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Impact Abdominal Injury Analysis Using a 6-Year-Old Pediatric Occupant Abdomen Finite Element Model

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Abstract: The understanding of pediatric abdominal injury mechanism using finite element (FE) human body models is of great importance to improve the design of vehicle safety. The whole thorax and abdomen finite element (FE) model of a 6-year-old occupant was integrated based on the individual thorax and abdomen FE models.Some soft tissue FE models suchas certain muscles, fat and skin were also developed in the whole FE model. The model was validatedby reconstructing impact experiments of paediatric cadaver abdomen experiments. The simulation results showed that the abdominal impact force-displacement curve and viscous criterion (VC) at three impact speed located in the cadaver experiment corridor, which means the validation of the model. The maximum force and the VCmax raised significantly with the increase of impactspeed. The simulation results also showedthatthe strainsof largeintestineat the three impact speed exceeded its failure strain while the strains of solid organs such as liver is lower than the failure strain. The FE model can be used to study the mechanism of child occupantabdominal injury in traffic accidents.

KeyWords: 6-year-old pediatric occupant; abdomen finite element model; model validation; pediatric cadaver experiment reconstruction; abdominal injury analysis

1 Introduction

The rapid increase in number of motor vehicles caused more traffic accidents nowadays. Though the application of seatbelt and airbag decreased the occupant injury rate of head, it may bring rib fractures and abdominal organ ruptures. Children are especially vulnerable to abdominal injury from seat belts, because they have softer abdominal regions and seat belts were not designed to fit them. Arbogast[1]et al.（2004）investigated 243,540 automobile crash involved 19,125 children under age of sixteen, and found thatchildren at 4-8 years of age were at highest risk of abdominal injury.They were 24.5 times and 2.6 times more likely to sustain an Abbreviated Injury Scale 2+ abdominal injury than those of 0-3 years and 9-15 years, respectively. In order to protect children in car crashes, child restraint systems are recommended by American Academy of Pediatrics (AAP) and the National Highway Traffic Safety Administration (NHTSA). For example, child car seat with harnesses should be used for children from birth to 4 years of age and belt-positioning booster (BPB) seats should be used for older children whenthey are lower than 1.45 m[2].Though BPB and adult seat belt can protect children during the traffic accidents, however, abdominal injury risk associated with seat belt constraints is still among the highest in the children aged 4 to 15 in developed countries[2]. Therefore, the investigationof the injury mechanism for pediatric abdomen is of great importance to the design of vehicle crash safety and clinical application.

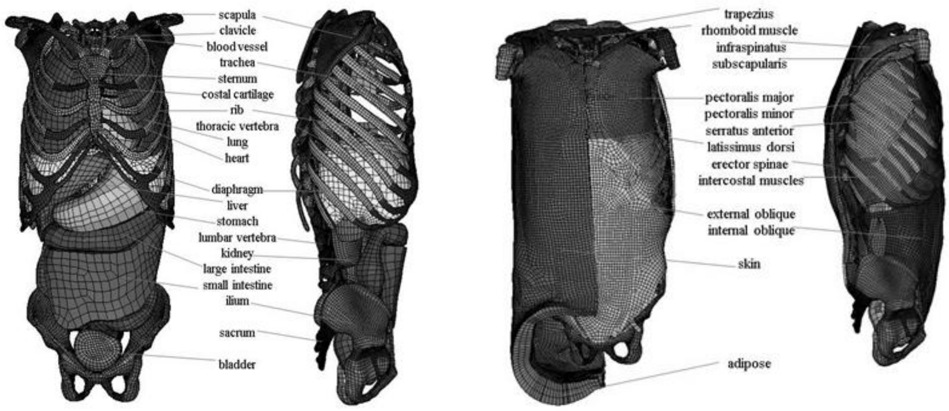
Cadaver experiments are an important method to study crush injury mechanism and obtain injury tolerance under different loading conditions, but it is very difficult to obtain pediatric cadaver experimental data from literature. Ouyang [3] et al. (2014) conducted front pediatric abdomen impact tests withdifferent impact speeds to investigatethe biomechanical responses and injury mechanisms of the pediatric abdomen using nine pediatric cadavers. The data such as abdomen impact force-compression curve, V*C-time curve and visceral injuries, wereobtained from the experiments.Though the geometrical characteristic of cadavers is the same as the real human, their response during the impact is not the same as that of real human body.On one hand, there are limitations in terms of muscle initiative for cadavers. On the other hand, theaccuracy and reliability of cadaver experiment results are limited because of the small cadaver-sample size. Regardless of the difference between the cadaver and real human body, these cadaver experiment results can not only be used to investigatethe injury tolerances and injury mechanism of abdomen, but also can provide data support to validate the pediatric abdomen finite element (FE) models.

