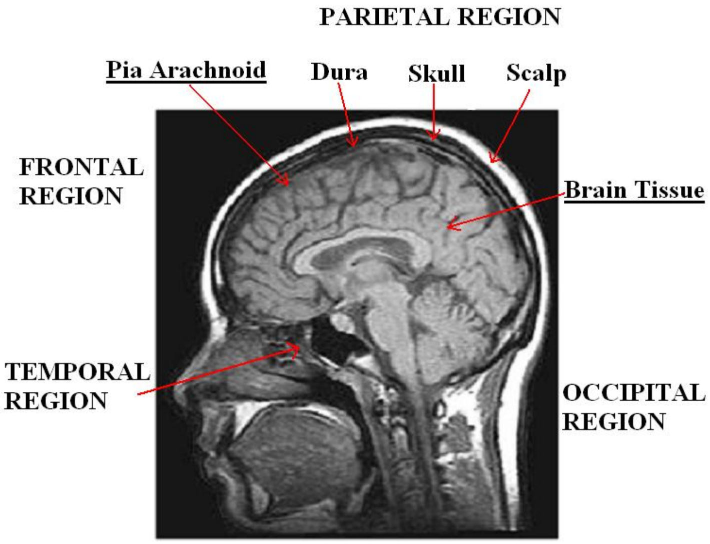


Figure 1: MRI image of human brain

Great progress has been made in preventing human brain from penetrating injuries. In recent years, the research focus has been shifted on to non-penetrated injuries. Research objectives have been mainly focused on the following aspects:

- For a given impact, predict the response of human head, including deformation of the skull, the maximum pressure and maximum stress, especially shear stress in the brain tissue [2, 9];
- To establish and to improve head injury criterion (HIC) [54];
- To design protective device to more effectively prevent non-penetrated brain injuries [6, 30, 60];
- To diagnose injury or pathological change in human brain in a non-invasive way;

Adopted research methodologies and tools mainly include: analytical methods [7], physical experiments [35], and numerical simulations [10, 12]. There are basically two analytical models. One is the lumped-mass system connected by springs and dashpots; The other is the continuum systems with simplified geometries and material properties. Some tissues are omitted to reduce complexity. Due to the adopted simplifications, an analytical model can only provide some conceptual and qualitative insight into brain injury. Physical experiment has been a commonly used tool in investigating human brain injuries. Due to safety and humanity reasons, physical experiment has not be allowed to conduct on living human body. Therefore, animals, human cadavers and inanimate physical models [14] have been used in physical experiments. For the new legislation of animal protection, live animal experiment is even now prohibited. Fortunately, in recent years with the great advances in computer capacity and in various computational methods, numerical simulation typically represented by Finite Element analysis has been becoming a more and more powerful tool complementary to physical experiment. Even without accurate geometric information and reliable material properties, numerical simulation is still helpful to investigate mechanical mechanisms involved in brain injury, and the number of required physical experiments can be largely reduced. The Finite Element Method has been successfully applied in the simulation of penetrating brain injuries and the produced data have been used in the design of helmet and other safety devices for head protection. The Finite Element Method can play an even more important role in revealing mechanical mechanisms of non-penetrating brain injuries.

The comprehensive survey conducted in [13, 14] set up a milestone for head injury biomechanics. Since then some progress has been made, especially in numerical simulation of brain injury. In this paper, only research on application of the Finite Element Method in investigating non-penetrating brain injury is reviewed. Although effort has been made to include all relevant information appeared in recent years, for the large volume of research conducted in this field, some important information may still not be included in the references. We apologize for any of such omissions.

2 Classification of recent research under a framework

For the variety of research work that has been done, it is favourable to classify them under a framework. There may be other ways for the classification, the input-system-output framework shown in Fig. 2 is used in this paper. In this framework, there are basically three major components involved in brain injury: excitation, human brain and response. The excitation can be an impact or non-contact acceleration (or deceleration). From the point of view of mechanics, the human head is considered as an isolated free body with support conditions from the neck and other safety constraints, and represented by a geometric model and a set of material parameters. The mechanical responses of the human brain under an excitation include deformation of the head, stress and strain distributions in the skull and in the brain tissue, natural frequencies, wave impedance [49], etc.

