Variation in Real World Crash Simulation Injury Metrics Given Crash Parameter Perturbations

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Abstract

Real world crash simulations of Motor Vehicle Crashes using human body finite element models (HBMs) have the potential to elucidate injury mechanism and predict injury risks. One limitation of these simulations is the inherent uncertainty of real world crash measurements compared to laboratory measurements. The purpose of this study was to develop a method to assess a potential range of response parameters of a HBM given slight perturbations of crash parameters. The Total HUman Model for Safety (THUMS) version 4 was used in the simulation of a Crash Injury Research and Engineering Network real-world crash. Vehicle models of the Ford Taurus and Toyota RAV4 from the National Crash Analysis Center Finite Element Model database were used as the struck and striking vehicles, respectively. The case was simulated and iteratively improved until the simulation crush profile was optimized based on the recorded case data. Next, crash parameters were varied over a range of values about the final case values for a one-factor-at-a-time variation study: lateral delta-V (0-3 m/s), longitudinal delta-V (13-17 m/s), crush location (239-289), and rotational velocity (3-5 rad/s). Injury metrics (Thoracic Trauma Index, half deflection, and pelvis force) were calculated for each variation simulation and analyzed to determine the effect of variation on injury metric outcome through confidence intervals and a sensitivity analysis. The variation in the thoracic injury metrics was low indicative of small changes in the crash parameters resulting in small changes in chest injury risk. In contrast, the pelvis risk of injury changed more with changes in the crash parameters. These differences in response were attributed to the initial location of the injury metrics on the corresponding injury risk curves and the model sensitivity to these changes. The baseline model already had a high risk of thoracic injury and rib fractures in the real world case occupant. Therefore, slight changes in the crash parameters did little to increase or reduce the already high risk. The pelvis load resulted in a low risk of injury and no pelvis injury in the case occupant. Slight changes in the model inputs resulted in large variations in pelvis force with the largest coefficient of variation, over 27%, with X-location change. Given these findings, this variation study gave some insight into the relationship between crash parameters and injury metrics. Future research will enhance the variation study design to vary more parameters, including interior vehicle and occupant variables.

Keywords: Human Body Modeling, Automotive Crash, Safety Injury Assessment.

1. Introduction

Motor vehicle crashes (MVCs) account for approximately 1.2 million deaths each year and are predicted to become the fifth leading cause of death in the world 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 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 2006). When investigating impact scenarios involving interactions with the entire body, human body models (HBMs) are a valuable tool. An example of a HBM is the Total Human Model for Safety (THUMS) (Lee and Yang 2001, Iwamoto et al. 2002). Using THUMS, Golman et al. (2012) and Danelson et al. (2011) evaluated the injury potential of different astronaut suit configurations in various loading configurations (Danelson et al. 2011a, Golman et al. 2012). Mroz et al. (2010) investigated...
the biomechanical response differences in a Hybrid III and THUMS when using various belt and airbag configurations in a frontal crash (Mroz et al. 2010). Hayashi et al. (2008) compared the kinematics, rib strains, and internal organ pressures in a simulated pole side impact with and without side airbags (Hayashi et al. 2008). All of these studies investigated the human body response by simulating controlled laboratory tests using THUMS as the HBM. Another application of using HBMs is to reconstruct real world crashes.

HBMs can be used to predict injuries from real world crashes, a capability desirable for automatic crash notification systems. Iwamoto et al. (2002) used one of the first versions of THUMS to successfully reconstruct the bone fractures in a real world frontal crash (Iwamoto et al. 2002), Siegel et al. (2010) and Belwadi et al. (2012) used the Crash Injury Research and Engineering Network (CIREN) database to reconstruct real world side impacts and investigate aortic rupture modes (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 evaluate the capability for a HBM to predict injuries in a real world MVC.

2. Materials and Methods

A real world crash from the CIREN database was reconstructed using complete vehicle finite element models from the National Crash Analysis Center (NCAC) 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 computer 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 the crash severity 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.

