AN APPROACH TOWARDS DEVELOPING A THEORETICALLY BASED, STATISTICALLY JUSTIFIED, THORACIC INJURY CRITERION

J. Quinn Campbell
Rabih E. Tannous
AASA, Inc.
Erik G. Takhounts
Peter Martin
Rolf Eppinger
Stephen Ridella
National Highway Traffic Safety Administration
Thuvan Nguyen
CSMI Inc.
United States
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ABSTRACT

As measurement capabilities in crash test dummies improve, new injury criteria should be considered to take advantage of these improvements. The THOR-NT dummy thorax has been designed with three-dimensional displacement measurement capability at four points in the chest. To correlate those measurements with injury, chestband displacements from Post Mortem Human Subjects (PMHS) tests corresponding to the THOR-NT chest displacement points were used to simulate thorax loading in a 2-D finite element model of the human thorax. The model, method and model validation were described in Campbell et al. (2005). In the current study, data from both upper and lower chestbands were used to predict rib fractures in the PMHS crash tests. Due to the close proximity of the two upper THOR-NT chest displacement points, some of the simulations did not adequately represent the PMHS loading. To improve the simulations, a new set of runs were created using wider chest displacement points to determine if they would be more successful in simulating injury. Rib stress and strain from the 2-D finite element model of the PMHS thorax were used to predict injury or non-injury in the PMHS tests. Statistical analysis using logistic regression was used to investigate a new thoracic injury criterion based on the finite element model simulations.

INTRODUCTION

Thoracic injuries are among the most prevalent and serious in automobile collisions. Head injuries were the only category ranked ahead of thorax injuries in area most often injured (Ruan et al., 2003), overall number of fatalities and serious injuries (Cavanaugh, 1993), and overall societal harm (Malliaris, 1985). Improving the understanding of thoracic injury mechanisms will lead to better restraint systems that can reduce injuries and save lives.

Factors such as crash speed and intrusion contribute to thoracic injuries, as well as the presence of restraint systems, including airbags, seatbelts, load limiters, and seatbelt pretensioners. Currently experimental research using cadavers and crash test dummies is used to understand thoracic injury mechanisms. While this is an important step, computer models offer more flexibility at a lower cost. Computer models also have the ability to produce more detailed observations of stress and strain than are possible with the instrumentation used with cadavers and test dummies. The information from chest deflection and spine acceleration can be used to calculate many thoracic injury criteria, but these measures do not provide much guidance in how to improve an automobile design. The flexibility and increased measurement possibilities of computer models allow researchers to pinpoint what dummies need to measure, which will improve the ability to regulate effectively.

To design more effective restraint systems and improve regulations, researchers need to be able to investigate hypothetical scenarios, not just focus on passing a specific metric. In fact, focusing on a single value could lead a researcher in the wrong direction. Computer models provide information on a variety of factors which are all related to injury risk. This paper presents a 2-D finite element model of the human thorax designed to study injury mechanisms and restraint conditions in an automotive crash environment.

METHODS

The purpose of this study was to research a new thoracic injury criterion based on finite element model simulations of the human thorax. The method was developed to predict injury based on the thoracic measurements obtained from THOR-NT, the advanced frontal impact dummy developed by the NHTSA. The THOR-NT dummy measures chest deflection relative to the spine at 4 crux points on the chest, two upper and two lower (Figure 1). Time histories for displacement of the crux points in the x, y, and z directions are recorded. To predict injury, two finite element simulations are completed, the first using the upper crux points and the second using the lower crux points. Crux point displacements are applied directly to the model and injury is predicted based on stresses and strains measured in the model.

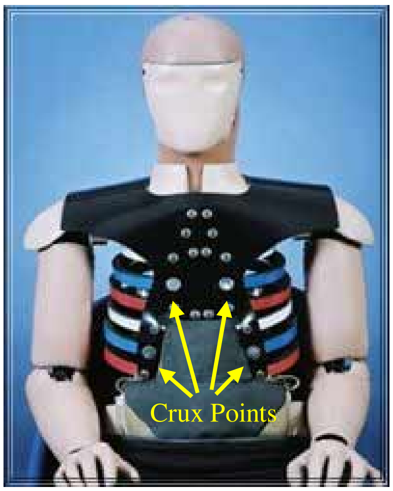

Figure 1. THOR Crux Points.

