

Regional-Level Injury Risk Sensitivity to Pre-Crash Driver Position within Simplified Real World Motor Vehicle Crash Reconstructions

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ABSTRACT

Two full-frontal Crash Injury Research and Engineering Network (CIREN) motor vehicle crashes (MVCs) were reconstructed using finite element (FE) models. A FE simplified vehicle model (SVM) was tuned to mimic the frontal crash response of the CIREN case vehicle using frontal NCAP crash test data. The Total HUMAN Model for Safety (THUMS) was positioned in 120 pre-crash configurations per case within the tuned SVM. Seat track position, seat back angle, D-ring height, steering column angle, and steering column telescoping position variables were varied. An additional baseline simulation was performed that aimed to match the pre-crash occupant position documented in CIREN for each case. FE simulations were performed using the delta-V pulse from the vehicle's event data recorder (EDR). HIC15, combined thoracic index (CTI), and femur forces were evaluated to predict regional-level injury risks. Tuning the SVM to specific vehicle models resulted in close matches between simulated and test injury metric data, allowing the tuned SVM to be used in each case reconstruction. Simulations with the most rearward seats and reclined seat backs had the greatest HIC15, head injury risk, CTI and chest injury risk. More than half of the Camry occupant positions tested indicated a risk of AIS 2+ chest injury such as the hemomediastinum seen in the real world case. The injury metrics evaluated for the Cobalt case occupant indicated a low risk of injury. The highest risk of injury was in the chest region. The baseline simulation estimated 33% risk of any AIS 2+ chest injury and only a 4% chance of AIS 3+ chest injury, while the Cobalt case occupant had an AIS 3 pulmonary contusion. The reconstruction process and analysis allows for quantification of the sensitivity of the injury risk predictions based on occupant position to further understand important factors leading to severe MVC injuries.

INTRODUCTION

More than 1.2 million motor vehicle crash (MVC) deaths occur annually worldwide, while an additional 20-50 million MVC occupants sustain non-fatal injuries (WHO, 2013). The frontal crash mode is most common within the United States, accounting for 60% of fatal MVCs and 54% of injurious MVCs in 2012 (NHTSA, 2014). Analysis of real world MVCs allows researchers to evaluate the effectiveness of occupant restraint systems under an array of variables not tested in a laboratory crash environment, potentially providing information that could better protect the occupant. Although anthropomorphic test devices (ATDs) are capable of predicting occupant kinetics and kinematics in physical tests which have been correlated to injury risks, modern human body finite element models (HBMs) have the ability to predict more specific organ-level injury metrics and risks (Shigeta, 2009). HBMs are advantageous to assess entire body impact events by allowing researchers to study occupant kinematics, bone strains, and internal soft tissue organ pressures/strains simultaneously (Hayashi, 2008). One commonly used HBM capable of predicting organ injuries for whole body impact simulations is the Total HUMAN Model for Safety (THUMS) (Shigeta, 2009).

While controlled laboratory experiments provide injury risk information related to a well-defined set of prescribed boundary and restraint conditions, simulations of real world MVCs can account for a variety of human and environmental factors. The Crash Injury Research and Engineering Network (CIREN) database contains real world MVC data that has been used for computational MVC reconstructions (Belwadi, 2012; Danelson, 2015). One study analyzed the HBM response to predict injury risks across the entire body in a side impact CIREN case, but the reconstruction protocol used an open source 2001 Ford Taurus National Crash Analysis Center (NCAC) full vehicle finite element model (FEM) and was thus limited due to the paucity of open source full vehicle FEMs (Golman, 2014).

One challenge of reconstructing CIREN cases is the uncertainty in the occupant's position and posture at the time of the crash (Danelson, 2015). Although CIREN collects information related to the occupant restraint mechanisms and positioning, this data is collected post-crash and is subject to an inherent amount of uncertainty. This study's purpose was to establish a protocol to reconstruct a broad range of CIREN frontal MVCs using FEMs and quantify the variability of injury risks associated with different driver positioning and posture.

