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Injury prediction in a side impact crash using human body model simulation

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ABSTRACT

Background: Improved understanding of the occupant loading conditions in real world crashes is critical for injury prevention and new vehicle design. The purpose of this study was to develop a robust methodology to reconstruct injuries sustained in real world crashes using vehicle and human body finite element models.
Methods: A real world near-side impact crash was selected from the Crash Injury Research and Engineering Network (CIREN) database. An average sedan was struck at approximately the B-pillar with a 290 degree principal direction of force by a lightweight pickup truck, resulting in a maximum crush of 45 cm and a crash reconstruction derived Delta-V of 28 kph. The belted 73-year-old midsized female driver sustained severe thoracic injuries, serious brain injuries, moderate abdominal injuries, and no pelvic injury. Vehicle finite element models were selected to reconstruct the crash. The bullet vehicle parameters were heuristically optimized to match the crush profile of the simulated struck vehicle and the case vehicle. The Total Human Model for Safety (THUMS) midsized male finite element model of the human body was used to represent the case occupant and reconstruct her injuries using the head injury criterion (HIC), half deflection, thoracic trauma index (TTI), and pelvic force to predict injury risk. A variation study was conducted to evaluate the robustness of the injury predictions by varying the bullet vehicle parameters.
Results: The THUMS thoracic injury metrics resulted in a calculated risk exceeding 90% for AIS3+ injuries and 70% risk of AIS4+ injuries, consistent with her thoracic injury outcome. The THUMS model predicted seven rib fractures compared to the case occupant's 11 rib fractures, which are both AIS3 injuries. The pelvic injury risk for AIS2+ and AIS3+ injuries were 37% and 2.6%, respectively, consistent with the absence of pelvic injury. The THUMS injury prediction metrics were most sensitive to bullet vehicle location. The maximum 95% confidence interval width for the mean injury metrics was only 5% demonstrating high confidence in the THUMS injury prediction.
Conclusions: This study demonstrates a variation study methodology in which human body models can be reliably used to robustly predict injury probability consistent with real world crash injury outcome.

1. Introduction

Motor vehicle crashes (MVCs) account for approximately 1.2 million deaths each year worldwide and are predicted to become the fifth leading cause of death by 2030 (WHO, 2009). Each year in the United States, MVCs are responsible for 30 thousand deaths, 1.5 million injuries, and over $70 billion of lifetime costs (Naumann et al., 2010). Improving the understanding of injury mechanisms and the effectiveness of injury mitigation systems in real world crash scenarios is important for the design of safer vehicles (Yoganandan et al., 2007). For this reason, human body finite element models (FEMs) have been developed to investigate injury and crashworthiness of motor vehicles at a level of detail difficult to achieve with physical tests with anthropomorphic test devices (ATDs).

The field of injury biomechanics has a long history of using numerical models of the human body (Yang et al., 2006). Previous studies have used FEMs of isolated anatomical regions including the brain (Zhang et al., 2001; Takhounts et al., 2008), eye (Stitzel et al., 2002), aorta (Shah et al., 2001), and lungs (Gayzik et al., 2007), to develop novel organ level injury metrics. When investigating impact scenarios involving interactions with the entire body, human body models (HBMs) are a valuable tool (Gayzik et al., 2012; Vavalle et al., 2012). An example of a HBM is the Total Human Model

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for Safety (THUMS) (Iwamoto et al., 2002; Shigeta et al., 2009). Using THUMS, the injury potential of different astronaut suit configurations in various loading conditions was evaluated (Danelson et al., 2011a; Golman et al., 2012). THUMS has also been used to study the effects of seatbelt location on bilateral carotid artery injuries in far side impact (Danelson et al., 2009). The biomechanical response differences in a Hybrid III and THUMS was investigated for various belt and airbag configurations in a frontal crash (Mroz et al., 2010). One of the advantages of using a HBM is that the kinematics, rib strains, and internal organ pressures can be analyzed to investigate the effectiveness of injury mitigation systems (e.g. side airbags) (Hayashi et al., 2008). All of these aforementioned HBM studies used THUMS to investigate the human body response in simulated controlled laboratory tests. Another application of using HBMs is to reconstruct real world crashes.

HBMs can be used to predict injury risk from real world crashes, a desirable capability for improving automobile safety. One of the first versions of THUMS was used to successfully reconstruct bone fracture in a real world frontal crash (Iwamoto et al., 2002). Aortic rupture modes were investigated by reconstructing real world side impacts from the Crash Injury Research and Engineering Network (CIREN) database (Siegel et al., 2010; Belwadi et al., 2012). While these studies reconstructed real world crashes, no study has comprehensively analyzed the HBM response and predicted injury risks. The purpose of this study was to build the framework and evaluate the THUMS capability to predict injuries in a real world MVC.