In order to further study the abdominal injury mechanism of child occupant, a 6-year-old pediatricthorax and abdomen FE model with detailed anatomic structures was developedand validated by reconstructing pediatric abdomen pendulum impact cadaver tests. The validated FE model can be impacted repeatedly under different loading conditions and can be used to evaluate the abdominal visceral organinjury of child, which is a good supplement for cadaver experiments.

2 Materials and methods

2.1 Development of the 6-year-old child FE model

Finite element models of soft tissues，such as the trapezius muscle, external oblique muscle, infraspinatus and subscapularismuscle, chest and abdominal fat and skin tissues, were constructed in Hypermesh 12.0 according to pediatric anatomical structure. And the final FE model of the 6-year-old pediatric chest and abdomen was developed based on the 6-year-old occupantthorax FE models by Wei zhi-qiang [4] and abdomen FE model Sun tian-jun[5]. The FE model shown in Figure1 not only included the thoracic and lumbar spine, rib, rib cartilage, sternum, clavicle, scapula, intervertebral disc and diaphragm, trachea, blood vessels, oesophagus, heart, lung, stomach, liver, spleen, kidney and other hard and soft tissue (figure 1 a), but also included the real anatomy structure of muscle, fat and skin tissue (figure 1 b). Solid elements were used to model cancellous bones, internal organs and muscles, and shell elements were used to model cortical bones, diaphragm, trachea, blood vessels, oesophagus, tendons, ligaments and skin. The total FE model contained 527680nodes, 399443 solid elements, 13772shell and membrane elements. In order to improve the biofidelity of FE models, the FE models of head and neck, pelvis, upper and lower extremities were also added to the chest and abdomen model.The whole pediatric occupant FE model was shown in Figure 2.



(a) Bones and internal organs (b) Muscles

Figure 1 The thorax and abodomen FE model of a 6-year-old pediatric occupant

2.2 material properties

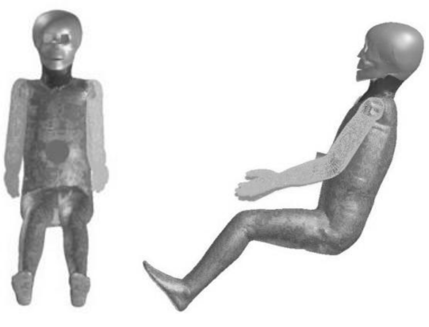
Owingto the lack of children's cadaver experiments, there existed only few material properties of pediatric abdominal organs in the publishedliterature, and most of the material propertiesused for the pediatric FE model study were obtained from adults by scaling law. Lv[6]et al.(2013)calculated the 6-year-old material propertiesof the thoracic and lumbar spine and rib, which was used in this article. Some studies showed that it is difficult to establish the definite relationship between the material propertiesof soft tissues and age, and some investigationson FE models of the old and child suggested that the material propertiesof soft tissues did not varywith age.Therefore, the material properties of soft tissues and internal organs usedin thismodel were same as that of adults [7-9].The final material properties adopted in the model are concluded in Table 1.

Table 1 Material properties used in the 6-year-old child thorax and abdomen FE model

	Element type	Density ρ （Ton/mm^3）	Young's modulus E（MPa）	Poisson ν（-）	Yield stress（MPa）
Rib cortical bone	solid	2.0E-9	7875	0.3	71.655
Rib cancellous bone	solid	1.0E-9	252.4	0.45	3.52
Sternum cortical bone	shell	2.0E-9	7875	0.3	71.655
Sternum cancellous bone	solid	1.0E-9	252.4	0.45	3.52
Thoracic/lumbar vertebral cortical bone	solid	1.83E-9	7215	0.3	56
Thoracic/lumbar vertebra cancellous bone	solid	1.0E-9	836	0.2	3.19
Skin	shell	1.0E-9	31.5	0.45	
	Element type	Density ρ （Ton/mm^3）	Bulk modulus K(MPa)	Short-term shear modulus G_0(MPa)	Long-term shear modulus G_∞(MPa)
Muscle	solid	1.1E-9	1.33	0.14	0.04
Lung	solid	6E-10	0.22	0.02	0.075
Heart	solid	1E-9	2.6	0.44	0.15
Spleen/liver/kidney	solid	1.1E-9	2.8	0.23	0.044

