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Thorax Injury Prediction in Finite Element Reconstructions of Crash Injury Research and Engineering Network Frontal Crashes

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ABSTRACT

Finite element reconstructions of real-world crashes using human body models are helpful tools for predicting injuries and supplementing crash investigations. 9 frontal impact Crash Injury Research and Engineering Network (CIREN) cases were reconstructed using a novel methodology involving the transformation of a simplified vehicle model to approximate exemplar vehicle 3D scans. Selection was limited to belted occupants with BMI between 20 and 35 and crashes involving vehicles with a model year of 2013 or later, a principal direction of force between 340° and 20°, and an available event data recorder report. The reconstruction process involved 3 steps. The first step involved acquiring a 3D scan of the interior of an exemplar version of the case vehicle and rigidly transforming a finite element simplified vehicle model to approximate the interior scan. The second step involved scaling the Global Human Body Models Consortium (GHBMC) 50th percentile male simplified occupant finite element human body model and settling it into the vehicle model. The third step involved applying the event data recorder reported delta-V velocity curve to the floor of the simplified vehicle model to simulate the crash. Post-processing analysis for each crash involved comparison of chest compression to the occupant's injuries. The average chest compression was 22.8% for occupants who sustained a soft-tissue injury and 22.4% for occupants who did not, 24.5% for occupants who sustained a sternum fracture compared to 20.2% for occupants who did not, and 24.3% for those who sustained ≥3 rib fractures and 19.2% for those who sustained <2 rib fractures. Beyond the quantitative results, CIREN finite element reconstructions provided a visualization of occupant kinematics and served as a helpful supplement to CIREN case reviews.

INTRODUCTION

Approximately 1.35 million people are killed in motor vehicle crashes (MVCs) annually worldwide and an estimated additional 20-50 million people sustain non-fatal injuries (WHO, 2018). Although laboratory crash tests using anthropomorphic test devices (ATDs) and sled tests using post mortem human subjects (PMHSs) provide essential information about occupant-restraint interactions and occupant injuries, the time and monetary cost required for each test limits the number of crash scenarios that can be tested (Jones et al., 2016). Real-world crashes rarely match the conditions of ATD and PMHS tests because of the wide variability in crash characteristics, including vehicle trajectories, occupant morphologies, and occupant postures. Some studies, such as the Crash Injury Research and Engineering Network (CIREN) and the National Automotive Sampling System/Crashworthiness Data System (NASS-CDS) conduct post-crash investigations of actual crashes to evaluate restraint systems and occupant injuries in real-world conditions.

The CIREN study investigates injury causation and mechanism in real-world crashes by collecting police records, medical records, and occupant interviews and conducting investigations of the crash vehicle and scene for each CIREN case. These investigations may be supplemented through the use of finite element (FE) human body models (HBMs) to visualize occupant kinematics and calculate organ level injury metrics in FE crash reconstructions (Shigeta et al., 2009). Previous studies have developed FE reconstructions of CIREN cases to predict injury. Golman et al. simulated a near-side impact of a 2001 Ford Taurus using an open-source full-vehicle FE model available from the National Crash Analysis Center (NCAC) public database in order to predict full-scale injury metrics using the Total Human Model for Safety (THUMS) FE HBM (Golman et al., 2014). This study was limited by the availability of full-scale vehicle models, however, which is a common limitation of crash reconstructions. To address this, a simplified vehicle model (Iraeus and Lindquist, 2016) representative of a range of vehicle interiors was implemented by multiple studies to increase the generalizability of real-world reconstructions (Gaewsky et al., 2014, Gaewsky et al., 2015, Jones et al., 2016, Jones et al., 2016, Ye et al., 2018, Ye et al., 2018). Together, these studies reconstructed 11 frontal crashes from the NASS-CDS and CIREN databases using the simplified vehicle model, the THUMS FE HBM, and the case vehicle event data recorder (EDR) information. The vehicle model safety parameters for these reconstructions were estimated by reverse-engineering National Crashworthiness Assessment Program (NCAP) frontal barrier crash tests involving the case vehicle. These reconstructions were limited to frontal crashes (350-10 PDOF) with occupants close to the 50^{th} percentile male in height and mass.