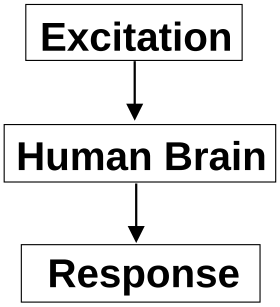


Figure 2: Response of human brain to accident excitation

Under the above framework, the relevant researches and their potential applications are classified into three categories:

- **Analysis and prediction**: For problems in this category, all geometrical information and material parameters related to human head are assumed known, excitation conditions are also provided, responses of human head are to be found. Based on the responses, potential injuries are evaluated.

- **Injury diagnosis:** A representative problem in this category is defined as follows: due to injury or pathological reason, there is some kind of change in brain tissue but the skull is still in a good condition. In clinic it is highly desired that the change can be diagnosed using a non-invasive way. To that end, a specific known excitation is applied and corresponding responses are collected by a non-invasive technique. The responses are then analyzed and compared with responses under normal conditions to evaluate the change. One example is the measurement of intracranial pressure (pressure within the brain). By applying a tolerable excitation and measuring natural frequencies or wave impedance, the pressure can be obtained without any damage to the skull.

- **Impact identification:** A typical problem in this category is defined as: the geometrical and material parameters of human head are known, the responses of human brain are somehow also measured, the aim is to find out the injury causation. One application of the above research is in the area of criminal investigation.

Several advances on application of FEM in study of non-penetrating brain injury have been made in recent years. Under the above framework, recent progress is classified and reviewed in the following.

2.1 Excitations

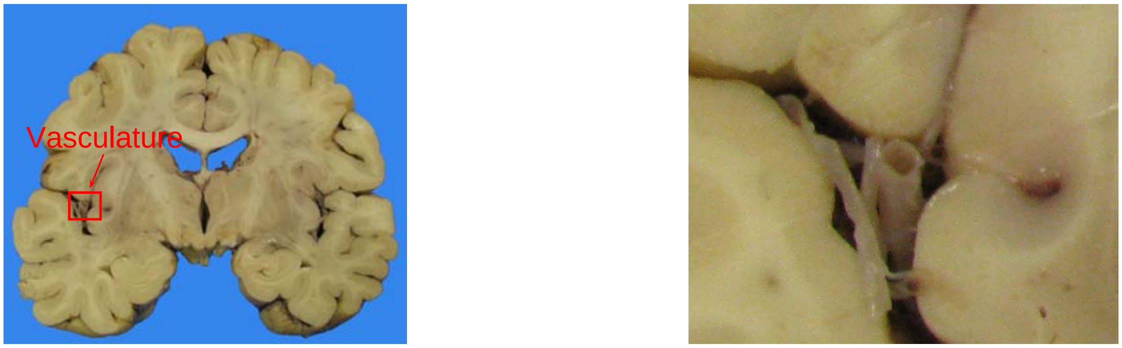
For the variety and complexity of excitations involved in human brain injuries, they may be described and classified in different way using different criterion. For example, excitations can be identified as static or dynamic. Dynamic excitations such as impacts are more often encountered in accidents. Or, excitations can be grouped into contacted [16, 15] and non-contacted [17]. In a contacted excitation, kinetic energy is transferred from an object having large momentum onto the head by a contact; Non-contacted excitation may be induced by acceleration or deceleration. Contacted excitations can be further described by its action location, direction, duration, the shape of the object, etc. The main objective of research on excitations is to find out the most dangerous case. It was found in recent research [1, 29], mainly by numerical simulations, that rotational impulse and rotational acceleration (or deceleration) may cause more severe damage to brain tissue.

2.2 Physical model

To uncover mechanical mechanism of brain injuries, the entire head must be studied under the theories of mechanics. For that purpose, a physical model must be established [34]. In mechanics, a physical model usually consists of a geometrical model or geometric domain, a distribution of material parameters over the geometrical domain, appropriate boundary conditions and excitation(s). The last one has been described in the previous section. The rest are reviewed in the following.