METHODS

Case Selection

Two full frontal CIREN MVCs with crash characteristics similar to regulatory crash tests were selected for reconstruction. Selected cases were limited to crashes that did not have a rollover event, crashed with a principal direction of force (PDOF) of 350° to 10°, resulted in very little occupant compartment intrusion and included an event data recorder (EDR) report. The most severe injuries reported in the CIREN medical reports were common MVC crash injuries and did not overlap between the two cases.

Camry Case Details. The first CIREN frontal crash reconstructed involved a 160 cm, 64 kg, 21 year old belted female driver in a 2010 Toyota Camry. The case vehicle struck a 1999 Jeep Cherokee at a 10° PDOF with an EDR longitudinal delta-V of 64 km/h, resulting in a maximum crush of 62 cm (Collision Deformation Code (CDC) 12FDEW3). The driver frontal and knee airbags deployed. The occupant was documented to be seated between the forward-most and mid-track position with the seat back "slightly reclined" before the crash. The D-Ring anchorage was at the lowest position. The occupant sustained a left bimalleolar fracture (AIS 3), hemomediastinum (AIS 2), and AIS 1 neck, upper arm, shoulder, breast, chest, and abdominal contusions.

Cobalt Case Details. The second CIREN frontal crash reconstructed involved a 183 cm, 77 kg, 80 year old belted male driver in a 2006 Chevrolet Cobalt. The case vehicle struck a 2002 Ford Expedition at 350° PDOF with an EDR longitudinal delta-V of 43 km/h, resulting in a maximum crush of 58 cm (CDC code 12FDEW3). The driver frontal airbag deployed. The occupant was documented to be seated between the mid-track and rearward-most position with the seat back in an upright position. The D-Ring anchorage was at the lowest position. The occupant sustained pulmonary contusion with pneumothorax (AIS 3), L1 and L3 burst fractures (AIS 2), loss of consciousness less than one hour (AIS 2), and AIS 1 shoulder and skin contusions/abrasions.

Case Reconstruction Process

The reconstruction process of each CIREN case involved three distinct phases. Phase I involved establishing a vehicle FEM that was suitable for simulating the CIREN frontal crash by tuning the occupant restraint systems of a generic simplified vehicle model (SVM) using regulatory crash test data. In Phase II, a variation study was conducted to automatically position THUMS v4.01 within the tuned SVM in a range of occupant positions and postures. Phase III applied the crash pulse derived from the CIREN case vehicle's EDR and assessed injury risks for each potential occupant position. The finite element solver used for each phase was LS-DYNA (MPP, Version 971, R6.1.1, LSTC, Livermore, CA) run on a computer cluster.

Phase I - simplified vehicle model (SVM) development and tuning. A FEM of a simplified vehicle was developed and tuned to accurately simulate frontal New Car Assessment Program (NCAP) crash tests of each CIREN case vehicle. For each case, an NCAP frontal crash test of the case vehicle model or a sister or clone vehicle model was reconstructed (Anderson, 2013). The 50th Percentile male Humanetics H3 ATD FEM was positioned within the SVM according to steering column position, seat back angle, pelvis and tibia angles, and nose to rim, chest to steering hub, knee to dash, knee to knee, and ankle to ankle measurements reported in the NCAP report (NHTSA, 2005; NHTSA, 2011). The occupant restraint systems were parameterized by ten variables in the Camry case and seven variables in the Cobalt case corresponding to properties of the frontal airbag (inflation rate; vent area), seatbelt (pretensioner force; load limiter force; buckle friction coefficient), steering system (shear bolt fracture force; stroke resistance; rim stiffness), knee airbag (foam modulus, maximum strain, damping factor, and thickness), or the knee bolster stiffness. Latin Hypercube design (LHD) of experiments sampling methods were used to assign restraint system parameter values to 200 simulations of the Camry NCAP test and 150 simulations of the Cobalt NCAP test (Stocki, 2005). The LHD is an effective space filling method used in design of experiment parameter studies. In a LHD, each parameter has as many levels as there are experiments in the design. The levels are spaced evenly from the lower bound to the upper bound of the parameter.

