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Finite element analysis of human thoracic injury criteria in side impact

Fang WANG [1], Jikuang YANG [2, 3], Yong HAN [1], Guibing LI [4], Xiaoqing JIANG [2]
[1]*School of Mechanical and Automotive Engineering, Xiamen University of Technology, Xiamen, China*
[2]*VTS, State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, China*
[3]*Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden*
[4]*Trinity Centre for Bioengineering, Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Dublin 2, Ireland*
E-mail: wangfang83715@163.com

Abstract

This study aimed at analyzing the correlation between injury responses of human thorax and the injury criteria of human thoracic injury under side impact, by using a previously developed and validated human thorax FE model. For this purpose, the human thorax model was used to simulate human thorax impactor tests at a range of certain angles in side impact. The normalized number of rib fracture (NRF) were calculated and analyzed for comparing with normalized simulated injury parameters based on various human thoracic injury criteria. The evaluation analysis with the human thorax FE model suggested that the Thorax Trauma Index (TTI) criterion correlated with the NRF better than the other criteria.

Keywords: human thorax; finite element model; side impact; injury criteria

1 Introduction

It was reported that the ratio of side impact accidents to the frontal impacts shows a downward trend in the period of 1997 to 2007 by using data from the FARS and NASS databases [1], while the ratio for fatal crashes caused by side impact and frontal impact accidents exhibits a generally increasing trend. The fact indicated that the effect of occupant injury prevention in side impact is not as significant as that in frontal impact. Actually the state of knowledge of injury biomechanics research on human body, especially human thorax in side impact is less advanced than that in frontal impact.

The experiments with PMHS were widely carried out for the early research on human thoracic injury in passenger vehicle crash events, including frontal and side impacts. The results from human thorax impactor experiments by Stalnaker et al. [2] suggested that side thorax deflection could be used for assessment of thoracic injury severity.

Four side impactor PMHS experiments were recorded in the research of Eppinger et al. [3] in 1984, and the experiment data was used for the development of injury index, mechanical response corridors and the NHTSA's Side Impact Dummy (SID). In 1998, a series of side impactor experiments were carried out by Talantikite et al. [4] with the aim of investigating the sensitivity of the injury criteria to loading mass and velocity variation. The impactor masses used were 12 and 16 kg and the velocities were 6 to 8.5 m/s. The impact surface was flat, rigid and of 150 mm diameter. It was concluded that the V*C and the deflection criteria are sensitive to the variations of the impact masses and velocities. The purpose of Chung et al's research [5] is to get more understanding of the thoracic response and injury mechanisms in side impact to the human chest wall. A series of cadaver tests were conducted to measure biomechanical response and injury data, which were used to correlate injury criteria for side impact to the number of rib fractures (NRF). It was suggested that chest deflection or the energy generated in a side impact correlated better with NRF than acceleration or the viscous response.

With more and more attention was paid to the research of human thoracic injury in side impact, the achievement has been made mainly by means of PMHS experiments. But as the most popular and intelligent approach in research field of vehicle safety and human injury biomechanics, the FE (Finite Element) method was not widely used yet in side impact.

Objective of the current study was to determine the correlation of the number of rib fractures (NRF) with the thoracic injury criteria under side impact by using a previously developed human thorax FE model.

2 Methods and materials

2.1 Model description

The current human thorax FE model was developed in a research project on human body model (HBM) of Hunan University [6, 7, 8, 9], as shown in Figure 1. The model has been validated against PMHS experiments [6].

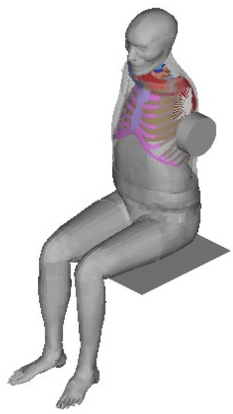


Figure 1. ISO view of current thorax FE model in impactor loading conditions

2.2 Definition of the boundary and loading conditions in side impacts

In research of human thoracic injury, impactor test is a quite useful and efficient experimental method, not only in frontal impact but also in side impacts. This method was also employed in current study, with the rigid impactor of 152mm diameter surface, 16kg mass, and impact velocity of 6m/s, referring to the research of Talantikite et al [4].

