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Development and validation of a generic finite element vehicle buck model for the analysis of driver rib fractures in real life nearside oblique frontal crashes

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ABSTRACT

Objective: Frontal crashes still account for approximately half of all fatalities in passenger cars, despite several decades of crash-related research. For serious injuries in this crash mode, several authors have listed the thorax as the most important. Computer simulation provides an effective tool to study crashes and evaluate injury mechanisms, and using stochastic input data, whole populations of crashes can be studied. The aim of this study was to develop a generic buck model and to validate this model on a population of real-life frontal crashes in terms of the risk of rib fracture.
Method: The study was conducted in four phases. In the first phase, real-life validation data were derived by analyzing NASS/CDS data to find the relationship between injury risk and crash parameters. In addition, available statistical distributions for the parameters were collected. In the second phase, a generic parameterized finite element (FE) model of a vehicle interior was developed based on laser scans from the A2MAC1 database. In the third phase, model parameters that could not be found in the literature were estimated using reverse engineering based on NCAP tests. Finally, in the fourth phase, the stochastic FE model was used to simulate a population of real-life crashes, and the result was compared to the validation data from phase one.
Results: The stochastic FE simulation model overestimates the risk of rib fracture, more for young occupants and less for senior occupants. However, if the effect of underestimation of rib fractures in the NASS/CDS material is accounted for using statistical simulations, the risk of rib fracture based on the stochastic FE model matches the risk based on the NASS/CDS data for senior occupants.
Conclusion: The current version of the stochastic model can be used to evaluate new safety measures using a population of frontal crashes for senior occupants.

1. Introduction

According to the Insurance Institute for Highway Safety (2015), more than 21 000 occupants were killed in passenger cars during 2013 in the US. Of these cases, approximately half were killed in frontal impacts. The thorax has been listed as the primary body part injured in frontal crashes by several authors, including Sherwood et al. (2009), Hallman et al. (2011) and Rudd et al. (2011), and rib fractures dominate among thorax injuries, according to Crandall et al. (2000) and Carroll et al. (2010).

As real-life crashes vary considerably, it is infeasible to test all possible configurations in the traditional manner, which is vehicle-to-barrier or vehicle-to-vehicle crash tests using physical vehicles. Instead, computer simulations provide an effective and cost-effective alternative. However, before a computer model can be useful, it must be validated, i.e., it must be shown that it can reproduce the characteristics of the physical vehicle and that it can reproduce the injury mechanisms and the injury risk.

An alternative to car-specific simulation models for the reconstruction of real-life crashes is to develop a generic and parameterized model that can be tuned to represent different vehicle models. This approach has previously been taken by Buzemanjewkes et al. (1999) and Kim et al. (2005). These models are usually validated by comparing the simulation model response, structural and/or crash dummy injury values, to physical barrier

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tests. However, the kinematics of the crash dummy in a barrier crash test is comparatively controlled and is only representative of a subset of the injury mechanisms observed in real-life crashes.

A way to further validate such a model is to perform crash reconstructions. However, there is one major problem with crash reconstructions: several parameters of the actual crash are usually uncertain or unknown. These parameters include, but are not limited to, the following:

- Geometrical parameters such as the initial position of the passenger, seat, steering wheel and seat belt.
- Pulse parameters such as shape of the pulse, the duration, the principle direction of the force (pdof) and the vehicle rotation.
- Occupant parameters such as injury thresholds for the specific occupant(s) of that crash.

This problem can to some extent be solved by performing parameter studies, as in Hasija et al. (2007), or by the optimization of unknown variables, which was performed in Hasija et al. (2009). However, the major problem in these studies is that occupant injury was evaluated according to a fixed level, namely the injury assessment reference level (IARV). In reality, IARV values represent a level or a percentage of injury risk level, measured in a population of individuals, and it is impossible to know whether this level is correct for the actual occupant in the injury reconstruction.

To overcome the fundamental problem of the parameter uncertainty in crash reconstructions, one can model a population of crashes instead. In such an approach, the distribution for each uncertain parameter is modeled by using, for example, a Gaussian distribution. Then, a large number of simulations are performed, in which the parameter values in each simulation are sampled from these parametric distributions. The result is a large number of simulations, each giving a risk of injury that can be compared to injury risk functions for each body region. Further, the injury risk can be linked to the input parameters using regression analysis. The distribution of the injury risk as a function of the input parameters can then be compared to the distribution of the injury risk in real-life crashes. If the distributions are similar, the model could then be considered to be validated for this population of car crashes. To the best of the authors' knowledge, this approach has not been taken previously.