For each NCAP reconstruction, kinematic boundary conditions were derived from video tracking the rear and middle floor sill photo-targets from the crash test video to capture the longitudinal translation and pitching of the vehicle for 150 ms. Boundary conditions were applied to the SVM at a rigidly constrained photo-target shown in Figure 1, as pitch angle (about the Y-axis), and vertical (Z-axis) and longitudinal (X-axis) displacements. Seven ATD and restraint system signals (head, chest, and pelvis accelerations; left and right femur and shoulder and lap belt forces) were compared between each simulated iteration of the crash test and the physical crash test as shown in Figure 1. The Sprague and Geers magnitude (M), phase (P) and comprehensive (C) error factors were calculated for the first 100 ms of each signal, which represented the portion of the crash event prior to the rebound phase (Sprague, 2004). The comprehensive error factors for each signal were combined using Eq. (1) to evaluate the total body response (C_{Body}) error between each simulated crash test iteration and the physical test. Simulations with the lowest C_{Body} error were identified as the most accurate sets of occupant restraint system parameters to reconstruct frontal crashes for a case vehicle using the SVM.

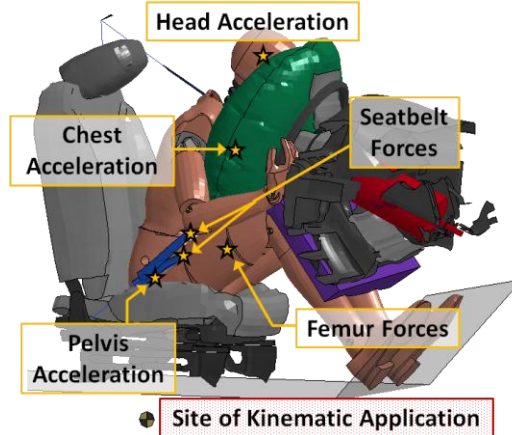


Figure 1: Parameters related to the frontal airbag (green), seatbelt (blue), steering column (red) and knee airbag/knee bolster (purple) were varied.

$$C_{Body} = \sqrt{\left(\frac{C_{R\ Femur} + C_{L\ Femur}}{2}\right)^2 + \left(\frac{C_{Lap\ Belt} + C_{Shoulder\ Belt}}{2}\right)^2 + C_{Head}^2 + C_{Chest}^2 + C_{Pelvis}^2} \quad (1)$$

Phase II - human body model (HBM) scaling and positioning. CIREN reconstructions were performed with the seated 50th percentile male THUMS v4.01 HBM (73.7 kg, 178.6 cm) (Shigeta, 2009), updated from v4.0 to consider the influence of the occupant’s weight in a seated posture and improve overall model stability (Toyota Central R&D Labs, Nagakute, Japan). THUMS v4.01 was length-scaled by the ratio of the case occupant’s height to the unscaled THUMS’s height (178.6 cm) for each case. Length scaling was selected rather than mass scaling to focus on the effects of occupant position and posture with respect to vehicle restraint systems. Scaling was achieved by length scaling occupant size isometrically along the X, Y, and Z-axes with no adjustments in occupant mass other than the mass changes due to size changes.

THUMS was initially settled into the SVM using gravitational loading and the arms and feet were repositioned to the steering wheel and floor, respectively in a series of LS-DYNA simulations. For each CIREN reconstruction five variables related to the occupant’s position within the vehicle were adjusted: 1) seat track position, 2) seat back angle, 3) D-ring height, 4) steering column angle, and 5) telescoping position of the steering column. Based on descriptions and photographs from the CIREN database, a baseline set of positioning variables was estimated for each CIREN case. The baseline estimation for the positioning variables were bounded by 120 sets of positioning variables assigned using a LHD. These positioning variables were used to automatically generate simulations to re-position THUMS and vehicle components from the “settled” state to a “pre-collision” state representing a specific occupant posture.

