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Sport Helmet Design and Virtual Impact Test by Image-based Finite Element Modeling *

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Abstract— **Head injury has been a major concern in various sports, especially in contact sports such as football and ice hockey. Helmet has been adopted as a protective device in such sports, aiming at preventing or at least alleviating head injuries. However, there exist two challenges in current helmet design and test. One is that the helmet does not fit the subject's head well; the other is that current helmet testing methods are not able to provide accurate information about intracranial pressure and stress/strain level in brain tissues during impact. To meet the challenges, an image-based finite element modeling procedure was proposed to design subject-specific helmet and to conduct virtual impact test. In the procedure, a set of medical images such as computed tomography (CT) and magnetic resonance image (MRI) of the subject's head was used to construct geometric shape of the helmet and to develop a helmet-head finite element model that can be used in the virtual impact test.**

I. Introduction

Although protective helmet has been adopted as protective gear in various sports for a long time, traumatic brain injuries are still often reported [1]. Head injuries can be roughly classified into two categories [2, 3]: open (or penetrating) and closed (or non-penetrating), mainly characterized by broken and unbroken skull respectively. Open head injuries are often reported in military battling field, violence and car accidents, while head injuries occuring in sports are mostly closed ones, for example concussion has been reported as the most often occurred head injury in sports. Helmet has been found very effective in preventing open head injuries but much less effective in reducing closed head injuries, as the two categories of head injuries are caused by different mechanical reasons. Open head injury is mainly caused by concentrated stress in the skull induced by sharp objects, resulting in fracture of the skull bone. While closed injury is usually caused by blunt object and involves mechanical mechanisms that are much more complicated, for example, excessive shear strain [4], negative intracranial pressure [5], brain tissue oscillation and mechanical wave propagation [6, 7], etc. Therefore, the principle adopted in the design of helmets for preventing open and closed head injuries should be different. To prevent penetration of sharp object in open head injuries, the shell of helmet should have adequate strength. While to alleviate closed head injuries, the shell and the cushion layer in the helmet is expected to absorb most of the mechanical energy and diverse the mechanical wave in such a way that it would not cause concentrated dynamic stress in the brain tissue.

Helmet unfitness has been found another factor in affecting the effectiveness of helmet in reducing closed head injuries [8, 9]. Sport helmets currently available in the market have standard sizes that are based on statistical anthropometric data of athletes [10]. For a specific individual, the helmet may not fit the head in a comfortable way and with a proper tolerance space. It has been reported that unfitness of sport helmet may greatly reduce the effectiveness of helmet in protecting the head [8, 9, 11]. A well fitted helmet is able to diverse impact pressure onto a larger area of the skull bone and it also reduces the strength of mechanical wave produced by impact. However, achieving subject-specific fitness of helmet is challenging.

Currently sport helmet testing mainly relies on physical experiment using dummies and cadavers [12-14]. The existing testing methods are useful in examining the strength of a helmet, but not able to provide reliable information about the intracranial pressure and stress/strain level induced by impact in the brain tissues. Closed head injury may have already occurred far before the helmet reaches its ultimate strength. Low biofidelity of the subjects (cadaver and dummy) used in testing is a major issue. Even for *in vivo* and cadaveric tissues, there are significant differences in their physiological conditions and mechanical properties. The differences between *in vivo* human body and dummy are even larger. Impact testing on *in vivo* human body is absolutely prohibited. There are also technical difficulties beside ethic issues, e.g. installation of strain sensors may have effect on tissue microscopic properties. Image-based finite element modeling is a promising method for resolving the above issues. In this paper, a finite element modeling procedure is proposed to resolve unfitness issue and to conduct virtual impact test. In the procedure, a set of medical images such as computed tomography (CT) or magnetic resonance image (MRI) of the subject's head was used to construct geometric shape of the helmet and to develop a helmet-head finite element model that can be used in the virtual impact test.

