Biomechanical performance of a bicycle helmet design on a six-year-old head impact protection

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Abstract: A previously developed and validated 6-year-old (6YO) Finite Element (FE) human head model was used to evaluate the biomechanical performance of a new bicycle helmet design for children. The cushion structure of the new helmet design is made of honeycomb paperboard and corrugated paperboard instead of Expanded Polystyrene (EPS) foam. Simulation results showed that the EPS foam helmet can effectively resist external shocks in a short period. However, based on biomechanical responses of the 6YO head model, honeycomb and corrugated paperboard helmets also had a promising cushioning performance. From the drop test of the head-helmet model simulations, the effects of paperboard thickness and material parameters on the helmet protection efficiency were further investigated. It was concluded that the EPS foam helmet can be replaced with honeycomb/corrugated paperboard helmets which are made of more environmental friendly manufacturing materials.

Keywords: bicycle helmet model; human head model; injury biomechanics; corrugated; honeycomb.

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1 Introduction

Head injury is the leading cause of fatality and disability in the USA (CDC, 2003). It poses a special challenge in the paediatric population, as early-age injury may lead to mental problems that can last for a life-time along with heavy economic burdens to the family and society. The most frequent causes of children's head injuries are motor-vehicle accidents, falls, and maltreatment (Hyde et al., 2014).

Numerous human head FE models have been developed over the past decades to study blunt traffic accidents (Iwamoto et al., 2015); injury in boxing (Hernandez et al., 2016); falls (Coats et al., 2007); contact sports (Ji et al., 2014; Ji and Zhao, 2015); and blast-induced injuries (Sevagan et al., 2013). Few of these studies focused on paediatric head injury, among which most paediatric head FE models age ranged from 0 to 3 years (Klinich et al. 2002; Coats et al., 2007; Roth et al., 2007; Ruan et al., 2012; Cui et al., 2015). All these studies provided encouraging insights for further investigating the head injury problems (McPherson and Kriewall, 1980; Davis et al., 2012; Li et al., 2015, 2016; Coats et al., 2007; Li et al., 2013a; Zhou et al., 2016; Li et al., 2013b).

Helmets have been recommended to be used whenever it is possible to reduce the risk of head injury. According to the Centre for Disease Control and Prevention, the probability of children's head injury and loss of consciousness decreased by 63% and 86%, respectively, when helmets were used. The Expanded Polystyrene (EPS) foamed plastic constitutes an absorption layer of the helmet; it has a good property of water resistance. However, EPS produces a very strong chemical substance as waste which is difficult to degrade and when incinerated produces a large number of toxic gases that endanger the human immune system and animal-plant ecosystems. On the contrary, cushion structure made from honeycomb paperboard and corrugated paperboard can also provide high cushioning performance while have large benefits of environmental protection.

Given these considerations, this study is the first innovative proposal to use corrugated and honeycomb structures made from paperboard in cushioning to develop a new safety helmet for children riding. The practicability and protective performance of paperboard helmet were analysed. Conclusions from this study can provide theoretical guidance for the development and manufacture of paperboard helmets.

2 Methods and materials

2.1 Model description

2.1.1 Helmet

The geometry of the helmet shell (including out shell and inner shell) and foam was provided by a manufacturer in a CAD file. The two parts of the helmet then were prepared to mesh into three finite element models with cushioning structure material made of EPS, honeycomb paperboard, and corrugated paperboard, respectively, by using Hypermesh software. The comfort liner is not included in the model as it is considered not to influence the headform response during impact. The outer shell and inner shell were meshed with shell elements with a thickness varying from 2.7 mm to 3.5 mm according to the considered helmet area. A specific attention is applied to the cushioning layer as its geometry is quite complicated. These layers are meshed with solid elements. The solid elements shared common nodes with honeycomb shell and corrugated shell. These models are illustrated in Figure 1, namely EPS foam, honeycomb paperboard and corrugated paperboard helmets. The thicknesses of these layers range from 13 mm for the chin to 20 mm for the vertex area.

Figure 1 Finite element models of children helmet (a) EPS (b) corrugated (c) honeycomb

2.1.2 Human head model

In this study, a 6-year-old child head FE model which was developed and validated by Tianjin University of Science and Technology (Ruan et al., 2012) was used to study the shock absorption of three bicycle helmet designs, as illustrated in Figure 2. For the paediatric head model, subject-specific CT images (acquired for medical purposes unrelated to the present study) from a local hospital were obtained to derive the skull geometry. Data access was approved by the Institutional Review Board at the Tianjin University of Science and Technology.