The objective of this study was to develop a more time-efficient methodology for reconstructing a wide range of MVCs, to apply this methodology to 9 CIREN frontal crashes, and to compare the computed thoracic injury risk to case occupant injuries. There is often a 2-week period in which CIREN cases are reviewed to determine occupant kinematics and injury causation. The proposed methodology can be completed within 1 week to allow for the reconstruction of multiple cases.

METHODS

9 frontal impact CIREN cases (Table 1) between 2018-2019 were selected from the list of upcoming Wake Forest cases that were currently under investigation. Selection was limited to belted occupants with BMI between 20 and 35 and crashes involving vehicles with a model year of 2013 or later, a principal direction of force (PDOF) between 340° and 20°, and an available event data recorder (EDR) report. Reconstructions were conducted using a three-step process. The first step involved acquiring a 3D scan of the interior of an exemplar version of the case vehicle and rigidly transforming a FE simplified vehicle model (SVM) to best approximate the exemplar vehicle scan. The second step involved positioning and settling the 50^{th} percentile male simplified Global Human Body Models Consortium (GHBMC) FE HBM into the vehicle model. The third step involved applying the EDR-reported delta-V velocity curve to the floor of the SVM to simulate the crash.

Step 1: SVM Preparation

The SVM for this study was created as a generic vehicle interior for analyzing rib fractures sustained in frontal and near-side oblique crashes. Full details of the development of the SVM are found in Iraeus and Lindquist (Iraeus and Lindquist, 2016). In short, detailed laser scans of 14 different vehicle interiors were averaged and merged and the vehicle safety parameters were estimated by reverse-engineering New Car

Assessment Program (NCAP) crash tests. Later studies augmented the model by including a seat back and a previously developed compressible steering column, steering wheel, and airbag (Marzougui et al., 2012, Gaewsky et al., 2015). The steering wheel frontal airbag (*AIRBAG_SIMPLE_AIRBAG_MODEL card in LS-DYNA) was based on an open source National Crash Analysis Center inflating airbag model (Marzougui et al., 2012).

Table 1. List of cases selected for reconstruction. A positive lateral delta-v indicates rightward motion.

Case	Vehicle	Sex	Age	Height (cm)	Mass (kg)	BMI	Long DV (km/hr)	Lat DV (km/hr)	PDOF
1	2013 Murano	F	61	180	82	25.3	-45	-2	0
2	2013 ES-350	M	66	180	75	23.1	-64	-5	10
3	2015 Accent	M	19	168	71	25.2	-79	-34	20
4	2018 Fiesta	F	49	173	79	26.4	-61	+6	350
5	2014 ATS	F	88	170	69	23.9	-56	-6	0
6	2017 Cruze	F	56	152	60	26.0	-71	+10	350
7	2016 Sedona	M	72	191	117	32.1	-44	-1	0
8	2013 Sonata	F	57	157	59	23.9	-47	-2	350
9	2015 Cherokee	M	87	182	82	24.8	-71	+11	0

The interior of an exemplar version of the case vehicle or a sister or clone of the case vehicle that had the same interior geometry was scanned using a Faro Freestyle 3D scanner. Three interior scans of the driver compartment were collected for each vehicle to capture all aspects of the interior geometry that must be adjusted in the SVM. These components included the seat bottom, seat back, steering wheel, a-pillar, b-pillar, door, roof, dashboard, knee bolster, and center console. Prior to scanning, the seat, d-ring, and steering wheel of the exemplar vehicle were adjusted to approximate the recorded positions and photos in the CIREN case report. The scans were processed to generate a shell representative of the exemplar vehicle geometry. The shell was aligned to the SVM in LS-PrePost and each part of the SVM was rigidly translated and rotated until it closely approximated the geometry of the same part of the exemplar vehicle shell (Figure 1). In cases where a knee bolster airbag deployed, the knee bolster airbag was represented by a low density foam block attached to the SVM knee bolster (Figure 2) (Ye et al., 2018).