With THUMS seated in the tuned SVM, the seat track position and seat back angle were simultaneously modified during a 300 ms re-positioning simulation so that the occupant’s joint angles would change to fit the resulting SVM geometry. To set the longitudinal seat track position, a prescribed displacement was applied to the entirety of the SVM except the seat (Figure 2a). The seat track position range for each case’s LHD was first defined by the seat track length for the driver’s seat in each case vehicle and then was narrowed to exclude positions where the legs of the scaled THUMS did not fit within the tuned SVM. The mid-track seat position was referred to as the zero position, while positive seat track positions indicated that the seat was moved away from the dashboard.

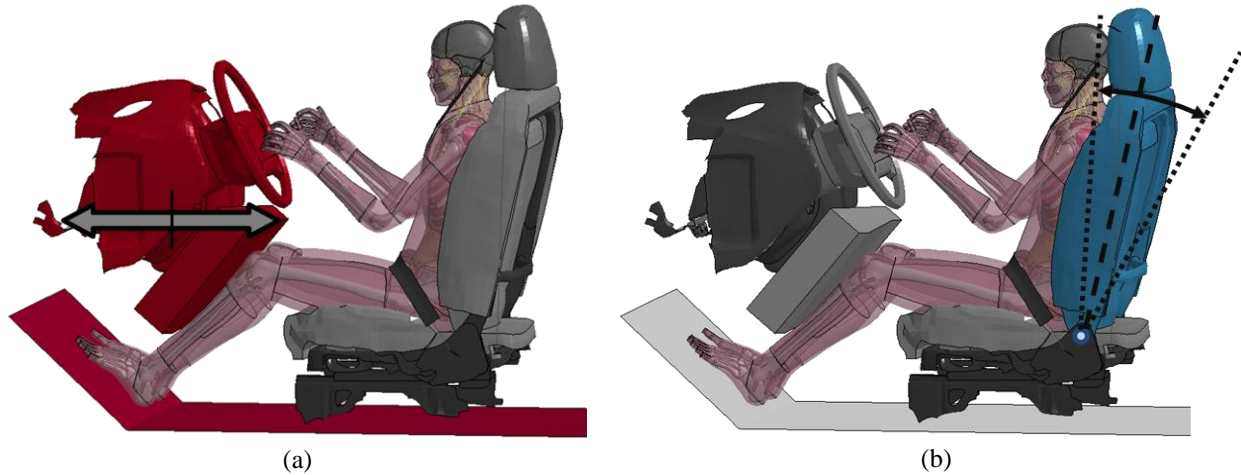


Figure 2: Positioning THUMS by (a) shifting the SVM with respect to the seat in order to simulate a change in seat track position and (b) rotating the seat back angle around a pivot point defined on the seat.

During the re-positioning simulation, the seat back and THUMS's back were concurrently rotated about an axis, maintaining contact between the occupant and seat back cushion (Figure 2b). The D-ring adjustment and steering column were programmatically adjusted between the re-positioning and crash reconstruction simulations using ranges defined for each vehicle in the NCAP report. The zero position for D-ring height was the lowest anchor point. Steering column angle was measured between the axis of the steering column and horizontal axis, while the steering column position was positive when moved closer to the occupant from the mid-position.

Phase III – CIREN MVC simulations and injury risk estimations. For each re-positioning simulation, a subsequent CIREN crash reconstruction simulation was automatically generated. The case occupant was re-belted and the longitudinal delta-V crash pulse from the CIREN case vehicle's EDR was applied as the boundary conditions (Figure 3). The Camry case had a maximum longitudinal delta-V of 64 km/h over a period of approximately 90 ms, while the Cobalt case had a maximum longitudinal delta-V of 43 km/h over a 110 ms period.



Figure 3: Application of the crash pulse derived from the CIREN case EDR to the tuned SVM.

Simulated accelerometer, load cell, and chest band instrumentation was adapted from THUMS v4.0 (Golman, 2015) for THUMS v4.01 to measure accelerations at the head center of gravity (CG), T1, T6, T9, T12, and pelvis, forces in the femur and pelvis, and chest deformations over time. Head Injury Criterion (HIC15) was calculated using the head CG accelerometer, while Combined Thoracic Index (CTI) was evaluated as a combination of chest acceleration (T1 accelerometer) and chest deformation (chestbands) (Eppinger, 1999). Injury metric risks for head (NHTSA, 1995), chest (Eppinger, 1999) and femur (Kuppa, 2001) injuries were used to estimate the likelihood of regional-level injury risks using logistic injury risk functions.