2.2.1 Geometric model

Acquisition of geometrical model of human head is a necessary step for a quick and realistic finite element modeling. The geometrical model is a base for the generation of a finite element mesh. Furthermore, the geometrical model is also a base for defining and associating material parameters. One big advance in recent years is the availability of various medical imaging technologies such as magnetic resonance imaging (MRI), computed tomography scanning (CT), ultrasonic imaging techniques (UI), etc., for constructing geometrical model of human head [3, 5, 26, 32, 37, 42, 44, 48, 53]. The complexity of a human head geometrical model comes from two aspects: one is the complex geometric structure of the bone; the other is the complexity of brain anatomy, which can be appreciated from a slice of the brain shown in Fig. 3 and the zoom-in structure around vasculature.



(a) (b)

Figure 3: Anatomy of human brain: (a) a slice, (b) zoom-in around vasculature

2.2.2 Material model

Attainment of accurate mechanical properties of the various materials of human head may be the most challenging task in numerical simulation, for the complexity in material composition and for the many factors affecting their properties. The constituents of human head are in multiple phases: solid, fluid and visco-elastic tissue. The skull and the tissue are also inhomogeneous and anisotropic. The layers consisting of the scalp, the skull, the dura and the pia-arachoid membranes form a natural protection to the inner soft brain tissue [27, 28, 47]. Even for the solid materials, their mechanical properties are very different. The skull is the hardest part, while the pia-arachoid membranes are much softer. Different liquid substances exist in human head, blood, water, cerebrospinal fluid, etc. These liquids have different viscosity and density. The brain tissue is basically visco-elastic, but its mechanical properties are even more complex for the inclusion of vasculatures and nerves [20]. On the other hand, material properties of human head are affected by many factors. First of all, there are big differences between a living body and a cadaver in their material properties. Even for living body [39], its material properties are affected by age [11, 35], gender, ethnic group, etc. Furthermore, the obtained material properties are influenced by test conditions such as experiment equipment [22], loading rate [38], temperature [43], etc. Recent progress on acquisition of material properties of human head include measurement of local material properties using non-invasive technique, e. g. the ”wave-in-a-tube” technique [33], and the availability of atomic force microscope indentation [4] for measuring material properties at micro and even nano scale.

2.3 Responses

Effects or responses caused by a non-penetrating impact on human head can be roughly divided into two categories. The first category includes the instantaneous mechanical responses such as skull deformation [59], stress and strain distribution [45, 46], pressure wave, etc. The other group consists of sequelae caused by the mechanical responses, e. g. change in intercranial pressure, damage of vasculature, coup and contrecoup brain contusion, etc. The correlation between mechanical responses and sequel effects is still not fully understood. For example, there are at least two theories developed for interpreting coup and contrecoup brain contusion. One is the shear strain theory advocated by Holbourn [21]; The other is the cavitation theory proposed by Gross [18]. Their limitations will be discussed later in Section 3. Obviously, acquisition of mechanical responses such as stress distribution in brain is a very important step to explore mechanisms of various brain injuries. Nevertheless, it is extremely difficult to obtain these mechanical data, especially from a living body, for their spatial variation, time dependence and limitations of currently available instruments.

2.4 Finite element model

Physical experiment and numerical simulation are two mutually complementary tools for investigating mechanisms of brain injuries. With more and more knowledge accumulated on material properties of human head, the role of numerical simulation is becoming more and more prominent. A finite element model is established based on the physical model described in Sub-sections 2.2. To reduce the required number of degrees of freedom (DOF), the head is usually considered as a separated free body in finite element simulation, with proper boundary conditions from the neck [31, 56, 57]. Finite element models have been advanced from two dimensional [51] to three dimensional [36, 52, 58, 61], from single-phase to multi-phase material model, from simple models considering only skull to more complicated ones consisting of both skull and brain tissue [62]. Early finite element models mainly concentrated on the skull [19, 41], the inner brain was completely ignored or simplified as liquid. More advanced finite element models were developed in recent years by approximating brain tissue as viscoelastic materials [39]. As assumptions and simplifications are introduced in a finite element model, validation of finite element model against original physical model is a necessary step before finite element results can be used for clinical purpose [24, 25, 50, 55]. Validation of finite element model has been done mainly against dummy model or cadaver. There are still a lot of challenges to validate finite element model against living body.