II. Methods and Materials

A sport helmet provides protection to the head mainly by the following mechanical principles: 1) to reduce the level of stress concentration at the contact point; 2) to absorb a portion of the mechanical energy induced by impact; 3) to increase the duration of the impact impulse; 4) to change the

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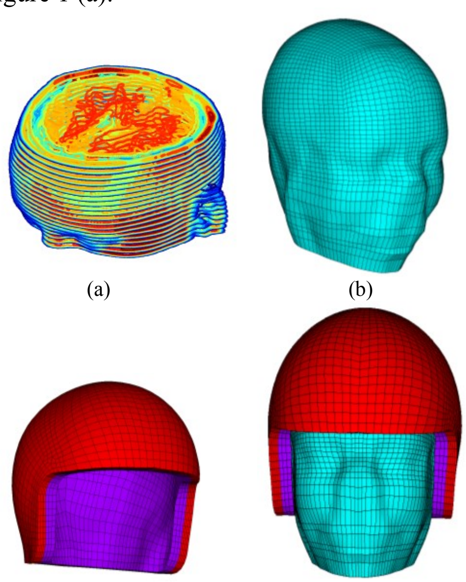
pattern and energy level of mechanical wave induced by the impact. In a sport helmet, the components that mainly provide protection are the shell and the liner. The stiffer shell is expected to resist penetration and diverse the impact pressure onto a larger area of the skull. Plastic deformation of the shell is also able to absorb some amount of impact energy. The softer liner is used to further absorb impact energy and to increase the duration of the pressure impulse. Based on dynamics, for a given mechanical impulse, if the duration of the impulse is increased, the peak value of the impact force will be reduced. The rest of the mechanical energy is transmitted into the brain tissues as mechanical wave and oscillation, which is believed the main cause of closed head injuries [15]. The pattern and energy level of the mechanical wave are mainly determined by the mechanical properties of the shell and the liner materials. It should be understood that a sport helmet can only provide limited protection to the head. However, a well-designed sport helmet should be able to provide its maximum protection. Helmets consisting of composite shell and lined with foam layer are currently the most popular ones in various sports [81, 82]. Compared with other alternative materials, composites have larger strength-weight ratio and foam liners have higher capacity of absorbing mechanical energy. Therefore, in our study the above type of sport helmet was selected.

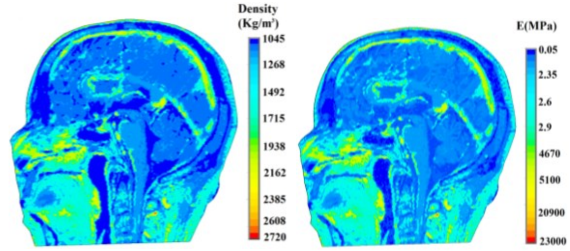
A. Subject-specific helmet design and construction of helmet-head finite element model

The proposed design process is started with a stack of medical images of the head, which can be CT (computed tomography) or MRI (magnetic resonance image), as shown in Figure 1 (a).



(c) (d)

Figure 1. (a) a stack of medical images of the head; (b) head finite element model; (c) subject-specific design of helmet; (c) helmet-head system model



(a) (b)

FIGURE 2. (a) Mass density distribution; (b) Young's modulus distribution

A finite element head model is first constructed from the medical images using the method described in [16]. The resulting finite element head model is displayed in Figure 1 (b), where the interior anatomic structures and tissue components of the head are represented with high biofidelity, as indicated in Figure 2.

To achieve subject-specific fitness of the helmet and the head, the outermost surface of the finite element head model is tailored and trimmed to obtain the innermost surface of the helmet. The surface is uniformly expanded outward so that there is a comfortable tolerance space between the head and the foam liner. The surface is then further expanded outward by the thicknesses of foam liner and composite shell in succession, to obtain the outer surface of the foam liner and the outer surfaces of the composite shell. The finite element model of resulting helmet is shown in Figure 1 (c). The helmet-head finite element model, as displayed in Figure 1 (d), is constructed by assembling the head and the helmet model. In the helmet-head model, it is assumed that there is no sliding between the foam liner and the composite shell. Interaction between the head and the foam liner is described by contact elements [17].