RESULTS

Simplified Vehicle Model (SVM) Tuning

Vehicle restraint parameters were selected for the two cases described above using the combined Sprague and Geers error factor, C_{body} . Sprague and Geers error factors and the injury metrics and seatbelt force comparisons between the simulated and physical crash test data are shown in Appendix A for the Camry case tuning.

Injury Risk Estimations

Injury metrics and risks were calculated for each simulation of the two case reconstruction variation studies, including one simulation (the baseline simulation) that best represented the positioning information reported in the CIREN case (Table 1). HIC15 and CTI for both case reconstructions are plotted against each independent occupant positioning variable in Figure 4 for the two case reconstructions.

Table 1: Summary of calculated injury metrics and risks of all simulated real world MVC occupant positions including baseline simulations positioned using CIREN information.

Case	Metric/Risk	Minimum	Maximum	Average	Baseline Simulation
Camry	HIC	220	1090	491	311
	AIS 1+ (%)	27	99.5	68	46
	AIS 2+ (%)	8.8	93	37	16
	CTI	0.694	1.113	0.885	0.832
	AIS 2+ (%)	34	88	61	54
	AIS 3+ (%)	3.6	46	15	9.1
	Max Femur Force (N)	767	5297	3170	4358
	AIS 2+ (%)	0.45	4.6	2.06	2.84
Cobalt	HIC	49	467	179	161
	AIS 1+ (%)	0.48	74	19	15
	AIS 2+ (%)	0.17	34	6.7	5.0
	CTI	0.398	0.963	0.678	0.690
	AIS 2+ (%)	8.0	72	34	33.5
	AIS 3+ (%)	0.45	20	4.3	3.6
	Max Femur Force (N)	1312	2737	2389	2287
	AIS 2+ (%)	0.60	1.25	1.05	0.99