3 Major Unresolved Issues and Future Work

Although advances have been made in recent years in applying the FEM to study various brain injuries, especially in helping understand mechanisms of non-penetrating brain injuries, there are still a lot of issues to be resolved before finite element simulation can help in a clinical room. There are various challenges, what discussed in the following are those issues that must be first resolved before the rest can be swept out.

3.1 Issues of material model

Despite the fact that a large amount of research effort has been devoted to the understanding and acquisition of material properties of human head, the obtained knowledge is still in pieces. Further research has to be done to obtain an integral picture about the material properties, especially on the following issues:

- Living material properties were mainly obtained from animal experiments. For the essential differences in species, it is not reliable to extend and map the data to human being.

- Material properties of human head were mainly acquired from experiments on cadaver that is very different from living human body.

- Material properties were obtained from macro scale, which might not be adequate for studying injuries happening at micro scale, e. g. damage of brain blood capillary by an impact.

- Dependence of head material properties on age, gender, ethnic group, etc., is not well understood and modeled.

- Material properties of human head constituents, skull, dura, brain, blood vessel, cerebrospinal fluid, blood, etc., were investigated individually. They were not studied in their natural conditions. The interactions between the constituents are still not understood, which is crucial to simulate the propagation of stress waves in the brain.

It is highly desired that a technique or instrument can be developed to collect material property data from individual patients in an inharmful and quick way. The collected data are then processed and a material model is esteblished for finite element simulation. One possibility in this direction is the use of ultrasonic image, as the propagation, reflection and scattering of ultrasonic waves in solid media is closely related to the mechanical properties of the media.

3.2 Issues of finite element model

A common misunderstanding about finite element simulation is that once all the geometric representation and the material description of human head are accurately obtained, the rest solution of the problem can be completely left to a general purpose commercial software. The reality is that to make use of a general purpose finite element software, assumptions and simplifications have to be made on the geometric model and material descriptions to fit into the frame work of the software. For example, in the reported finite element simulations, blood vessels and nerves are simply excluded from the model, for inconvenience or difficulties in simulating these details. Nevertheless, fracture of blood vessel or damage in neural net is a major cause for death or for physiological sequelae. A desired finite element model is a one that is not only able to predict distribution of stresses and strains over the shull and the brain tissue, but also has the ability to zoom-in to capture local stress concentration around vasculature. Another issue is related to the compxity of material composition of human head. The material includes inviscid fluid, viscous fluid, very soft and viscous tissue, more solid tissue and very stiff skull, etc. A finite element model that is able to naturally incorporate all these materials and realistically consider interaction between them is still not available. Actually, the kinematics of these material ingredients should be described by different finite element formulations. The solid materials should be described by the

Lagrangian formulation, while the fluids are more appropriate to be represented by the Eulerian formulation. Furthermore, the Finite Element Method itself also has some issues to be resolved. For example, large local deformation may occur in brain tissue under impact. But it is well known that element distortion due to large deformation is still an issue that is not well resolved.

3.3 Issues on understanding mechanical mechanisms of brain injuries

Understanding mechanical mechanism of brain contusion is a very important step for designing effective devices to prevent or to alleviate brain injury. Some significant mechanical mechanisms of brain contusion have been revealed by studies in recent years. For example, it is generally agreed that acceleration and deceleration play an important role in brain injury. It was found that the cerebrospinal fluid provides an effective damping to translational impulses. But as a fluid can barely sustain any shear force, therefore, shear stresses and shear strains induced by a rotational impulse can easily cause damage to the bridging veins and lead to haemorrhaging and haematomas. Nevertheless, not all mechanical mechanisms of brain injury are well understood. One example is the coup and contrecoup brain contusion. Coup-contrecoup brain contusion can occur with or without skull fracture. The case shown in Fig. 4 is one with skull fracture. A strange phenomenon occurring in some coup-contrecoup brain contusions is that a bruise not only appears at the impact (coup) site but