B. Material properties

In the helmet-head finite element model, three groups of material properties are required: the composite shell, the foam liner and the head tissues. Material properties of head tissues are correlated to Hounsfield Units in medical images by empirical functions, which have been described in detail in [16]. There are many composites and foams available in the market for manufacturing sport helmets. In this study, a composite made of carbon fibers and polyester [18, 19] is adopted for the helmet shell and polystyrene foam [20, 21] is employed for the helmet liner. The composite has five plies (0/90/0/90/0) and is considered as linear orthotropic material. Its material properties including elasticity moduli E_{11}, E_{22}, E_{33}, Poisson's ratios ν_{12}, ν_{12}, ν_{12}, and shear moduli G_{12}, G_{13}, G_{23}, are obtained from [19] and listed in Table I.

TABLE I. Mechanical properties of carbon fabric reinforced polyester

Density (Kg/m^3)	1800				
E_{11} (GPa)	61.3	υ_{12}	0.3	G_{12} (GPa)	2.8
E_{22} (GPa)	61.3	υ_{13}	0.4	G_{13} (GPa)	2.0
E_{33} (GPa)	10.0	υ_{23}	0.4	G_{23} (GPa)	2.0

Foams are mostly used to support pressure and their compressive stress-strain relations are determined by experiments [20]. A typical stress-strain curve is shown in Figure 3.

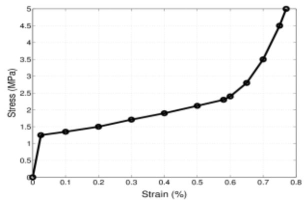


Figure 3. Typical compressive stress-strain relation of foam

The deformation of typical foam can be characterized into three stages: a linear elastic stage occurring at very low stress level, followed by a linear plastic stage where large plastic deformation occurs with very little increase in stress, and in the last stage there is very small deformation and the stress increases sharply. The second stage is the most crucial one for a helmet lined with the foam to provide effective protection, as mechanical energy is mostly absorbed during this stage. It is generally desired that this stage is longer to absorb more mechanical energy and also to increase the impact time. Foam mechanical properties are closely related to its initial density. The foam used in this study is polystyrene foam. Its mechanical properties were reported in [20] and listed in Table II.

TABLE II. Polystyrene foam compressive stress-strain relation (ρ = 80 kg/m^3)

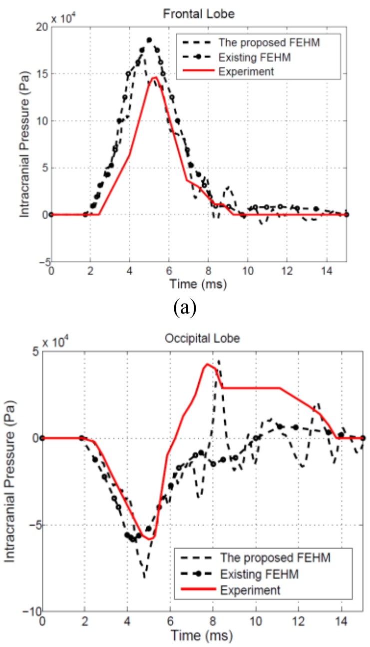
Strain (%)	Stress (MPa)	Strain (%)	Stress (MPa)
0.000	0.00	0.500	2.12
0.025	1.25	0.580	2.30
0.050	1.30	0.600	2.40
0.100	1.35	0.650	2.80
0.200	1.50	0.700	3.50
0.300	1.71	0.750	4.50
0.400	1.90	0.770	5.00

C. *Virtual impact test*

Virtual impact tests were conducted using the head model in Figure 1 (b) and the helmet-head model in Figure 1 (d) respectively, to investigate effectiveness of the designed helmet in protecting the head. Intracranial pressure and effective strain level in the brain tissues have been proposed as criteria for brain injury risk or as measurements of injury severity [15, 22]. Therefore, the effectiveness of helmet protection can be evaluated by comparing intracranial pressure and strain level in the helmeted and non-helmeted model. To corroborate our finite element model with experiment results, the experiment reported in [23] was simulated. In the experiment, a whole body cadaver was seated and impacted by an object onto the middle forehead. The cadaver was not helmeted in the experiment and intracranial pressure was measured. The loading and constraint conditions in the experiment were extracted and used in the simulation of the non-helmeted model, Figure 1 (b). The simulated intracranial pressure is compared with the experiment data in [23] and existing finite element results in [7]. The same virtual impact test was conducted to the helmeted model, Figure 1 (d). Intracranial pressure and strain level in helmeted and non-helmeted models were compared.

