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TECHNICAL NOTE

Finite element analysis of impact and shaking inflicted to a child

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Abstract This study compares a vigorous shaking and an inflicted impact, defined as the terminal portion of a vigorous shaking, using a finite element model of a 6-month-old child head. Whereas the calculated values in terms of shearing stress and brain pressure remain different and corroborate the previous studies based on angular and linear velocity and acceleration, the calculated relative brain and skull motions that can be considered at the origin of a subdural haematoma show similar results for the two simulated events. Finite element methods appear as an emerging tool in the study of the biomechanics of head injuries in children.

Keywords Child abuse · Finite element head model · Forensic medicine · Shaken baby syndrome

Introduction

The "shaken baby syndrome" is the leading cause of death or serious neurological injury resulting from child abuse. Injuries that characterize the shaken baby syndrome are subdural haemorrhage and retinal haemorrhage. For the past 20 years, child head injury biomechanics have been studied through the evaluation of rotational and linear velocities and acceleration. When comparing a shaking event with an impact, the results have shown significant differences. In addition to these global parameters, other biomechanical parameters have to be taken into account for a complete evaluation of the injury mechanisms. Brain injury can be caused either by vigorous shaking, by a shaking followed by an impact on a soft or hard surface or by direct blows to the head. Vigorous shaking will initiate for a certain frequency a relative motion of the brain and skull, tearing the bridging veins that extend from the cortex to the dural venous sinus and leading to a subdural haematoma. Vigorous shaking can also cause neck injuries, and the younger is the child, the greater is the effect of force exerted during shaking. Injuries to the neck will be either articular or ligamental injuries of the cervical spine as well as injuries to the spinal cord. When a significant amount of force is applied on the neck, apnoea and breathing problems will be the major clinical signs. In the other case, seizure or less specific signs, such as irritability, vomiting or lethargy, will dominate the clinical presentation. Since the article by Guthkelch in 1971, who postulated that a subdural haematoma as a feature of the "battered child syndrome" could be caused by shaking, biomechanical studies of falls, shakes or inflicted impacts to children have been widely described and studied in the literature especially for the past 20 years [1–5]. Studies using dummies or analytical models have compared child head injuries as a function of angular and linear acceleration, but this scientific approach is insufficient when the local behaviour of biological tissues must be taken into account. To evaluate the consequence of head injuries with a maximum biofidelity, finite element models are by far the most reliable tools. Finite element models have been recently used to investigate adult head injuries in forensic cases [6–8]. Whereas more than ten

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different three-dimensional finite element models of the adult head exist in the literature, very few finite element models of the child head have been developed. This is mainly due to the difficulties in validating such models against experimental data. However, child head material properties have been studied and are available in the literature [9–12]. In the present paper, we developed a 6-month-old child head model and simulated a vigorous shake and an inflicted impact, defined as the terminal portion of a vigorous shake, to study their consequences in terms of intracerebral pressure, shearing stress and relative motion of brain and skull. The aim of this paper is not to establish new pediatric injury criteria but to use a new finite element model to compare intracerebral mechanical response under two different loading conditions.

Materials and methods

The head of a child cannot be considered as a “small-scale model” of an adult. Therefore, the present study proposes a finite element model using computed tomography (CT) scan slices of a representative 6-month-old child who underwent a radiological examination after minor head trauma. Meshing was performed using the Hypermesh code (Altair Hyperworks 7.0 software, Michigan, USA). The main anatomical features modelled were the skull, tentorium, fontanels, falx, cerebro-spinal fluid (CSF), scalp, cerebrum and cerebellum. The finite element mesh is continuous. Falx, tentorium, fontanels, sutures and skull were simulated with one layer of shell elements; brain, CSF and scalp were modelled with brick elements. Bridging veins were modelled with springs. Globally, the model consists of 69,324 brick elements and 9,187 shell elements.

Material properties were taken from the literature, where several studies have been carried out on cranial sutures, cranial bone and brain [9–11, 13, 14]. In 1998, Thibault and Margulies [12] reported the mechanical properties of a porcine brain to find age-dependence in comparing visco-elastic properties of 1-year-old pigs (similar to a 4-year-old child) to those of 2- to 3-day-old pigs (similar to a 1-month-old human). They established a viscoelastic law that is used for paediatric brain models. Mechanical properties of the scalp, the CSF and the membranes (tentorium and falx) are issued from the adult finite element model and have already been published [7]. For the skull, fontanels and sutures, the material properties were taken from Margulies and Thibault [10]. The face is considered as a part of the skull and has the same constitutive law. Figure 1 shows the three-dimensional finite element model, and Table 1 summarizes the material properties.

