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Prediction of thoracic injury severity in frontal impacts by selected anatomical morphomic variables through model-averaged logistic regression approach

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ABSTRACT

This study resulted in a model-averaging methodology that predicts crash injury risk using vehicle, demographic, and morphomic variables and assesses the importance of individual predictors. The effectiveness of this methodology was illustrated through analysis of occupant chest injuries in frontal vehicle crashes.

The crash data were obtained from the International Center for Automotive Medicine (ICAM) database for calendar year 1996 to 2012. The morphomic data are quantitative measurements of variations in human body 3-dimensional anatomy. Morphomics are obtained from imaging records. In this study, morphomics were obtained from chest, abdomen, and spine CT using novel patented algorithms. A NASS-trained crash investigator with over thirty years of experience collected the in-depth crash data. There were 226 cases available with occupants involved in frontal crashes and morphomic measurements. Only cases with complete recorded data were retained for statistical analysis.

Logistic regression models were fitted using all possible configurations of vehicle, demographic, and morphomic variables. Different models were ranked by the Akaike Information Criteria (AIC). An averaged logistic regression model approach was used due to the limited sample size relative to the number of variables. This approach is helpful when addressing variable selection, building prediction models, and assessing the importance of individual variables. The final predictive results were developed using this approach, based on the top 100 models in the AIC ranking. Model-averaging minimized model uncertainty, decreased the overall prediction variance, and provided an approach to evaluating the importance of individual variables.

There were 17 variables investigated: four vehicle, four demographic, and nine morphomic. More than 130,000 logistic models were investigated in total. The models were characterized into four scenarios to assess individual variable contribution to injury risk. Scenario 1 used vehicle variables; Scenario 2, vehicle and demographic variables; Scenario 3, vehicle and morphomic variables; and Scenario 4 used all variables. AIC was used to rank the models and to address over-fitting.

In each scenario, the results based on the top three models and the averages of the top 100 models were presented. The AIC and the area under the receiver operating characteristic curve (AUC) were reported in each model. The models were re-fitted after removing each variable one at a time. The increases of AIC and the decreases of AUC were then assessed to measure the contribution and importance of the individual variables in each model. The importance of the individual variables was also determined by their weighted frequencies of appearance in the top 100 selected models.

Overall, the AUC was 0.58 in Scenario 1, 0.78 in Scenario 2, 0.76 in Scenario 3 and 0.82 in Scenario 4. The results showed that morphomic variables are as accurate at predicting injury risk as demographic variables. The results of this study emphasize the importance of including morphomic variables when assessing injury risk. The results also highlight the need for morphomic data in the development of human mathematical models when assessing restraint performance in frontal crashes, since morphomic variables are more "tangible" measurements compared to demographic variables such as age and gender.

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1. Introduction

Over the last five decades, crash safety research has evaluated field data to identify predictive factors on occupant injury risks. In the earliest research, vehicle variables were investigated, including crash type, frequency, severity, intrusion, vehicle dynamics, crashworthiness, and restraint systems (Trinca and Dooley, 1975; Newman and Jones, 1984; Evans, 1984; Campbell, 1987; Mackay et al., 1992). Researchers then began assessing demographic factors such as age, gender, height, weight, and body mass index (BMI). These were shown to influence occupant response and injury outcome (Fife et al., 1984; Evans, 1985; Massie et al., 1985; Whitefield et al., 1985; Whitefield and Fife, 1987; Mock et al., 2002; Kent et al., 2003; Viano et al., 2008; Zhu et al., 2010). Today, individual occupant factors are now considered. These include medical history (Sjögren et al., 1996) and anatomical morphomic variables such as the geometry, distribution, and alignment of bone, fat, organ, muscle, and ligaments (Wang, 2001; Wang et al., 2003; Kent et al., 2005; Holcombe et al., 2008). Morphomics are obtained through a novel and patented algorithm and accurately and quantitatively measured from CT images. Being more granular level information, it will be shown in this paper to improve the risk of prediction of thoracic injury.