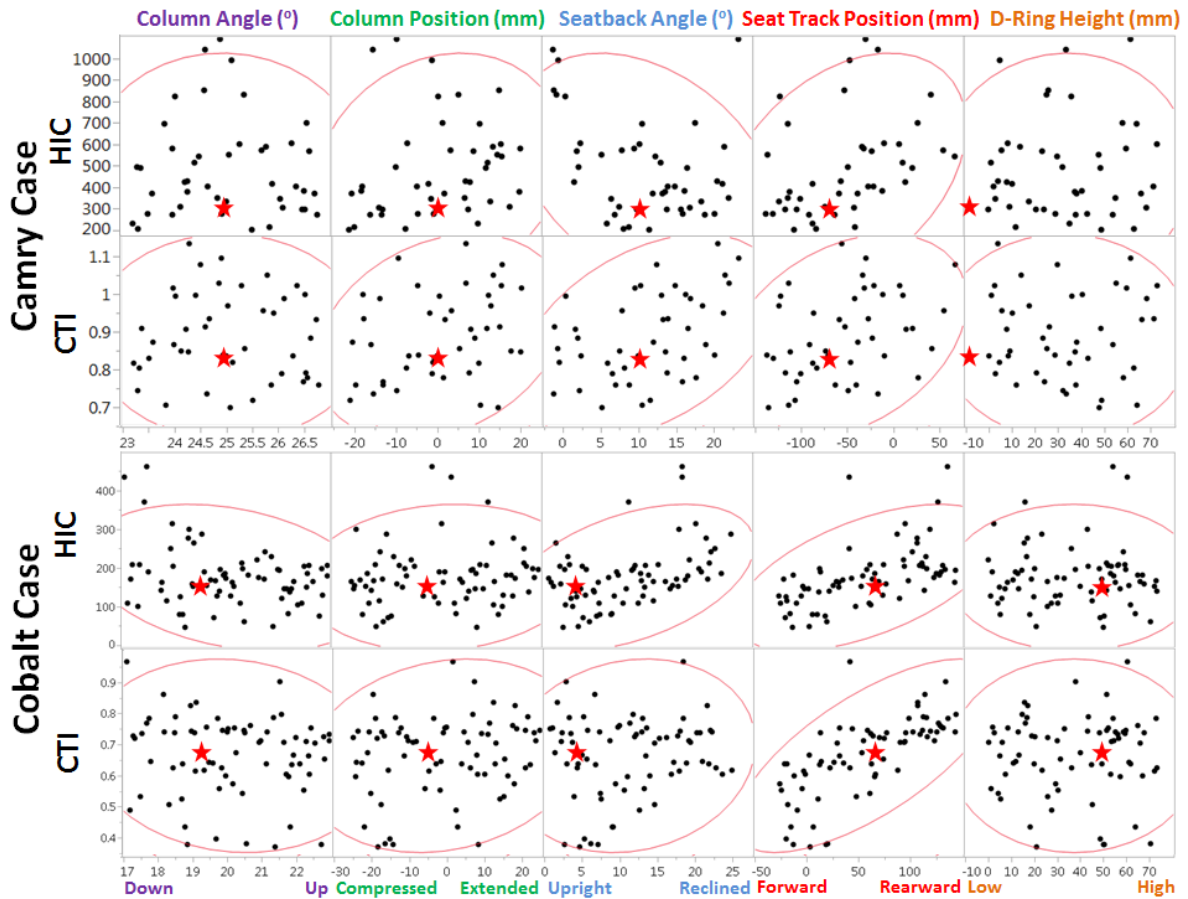


Figure 4: HIC15 and CTI as a function of five positioning variables in the Camry and Cobalt cases. HIC15 and CTI values in the baseline simulation that most closely matched the occupant position documented in CIREN are indicated by the red star.

The Camry case occupant’s most severe injuries included an AIS 3 bimalleolar fracture and AIS 2 hemomediastinum. While none of the injury metrics evaluated in this study correlate to bimalleolar fracture, the hemomediastinum can be evaluated with the CTI injury risk function. Across all the potential occupant positions simulated, the average risk of AIS 2+ chest injury was estimated to be 61% (range: 34% to 88%), while the estimated risk according to the best estimate of the occupant’s position in CIREN (baseline position) was 54%. The reconstruction simulations and injury risk functions provide a good indicator of the likelihood of chest injury for this case. The range of occupant position simulations predicted a 27-99% risk of any AIS 1+ head injury, while the baseline CIREN occupant position simulation predicted a 46% risk of AIS 1+ head injury. Consistent with this prediction, the case occupant did not sustain any head injuries. Additionally, the case occupant had no knee, thigh, hip or femur injuries and all simulations predicted less than 5% risk of these injuries.

The three most severe injuries of the Cobalt case occupant were pulmonary contusion (AIS 3), L1 and L3 burst fractures (AIS 2) and loss of consciousness less than one hour (AIS 2). However, none of the injury metrics evaluated in the study directly correlated to pulmonary contusion, lumbar vertebra burst fracture, or unconsciousness. The injury metric models predicted low levels of injury risk in the head, chest and femur regions. Using the CIREN pre-

crash occupant position documentation, there was a 15% probability of AIS 1+ head injury, 4% chance of AIS 3+ chest injury and less than 2% chance of AIS 2+ knee, thigh, or hip injury. A higher calculated probability of head and chest injury was expected, based on the pulmonary contusion and unconsciousness injuries, which may warrant further investigation.

DISCUSSION

A few distinct relationships are present between the occupant positioning variables and the head and chest injury metrics. In both cases, the simulations with the most rearward seats had the greatest head acceleration and HIC. This is a function of the vehicle decelerating over an extended period of time before the occupant strikes the airbag. A similar, but weaker, relationship existed between CTI and seat track position. In both cases, the most reclined occupants had increased CTI and in the lower velocity Cobalt reconstruction case, the most reclined occupants also had increased HIC. However, in the higher velocity Camry case, it should be noted that some of the cases with the highest HIC values were the most upright occupants. This inverted relationship could be attributed to the airbag deploying in close proximity to the occupant. The other three occupant positioning variables in this study did not have notable effects on HIC or CTI compared to the effect of the seat back angle and seat track position.