The principal direction of force (PDOF) has been introduced, which were categorized for side impact-induced injuries [10, 11, 12]. The loadings were defined in a clockwise sequence with impact directions varied from PDOF of 90° to PDOF of 35° (Figure 2). Total of 12 impact simulations was conducted. In the simulations, the center of the impactor was aligned at the same vertical height as that in research of Shaw et al. [13] and with the axis of force through the center of gravity of the torso, as described in Figure 2.

Rib fractures are the most frequent type of thoracic serious injuries [14], so in the research of human thoracic injury, NRF is treated as the assessment index of human thoracic injury severity [5, 15]. In the current study, NRF was obtained through simulating the thorax response in 12 different directions of side impact loadings with an impactor. The results were analyzed for comparing with simulated injury parameters based on various human thoracic injury criteria in side impact.

2.3 Analysis of impact responses using thorax injury criteria

The validated model was utilized in simulations of thorax impact responses for obtaining the NRF in total 12 impact directions. Output of injury parameters was analyzed for rib fracture based on existing human thoracic injury criteria in side impact [5, 14, 16], including contact force, chest deflection, compression, Viscous Criteria (VC), upper spine acceleration and Thoracic Trauma Index (TTI). For analyzing the rib fracture in side impact, by correlating the various injury criteria and NRF, all of the injury parameters were normalized in terms of injury criteria, as well as NRF, with the following normalization Equation 1.

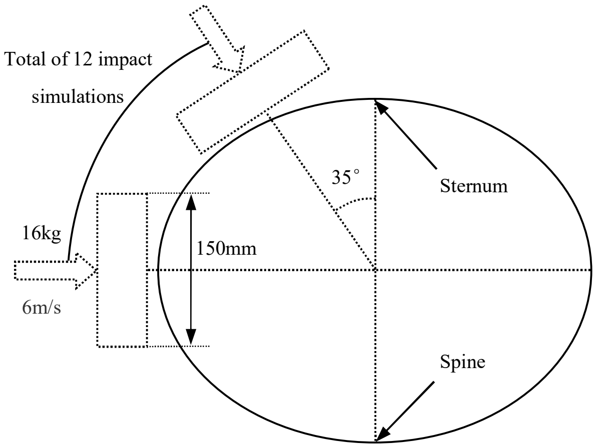


Figure 2. Distribution of impact directions in side impacts

$$N_i^C = \frac{X_i^C - X_{\min}^C}{X_{\max}^C - X_{\min}^C} \tag{1}$$

Where:N is the normalized value;i=12;C means the injury parameters including NRF and the six different injury criteria; X_i, X_{max}, and X_{min} represent the non-normalized value of sample number i, maximum value, and minimum value for each injury parameter.

The correlation of normalized NRF with the six normalized injury parameters can be described by the evaluation function f which is given in Equation 2:

$$f(X_i^R, Y_i^R) = \sum_{i=1}^{N} \sqrt{(X_i^R - X_i^B)^2 + (Y_i^R - Y_i^B)^2} \tag{2}$$

Where:N=12;Xi and Yi represent abscissa and ordinate of data-point of sample number i, R and B mean predicted parameter data and baseline y=x.

3 Results

The model was used for simulation of thorax impact responses and calculation of injury parameters. The peak values of corresponding injury parameters are presented in Table 1, including NRF, impact force, deflection, compression, deflection velocity, T1 (the 1st thoracic vertebra) acceleration, and TTI. The maximum of rib fractures is 11 at impact angle of 70 degrees. All of the normalized results were as shown in Table 2.