The aim of this study is to develop a generic buck model and to verify and validate this model using a population of real life collinear and nearside oblique frontal crashes in terms of the risk of rib fractures. After validation, such a model can be used to test new chest injury countermeasures in real-life crashes.

2. Method

The development and validation procedure used in this study can be briefly summarized in four phases:

1. Analyze NASS/CDS data to find distributions for crash parameters such as ΔV, PDOF and intrusions and to determine the validation set.
2. Create a generic, parameterized finite element (FE) model of a vehicle interior. Define the related parameter distributions found in the literature.
3. Estimate the remaining model parameters using reverse engineering based on NCAP testing.
4. Simulate a population of real-life crashes using the FE model, create rib fracture risk curves and compare the result to the NASS/CDS risk curves in phase 1.

Parameter distributions for the generic model will thus be collected from three sources. NASS/CDS includes information on the crash parameters ΔV, PDOF and intrusions, and the distributions for these will be derived during phase 1. Distributions for the vehicle parameters that can be found in the literature will be defined during phase 2. The remaining parameter distributions will be estimated using reverse engineering of NCAP frontal tests during phase 3. All parameter distributions defined during phases 1–3 have been collected in Appendix B.

2.1. Analyze NASS/CDS data to find distributions for crash parameters and to create a validation set

The primary inclusion criteria for the study were frontal impacts (GAD1 = "F") of modern vehicles (MY = 2000+) that occurred in 2000 through 2012, with drivers only (SEATPOS = 11). Collinear and near-side oblique collisions was defined as collisions in which it could be expected that the driver would interact with the airbag and/or the side structure, and these cases were selected based on the principal direction of force (315 < PDOF < 360 or PDOF < 11). All cases where the vehicle had rolled (ROLLOVER > 0) were excluded. Finally, only cases where the driver was belted (determined from vehicle inspection) and the steering wheel airbag inflated during the crash were used. These criteria resulted in a raw data set of size n = 6944 (2,096,970 cases weighted).

In addition, as ΔV and occupant age were considered to be important parameters by Ryb et al. (2007), Zhang et al. (2013) and Carter et al. (2014), only cases containing these parameters were selected. This exclusion resulted in a final sample size of n = 5083 cases (1,474,869 cases weighted) with 185 occupants (17,810 occupants weighted) who sustained an AIS2+ rib fracture injury and 120 occupants (11,271 occupants weighted) who sustained an AIS3+ rib fracture injury.

Covariates from NASS/CDS were pulse parameters: total change in velocity (DVTOTAL) and pulse direction (PDOF); vehicle buck deformation parameters: intrusion of instrument panel (LPINTR) and floor (LTPINTR); and finally the occupant age parameter (AGE).

The statistical analysis was conducted in R version 3.0.3, R Core Team (2014). To use the NASS/CDS case weights (RATWGT), the R package 'survey', Lumley (2015), was used for the logistic regression. Conditional plots with 95% confidence bands were computed and created using the R package 'visreg' by Breheny and Burchett (2015).

Rib cage injuries with AIS2+ and AIS3+ levels, according to AIS 2005, were analyzed. These injuries were defined in NASS/CDS as REGION90 = 4 (chest), STRUCTURE = 5 (skeletal) and STRUSPEC = 02 (ribcage). For case years 2000–2009 the AIS 1990 (update 1998) codes were recoded to AIS 2005, by analyzing the medical information in NASS/CDS. 25 injuries were originally coded as "Multiple rib fractures NFS" or "Rib cage fracture 2–3 ribs", which means that it is not possible to know if these are AIS2+ or AIS3+ injuries according to AIS2005. These injuries were conservatively coded as AIS2+ injuries. Finally two binary (0/1) variables (AIS2+ and AIS3+) were created, which were used as dependent variables in the regression analysis.

In addition, the distributions of ΔV, PDOF, instrument panel intrusion and floor panel intrusion were analyzed, and parametric distributions were fitted to each of these parameters for later use in the simulation model in Section 2.4.

2.2. Create a generic, parameterized finite element (FE) model of a vehicle interior

The important parts for this study of the vehicle interior are the structures that the occupant will interact with during a purely longitudinal or nearside oblique frontal crash. The important