Simulation of both inflicted impact and vigorous shaking is based on the work reported by Prange et al. [3] who recorded the angular velocity of the head of a dummy

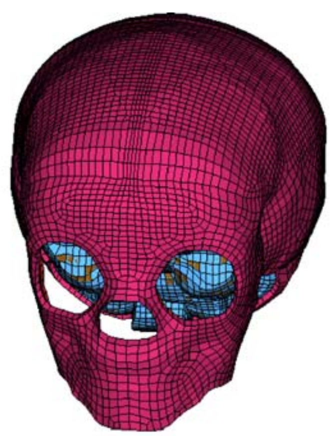


Fig. 1 Finite element model of a 6-month-old infant head

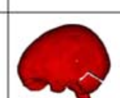
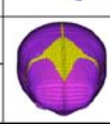
Tissue	Element type	Constitutive law		Tissue	Element type	Constitutive law	
Brain	Brick	Viscoelastic		Subarachnoid space	Brick	Elastic	
Membranes (Tentorium and falx)	Shell	Elastic		Facial bone	Shell	Elastic	
Skull	Shell	Elastic		Scalp	Brick	Elastic	
Fontanel and sutures	Shell	Elastic					

Table 1 Material properties of the 6-month child head model

	Young modulus (MPa)	Poisson's ratio	Density (kg/m^3)	References
Membranes	31.5	0.45	1,140	Zhou et al. [24]
CSF	0.012	0.49	1,040	Willinger and Taleb [25]
Scalp	16.7	0.42	1,200	Zhou et al. [24]
Skull	2,500	0.22	2,150	Margulies and Thibault [10]
Sutures and fontanels	1,500	0.22	2,150	
Brain	$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$, where $G_0 = 5.99 \times 10^{-3}$MPa, $G_\infty = 2.32.10^{-3}$MPa and $\beta = 0.09248$ s^{-1}, with a bulk modulus of K=2,110 MPa			Thibault and Margulies [12]

submitted to these loadings. They performed several tests with perpetrators of different height and strength. Their experiments consisted of a shaking event followed by an inflicted impact on a concrete surface.

The simulation of the vigorous shake consists of one cycle extracted from Prange et al.'s experiments. The input of the vigorous shake lasts one cycle of the angular velocity curve as shown in Fig. 2 and is applied at the centre of rotation of the system, which is assumed to be located at the C5–C6 junction according to Swischuk [15].

For the simulation of inflicted impact, the input consisted of a linear velocity of 3 m/s against a rigid wall.

Intracerebral pressure and shearing in terms of Von Mises stress were computed throughout the brain. The CSF layer allows a relative motion of the brain and skull under dynamic loading. In the present study, relative displacement in the sagittal plane was computed to evaluate elongation of the bridging vein.

The strain of the bridging veins is a function of the initial and final lengths as illustrated in the following equation:

$$\varepsilon = \frac{l - l_0}{l_0} \qquad (1)$$

where ε represents the strain and l and l_0 are the length and initial length, respectively.

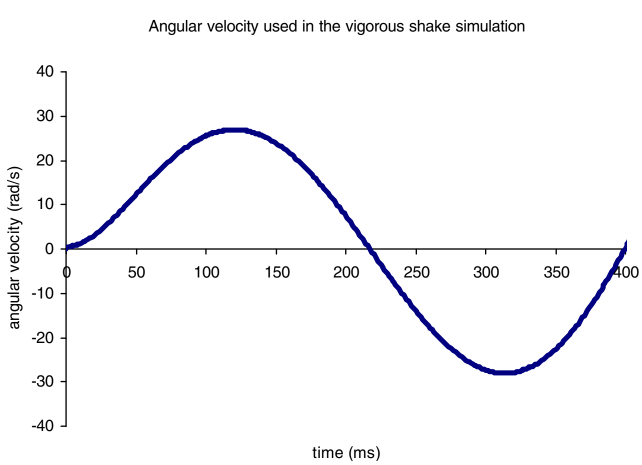


Fig. 2 Representative angular velocity of a shaking event

Results

For the inflicted impact simulation, maximum Von Mises stress was located in the occipital region and reached 14 kPa for an initial linear velocity of 3 m/s. In the vertex area, the stress reached 10 kPa.

Like Von Mises stress, maximum pressure was located in the impact area, and the computed value was 80 kPa. The minimum pressure was located in the frontal area for the contre-coup and reached −120 kPa.