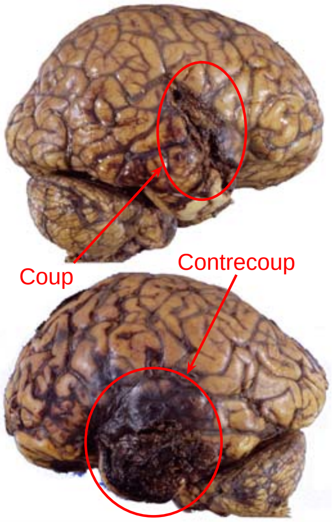


Figure 4: Coup and contrecoup brain injury

also on the opposite (contrecoup) site of the brain; Furthermore, the bruise on the opposite site may be even more severe. There are basically two theories available for interpreting this phenomenon, one is the shear strain theory [21], the other is the so-called cavitation theory [18]. The shear strain theory is based on the observation that the brain tissue is almost incompressible and has a very low shear modulus. Therefore brain bruises can more often occur at places where high shear strains are developed. Shear strain theory is highly supported by Chu [8] and Hunag [23]. By the cavitation theory, the phenomenon is explained as, when the brain is struck by an impulse, a positive pressure is produced on the coup side, and a negative pressure is generated on the contrecoup side. A bubble is developed due to the negative pressure. A sudden and violent collapse caused the contrecoup contusion.

However, it seems neither of them can satisfactorily explain the phenomenon. For the shear strain theory, the contradiction is that high shear strain is more possibly developed when a rotational impulse is applied; However, in clinic it is more often observed that coup-contrecoup brain contusions are related to translational rather than rotational impulses. The case shown in Fig. 4 was quite probably due to a translational impulse. The impact action line is approximately through the mass center. Therefore, a large rotational acceleration was not likely to develop. For the cavitation theory, the required negative pressure for the bubble to collapse is thousands time higher than what has been observed in clinic or simulated by the Finite Element Method [28]. Furthermore, both of the theories can not explain why the injury severity at the contrecoup side is higher than that at the coup side, cf Fig 4. A more convincing mechanism has to be explored.

References

[1] M. Aare and S. Kleiven. Evaluation of head response to ballistic helmet impacts using the finite element method. *International Journal of Impact Engineering*, 34:596 – 608, 2007.

[2] A. Al-Bsharat, C. Zhou, K. H. Yang, T. Khalil, and A. I. King. Intracranial pressure in the human head due to frontal impact based on a finite element model. *American Society of Mechanical Engineers, Bioengineering Division (Publication) BED*, 42:113 – 114, 1999.

[3] M. Beek, J. Koolstra, L. van Ruijven, and T. van Eijden. Three-dimensional finite element analysis of the human temporomandibular joint disc. *Journal of Biomechanics*, 33:307 – 316, 2000.

[4] K. D. C. B. M. I. Benjamin S. Elkin, Evren U. Azeloglu. Mechanical heterogeneity of the rat hippocampus measured by atomic force microscope indentation. *Journal of Neurotrauma*, 24:812–822, 2007.

[5] D. Bouattoura, P. Gaillard, P. Villon, and F. Langevin. Brain evoked potential topographic mapping based on the diffuse approximation. *Medical & Biological Engineering & Computing*, 36:415 – 421, 1998.

[6] D. L. Camacho, R. W. Nightingale, J. J. Robinette, S. K. Vanguri, D. J. Coates, and B. S. Myers. Experimental flexibility measurements for the development of a computational head-neck model validated for near-vertex head impact. In *Stapp Car Crash Conference Proceedings*, pages 473 – 486, Lake Buena Vista, FL, USA, 1997.

[7] H. S. Chan. Mathematical model for closed head impact. *Rand Corporation, Reports*, pages 557 – 578, 1974.