Calculated injury risk ranges for the three anatomical regions closely correlated to the injury patterns observed in the CIREN occupants. THUMS injury metrics correctly predicted the AIS 2 hemomediastinum (54% baseline risk) and lack of head and knee, thigh, and hip injuries (46% and 3% baseline risk, respectively) in the Camry CIREN occupant. For the Cobalt CIREN occupant, THUMS injury metrics correctly predicted the lack of knee, thigh, and hip injuries (1% baseline risk), but underestimated the AIS 3 pulmonary contusion (4% baseline risk) and AIS 2 head injury (5% baseline risk). The injury risk curves may underestimate head and chest injury risks in elderly occupants such as the 80 year old Cobalt driver. For instance, CTI evaluates chest acceleration and chest compression, while chest compression is increased in elderly crash occupants, yielding an overall increased risk of injury according to CTI (Ruan, 2003). Future implementation of organ-level injury metrics, such as strain-based metrics for lung or brain injury, may yield more accurate injury predictions for the pulmonary contusion and head injury in the Cobalt occupant (Danelson, 2015; Golman, 2014).

Limitations

Due to the limited availability of occupant specific FE HBMs and detailed vehicle models, several assumptions and simplifications used in this study may have influenced the results. Many of the most significant assumptions involved the SVM tuning. Frontal NCAP crash tests are only performed at one speed and are not performed on every vehicle model year. Because each vehicle was not tested each year, sisters and clones were used to match the crash test vehicle calibration to the CIREN case vehicle. For a given model year, the occupant restraint systems could vary from a sister or clone vehicle despite having matching vehicle stiffness characteristics. Additionally, if the simulated H3 occupant response closely matched the frontal NCAP crash test, it was assumed that the THUMS occupant response within the same vehicle model would match a human's response in crash events occurring with similar velocities.

Using the THUMS 50th percentile male model for all case reconstructions was another limitation in this study. The chosen scaling method was selected to maintain the same regional and organ-level mesh geometries. There was no variation in the occupant girth or weight to create occupant-specific models. To account for significant variation of occupant girth from the scaled THUMS model, morphing techniques could be used to modify the shape of the case occupant or scaling could be performed on the 5th percentile female or 95th percentile male THUMS. Similarly, anatomical material properties remained the same for each case reconstruction. Material properties of individual organs and bones could be modified to account for age and sex differences.

Future Work and Applications

The breadth of this study involved detailed reconstruction of two CIREN cases and evaluation of select regional-level injury metrics. The reconstruction methodology can be directly applied to reconstruct a larger number of frontal MVCs of varying vehicle types from CIREN and the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS). The methodology could potentially be extended to reconstruct a variety of crash modes through the addition of vehicle structures such as the door and A-pillar that engage the occupant in offset frontal and near-side impacts. Additional injury metrics will be implemented in THUMS to evaluate risk for specific injuries rather than the regional injury risks described by this study. By evaluating additional cases in further detail, new injury metrics and risk functions could be developed from the real world crash data to assess the effectiveness of restraint systems to prevent and mitigate injuries that are not easily studied using post-mortem human subjects (PMHS) or ATDs. Additionally, the ability to place bounds on injury risk as a function of pre-crash occupant position is valuable for assigning confidence levels to injury mechanism predictions in real world MVC analysis.

CONCLUSIONS

A three phase process was developed to reconstruct CIREN MVCs of varying vehicle types using a tuned simplified vehicle FEM. CIREN MVCs were reconstructed with various THUMS occupant positions by varying the seat track position, seat back angle, steering column angle and telescoping position, and the seatbelt D-Ring anchor height. The reconstruction process allows for quantification of the sensitivity and uncertainty of the injury risk predictions based on occupant position, which is often uncertain in real world MVCs. This study provides perspective on the sensitivity of pre-crash occupant positioning within the vehicle compartment. By studying a variety of potential occupant positions, we can understand important factors that lead to more severe injuries.