The NCAC Ford Taurus FEM is the same vehicle as the CIREN case struck vehicle. The updated Taurus FEM has additional validation from side impact crash tests as well as a wider variety of frontal crash test comparisons (NCAC 2012). The bullet vehicle in the CIREN case was a Toyota Tacoma; however, the Tacoma FEM was not available in the NCAC database. The most similar vehicle FEM was a RAV4 based on the vehicle weight and outer dimensions. The RAV4 and Tacoma frontal stiffness was calculated from the force-stroke data for the from full frontal crash tests which indicated that the RAV4 was a valid substitute for the Tacoma up until 15 cm of stroke. The Tacoma estimated average frontal stiffness from NHTSA Test Number 2992, 3673, and 4478 and RAV4 estimated average frontal stiffness from NHTSA Test Number V02496 and 3613. The RAV4 FEM was validated using frontal NCAP test number 2496 as the only crash test comparison (NCAC 2008).

The case occupant was assumed to be seated in an upright posture with the seat adjusted to a mid-track position. She sustained AIS2+ injuries to her ribs, left lung, and brain that were reconstructed through the simulations. She also sustained other injuries that were not compared to the simulation results. 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, injury volumes of 0.52% of the brain, 19.9% of the lung, and 0.15% of the spleen were calculated (Danelson et al. 2007, Danelson et al. 2011b, Urban et al. 2012).

The difference between the simulated and case vehicle crashes was heuristically optimized to determine the vehicle FEMs initial positions and velocities. The input variables were striking vehicle longitudinal velocity, lateral velocity, rotational velocity, angle, location, and the struck vehicle speed (Table 1 and Figure 1). The initial orientation of the two vehicles was estimated using the PDOF and the Delta-V from the CIREN case data. To implement a lateral velocity component for the RAV4, friction was removed between the RAV4 wheels and the ground. The bullet location was measured from the front of the Taurus to the initial impact point on the RAV4 bumper. The simulated crash points were selected to match the approximate location of the crush measurements as
the CIREN case. The sum squared error (SSE) between the simulation and case was calculated for each vehicle to vehicle simulation. SSE was calculated for the front portion (C6, C5, C4), back portion (Maximum crush point, C3, C2, C1), and the total crush profile. Once the crush profile match was optimized, the HBM injury metrics and predicted risk were compared to the occupant injuries.

Table 1. Input Parameters varied for crush correlation optimization.

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Variable</th>
<th>Min Value</th>
<th>Max Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet longitudinal velocity (m/s)</td>
<td>LongV</td>
<td>13.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Bullet lateral velocity (m/s)</td>
<td>LatV</td>
<td>0.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Bullet rotational velocity (rad/s)</td>
<td>RotV</td>
<td>0.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Bullet angle (degrees)</td>
<td>PDOF</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td>Bullet location (cm)</td>
<td>BLoc</td>
<td>250</td>
<td>313</td>
</tr>
</tbody>
</table>

Figure 1. Input Parameters for crush correlation optimization. Note that the PDOF in this figure is 290 degrees.

2.2. THUMS Injury Metrics

The THUMS response was evaluated using several injury metrics implemented to mirror the instrumentation used in regulatory crash tests (Kuppa et al. 2003) and validated for THUMS in side impact configurations (Golman et al. 2013). Head, rib, spinal, and pelvic accelerations were measured at the center of gravity of the anatomical region of interest using the constrained interpolation method described by Golman et al (2013). Head acceleration was used to calculate the Head Injury Criterion (HIC36). Left rib 4, rib 8, and the 12th thoracic vertebrae accelerations were used to calculate the Thoracic Trauma Index (TTI) (NHTSA 2011). Virtual chestbands were used to determine maximum half deflection by measuring