2.3 Abdomen FE model validations

Ouyang[3]et al. (2014) conducted front pediatric abdomen impact tests using five pediatric cadaver aged 5–12 years.In the experiment, the impactor with a diameter of 75 mm and mass of 3.5 kg directly impacted the pediatric abdomen at a speed of 6.1, 6.3 and 6.9 m/s. The abdomen impact force-compression corridorwas obtained by integrating impact force-compression curves of five cadaver results at different speeds. The cadaver experiments were reconstructed usingthe developed pediatric occupant model. A rigid cylinder with 75 mm diameter and3.5 kg mass was constructed to simulate the impactor in the cadaver experiments.According to the cadaver experiments set up; the FE model was set in a seated position and faced the impactor. The head and spine of FE model keep straight, and the axis of the impactor horizontally pointed to one third the distance from the navel to the bottom of the sternum（Figure 2）. Impact velocities used in simulations were 6.1 m/s, 6.3 m/s and 6.9 m/s, and is same as the cadaveric tests.



（a）Front view （b）Side view

Figure2 The simulation of pediatric abdomen impact test

3 Results and Discussion

3.1 Validation results

Figure 3 shows the abdomen impact force-compression curves in simulations and pediatric cadaver experimentsat different impact speed. The peak impact forces at impactspeed of 6.1 m/s, 6.3 m/s and 6.9 m/s were 846 N, 895 N and 970 N, respectively.Andthe maximum compressions of abdomen were 88.0 mm, 89.9 mm and 96.7 mm, respectively. It could be seen that both the peak impact force and compression increased with the increase of speed. From Figure 3, we can know that simulation curves located in the cadaver experiment corridor, and the trend of simulation curves had a good consistency with that of the corridor. It also can be seen that the peak compressions in simulations were a bit smaller than that of cadaver experiment. The maximum compression rate of abdomen ranged from 60.7% to 66.5%, which was also in the range variation between 53.85% and 71.25% in the cadaver experiments.

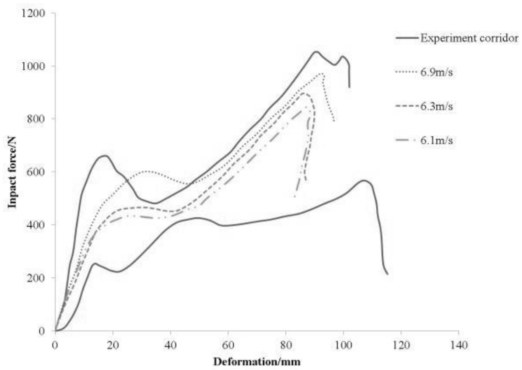


Figure 3 Abdominal impact force-displacement curves at different impact speed and cadaver experiment results

Figure 4 shows the variation history of pediatric abdominal viscous criterion(VC) in simulations. The maximum VC values of abdomen at different impact speed (6.1 m/s, 6.3 m/s and 6.9 m/s) were 1.98m/s，2.07m/s，2.32m/sand the peak VC value appearedat 9.34ms，8.50ms，8.00ms, respectively.It also could be found from Figure 4 that the maximum VC value of abdomen increased with the increasing of speed. All the three Maximum VC values of simulations were within the VC range of (2.53±0.59) m/s obtained by Ouyang[3].

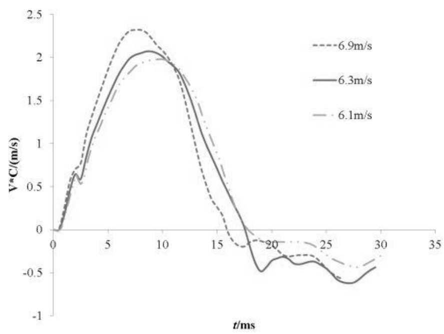


Figure 4 Abdominal VC value history of FE model at different impact speeds

3.2 Abdominal Organs injury

Melvin[10] et al. (1973) found that the liver failure strain was 30% from macaqueliver loading tests. Yamada (1970) pointed out that the failure strain of intestines was120%. Therefore, the failure strains of liver and intestineswere defined as 30% and 120%, respectively.Figure5, 6, 7 shows the maximum first principal strain contour of large intestine, small intestine and liver at the impact speedof 6.9m/s. It could be found that the peak strains of large intestine and small intestine weremuch greater than the injurythreshold, and the liver's maximumfirst principal strain was slightly greater than the injury threshold.