To correlate the model with injury, a set of 62 Post Mortem Human Subjects (PMHS) frontal crash tests were used. Upper and lower chestband data was recorded in each of the tests. The chestband data was processed to develop displacement time histories of points on the PMHS chest, normalized to a 50th percentile male and corresponding to the 4 crux points on the THOR-NT dummy. The displacement time histories were used to run an upper and lower thorax simulation for each PMHS test. Logistic regression was used to correlate stresses and strains in the model to the injury found during the PMHS tests.

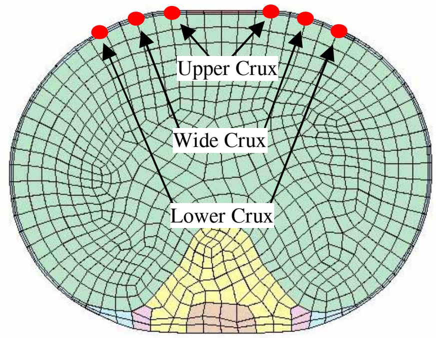

Figure 2. Crux Point Locations on 2-D Thorax Model.

A second set of PMHS simulations were also completed to test the crux point locations. The THOR-NT upper crux points are relatively close together which may affect the loading of the model. When loading occurs far away from the crux points, that loading is not simulated as well. Having the upper crux points so close together reduces the model's ability to simulate lateral loading. The second set of simulations used wider spacing for the upper crux points (Figure 2). The lower, upper, and wider crux points are spaced at 16.1cm, 11.8cm, and 7.2cm respectively. Using the wider crux points may results in more accurate simulations. To test this hypothesis these simulations were compared to the first set to determine if either set of simulations correlated more closely with injury.

In addition to peak stresses and strains, a cumulative strain damage measure (CSDM) was developed and correlated with injury. CSDM records the percent volume in the rib that has exceeded a particular strain threshold. This metric may be better suited to predicting multiple rib fractures than peak stress or strain because it takes into account the whole rib volume rather than just a localized peak stress or strain**.**

The finite element model of the thorax and its validation was presented in Campbell (2005). The model was designed using the LS-Dyna software package. The model represents a 50th percentile male thorax. It was created in two dimensions to allow simulation of the overall thorax response while dramatically reducing the solution time. The thorax model (Figure 3) contains six parts: rib, sternum, viscera, elastic spine, rigid spine, and spine/rib joint. The material properties for the model were determined through a review of the literature. The model was validated using fourteen experimental tests from Kroell et al. (1971 and 1974).

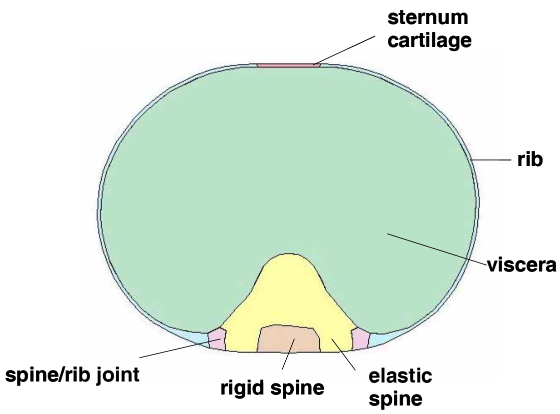

Figure 3. 2-D Human Thorax Finite Element Model.

RESULTS

Two sets of PMHS simulations were completed. Set 1 used crux points corresponding to the THOR-NT and Set 2 used wider upper crux points. A variety of logistic regressions were performed for each data set using different outputs from the simulations and different injury thresholds from 2-6 rib fractures. Simulations for the upper and lower ribs were considered both separately and together. Confounding variables were tested in the regressions as well, including PMHS age, weight, and sex. The regression with the most significance (p-value 0.0001) and highest Chi^2 (20.2) used CSDM (strain threshold of 0.01) from the lower crux simulations with cadaver age to predict injury defined as greater than four rib fractures in the entire thorax. 77% of the tests used in the regression had correct prediction of injury using the model. Figure 4 shows the probability of injury for this model at different ages using the following equation:

P = 1 / (1 + EXP(-(-3.01 + 27.5*CSDM0.01 + 0.0365*OCCAGE))).