[8] C.-S. Chu, M.-S. Lin, H.-M. Huang, and M.-C. Lee. Finite element analysis of cerebral contusion. *Journal of Biomechanics*, 27:187 – 194, 1994.

[9] G. Dassios, M. Kiriakopoulos, and V. Kostopoulos. On the sensitivity of the vibrational response of the human head. *Computational Mechanics*, 21:382–388, 1998.

[10] L. Dharani and F. Ji. Dynamic analysis of normal impact of occupant head on laminated glass. In *SAE Special Publications*, volume 1320, pages 49 – 54, Detroit, MI, USA, 1998.

[11] A. Gefen, N. Gefen, Q. Zhu, R. Raghupathi, and S. S. Margulies. Age-dependent changes in material properties of the brain and braincase of the rat. *Journal of Neurotrauma*, 20:1163–1177, 2003.

[12] M. Gilchrist and D. O'Donoghue. Simulation of the development of frontal head impact injury. *Computational Mechanics*, 26:229 – 235, 2000.

[13] W. Goldsmith. The state of head injury biomechanics: past, present, and future. Part 1. *Critical Reviews in Biomedical Engineering*, 29:441–600, 2001.

[14] W. Goldsmith and K. L. Monson. The state of head injury biomechanics: Past, present, and future. Part 2: Physical experimentation. *Critical Reviews in Biomedical Engineering*, 33:105–207, 2005.

[15] S. Gong, H. Lee, and C. Lu. Computational simulation of the human head response to non-contact impact. *Computers and Structures*, 86:758–770, 2008.

[16] S. W. Gong, H. P. Lee, and C. Lu. An approach for the estimation of contact force on a human head induced by a foreign-object impact. *IEEE Transactions on Biomedical Engineering*, 54:956–958, 2007.

[17] S. W. Gong, H. P. Lee, and C. Lu. Dynamic response of a human head to a foreign object impact. *IEEE Transactions on Biomedical Engineering*, 55:1226–1229, 2008.

[18] A. G. Gross. A new theory on the dynamics of brain concussion and brain injury. *J. Neurosurg.*, 15:548–561, 1958.

[19] C. Hardy and P. Marcal. Elastic analysis of a skull. *American Society of Mechanical Engineers (Paper)*, n 73-APMW-36:838842, 1973.

[20] J. Ho and S. Kleiven. Dynamic response of the brain with vasculature: A three-dimensional computational study. *Journal of Biomechanics*, 40:3006–3012, 2007.

[21] A. Holbourn. Mechanics of head injuries. *Lancet*, 2:438–441, 1943.

[22] M. Hrapko, J. A. W. van Dommelen, G. W. M. Peters, and J. S. H. M. Wismans. The influence of test conditions on characterization of the mechanical properties of brain tissue. *Journal of Biomechanical Engineering*, 130(031003), 2008.

[23] H.-M. Huang and M.-C. Lee. Three-dimensional finite element analysis of brain contusion. *Chinese Journal of Medical and Biological Engineering*, 15:127 – 141, 1995.

[24] O. Jirousek and J. Jira. Comparison of finite element and experimental simulation of human head response to impact. *VDI Berichte*, (1899):463 – 472, 2005.

[25] O. Jirousek, J. Jirova, and J. Jira. Development and validation of FE model of human head in frontal impact. In *Proceedings of the Fourth IASTED International Conference on Biomechanics*, page 6 pages, Palma de Mallorca, Spain, 2006.

[26] E. Johnson and P. Young. On the use of a patient-specific rapid-prototyped model to simulate the response of the human head to impact and comparison with analytical and finite element models. *Journal of Biomechanics*, 38:39 – 45, 2005.

[27] T. Khalil and D. Viano. Impact response of a viscoelastic head model. In *The 30th Annual Conference on Engineering in Medicine and Biology (papers in summary form only received)*, pages 234 – 238, Los Angeles, CA, USA, 1977.

[28] T. B. Khalil and D. C. Viano. Critical issues in finite element modeling of head impact. In *Proceedings of Stapp Car Crash Conference*, pages 87 – 102, Ann Arbor, Mich, USA, 1982.