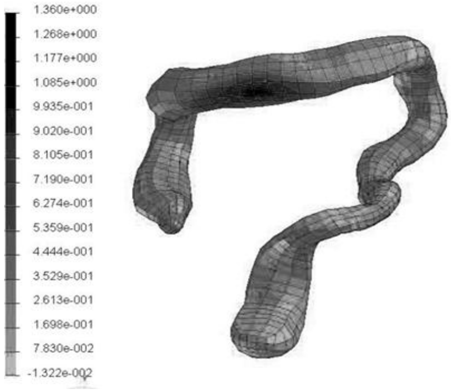


Figure 5 The first principal strain contour of the large intestine at impact speed of 6.9m/s

Figure 8 shows the peak first principal strains of abdominal organs in simulations. As shown in the figure, the maximum first principal strains of large intestine, small intestine and liver raised along with the increase of impact speeds. The maximum principal strains of large intestine exceed its corresponding injury threshold values under all three impact speeds, which meant that large intestine was ruptured. The maximum principal strains of small intestine and liver was greater than its corresponding injury threshold values only at speed of 6.9m/s. Therefore, there was some risk of small intestine and liver rupture injury at the speed of6.1m/sand 6.3m/s. The maximal first principal strains of spleen and kidneys were affected weakly by speeds, and whether they appeared injury at this time cannot be recognized due to the lack of injury threshold values. The maximum first principal strain of intestines was much greater than that of liver, spleen and kidney. This may be caused by two reasons. On one hand, the intestines are hollow organs while the liver, spleen and kidney are solid organs. Usually the solid organs can resist much more compression than hollow organs. On the other hand, the impactor directly compressed the intestines in the experiments, which may cause the intestines to endure greater contact forces than other abdominal visceral organs.

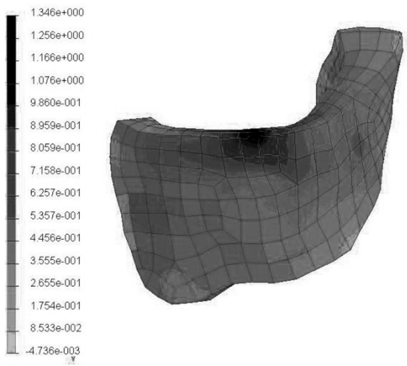


Figure 6 The first principal strain contour of the small intestine at impact speed of 6.9m/s

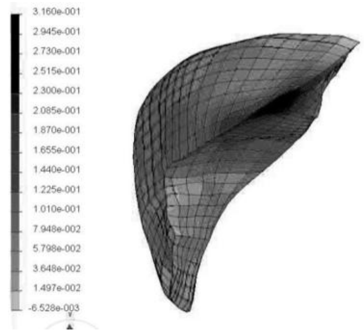


Figure 7 The first principal strain contour of the liver at impact speed of 6.9m/s

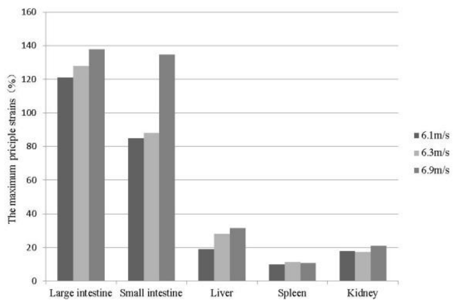


Figure 8 Maximumfirst principal strains of abdominal organs atdifferent impact speeds

4 Conclusion

A whole thorax and abdomen finite element (FE) model of a 6-year-old occupant with detailed anatomical structuresincluding internal organs such as liver, heart, was developed were developed.The FE model was used to reconstruct cadaver experiments of pediatric abdomen front impact and the internal organs injuries were predicated by the first principal strain respectively. In the simulation, the abdominal impact force-displacement curve, the viscous criterion（VC）and injuries to internal organs were in accordance with the cadaver results, which showed the validation of the FE model. The injury analysis of internal organs showed that the large intestine was injured while the liver may be safe under three impact speed.

As for the FE model, there existed some limitations. For example, small intestine is usually hollow and coilsin the abdomen from human anatomy, however, the Fe model of small intestine wasbuilt as solid in orderto simplify the model.

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