The receiver operator characteristic (ROC) curve in Figure 5 shows the fraction of true positives to the fraction of false positives over all possible CSDM volume thresholds. A volume of 4.6% of the rib exceeding a strain of 0.01 results in a 50% probability of injury (greater than four rib fractures).

Using both lower and upper crux simulations together did not improve the model. The best model using this scenario had a p-value=0.0007 with Chi^2=17.1 and 69% predicted correctly. Using wider crux points for the upper rib simulations resulted in little change in the results. The best model using the THOR upper crux points had a p-value=0.0007 with Chi^2=17.1 and 70% predicted correctly. The best model using the wider crux points had a p-value=0.003 with Chi^2=14.2 and 73% predicted correctly.

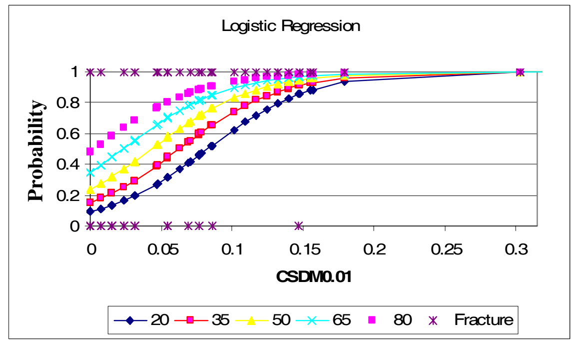

Figure 4. Logistic Regression, separated by age, with injury defined as greater than four rib fractures.

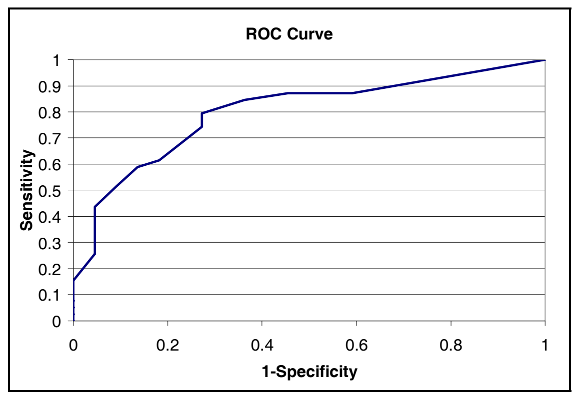

Figure 5. ROC Curve for regression model using lower rib CSDM with strain threshold of 0.01.

DISCUSSION

The results from the simulations of the PMHS tests showed that the best model for predicting injury used lower rib simulation CSDM with a strain threshold of 0.01 with PMHS age as a confounder. This result shows that CSDM is a promising method for predicting rib fractures. Since strain is linked to fracture, calculating the volume of rib that exceeds a strain threshold is a logical way to predict multiple fractures.

Figure 4 shows the regression curves for the chosen model. One may note that there is a non-zero probability when the CSDM volume equals zero. While this is a function of logistic regression, we acknowledge that it implies an unrealistic result.

A variety of other factors were tested using logistic regression including: maximum principal strain, strain rate, the product of strain and strain rate, and maximum principal stress. These factors resulted in less significant models than CSDM.

A surprising result is that the lower rib simulations had far more significance in predicting rib fractures than either of the upper rib simulations. The two different upper crux widths were tested and only a small difference was found in the results. Therefore the wider crux points do not seem to improve the loading of the model. This also suggests that the crux position is not the cause of the upper versus lower rib discrepancy. Also, based on the success of the lower rib simulations, the basic method of applying two displacement points does not seem to account for the problem with the upper ribs. It is possible that for the current dataset more information is provided in the lower chestbands.

The method of simulating thoracic loading with a 2-D finite element model provides a way to get more information out of dummy measurements and relate those measurements to injury. However, this method has some drawbacks. A 2-D model cannot account for any displacement in the z-direction. Using only two points to load the model can also result in errors in the loading depending on how close the primary deformation occurs to the crux points. Simulating PMHS tests using a large number of loading points would be useful to quantify how much error occurs with only two loading points.

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