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Computational methodology to predict injury risk for motor vehicle crash victims: A framework for improving Advanced Automatic Crash Notification systems

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ABSTRACT

Advanced Automatic Crash Notification (AACN) systems, capable of predicting post-crash injury severity and subsequent automatic transfer of injury assessment data to emergency medical services, may significantly improve the timeliness, appropriateness, and efficacy of care provided. The estimation of injury severity based on statistical field data, as incorporated in current AACN systems, lack specificity and accuracy to identify the risk of life-threatening conditions. To enhance the existing AACN framework, the goal of the current study was to develop a computational methodology to predict risk of injury in specific body regions based on specific characteristics of the crash, occupant and vehicle. The computational technique involved multibody models of the vehicle and the occupant to simulate the case-specific occupant dynamics and subsequently predict the injury risk using established physical metrics. To demonstrate the computational-based injury prediction methodology, three frontal crash cases involving adult drivers in passenger cars were extracted from the US National Automotive Sampling System Crashworthiness Data System. The representative vehicle model, anthropometrically scaled model of the occupant and kinematic information related to the crash cases, selected at different severities, were used for the blinded verification of injury risk estimations in five different body regions. When compared to existing statistical algorithms, the current computational methodology is a significant improvement toward post-crash injury prediction specifically tailored to individual attributes of the crash. Variations in the initial posture of the driver, analyzed as a pre-crash variable, were shown to have a significant effect on the injury risk.

1. Introduction

Traffic data indicated that approximately 835,000 motor vehicle occupants sustain moderate to severe injuries and another 30,000 succumb to fatal injuries each year in the United States (NHTSA, 2008). A significant portion of the fatal victims (56% in year 2002) did not receive medical treatment. Additionally, as Champion et al. (2004) described in an earlier work, there is certainty that a substantial portion of the injured victims received less than optimal care in terms of timeliness, appropriateness, or effectiveness of treatment. Towards solving that problem, researchers expect that improvements in emergency care including technological advances in automatic crash notification and injury assessment will save up to an additional thousand lives every year (Clark and Cushing, 2002; Evanco, 1999). In contrast, about 7 million people in the

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US suffer minor or no injuries in motor vehicle crashes each year, of which an unknown portion are over-triaged to inappropriate hospitals and trauma centers resulting in an unnecessary burden on emergency medical resources, and health care costs (Champion et al., 2005). Thus, a more timely and accurate assessment of the injury severity and condition of the occupant involved in a motor vehicle crash could significantly improve the allocation of the emergency medical resources.

Efforts towards the assessment of injury severity sustained by motor vehicle crash victims have been helped by technologies such as Advanced Automatic Crash Notification (AACN) systems. While a standard crash notification system is capable of determining the geographic location of the crash and the severity of damage to the vehicle, an AACN can also be configured to estimate the extent of injuries sustained by the occupant, thus facilitating the appropriate Emergency Medical Services (EMS). For instance, the BMW Assist™ technology estimates the injuries sustained by passengers and transmits that information to emergency and medical care personnel (Belson, 2009). Such technologies require accurate assessment of parameters which are crash-specific, for example crash direction, severity, restraint usage, airbag deployment and vehicle properties. These data along with occupant specific information can be used to evaluate injury risk as a function of the crash using traditional statistical regression models. The most widely used algorithm is the Urgency Algorithm developed through a collaboration of researchers at the University of Miami School of Medicine, George Washington University, and the National Highway Traffic Safety Administration (NHTSA) (Malliaris et al., 1997). While the Urgency Algorithm may accurately predict the overall occurrence of severe occupant injuries (i.e., Abbreviated Injury Score(AIS) 3+ injury, AAAM, 1990), the applicability of this algorithm for the EMS and medical personnel is rather limited due to its lack of specificity regarding the injured body region(s) and it's inability to detect life-threatening occult injuries (Champion et al., 2005; Augenstein et al., 2003).

Improvements in statistical algorithms to predict the region-specific risk of injury have been conceptualized (c.f. Segui-Gomez et al., 2009). However, the limitations of regression models based on field observations must be realized. For instance, Nordhoff (2005) has discussed the potential bias and inaccuracies associated with recording injury data in the National Automotive Sampling System Crashworthiness Data System (NASS CDS) which is currently used in most injury severity assessment algorithms. Moreover, regression models described in the literature are typically linear models which fail to capture the non-linear effects or interactions between the variables in the crash environment (e.g., effectiveness of wearing a seat belt on injury outcome is dependent on the direction of the crash). This is particularly true when certain variables (like crash direction) being controlled in the model dominate the injury response. Finally, current statistical models lack details on crash information necessary for accurate and specific injury risk prediction. Future revisions to injury prediction algorithms may incorporate details such as seating positions of occupants, seat track location (proximity to the air bag), crash pulse time history, timing of air bag deployment, pattern of airbag loading, deployment of seat belt tensioning retractors, failure of the seat back, steering column integrity, and additional injury risk predictors in the occupant compartment.

Based on the known limitations of current injury predicting algorithms, an alternate computational methodology for predicting body region-specific injury risk adjusted to the specific crash scenario is presented in this study. The proposed computational framework is based on a *deterministic* approach involving reconstruction of the crash event using validated simulation models. It is envisioned that the next generation of sensor technology used for active crash protection will be able to measure or store information describing occupant anthropometry, pre-crash positioning, restraint usage, and accurate estimation of the crash pulse. The information collected during the pre-crash phase may be processed in real-time using either onboard computing facilities or by transmitting the information elsewhere. Processing of information will involve simulating the specific crash and loading scenario and using existing injury risk functions to calculate full body injury risk assessment. Additional strategies such as a pre-computed database of simulation results coupled with interpolation methods may further reduce the time required for injury risk estimation. It is anticipated that access to real-time information specific to the crash will reduce errors and inaccuracies associated with field observational studies. Also of interest is the stochastic estimation of the injury risk using parametric sensitivity analysis which would account for the errors in the sensor estimates involving the crash and occupant parameters. The output estimated by the computational methodology may be represented by probability density functions of the injury severity risk in individual body regions.