[29] S. Kleiven. Evaluation of head injury criteria using a finite element model validated against experiments on localized brain motion, intracerebral acceleration, and intracranial pressure. *International Journal of Crashworthiness*, 11:65 – 79, 2006.

[30] K. Kormi and R. Etheridge. Application of the finite-element method to simulation of damage to the human skull as a consequence of missile impact on

a multi-layered composite crash helmet. *Journal of Biomedical Engineering*, 14:203 – 208, 1992.

[31] A. Kuijpers, M. Claessens, and A. Sauren. A two-dimensional FEM analysis of the response of the human head to impact: the importance of boundary conditions. In *Computer Methods in Biomechanics and Biomedical Engineering*, pages 207 – 216, Swansea, UK, 1996.

[32] R. Lapeer and R. Prager. 3D shape recovery of a newborn skull using thin-plate splines. *Computerized Medical Imaging and Graphics*, 24:193 – 204, 2000.

[33] S. A. Lippert, E. M. Rang, and M. J. Grimm. The "wave-in-a-tube" technique to determine material properties of brain tissue and other gel-like solids. *Advances in Bioengineering*, 50:313–314, 2001.

[34] A. Lovas. Mechanical models of the human skull brain system. *Acta Technica Academiae Scientiarum Hungaricae*, 107:83 – 98, 1995-1996.

[35] S. Margulies and K. Thibault. Infant skull and suture properties: measurements and implications for mechanisms of pediatric brain injury. *Transactions of the ASME. Journal of Biomechanical Engineering*, 122:364 – 371, 2000.

[36] B. V. Mehta and S. Rajani. 3D modeling and analysis of human bones: generating 3D models to accommodate varying material properties for finite element analysis. In *American Society of Mechanical Engineers, Petroleum Division (Publication) PD*, volume 77, pages 117 – 125, Montpellier, Fr, 1996.

[37] B. V. Mehta, S. Rajani, and G. Sinha. Comparison of image processing techniques (magnetic resonance imaging, computed tomography scan and ultrasound) for 3D modeling and analysis of the human bones. *Journal of Digital Imaging*, 10:203 – 206, 1997.

[38] K. Miller and K. Chinzei. Mechanical properties of brain tissue in tension. *Journal of Biomechanics*, 35:483–490, 2002.

[39] K. Miller, K. Chinzei, G. Orssengo, and P. Bednarz. Mechanical properties of brain tissue in-vivo: experiment and computer simulation. *ournal of Biomechanics*, 33:1369–1376, 2000.

[40] A. Mota, W. Klug, M. Ortiz, and A. Pandolfi. Finite-element simulation of firearm injury to the human cranium. *Computational Mechanics*, 31:115 – 121, 2003.

[41] R. Nickell and P. Marcal. In vacuo model dynamic response of the human skull. *Journal of Engineering Industry*, 4:490–494, 1974.

[42] M. K. Ozdemir, H. S. Savci, J. R. Mautz, and E. Arvas. A new FEM formulation for electromagnetic source imaging of the brain using realistic head models. *Applied Computational Electromagnetics Society Journal*, 19:1 – 9, 2004.

[43] E. M. Rang, S. A. Lippert, and M. J. Grimm. The degradation of the material properties of brain tissue as a function of time postmortem. *Advances in Bioengineering*, 50:887–888, 2001.

[44] D. Remmler, L. Olson, R. Ekstrom, D. Duke, A. Matamoros, D. Matthews, and C. G. Ullrich. Pre-surgical CT/FEA for craniofacial distraction: I. methodology, development, and validation of the cranial finite element model. *Medical Engineering & Physics*, 20:607 – 619, 1998.

[45] J. Ruan, T. Khalil, and A. King. Human head dynamic response to side impact by finite element modeling. *Journal of Biomechanical Engineering, Transactions of the ASME*, 113:276 – 283, 1991.

[46] J. Ruan and P. Prasad. Skull isostress and brain isostrain responses of a finite element human head model. In *American Society of Mechanical Engineers, Bioengineering Division (Publication) BED*, volume 29, pages 319 – 320, Beever Creek, CO, USA, 1995.