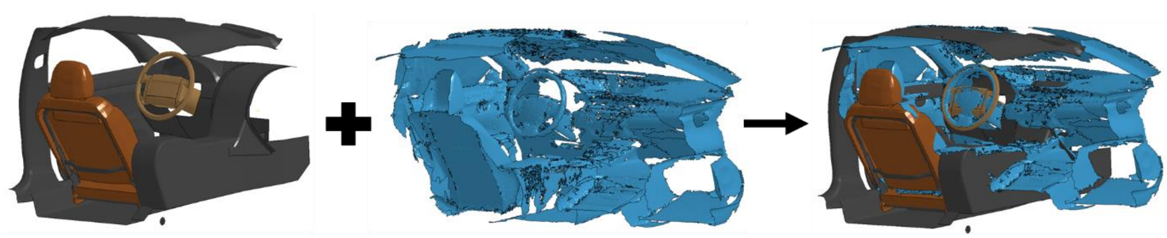

Figure 1. Rigid transformation of the simplified vehicle model to approximate the shell geometry of the interior of the case vehicle.

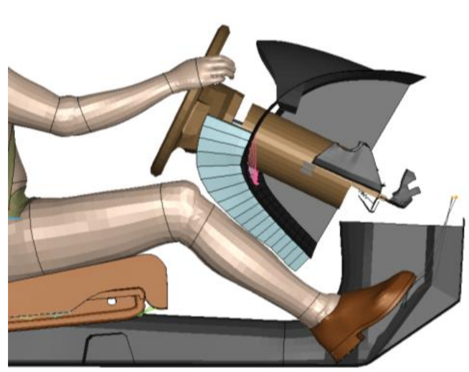

Figure 2. Foam block representative of a knee bolster airbag (Ye et al., 2018)

Step 2: HBM Settling

The GHBMC simplified 50th percentile male occupant (M50-OS) model was used in all reconstructions. The M50-OS model was scaled with respect to height and mass to approximate the case occupant height and mass using a scaling factor determined from Eq. (1). This scaling factor was used to isometrically scale the M50-OS model node coordinates in the X-, Y-, and Z-axis directions (Ye et al., 2018). The M50-OS model was then positioned just above the seat to prepare it for settling. At this point, if the HBM did not fit properly into the SVM (i.e. the hands could not realistically reach the steering wheel or the knees intersected the knee bolster), the SVM seat was adjusted as little as possible to obtain a more suitable fit for the HBM. During crash investigations, the current location and posture of the case vehicle seat is recorded, but it is not entirely reliable due to adjustments performed by emergency medical services during extraction or vehicle lot staff during cleaning.

$$Scale\ Factor = \frac{\left(\frac{Case\ Occupant\ Height}{GHBMC\ Height}\right) + \left(\sqrt[3]{\frac{Case\ Occupant\ Mass}{GHBMC\ Mass}}\right)}{2} \tag{1}$$

During settling the M50-OS model was subjected to a gravitational force of 7.85 N in the Z-axis direction and -4.90 N in the X-axis direction while moving the extremities to the proper locations. The hands were placed at the 10 o'clock and 2 o'clock steering wheel positions. If there was evidence of pre-impact braking or acceleration from the EDR, the right foot was moved to the appropriate pedal. All adjustments were conducted in a single 500 ms settling simulation. Application of the 3-point belt restraint was performed in LS-PrePost. Fat renderings that reveal subcutaneous fat bruising were generated for each occupant to assist in determining the correct placement of the belt (Hartka et al., 2014).