Finally, the computed maximum bridging vein strain occurred at the time of 6 ms after the impact and reached 100%.

For the shaking simulation, the maximum calculated Von Mises stress was 3.2 kPa and was located in the vertex area. For the pressure, a maximum of 22 kPa located in the frontal area was observed.

Moreover, the maximum strain of the bridging veins reached 90% and occurred at the time of 140 ms after the beginning of the shaking motion.

Comparison of intracranial mechanical response under both loading conditions (shaking and impact) clearly showed that brain pressure and shearing stresses are significantly lower for shaking than for an impact as illustrated in Figs. 3 and 4. However, for brain–skull relative motion, the conclusions are different. Results illustrated in Fig. 5 show that the maximum strain value of the bridging veins is equivalent for shaking and for an impact. These results are in accordance with values found by Lee and Haut [16]. The rupture of a bridging vein can occur in both a shaking event and an inflicted impact, leading to the formation of a subdural haematoma.

Discussion

For the last two decades, the biomechanical evaluation of child head injury has been based on the comparison of angular and linear acceleration and velocity. Duhaime et al. [2] and Prange et al. [3] found a peak of angular and linear acceleration and velocity very different for inflicted impacts and shaking events using a dummy model. This led to the

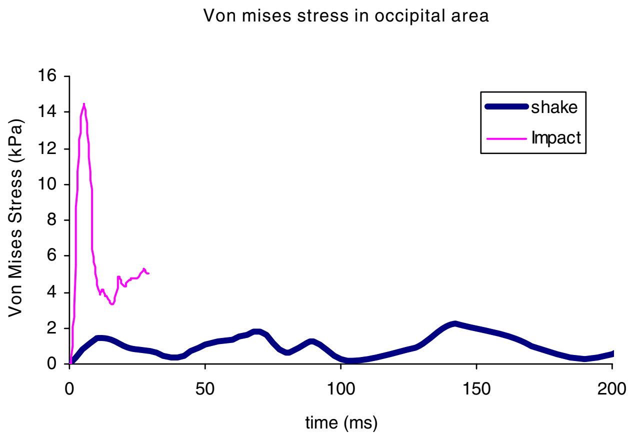


Fig. 3 Von Mises stress in the occipital area for the inflicted impact and the shaking event

idea that what was supposed to be a shaking event was in fact a shaken–impact event, and what was called the *whiplash shaken infant syndrome* by Caffey [17] would be an inappropriate description and should better be called *shaking impact syndrome*. This idea has recently been reinforced by Bandak [5] who tried to demonstrate that the force involved for creating intracranial injuries by shaking a baby exceeds the limit for failure of the spine.

The use of β-amyloid precursor protein, the most reliable marker of axonal damage, has recently helped to distinguish between hypoxic and traumatic axonal injury [18, 19]. These works have demonstrated that in cases of violent shaking, the initial brain injury is caused by hypoxia. Hypoxia is caused by respiratory difficulties such as apnoea, which is a usual presentation in cases of shaking

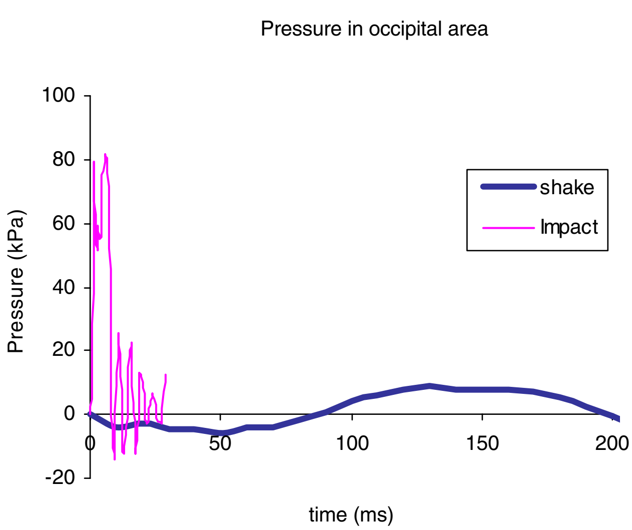


Fig. 4 Pressure in the occipital area for the inflicted impact and the shaking event