[47] S.-J. Ruan, X.-K. Wang, W.-L. Liu, and H.-Y. Li. Study on the sensitivity of cranial materials and their responses to the infrancranial pressure during head impact. *Chinese Journal of Biomedical Engineering*, 23:252 – 258, 2004.

[48] S. Takahashi, D. Imai, Y. Tanikawa-Takahashi, and Y. Yamada. Fundamental 3D FEM analysis of light propagation in head model toward 3D optical tomography. volume 2979, pages 250 – 260, San Jose, CA, United States, 1997.

[49] C. Towers, H. McCann, M. Wang, P. Beatty, D. Poinfrett, and M. Beck. 3D simulation of EIT for monitoring impedance variations within the human head. *Physiological Measurement*, 21:119 – 124, 2000.

[50] F. Turquier, H. S. Kang, X. Trosseille, R. Willinger, F. Lavaste, C. Tarriere, and A. Domont. Validation study of a 3D finite element head model against experimental data. In *Stapp Car Crash Conference Proceedings*, pages 283 – 294, Albuquerque, NM, USA, 1996.

[51] K. Ueno, J. W. Melvin, M. E. Rouhana, and J. W. Lighthall. Two-dimensional finite element model of the cortical impact method for mechanical brain injury. In *American Society of Mechanical Engineers, Applied Mechanics Division, AMD*, volume 126, pages 121 – 154, 1991.

[52] L. Voo, F. Kumaresan, S.; Pintar, N. Yoganandan, and A. J. Sances. Finite-element models of the human head. *Medical & Biological Engineering & Computing*, 34:375–381, 1996.

[53] C. Wang, R. Liu, F. Fu, F. You, X. Shi, and X. Dong. Image reconstruction for magnetic induction tomography and preliminary simulations on a simple head model. In *29th Annual International Conference of IEEE-EMBS, Engineering in Medicine and Biology Society, EMBC'07*, pages 4406 – 4409, Lyon, France, 2007.

[54] R. Willinger and D. Baumgartner. Numerical and physical modelling of the human head under impact - towards new injury criteria. *International Journal of Vehicle Design*, 32:94 – 115, 2003.

[55] R. Willinger, H.-S. Kang, and B. Diaw. Three-dimensional human head finite-element model validation against two experimental impacts. *Annals of Biomedical Engineering*, 27:403 – 410, 1999.

[56] A. Wittek and K. Omori. Parametric study of effects of brain-skull boundary conditions and brain material properties on responses of simplified finite element brain model under angular acceleration impulse in sagittal plane. *JSME International Journal, Series C: Mechanical Systems, Machine Elements and Manufacturing*, 46:1388 – 1399, 2003.

[57] J.-K. Yang, W. Xu, and X.-M. Wan. Development and validation of a head-neck finite element model for the study of neck dynamic responses in car impacts. *Journal of Hunan University Natural Sciences*, 32:6 – 12, 2005.

[58] K. H. Yang and A. I. King. A limited review of finite element models developed for brain injury biomechanics research. *International Journal of Vehicle Design*, 32:116–129, 2003.

[59] X. Yue, L. Wang, and F. Zhou. Strain analysis on the superficial surface of skull as intracranial pressure changing. *Journal of University of Science and Technology Beijing*, 28:1143 – 1151, 2006.

[60] G.-F. Zhao, X.-Q. Zhang, and X.-W. Du. Head and engine hood impacting injury simulation. *Journal of Harbin Institute of Technology*, 35:719 – 722, 2003.

[61] Z. Zonga, H. Leeb, and C. Lub. A three-dimensional human head finite element model and power flow in a human head subject to impact loading. *Journal of Biomechanics*, 39:284–292, 2006.

[62] H. Zou, S. Kleiven, and J. Schmiedeler. The effect of brain mass and moment of inertia on relative brain-skull displacement during low-severity impacts. *International Journal of Crashworthiness*, 12:341 – 353, 2007.

Received: July 24, 2008