Figure 2 Head (a) and brain (b) FE models representing 6-year-old children

The brain anatomical regions included the cerebrum, the cerebellum, the brainstem, the diencephalon, ventricles, and the corpus callosum, and they were modelled using hexahedral elements. The models also included the flax and the tentorium, and these were represented by quadrilateral shell elements.

The skull was developed using hexahedral elements. The meningeal membranes and the Cerebral Spinal Fluid (CSF) between the brain and skull were modelled as hexahedral solid elements by sharing nodes with the brain outer surface and skull inner surface, similarly to other head models (Takhounts et al., 2008; Ji and Zhao, 2015). The models also include facial bones, the maxilla, the mandible, the scalp and the eye structure.

2.2 Material properties

2.2.1 Helmet model

The EPS foam has a density of 83 kg/m^3 (Mills and Gilchrist, 2008), and it was modelled with the constitutive material model which is only defined by the compressive stress-strain curve of EPS (MAT-63-CRUSHABLE-FOAM from LS-Dyna material library) (Ghajari et al., 2009; Cernicchi et al., 2008). Paper and paperboard generally exhibit anisotropic and non-linear mechanical material behaviour (Mäkelä and Östlund, 2003). The orthotropic material parameters of honeycomb paperboard and corrugated paperboard were obtained by calculating the point of linear phase of material stress-strain curve, as illustrated in Tables 1 and 2 (Yuping, 2014). The outer shell of the bicycle helmet is usually made from Polycarbonate (PC). An isotropic linear elastic model was chosen to simulate the mechanical behaviour of the PC. It was assumed that all helmet models have the same shell material properties because the in-mould bonding between helmet shell and liner prevents proper removal of the shell without damaging the helmet. The density, Young's modulus and Poisson ratio of the PC used in all material models of shell were 1200 kg/m^3 , 2.2 GPa and 0.37 , respectively (Fernandes et al., 2013).

Table 1 Material parameters of honeycomb structure cushioning paperboard

$E_x \text{ (Mpa)}$	$E_y \text{ (Mpa)}$	$E_z \text{ (Mpa)}$	$G_{xy} \text{ (Mpa)}$	$G_{yz} \text{ (Mpa)}$	$G_{xz} \text{ (Mpa)}$	μ_{xy}	μ_{yz}	μ_{xz}
2.75	3.58	2.8	1.21	0.1	0.05	0.33	0.01	0.01

Table 2 Material parameters of corrugated structure cushioning paperboard

$E_x \text{ (Mpa)}$	$E_y \text{ (Mpa)}$	$E_z \text{ (Mpa)}$	$G_{xy} \text{ (Mpa)}$	$G_{yz} \text{ (Mpa)}$	$G_{xz} \text{ (Mpa)}$	μ_{xy}	μ_{yz}	μ_{xz}
1.7	5	0.85	1.13	0.14	0.03	0.5	0.01	0.01

2.2.2 Head model

There is a considerable paucity of mechanical properties concerning the evolution of brain tissue with age due to the lack of experimental test data. In this study, therefore, the 6YO children brain material properties and brain-skull boundary conditions were referred to that of Simulated Injury Monitor (SIMon) (Takhounts et al., 2008), as summarised in Table 3.

The skulls were defined as rigid because acceleration is directly applied to the skull; this paper was not showed in the reference list.

2.3 Simulation tests

2.3.1 Effect of cushioning structure on helmet protection efficiency

Drop test simulations were performed to evaluate the effect cushioning structure on energy absorption. The 6YO head model coupling with the helmet models were released from a height of 30 cm , and were dropped onto a flat aluminium surface. The orientation of the head was set to vertically drop to the plate with the forehead region facing downward. Von-Mises stress, strain, and contact force of the helmet models were used to

investigate the effect of cushioning structure of EPS foam, honeycomb paperboard and corrugated paperboard on helmet protection efficiency.