Step 3: Crash Simulation

The longitudinal and lateral delta-V crash pulse curves from the EDR report were applied as boundary prescribed velocities to the floor of the SVM. If available from the EDR report, roll was included. Otherwise, roll was ignored. EDR-reported airbag deployment and belt pretensioner actuation times were implemented into the simulation. Simulation length was determined by the length of the delta-V curves recorded by the EDR, which was generally between 250-300 milliseconds.

Data Analysis

Anterior-to-posterior chest compression was calculated for each reconstruction by measuring the distance from the superficial skin anterior to the sternum at the level of the 4^{th} intercostal space to the posterior end of the T7 spinous process (Figure 3) (Viano and Lau, 1988). Chest compression was calculated as a percentage of the undeformed chest depth and the maximum value was recorded for analysis. A timeline of the reconstruction process is given in Table 2.

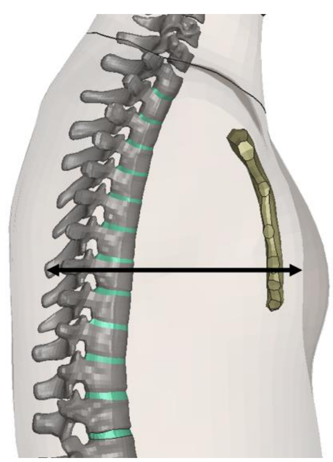

Figure 3. Measurement of chest compression

Table 2. Reconstruction timeline.

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Obtain and process exemplar vehicle scans	Extract scans and develop exemplar shell	Transform the simplified vehicle model	Settling simulation setup and execution	Crash simulation setup and execution	Data analysis

RESULTS

Five case occupants sustained at least 1 thorax soft-tissue injury, 5 occupants sustained a sternum fracture, and 6 sustained 3 or more rib fractures (Table 3). All simulations normal terminated once they reached the end of the EDR-reported delta-v curves (250-300 ms). Thorax injuries were divided into 3 groups: soft-tissue, rib, and sternum. Soft-tissue injuries included any AIS 2+ injuries of the lungs or mediastinum, such as contusions, hematomas, and/or pneumothoraces.

The highest maximum chest compression in a reconstruction was 29.5% in Case 2 and the lowest was 14.2% in Case 4 (Range: 15.3%). The maximum reconstruction chest compression for occupants with thorax soft-tissue injuries was not significantly higher than those without soft-tissue thorax injuries (injured 22.8%, non-injured 22.4%, Table 4). When comparing reconstruction chest compression between occupants with a sternum fracture to those without a sternum fracture, there was a more observable difference (injured 24.5%, non-injured 20.2%). A similar result was identifiable when comparing reconstruction chest compression between occupants with 3 or more rib fracture to those with less than 3 rib fractures (injured 24.3%, non-injured 19.2%).

Table 3. Case occupant injury status. An X indicates the presence of that type of injury for that case occupant.

Case Number	Sex	Age	Injury Status		
			Soft-Tissue	Sternum Fracture	≥3 Rib Fractures
1	F	61	X	X	X
2	M	66	X	X	X
3	M	19	X	X	X
4	F	49	X		
5	F	88			X
6	F	56			X
7	M	72	X	X	X
8	F	57		X	
9	M	87			

Table 4. Average reconstruction maximum chest compression for occupants with (+) vs. without (-) injury based on injury type.