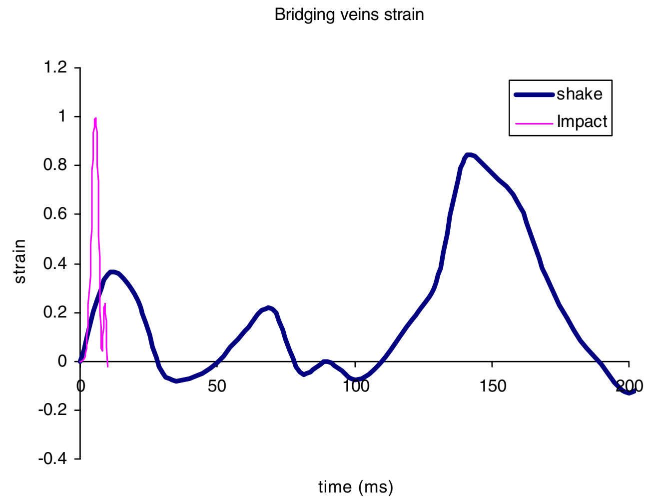


Fig. 5 Bridging veins strain evaluation as a function of time for a shaking event and an inflicted impact

events. It is obvious that the primary lesion in cases of shaking leading to apnoea is a cervical spinal cord injury because the infant spine is immature, giving no protection to a whiplash event. It is of major importance to distinguish between two clinical presentation entities after a shaking event. The first is encountered when the child is very young and/or the perpetrator is very strong. In this case, the spinal injury is the *prime cause* leading to apnoea and hypoxic axonal injuries and accompanied by a subdural haematoma. The second is dominated by the consequence of the subdural bleeding leading to seizure and possible raised intracranial pressure, ischaemia and hypoxic axonal injury. In these two clinical presentations, a subdural haematoma and retinal haemorrhage can be encountered.

Finite element models allow the dynamic response of the brain and skull to different forces to be understood. The finite element method is used in biomechanics especially of the adult head for which different finite element models have been developed for 30 years. Recently, research interests in child head modelling appeared, but very few models have been proposed [13, 20–22]. De Santis Klinich and Hulbert [22] developed a finite element model of a 6-month-old child to simulate different accidental load cases (real-world cases) and to compute stress distribution. Their finite element model is based on a 27-week-old child geometry. Scalp, skull and sutures were modelled as shell elements, whereas brain, dura and CSF were modelled as solid elements. The face was modelled as a rigid body. They investigated the tolerance to skull fracture, studying the role of cranial suture. They found a negligible effect of sutures and correlated the response of the model in terms of deformation and stress distribution with the severity of the real-world cases. Prange and Kiralyfalvi [23] studied the influence of mechanical properties, geometry and loading of the brain by creating a finite element model of a mid-coronal slice of the brain and skull. The geometry was obtained from a 2-week-old infant, and the adult model was obtained by scaling up the child's geometry. The aim of the study was to determine the influence of brain size and mechanical properties on pediatric inertial injuries, running several simulations to see the influence of those parameters (size and material laws).

We developed a realistic finite element model using CT scan slices and used to simulate a vigorous shaking and an impact. The difference in the values obtained in terms of Von Mises stress and pressure is obvious and higher for an inflicted impact than for a shaking event. In adult head injury cases, Von Mises stress and pressure have been correlated to severe traumatic neurological injuries, concussion and loss of consciousness [6–8]. This is usually the case when a child suffers an impact of any kind, whether it is an impact against a wall or a violent blow. However, vigorously shaken babies often present with no concussion but with subdural haematoma and the consequence of hypoxic neurological injuries. The differences we observed in our study between vigorous shaking and inflicted impact therefore appear to be relevant. In fact, what is of major importance when comparing the effect of shaking to an impact is to measure the relative motion of the brain and skull, which gives information on the chance of creating a subdural haematoma by the rupture of a bridging vein. In the two simulations, the brain moves in a sagittal plane. When compared to one another, shaking and impact cause similar relative displacement of the brain and skull but in a different time scale. A vigorous shaking can therefore have the same consequence as an impact in term of subdural bleeding. For an impact, the subdural bleeding will sometimes be associated with cerebral contusion or a skull fracture, and the shaking will lead to subdural bleeding and sometimes spinal injuries. In the two cases, the subdural bleeding will occur; the difference stands in the associated injuries.

Conclusion

In the past years, biomechanical studies have focused on the comparison of velocity and acceleration between different scenarios of head injuries to children. This extreme simplification has led to wrong ideas concerning the consequences of shaking a baby. Based on a detailed finite element model of the 6-month-old child head, it has been demonstrated that vigorous shaking can have the same consequence as an impact in terms of subdural bleeding. Finite element methods can be used as a complementary tool in understanding and analysing cases of child abuse.