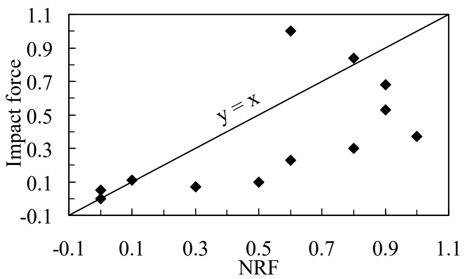
Table 1. Simulated values of injury parameters

Impact angle	NRF	Peak Force (kN)	Peak Deflection (mm)	Peak Compression (%)	Peak Deflection velocity (m/s)	Peak T1 Acceleration (g)	TTI
90	7	4.77	61.3	22.7	5.4	182.3	179.9
85	9	4.62	61.1	22.8	6.0	222.5	182.3
80	10	4.46	64.9	24.2	6.7	186.0	177.9
75	10	4.31	66.5	24.4	6.7	159.8	155.7
70	11	4.15	68.4	25.1	6.2	146.5	180.9
65	9	4.08	70.5	25.8	9.4	132.9	178.1
60	7	4.01	69.2	25.1	6.8	162.7	178.5
55	6	3.88	69.0	25.0	6.0	173.7	166.1
50	4	3.85	70.6	25.4	7.2	194.8	162.3
45	2	3.89	69.4	24.8	8.2	164.1	164.0
40	1	3.83	72.4	26.0	8.8	159.7	156.5
35	1	3.78	74.9	27.1	9.1	156.8	150.9

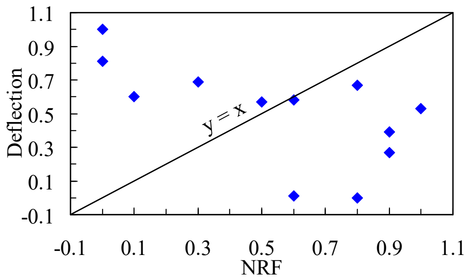
Table 2. Normalized values of injury parameters

Impact angle	NRF	Peak Force	Peak Deflection	Peak Compression	Peak Deflection velocity	Peak T1 Acceleration	TTI
90	0.6	1.00	0.01	0.00	0.00	0.55	0.93
85	0.8	0.84	0.00	0.01	0.16	1.00	1.00
80	0.9	0.68	0.27	0.34	0.32	0.59	0.86
75	0.9	0.53	0.39	0.38	0.33	0.30	0.15
70	1.0	0.37	0.53	0.56	0.21	0.15	0.96
65	0.8	0.30	0.67	0.70	1.00	0.00	0.87
60	0.6	0.23	0.58	0.54	0.35	0.33	0.88
55	0.5	0.10	0.57	0.51	0.15	0.46	0.49
50	0.3	0.07	0.69	0.61	0.44	0.69	0.36
45	0.1	0.11	0.60	0.49	0.70	0.35	0.42
40	0.0	0.05	0.81	0.75	0.85	0.30	0.18
35	0.0	0.00	1.00	1.00	0.94	0.27	0.00