the maximum change in distance between left side and the centerline (sternum to spine) of THUMS (Golman et al. 2013). Pelvic force measured the lateral force applied directly to the pelvis. These injury metrics were used to calculate injury risk from logistic functions found in the literature (Kuppa et al. 2003). Pelvic force was converted to pelvic impactor force by multiplying by 1.859, based on previous validation simulations, to calculate injury risk based on PMHS pelvic impactor based risk functions. Injury was considered to occur when the injury risk exceeded the injury risk used to set the Injury Assessment Reference Value (IARV) in Federal Motor Vehicle Safety Standard (FMVSS) 214: head AIS2+ risk exceeded 50% for HIC36, thoracic AIS3+ risk exceeded 50% for half deflection and TTI, and pelvic AIS3+ risk exceeded 25% for pelvic force (Kuppa 2006). Rib fractures were simulated using the element deletion method (Li 2010).

In the past, the rib material properties of human body models were aged based on the femoral cortical data due to limited data on the ribs (Kent et al. 2005, El-Jawahri et al. 2010). However, by combining the data sets from Kemper 2005 and 2007, a statistically significant (p<0.0001) linear correlation between age and ultimate strain can be constructed ($r^2=0.30$). This function was transformed from ultimate strain to plastic strain by subtracting yield strain (0.88% per Kemper et al 2005). An ultimate plastic strain of 0.88% was used to represent the case occupant.

2.3. Variation Study

Due to the many assumptions involved in reconstructing a single CIREN case (e.g. boundary conditions, vehicle and occupant models, etc.), a variation study was performed. The objective of this variation study was to quantify the sensitivity of the THUMS to variations in crash parameters and develop a 95% confidence interval (CI) for the THUMS response for this CIREN case based on the variation study distribution. In order to achieve these objectives the bullet vehicle input parameters were varied one-factor-at-a-time (OFAT) from the baseline value to potential alternative values specific to the CIREN case. The sensitivity of each variation parameter was quantified using the covariance in each variation parameter group (LongV, BLoc, etc.). The mean and CI of each injury metric and injury risk was determined using all 35 simulations.

3. Results

3.1. Real World Crash
The final simulation boundary conditions, following the heuristic optimization that best matched the simulated and case crush profile, are listed in Table 2. The final simulated crush was a close match to the case crush (Figure 2). The simulated crush had a frontal, back, and total SSE of 49, 253, 302 cm², respectively and the crush area was 16.9% less than the case. Most notably, the simulation crush at C4 (the location of the occupant in the case) was within 2.24 cm of the real-world case (Figure 2).

Table 2. Final parameter values for the optimized simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LongV (m/s)</td>
<td>15</td>
</tr>
<tr>
<td>RotV (rad/s)</td>
<td>4</td>
</tr>
<tr>
<td>PDOF (degree)</td>
<td>290</td>
</tr>
<tr>
<td>LatV (m/s)</td>
<td>1.5</td>
</tr>
<tr>
<td>BLoc (cm)</td>
<td>264.2</td>
</tr>
</tbody>
</table>

Figure 2. Final vehicle crush comparison between case (black) and simulation (gold). The difference (cm) is shown between each crush point.

Unlike the CIREN case, no head contact occurred for the baseline simulation. Similar to the case, the intruding door contacted the THUMS thorax resulting in high risk values for thoracic injury. The door caused high lateral accelerations to rib 4 (70 g), rib 8 (85 g), and T12 (99 g) resulting in a TTI of 200 g. Using TTI to predict thoracic injury risk produced a 92% risk of AIS 3+ injuries and 72% risk of AIS4+ injuries. Using the simulated chest bands, the contours at three different heights on the thorax were analyzed. The average maximum half deflection was calculated for the upper (21%), middle (28%), and lower (26%) chest bands to assess injury risk. Using the maximum average maximum deflection (28%) a 96% risk of AIS 3+ injuries and 75% risk of AIS4+ injuries was predicted.