Injury Status	Average Maximum Chest Compression (%)		
	Soft-Tissue	≥3 Rib Fractures	≥3 Rib Fractures
+	22.8 ± 6.0	24.5 ± 3.2	24.3 ± 3.2
−	22.4 ± 2.1	20.2 ± 5.2	19.2 ± 5.3

DISCUSSION

The current study developed a novel methodology for reconstructing a wide range of real-world crashes using cases from the CIREN database tested the effectiveness of this methodology by comparing thorax injuries between reconstructions and corresponding case occupants in 9 frontal crash reconstructions. When assessing maximum chest compression, there were observable differences between reconstructions of injured vs. non-injured occupants for sternum fractures and 3 or more rib fractures, but not for thorax soft-tissue injuries. However, maximum chest compression values were lower than would be expected for the given injury severities. Kroell et al. analyzed a series of thoracic blunt impact experiments and determined the following linear relationship between AIS injury rating and chest compression:

$$AIS = -3.78 + 19.56C \quad (2)$$

where C is the maximum chest compression. In this relationship, an AIS rating of 2 corresponds with a maximum chest compression of 29.5% (Kroell et al., 1971, Kroell et al., 1974). As stated previously, the maximum chest compression for all reconstructions was 29.5%, which is right at the AIS 2 injury threshold. Considering 8 out of the 9 cases experienced at least one AIS 2 thorax injury and 7 out of the 9 experienced at least 1 AIS 3 thorax injury, these chest compression values are lower than would be expected for the given injury severity.

Low chest compression values are not abnormal in the M50-OS model. In a series of validation tests for the M50-OS model, Schwartz et al. found that thoracic hub impact tests resulted in anterior-to-posterior chest compression results that were approximately 5-7% lower than the experimental mean (Schwartz, 2015, Schwartz et al., 2015). Using a more recent version of the GHBMC model, Decker et al. performed a series of validation tests to compare the biofidelity of the detailed GHBMC model, the simplified GHBMC model, and the simplified GHBMC model with internal organs from the detailed GHBMC model and found that, though the maximum chest compression values were 2-3% higher than those found by Schwartz et al., they were still lower than the average experimental chest compression (Decker et al., 2018). This reveals that the relationship between AIS and chest compression defined by Kroell et al. is not optimal for comparing the chest compression of the M50-OS model to occupants in real-world crashes.

There are several key limitations to this study. Reconstructions, by nature, are simply approximations of the actual crash and must assume several details about the actual case that are unknown. Occupant posture, seat position, steering wheel position, and seatbelt placement, for example, are not known with complete certainty and must be assumed in many cases. Occupant compartment intrusion and side airbags were not included in any simulations, which affected the accuracy of cases with significant intrusion, such as Case 4, and cases with 340-350 PDOFs that likely involved interaction with the side airbags. Though isometric scaling was used to approximate the height and mass of case occupants, there is a large amount of variability in occupant age and morphology for which the models did not account. Only anterior-to-posterior chest compression was measured, though some of the cases involved more complex loading scenarios that would have been better accounted for using chest-band measurement techniques. Lastly, only 9 cases were reconstructed, making it difficult to determine statistical significance for any injury metrics when comparing injured vs. non-injured occupants.

Future work will be focused toward conducting more reconstructions, streamlining the methodology, addressing study limitations, and expanding the use of the reconstructions. Currently, reconstructions take around 5-6 days to complete from beginning to end once the exemplar vehicle scan is obtained. Parameterization of specific components, such as the seat position, steering wheel position, and shoulder belt anchorage adjustor height will help to address uncertainties associated with occupant positioning and provide some automation of the methodology, shortening the reconstruction timeline. Driver compartment intrusion and side airbags will be included, which will allow for the reconstruction of near-side crashes and improve the accuracy of frontal crashes. Morphed M50-OS models will be investigated as an alternative to scaling, particularly for individuals with higher BMIs, to determine which approach is more appropriate. Age will be factored in either using adjustable parameters in the models or variables in the post-simulation data analyses.

CONCLUSIONS

A methodology for reconstructing CIREN cases was developed using a simplified vehicle model and the 50th percentile male GHBMC simplified occupant human body model and tested in 9 CIREN cases with primarily frontal PDOFs. There was a difference in average maximum chest compression values between occupants with vs. without sternum fractures and 3 or more rib fractures. Overall, finite element CIREN reconstructions provide a visualization of occupant kinematics and may serve as a helpful supplement to CIREN case reviews.

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