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Appendix A – Simplified Vehicle Model (SVM) Tuning Injury Metric Comparison

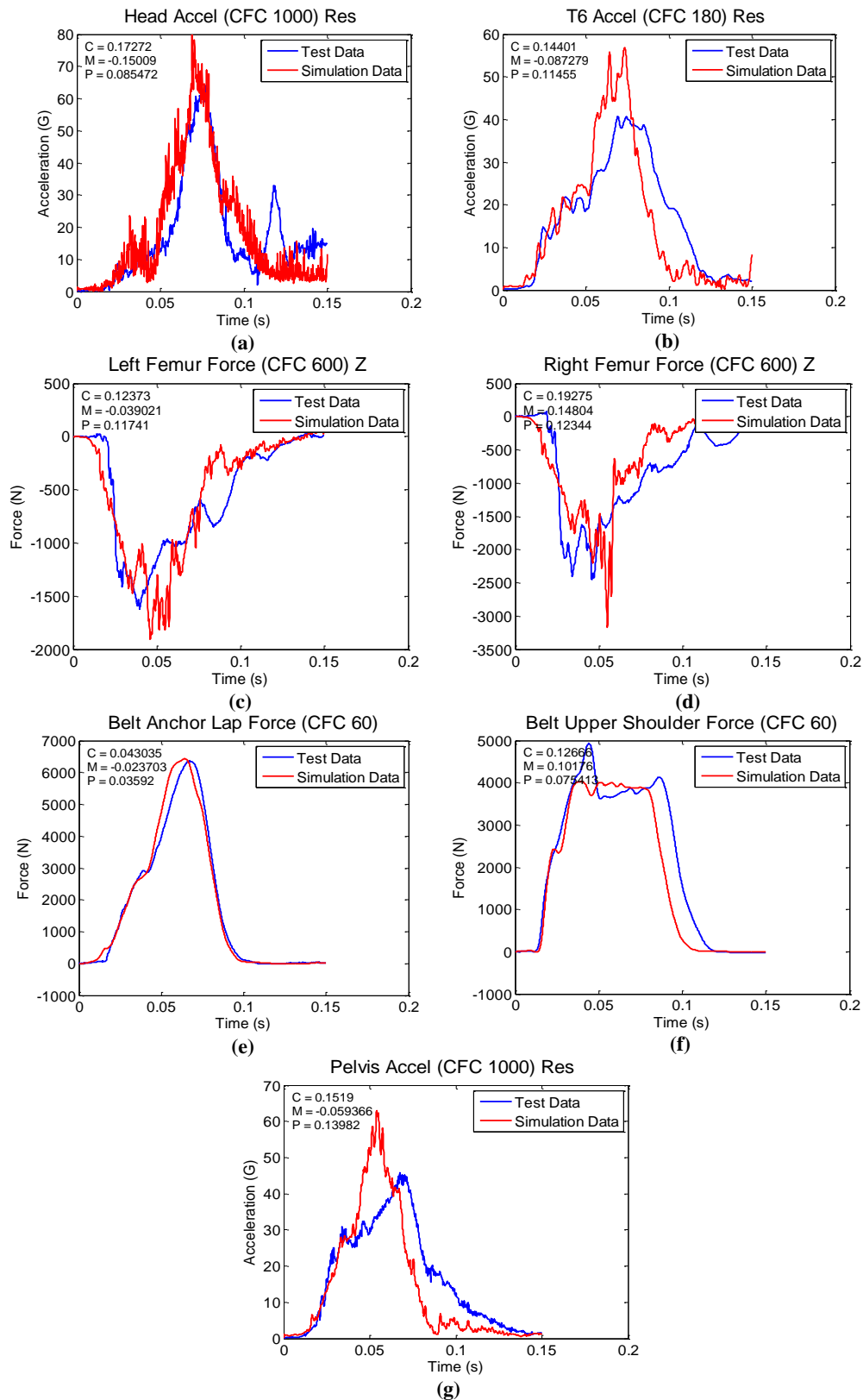


Figure A1: Injury metric comparisons between the simulated and physical 2010 Camry crash tests.