Seven rib fractures were predicted compared to the case occupant’s 11 (Figure 3). While the simulation did not predict all of the case occupant’s rib fractures, it did predict four on the left side for ribs 7-10 and three on the right side for ribs 4-6. The simulation under predicted the fractures for the left rib fractures and over predicted the right rib fractures.

Figure 3. Case occupant rib fractures (highlighted with red boxes) from CT reconstruction (left) and predicted rib fractures from baseline simulation (right). Note that case occupant right rib 3 fracture not shown.

The simulation results predicted a low risk of pelvic injury which agrees with the absence of a pelvic injury in the case occupant. The maximum pelvic acceleration of 87 g is below the injury threshold of 130 g from the FMVSS 214 IARV. The THUMS pelvic force of 4.3 kN (adjusted pelvic force of 7.9k N), resulted in a AIS2+, AIS3+ pelvic injury risk of 37% and 2.6%, respectively.

3.2. Variation Study

Head contact did not occur in either the baseline or OFAT simulations; therefore, head injury metrics were not further considered. The thoracic and pelvic injury metric sensitivity to each variation parameter was quantified using CV (Figure 4). BLoc has the greatest effect on the injury metrics. The order of the remaining four parameters was dependent on the specific injury metric. For TTI, LongV had the next greatest effect, while the effects of the other three (RotV, PDOF, LatV) were approximately equal. PDOF had the next greatest effect on half deflection followed, in order, by LongV, LatV, and RotV. In the pelvic region, BLoc was followed, in order, by LatV, PDOF, RotV, and LongV. The injury risks follow the same trends as the input injury metric; however, the CV changes proportionally to the position on the injury risk curve. In other words, the risk curves can be very steep or very shallow where these parameters are changing which directly affects the sensitivity of that parameter.
The results from the variation study indicate a high risk of AIS 3+ thoracic injury, a medium risk for AIS 4+ thoracic injury, and a low-medium risk of AIS 2+ pelvic injury. These injury risks compare well with the injuries sustained by the case occupant, because she had AIS 3 rib fractures an AIS 4 lung contusion, and no pelvic injury except for bruising of the hip and thigh from the pelvic impact (AIS 1).

The CIs for the mean injury risk and critical injury metrics were very low, except for pelvic AIS3+ injury risk (Table 3). The mean and median CI for all CI values was 9% and 5% respectively. Despite a low CI for pelvic force, the pelvic AIS3+ risk CI was large due to the steep slope of the injury risk curve at these force values. Therefore, small changes in force resulted in large changes in risk.

The uncertainty in the real world crash estimates was simulated by simulating variations of the BLoc because BLoc has the strongest influence on door intrusion, which is directly responsible for injury. The CV of the other parameters was similar and challenging to explain due to interaction effects that are not accounted for in an OFAT variation study. This limitation provides motivation for performing a design of experiment (DOE) variation study in the future.

The uncertainty in the real world crash estimates was simulated by simulating variations of the CIREN case. Using CIs, the effects of this uncertainty was bounded. The resulting small CI width demonstrates that a high level of confidence can be placed in the THUMS response. This variation quantification approach is more comprehensive compared to simply reporting a single measurement.
5. Conclusion

This study demonstrates human body models can reliably be used to robustly predict injuries sustained in real world crashes. A real world CIREN crash was reconstructed using THUMS and NCAC vehicle FE models. Besides the lack of head contact, the occupant kinematics and predicted injuries match the CIREN case. Following the completion of the baseline reconstruction, an OFAT variation study was performed to understand the parameter effect sizes and to bound the uncertainty in the crash parameters. The mean injury risks and small CI widths from this variation study demonstrated that the THUMS injury predictions were precise and accurate. While this variation study was useful to understand the parameter effect size on injury prediction, a larger DOE variation study is necessary to more fully quantify correlations between the parameters and the injury predictor. Future work could simulate a wide range of side impacts to further understand crash parameter effects, seat position, and age on injury metrics, organ strain metrics, rib fractures, and the effectiveness of injury mitigation systems.

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