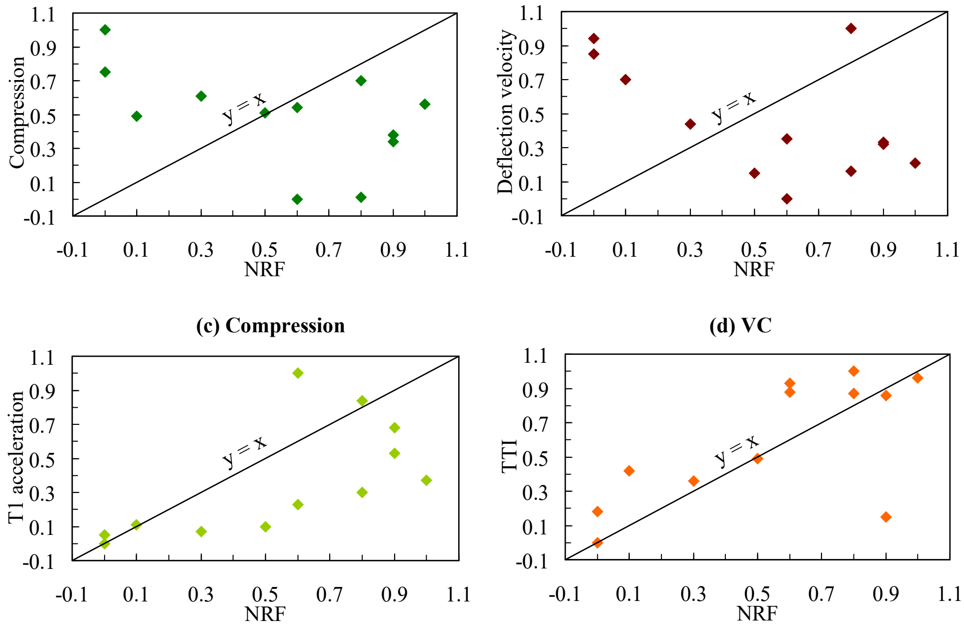
The correlation of normalized NRF with the six normalized injury parameters can be identified in Figure 3. According to the Equation 2, the lower f means the higher correlation. The function f was calculated for all the six injury criteria as showed in Table 3. Obviously the function values for TTI was the lowest and that for impact force, deflection, compression, deflection velocity were higher, so it was indicated that the TTI criterion well correlated with the NRF. The correlations of the other injury parameters are not relevant, including contact force, the upper spine acceleration, chest deflection, compression, and Viscous Criteria (VC).



(a) Contact force



(b) Deflection



(c) Compression **(d) VC**

(e) Upper spine acceleration **(f) TTI**

Figure 6. Normalized NRF as functions of the various injury criteria

Table 3. Calculated values from correlation Equation 2 for various injury criteria

	Contact force	Deflection	Compression	VC	Upper spine accelaration	TTI
$f(X_i^R, Y_i^R)$	2.28	4.19	3.91	4.60	3.06	1.61

4 Discussions

It was indicated in the current paper that the TTI criterion in side impact correlated with the number of rib fractures best. However, it was suggested from the research of Viano [17] that the VC criterion had the best correlation with injury risk for chest. With the PMHS experiments in different impact directions, Kent et al. [18] thought that the chest deflection was the most appropriate injury criterion because it was the most related to injuries independent of the loading conditions.

Several different thoracic injury criteria were involved in the current research. The criterion of acceleration was the product of early attempts to quantify thoracic loading and injury, and it was a basic injury criterion for assessment of thorax injury in impact loadings. The criterion of contact force is similar to acceleration criterion, and directly relates to acceleration criterion. Afterwards, there were more thoracic injury criteria with the development of research on thoracic injury in vehicle safety, which originated from human even animal experiments in various loading conditions. TTI was developed using data from series of side impact cadaver sled tests [18]; the criteria of deflection and compression were both based on data from frontal impactor cadaver experiments [19, 20, 21]; and VC was proposed by analyzing data from 123 frontal impacts to rabbits [22]. Generally all of the criteria were developed based on macro level injury responses such as impact force, deflection, acceleration and so on. However, considering the variations from subject to subject in terms of age, gender, body size even health situation, the occurrences of all the thoracic injuries, whether skeleton injuries or soft tissue injuries, must have something to do with the micro level biomechanical parameters including stress and strain etc, which should be focused on in the future work with the basis of the current study.

5 Conclusions

The correlation of different criteria for thorax injuries could be determined by using an evaluation function based on calculated injury parameters from FE modeling of the thorax impact. It indicated that among all the injury criteria, the TTI criterion well correlated the NRF. Other injury criteria have a weak connection to the NRF, including the contact force criterion, thorax deflection criterion, compression criterion, VC and upper spine acceleration criterion.

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