2. Methods

A real world crash from the CIREN database was reconstructed using complete vehicle finite element models from the National Crash Analysis Center publically available database and a state-of-the-art human body model. Simulations were performed using the explicit finite element software, LS-DYNA MPP971 R4.2.1 (Livermore Software Technology Corporation, Livermore, CA), on a Red Hat Linux computational cluster. All output data from the LS-DYNA simulation was automatically batch processed using the Injury Prediction Post Processor (IPPP), custom in-house MATLAB (MathWorks, Natick, MA) software.

2.1. The real world crash

The real world side impact crash was selected from the CIREN database based on its similarities to the Federal Motor Vehicle Safety Standard (FMVSS) 214 and common injury frequency reported in side impact crashes. The case occupant was a 73-year-old female with 173 cm height and 75 kg weight; therefore, her anthropometry approximately represented a 50th percentile male (175 cm and 77 kg). She was the belted driver of a 2001 Ford Taurus sedan with no side air bag. The case vehicle was struck while performing a left hand turn through an intersection by a 1997 Toyota Tacoma pickup truck resulting in moderate left side damage (CDC 10LZEW3), a maximum crush of 44 cm at the B-Pillar, 11.7 kph lateral Delta-V and 20.1 kph longitudinal Delta-V as measured by the event data recorder (EDR), and WINSMASH Delta-V of 28 kph.

The case occupant was presumed to be seated in an upright posture with the seat adjusted to a mid-track position. She sustained AIS2+ injuries to her left lung, ribs, and brain that were reconstructed through the simulations (Table 1). She also sustained other injuries that were not compared to the simulation results (Table 2). Her thoracic and abdominal injuries were caused by the intruding left front door with documented contacts on the upper door quadrants. The age of the occupant and her fragility was determined to be a contributing factor to the severity of rib fractures (Kent et al., 2009). Her head contact to the roof rail was inferred, as there was no contact evidence. The case occupant had no AIS2+ pelvic injury, but large amounts of bruising due to a partial gluteal muscle avulsion. Using semi-automatic medical image segmentation techniques (Danelson et al., 2007, 2011b; Urban et al., 2012) 0.52% of the brain, 19.9% of the lung, and 0.15% of the spleen were identified as volumes indicative of the location and severity of injury.

Table 1
Reconstructed case occupant AIS2+ injuries.

AISCODE	Description
442203.4	Left pneumothorax
441408.3	Left upper and lower lobe contusions
450203.3	Left 1st thru 10th; Right 3rd rib fracture
140651.3	Left frontal subdural hemorrhage (SDH)
140694.2	Left temporoparietal subarachnoid hemorrhage (SAH) in the cortical sulci

Table 2
Additional case occupant AIS2 injuries not compared to simulation results.

AISCODE	Description
544222.2	Grade 1 splenic injury with small amount of fluid at the inferior pole
541610.2	Left kidney contusion
840405.2	Minimally displaced medial tibial plateau avulsion fracture
854463.2	Right bimalleolar fracture
650220.2	Left C7 transverse process fracture

Table 3
Validation tests conducted by NCAC for the updated Taurus model using National Highway Traffic Safety Administration (NHSTA) and Insurance Institute for Highway Safety (IIHS) crash test data. MDB = moving deformable barrier.

Crash test type	Comparison crash test data
Frontal, full wall (56 kph)	NHTSA: 3248, 4150, 4776, 5143
Frontal, full wall (48 kph)	NHTSA: 3150, 3224, 4134, 4135, 4174
Frontal, offset (64 kph)	NHTSA: 3365
Rigid pole, offset (56 kph)	IIHS: CF05001
Rigid pole, offset (64 kph)	IIHS: CF05002
Side impact, MDB (62 kph)	NHTSA: 3263

2.2. Vehicle finite element models

Vehicle FEMs were chosen from the National Crash Analysis Center (NCAC) publically available database. The 2001 Ford Taurus FEM, which was the same model and year as the case vehicle, was selected to represent the struck vehicle. The updated Taurus FEM has additional validation from a side impact crash test as well as a wider variety of frontal crash tests (NCAC, 2012) (Table 3). The bullet vehicle in the CIREN case was a 1997 Toyota Tacoma; however, the Tacoma FEM was not available in the NCAC database. The most similar vehicle FEM was a 1997 Toyota RAV4 based on the vehicle weight and outer dimensions (Table 4). The RAV4 and Tacoma frontal stiffness was calculated from the force-stroke data from full frontal crash tests which indicated that the RAV4 was a valid substitute for the Tacoma up until 15 cm of stroke. The

Table 4
Tacoma to RAV4 vehicle comparison.

Comparison parameter	1997 Toyota Tacoma	1997 Toyota RAV4
Weight (kg)	1245	1265
Front overhang (cm)	72	74
Front track width (cm)	143	148
Overall width (cm)	169	170
Bumper height (cm)	46.5	47.7
Frontal stiffness (kN)	1360	1600