Table 3 Material models and properties used in 6YO children head FE model

Components	Material type	Material properties
Cerebrum	Kelvin-Maxwell Viscoelastic	$\rho = 1040 \text{ kg/m}^3$
Cerebellum		$K = 558.47 \text{ MPa}$
Brain stem		$G_0 = 0.00166 \text{ MPa}$
		$G_I = 9.28\text{e-}04 \text{ MPa}$
		$\beta = 16.95$
Falx & Tentorium	Elastic	$\rho = 1130 \text{ kg/m}^3$
		$E = 31.5 \text{ MPa}$
		$\nu = 0.45$
CSF	Kelvin-Maxwell Viscoelastic	$\rho = 1050 \text{ kg/m}^3$
		$K = 4.966 \text{ MPa}$
		$G_0 = 0.1 \text{ MPa}$
		$G_I = 0.02 \text{ MPa}$
		$\tau = 0.01$
Skull	Rigid	$\rho = 35,200 \text{ kg/m}^3$
		$E = 6900 \text{ MPa}$
		$\nu = 0.3$

Notes: ρ =Density, K =Bulk Modulus, G_0 =Short Time Modulus, G_I =Long Time Shear Modulus, β and τ =Decay Constant, E =Young's Modulus, ν =Poisson's Ratio

2.3.2 Effect of paperboard thickness and material properties on helmet protection efficiency

Studies have shown that the height of children's bicycles ranges from 435 mm to 635 mm and the sitting height of children aged 6–7 is around 680 mm. Therefore, in this study, the honeycomb paperboard helmet-head model was dropped by 30 cm, 60 cm, 90 cm and 120 cm, respectively, to investigate the protection efficiency of paperboard helmet at the different drop height. Based on the drop height of 30cm, then, the influence of paperboard thickness and elastic moduli on the brain response was investigated with honeycomb structure helmet model. During simulation, the thickness of paperboard varied from 4.8 mm to 8.8 mm. And a parametric study was done with elastic modulus of the paperboard varied from 0.1 to 10 times of its base value.

2.3.3 Drop test reconstruction

In simulations, head model dropped onto stone-tile surface at the height of 120 cm with use of a honeycomb paperboard helmet. Four typical impact locations around occipital-parietal area were simulated to account for the uncertainty of the contact location. The peak head acceleration and contact force were compared to the results of head drop test without helmet.

2.4 Contact and boundary conditions

Before simulation test, the head model fitted with helmet models. An automatic surface-to-surface contact option was defined between head and inner shell, outer shell and plate, with a friction coefficient of 0.4 and 0.2, respectively. The helmet model was allowed to move freely and no other constraints were placed on helmet.

Five helmet model-predicted responses were considered as the helmet cushioning performance predictors, including compression, contact force, acceleration, strain, and Von-Mises stress. Head element-wise Von-Mises stress and intracranial pressure during the entire simulation, regardless of the time of occurrence, were extracted for each simulation. An additional linear regression was performed using intracranial pressure, Von-Mises stress and shear stress as the single independent variable, and their performances were compared in terms of coefficients of determination (R^2). The nonlinear dynamic finite element analysis software LS-DYNA was used to perform the analysis.

3 Results

3.1 Effect of cushioning structure on helmet protection efficiency

The compression of three baseline helmet models is 1.4 mm for the EPS foam, 2.98 mm for the honeycomb paperboard, and 5.3 mm for the corrugated paperboard, respectively. From Figure 3, it is evident that the EPS foam helmet yielded lower linear acceleration than those of two paperboard helmets because of the lower density of the EPS foam. The three helmet models yielded nearly identical effective strain (0.098 for EPS foam, 0.11 for honeycomb paperboard, and 0.10 for corrugated paperboard) as seen in Figure 4. It is observed from Figure 5 that the EPS foam helmet model sustained the highest Von-Mises stress response.

Figure 3 The time-history of helmet acceleration

Figure 4 Effective strain contour of helmet (a) EPS foam helmet (b) and (c) honeycomb and corrugated paperboard helmet

Figure 5 Von-Mises stress (MPa) contour of helmet when impact force attained the peak value (a) EPS foam helmet (b) and (c) honeycomb and corrugated paperboard helmet

When three baseline helmet models were coupled with the 6YO human head model, Von-Mises stress magnitudes of the brain with the use of honeycomb and corrugated paperboard helmets yielded nearly identical stresses (0.0031 MPa and 0.0033 MPa, respectively). However, the head-EPS model exhibited lower (15%) stress (0.0028 MPa). The whole brain Von-Moses stress distributions of the three head models were largely similar in the cerebrum with large stress in the brainstem, but different in the corpus callosum with substantial stress presented in the head with two paperboard helmet models as seen in Figure 6.