References

1. Guthkelch AN (1971) Infantile subdural haematoma and its relationship to whiplash injuries. Br Med J 2:431 (May 22)
2. Duhaime AC, Gennarelli TA, Thibault LE, Bruce DA, Margulies SS, Wiser R (1987) The shaken baby syndrome. A clinical, pathological, and biomechanical study. J Neurosurg 66:409–415
3. Prange MT, Coats B, Duhaime AC, Margulies SS (2003) Anthropomorphic simulations of falls, shakes, and inflicted impacts in infants. J Neurosurg 99:143–150
4. Cory CZ, Jones BM (2003) Can shaking alone cause fatal brain injury? A biomechanical assessment of the Duhaime shaken baby syndrome model. Med Sci Law 43:317–333
5. Bandak FA (2005) Shaken baby syndrome: a biomechanics analysis of injury mechanisms. Forensic Sci Int 151:71–79
6. Willinger R, Baumgartner D (2003) Human head tolerance limits to specific injury mechanisms. Int J Crashworthiness 6(8):605–617
7. Raul JS, Baumgartner D, Willinger R, Ludes B (2005) Finite element modelling of human head injuries caused by a fall. Int J Legal Med 30:1–7
8. Raul JS, Deck C, Meyer F, Geraut A, Willinger R, Ludes B (2005) A finite element model investigation of gunshot injury. Int J Legal Med 17:1–4
9. Jans G, Van Audekercke R, Vander Sloten J, Gobin R, Van der Perre G, Mommaerts MY (1998) Bending properties of cranial bone segments of new-born children. J Biomech Supplement 31:65
10. Margulies SS, Thibault KL (2000) Infant skull and suture properties: measurements and implications for mechanisms of pediatric brain injury. J Biomech Eng 122(4): 364–371
11. Coats B, Margulies SS (2003) Characterization of pediatric porcine skull properties during impact. IRCOBI conference, Lisbon, Portugal, pp 57–66
12. Thibault KL, Margulies SS (1998) Age-dependent material properties of the porcine cerebrum: effect on pediatric inertial head injury criteria. J Biomech 31:1119–1126
13. Mc Pherson GK, Kriewall TJ (1980) Fetal head moulding: an investigation utilizing finite element model of the fetal parietal bone. J Biomech 13:17–26
14. Currey JD, Butler G (1975) The mechanical properties of bone tissue in children. J Bone Jt Surg Am 57:810–814
15. Swischuk LE (1997) Imaging of the newborn, infant, and young child, 4th Edn. Williams & Wilkins, Baltimore
16. Lee MC, Haut RC (1989) Insensitivity of tensile failure properties of human bridging veins to strain rate: Implications in biomechanics of subdural hematoma. J Biomech 22(6/7):537–542
17. Caffey J (1974) The whiplash shaken infant syndrome: manual shaking by the extremities with whiplash-induced intracranial and intraocular bleedings, linked with residual permanent brain damage and mental retardation. Pediatrics 54:396–403
18. Geddes JF, Hackshaw AK, Vowles GH, Nickols CD, Whitwell HL (2001) Neuropathology of inflicted head injury in children. I. Patterns of brain damage. Brain 124:1290–1298
19. Geddes JF, Vowles GH, Hackshaw AK, Nickols CD, Scott IS, Whitwell HL (2001) Neuropathology of inflicted head injury in children. II. Microscopic brain injury in infants. Brain 124:1299–1306
20. Lapeer RJ, Prager RW (2001) Fetal head moulding: finite element analysis of a fetal skull subjected to uterine pressures during the first stage of labour. J Biomech 34:1125–1135

21. Mizuno K (2004) Development of three-year old child human FE model. IRCOBI Conference, Graz, Switzerland, pp 335–336
22. De Santis Klinich KD, Hulbert GM (2002) Estimating infant head injury criteria and impact response using crash reconstruction and finite element modeling. Stapp Car Crash J 46:165–194
23. Prange MT, Kiralyfalvi G (1999) Pediatric rotational inertial brain injury: the relative influence of brain size and mechanical properties. Proceedings of the 43rd Stapp Car Crash Conf, SAE, 333–341
24. Zhou C, Kahlil TB, Dragovic LJ (1996) Head injury assessment of a real world crash by finite element modelling. Proceedings of the AGARD conference, New Mexico, USA, 81–87
25. Willinger R, Taleb L (1995) Modal and temporal analysis of head mathematical models. J Neurotrauma 12(4):743–754