III. Results and Discussions

Comparison of predicted intracranial pressure by the non-helmeted head model in Figure 1 (b), experiment results [23] and other finite element model [7] is shown in Figure 4.



(a)

(b)

Figure 4. Corroboration of intracranial pressure

Reasonable agreement between the predicted and experimental intracranial pressure can be observed from Figure 4, indicating that the developed finite element head model and the corresponding procedure are reliable in predicting head responses to impact. Oscillation in the intracranial pressure predicted by the helmeted model was probably caused by consideration of a layer of inviscid cerebrospinal fluid (CSF) in the finite element head model [16], while in the cadaver the CSF may either have drained into the spine canal or have very higher viscosity. Intracranial pressure at a point in the posterior frontal lobe and predicted by respectively the helmeted and non-helmeted finite element head model are presented in Figure 5.

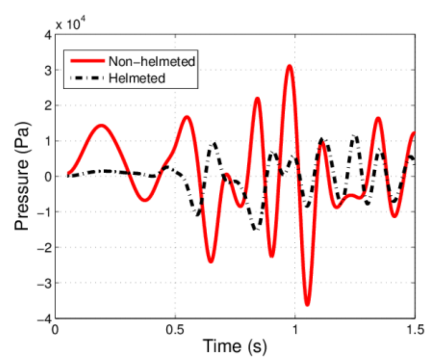


Figure 5. Intracranial pressure predicted by helmeted and non-helmeted model

By wearing the helmet, the maximum intracranial pressure at the point was reduced by 61%. Distributions of effective strain over a transverse plane of the head with and without the helmet are plotted in Figure 6. By using the helmet, the maximum peak effective strain was reduced by 58%.

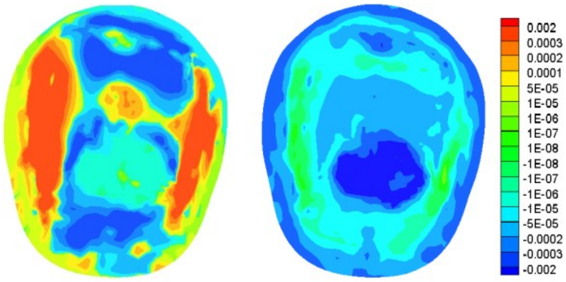


Figure 6. Effective strain distribution over a transverse plane and predicted by (a) non-helmeted and (b) helmeted model

From the results produced by the virtual impact test, it can be concluded that use of helmet can greatly reduce intracranial pressure and tissue strains induced by impact and thus prevent or at least alleviate head injury. The intracranial pressure and strains at a concerned location in the brain tissues can be easily predicted by the developed helmet-head finite element model, which, however, are difficult to measure using currently available experiment methods. The proposed finite element procedure can be used to evaluate the effectiveness of an existing helmet in protecting the head or it can be incorporated into helmet design process to improve helmet design. By selecting optimal materials for the shell and the liner, it is possible to further reduce the intracranial pressure and the strain level for a given impact.

IV. CONCLUSIONS

It was confirmed in the reported research that a helmet is able to reduce impact-induced maximum peak intracranial pressure and the maximum peak strains in the brain tissues, which are believed the two main causes leading to closed head injuries, and thus to provide protection to the head in sports. Although a helmet can only provide limited protection, by applying the proposed procedure in helmet design process it is possible to maximize the protection effect of the helmet via selecting a set optimal of parameters such as composite elasticity modulus, foam plasticity, foam thickness, etc.

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