Figure 6 Von-Mises stress (MPa) contour of brain (a) EPS foam helmet (b) and (c) honeycomb and corrugated paperboard helmet

With identical impact velocity, the head with EPS helmet model yielded lower pressure than that of two paperboard helmets (0.11 MPa for EPS, 0.16 MPa and 0.24 MPa for

honeycomb and corrugated paperboard helmets). The pressure gradient distributions of the head-EPS model were similar to the head-honeycomb model with large pressure in the frontal. However, it dramatically differed in the cerebrum region with head-corrugated model yielded overestimation as seen Figure 7.

Figure 7 Intracranial pressure (MPa) contour (a) EPS foam helmet (b) and (c) honeycomb and corrugated paperboard helmet

3.2 *Effect of paperboard thickness and material properties on helmet protection efficiency*

In general, the compression of helmet decreased by about 10% as the thickness of paperboard increased by 1 mm (see Figure 8). It is indicated that the protection efficiency of the helmet can be improved by increasing the thickness of paperboard. Firstly, the linear regression from Figure 9 suggested a significant relationship between paperboard thickness and Von-Mises stress of the helmet. Besides that, the thickness of paperboard has the highest correlation with head FE stresses for Von-Mises stress and shear stress ($R^2 = 0.96$ and 0.97 as showed in Figures 10(c) and 10(d)), but not for coup and contrecoup pressures, as seen in Figures 10(a) and 10(b). From Figures 11 and 12 we can see that intracranial pressure and Von-Mises stress distributions in the brain was largely similar in the cerebrum with maximum value occurred in the impact region and brainstem.

Figure 8 Helmet displacement-time history curve at different paperboard thickness

Figure 9 Scatter plots showing correlations between helmet Von-Mises stress and paperboard thickness

Figure10 Scatter plots showing correlations between biomechanical responses of brain and paper thickness (a) coup intracranial pressure (b) contrecoup intracranial pressure (c) Von-Mises stress (d) Maximum shear stress

(a)

(b)

(c)

(d)

Figure 11 Intracranial pressure (MPa) contour at different paper thickness (a) 4.8 mm (b) 5.8 mm (c) 6.8 mm (d) 7.8 mm (e) 8.8 mm

Figure 12 Von-Mises stress (MPa) contour at different paper thickness (a) 4.8 mm (b) 5.8 mm (c) 6.8 mm (d) 7.8 mm (e) 8.8mm

Model simulations were performed with the elastic modulus of paperboard varied from 0.1 E to 10 E of its base value. The compression of the helmet seen in Figure 13 shows the helmet compression was inversely proportional to elastic modulus of paperboard. On the contrary, the Von-Mises stress of the helmet increased with the elastic modulus of

paperboard as shown in Figure 14. Most energy was absorbed by the helmet due to its high deformability. Therefore, it can be seen that the energy absorption performance of the helmet is highly sensitive to the elastic modulus of paperboard. Intracranial pressures, Von-Mises stresses and shear stresses of the brain increased with the elastic modulus of helmet paperboard as seen in Figure 15. However, the pattern of the stress distributions of the 6YO head model shows no proportionate behaviour with varying elastic modulus. It remained similar in cerebrum with large intracranial pressure and Von-Mises stress presented in the impact region and brainstem as seen in Figures 16 and 17. When the elastic modulus is reduced by five or ten times, the brain experienced the same distributions. When the elastic modulus exceeded 5 E and 10 E, changes in intracranial pressure and Von-Mises stress were very significant. The brain stress distributions dramatically differed in the cerebrum with substantial higher occurred in the corpus callosum.

Figure 13 Comparison of helmet displacement resulted different elastic moduli of paper

Figure 14 Scatter plots showing correlations between helmet Von-Mises stress and paper elastic modulus

Figure 15 Scatter plots showing correlations between biomechanical responses of brain and paper elastic moduli (a) Coup intracranial pressure (b) Contrecoup intracranial pressure (c) Von-Mises stress (d) Maximum shear stress

Figure16 Intracranial pressure (MPa) contour at different paper elastic moduli (a) 0.1 E (b) 0.5 E (c) E (d) 5 E (e) 10 E

Figure 17 Brain Von Mises stress (MPa) contour at different paper elastic moduli (a) 0.1 E (b) 0.5 E (c) E (d) 5 E (e) 10 E

3.3 Bicycling falls reconstruction

In this section, the head was dropped from 120 cm in four typical impact locations to mimic the fall from a bicycle. The Von-Mises stress of helmet model is 5.85 MPa (Frontal), 4.38 MPa (Vertex), 4.88 MPa (Occipital) and 4.2 MPa (Parietal), respectively. From Figure 18, it can be found that the impact region of helmet model experienced the highest stress and deformation. However, the honeycomb structure was not crushed.