Chest injuries account for 29% of all serious-to-fatal (AIS 3+) injuries (Ruan et al., 2003). Vehicle and demographic variables have been evaluated to assess chest injury risks in frontal crashes. Zhou et al. (1996) reported that thoracic injuries are particularly dangerous for older occupants. Cormier (2008) developed statistical models to assess the probability of thoracic injury by crash severity, belt status, occupant age, gender, weight, and BMI. This research showed that an increase in BMI is associated with a higher injury risk in males. Stitzel et al. (2010) used logistic regression models to assess age thresholds associated with serious thoracic injuries.

Generalized linear models (GLM), such as logistic regression models and probit models are traditionally used to model binary outcome such as risk of serious thoracic injuries. However, the benefit of this methodology is greatly reduced when analyzing a large number of variables with a limited sample size and can result in model over-fitting.

The objective of this study was to develop a methodology to investigate the performance of crash and anatomical morphomic variables on prediction of injury responses. Morphomic variables are 3-dimensional measurement of the human body anatomy obtained from imaging. This study focuses on the prediction of chest injury risks for occupants involved in frontal crashes. The methodology uses a model-averaging approach to address model over-fitting. The methodology will be helpful in evaluating the importance of individual variables, minimizing model uncertainty, and providing more robust predictions on occupant injury risks.

2. Materials and methods

2.1. Crash data

The data was obtained from the University of Michigan ICAM database for calendar years 1996–2012. The data included 1990+ model year vehicles involved in frontal motor vehicle crashes. Rollovers were excluded if the extent of rollover was greater than two-quarter turns. Only cases with available CT scans were included. The analysis focused on predicting serious (MAIS 3+) chest injuries.

The data contain more than 300 crash variables, which can be divided into vehicle and demographics categories. In this study, the following variables were selected based on field relevance:

2.1.1. Vehicle data include

- Crash severity: defined as the change in vehicle velocity or Delta V.
- Longitudinal intrusion: the sum of maximum resultant displacement of intrusions in the lower, middle, and upper instrument panel areas from the longitudinal direction.
- Intrusion count: the total number of resultant displacement of intrusions to all vehicle components.
- Belt use: defined as not worn or worn (lap belt and lap-shoulder belts). Note: Belt use may be considered an occupant variable. It was included in the vehicle variables since the occupant variables were based on demographic data.

2.1.2. Demographics data include

- Gender
- Age
- Height
- Body mass index (BMI)

2.2. Anatomical morphomic data

Occupant CT scans were processed and analyzed using a proprietary, semi-automated process developed using MATLAB® software (MathWorks Inc., Natick, MA). There were 93 anatomical morphomic variables available for the analysis. The following were chosen based on the need to represent the shape and material properties of each individual occupant's body (Fig. 1):

- Body area: the cross-sectional area of the body.
- Lower chest eccentricity: the ratio of the distance between the foci of the thoracic ellipse (depth) and its major axis length (lateral width). The value is between 0 and 1 where 0 represents chest with a circular dimension.
- Visceral fat area: the area inside the fascial envelope meeting fat density thresholds.
- Body depth: the longitudinal distance from the front of the vertebral body to the fascia.
- Spine angulation: the lower thoracic spine angle along the lateral axis.
- Muscle density: the average pixel intensity of a cross-sectional area of psoas muscle.
- Trabecular bone density: the average pixel intensity of trabecular bone in a vertebral cross-section.
- Cortical bone density: the cortical bone signal at the level of half-max of the bone signal peak.
- Cortical bone variation: the cortical bone signal Std. Dev. from all 60 "Full-width-by-half-max" measurements (at 1° increments in a 60° anterior wedge).

Measures for area, depth, and density have been standardized based on a cohort of 13,000 patients in the University of Michigan morphomic database.

2.3. Consent

Informed consent to use patient CT scan was obtained as per protocol approved by the Institutional Review Board (UM HUM00041441).

2.4. Statistical models

The statistical analysis was based on the combination of the crash (vehicle and demographics) and morphomic data. There were 226 cases available with occupants involved in frontal crashes and morphomic measurements, among which there are 188 cases with complete recorded data. These account for 83.2% of total cases. The