For brain biomechanical responses, it can be seen that the largest stress occurred in the brainstem (Frontal view), the corpus callosum (Vertex view), the corpus callosum and the brainstem (Occipital and Parietal views) as seen in Figure 19 which is the contour plots of Von-Mises stresses and in Figure 20 which is shear stress contour plots. It is suggested that the injury risk in the corpus callosum and brainstem is higher when the head falls from a height of 120 cm. Besides that, it is obvious that in the forehead drop simulation test, the brain experienced the lowest stress. Compared with the results of the head drop test without a helmet, the biomechanical response of the head is dramatically reduced when the head uses the paperboard helmet model. As illustrated in table 4, head accelerations in four impact locations were reduced by 28.2% (Frontal), 1.4% (Vertex), 29.6% (Occipital) and 12.8% (Parietal), respectively. The contact force of the head was reduced by 21.2% (Frontal), 5.4% (Vertex), 27.7% (Occipital), 11.8% (Parietal), respectively. It is concluded that the paperboard honeycomb riding helmet can significantly reduce the risk of head injury for children.

Figure 18 Von-Mises stress (MPa) contour of honeycomb helmet at drop height of 120 cm
(a) Frontal (b) Vertex (c) Occipital (d) Parietal

Figure 19 Von-Mises stress (MPa) contour of brain at drop height of 120 cm (a) Frontal (b) Vertex (c) Occipital (d) Parietal

Figure 20 Shear stress (MPa) contour of brain at drop height of 120 cm (a) Frontal (b) Vertex (c) Occipital (d) Parietal

Table 4 The acceleration and contact force responses of head

<i>Head</i>		<i>Frontal</i>	<i>Vertex</i>	<i>Occipital</i>	<i>Parietal</i>
Peak linear acceleration (g)	Honeycomb helmet	152.7	158.4	144.3	161.8
	No helmet	212.7	160.7	205.2	185.7
Contact force (N)	Honeycomb helmet	6404	5823	5677	6270
	No helmet	8127	6158	7859	7115

4 Discussion

A previous developed and validated 6YO child head model was used to investigate the injury protection performance between EPS foam helmet and paperboard helmets through frontal drop simulation. The results showed that the EPS foam helmet can effectively resist external shocks in a short time, resulting in smaller deformation. However, the biomechanical responses, in terms of Von-Mises stresses and shear stresses of the brain, were significantly reduced when the head model used the honeycomb paperboard helmet, which shows that the honeycomb paperboard helmet can provide better cushioning performance for the head. Based on the drop test of the head-helmet model, the effects of honeycomb paperboard thickness and paper material properties on the helmet protection efficiency were investigated. The results showed that the cushioning of the paperboard helmet is sensitive to the honeycomb thickness. The compression of the helmet is inversely proportional to the thickness of the helmet. Brain stress distributions were largely similar in the cerebrum with large intracranial pressure and Von-Mises stress occurring in the impact region and brainstem. Similarly, the elastic modulus of paperboard has a great influence on the cushioning of the helmet. Specifically, the stress distributions of the brain remained similar when elastic modulus of paperboard was reduced. However, when the elastic modulus exceeded 5E and 10E, changes in intracranial pressure and Von-Mises stress were significant. Brain stress distributions dramatically differed in the cerebrum with a high value occurring in the corpus callosum.

The protective effect of honeycomb paperboard helmet on four falling parts of 6YO child head was analysed when the head fell from bicycle to the ground. Compared with the results of head drop test without a helmet, the biomechanical response of the head is dramatically reduced when using the paperboard helmet model, indicating that the honeycomb paperboard riding helmet can effectively resist external shocks when the head falls during accident.

5 Conclusion

This study is the first proposal to use corrugated and honeycomb structures in cushioning with paperboard to produce safety helmets for children's bike riding. The practicability and protective performance of paperboard helmet has been analysed. Results showed that the honeycomb/corrugated paperboard helmet also has acceptable injury protection performance while its manufacturing materials are more environmentally friendly.

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