Towards the development of a conceptual computational methodology for injury risk prediction, the objectives of the study may be summarized as follows:

- To develop a computational methodology to predict body region-specific injury risk in a crash using occupant, vehicle and collision property data.
- To validate the computational methodology using real world crash data and to compare the predicted injury outcomes with results obtained using the NHTSA Urgency Algorithm and the body-region regression model developed by Segui-Gomez et al. (2009).

2. Methodology

The computational injury prediction methodology described in this study is based on a multibody simulation platform, MADYMO™ v6.3.2 (TNO MADYMO BV., Netherlands) designed to evaluate occupant dynamics in a crash loading environment. The computational methodology is developed and validated as a proof of concept focusing on representative injuries sustained by a motor vehicle driver in frontal crashes. To validate the methodology, three cases of frontal crashes of varying severities involving a unique compact-class vehicle model were obtained from the NHTSA's Crash Injury Research and

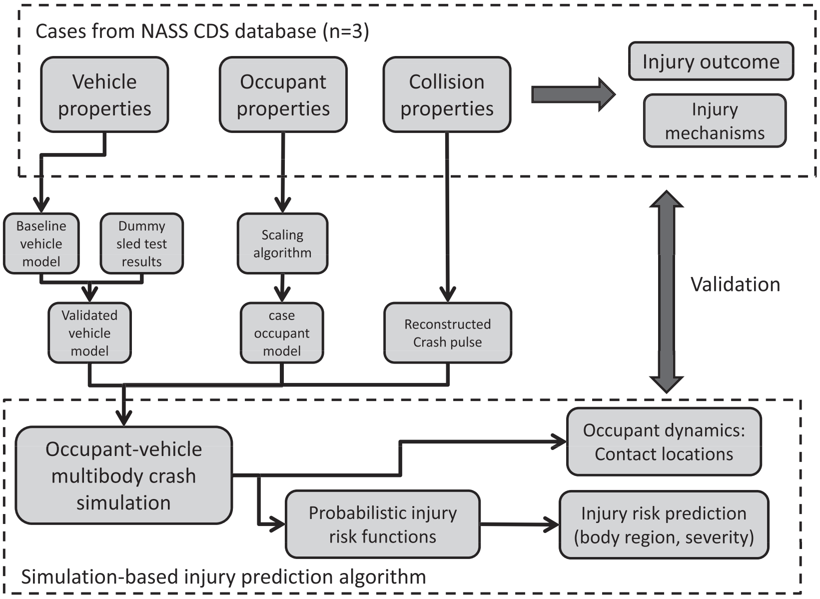

Fig. 1. Overview of the simulation-based injury prediction methodology.

Engineering Network (CIREN) database. The case information included details on the crash kinematics, occupant characteristics, usage of safety restraint systems, vehicle properties and detailed injury reports consisting of standardized injury classification, radiographic images and physician notes.

For the simulation framework, a compact-class vehicle multibody model was modified and validated to match the selected case vehicle using dummy sled test data available from the US New Car Assessment Program (USNCAP) reports. An occupant scaling algorithm was used to develop case-specific occupant models with matched anthropometric properties. To determine the crash kinematics, an equivalent barrier impact speed was determined for each of the frontal crashes using the information obtained from the vehicle Event Data Recorder (EDR). Using the validated vehicle model, scaled occupant model, standard restraint models and crash kinematics information, the crash-event was simulated in order to estimate five injury metrics-head injury criteria, neck injury criteria, chest deflection, femur force, and tibial force-for each of the crash cases. The body-region specific, probabilistic risk of injury was then calculated based on the injury metrics in conjunction with the NHTSA injury risk functions (Eppinger et al., 1999).

The whole body and region-specific injury risk estimated by the computational methodology, blinded to the true injury outcome, was then compared to the CIREN medical reports. In addition, the injury mechanism as hypothesized in the CIREN biomechanical analysis was cross-validated with the gross occupant kinematics as observed from the simulated animation. The sensitivity of estimated injury risk to variability in occupant posture and crash speeds was investigated using parametric simulations. As a comparison with existing injury predicting algorithms, the computationally predicted injury risk was compared with the results from the NHTSA Urgency Algorithm and the body-region regression model. An overall summary of the study methodology is shown in Fig. 1. Details about the CIREN cases, multibody model development and validation as well as the methodology for injury prediction is presented in the following subsections.

2.1. CIREN case description

The sampled cases in the CIREN include motor vehicle occupants seriously injured in a crash and admitted to one of six CIREN Level-1 trauma centers in the United States (NHTSA, 2002). Inclusion criteria for the CIREN database include restrictions on vehicle model year (newer than six years), serious injury (i.e., AIS 3+ or certain combinations of two AIS 2 injuries). Details available in the database regarding reconstructed crash kinematics, occupant characteristics, vehicle damage profiling, evidence-based occupant contacts, and detailed injury causation analysis determined through peer-reviewed interdisciplinary research, provides the necessary information for validating the injury predicting algorithms. For the purposes of this study, occupants involved in representative frontal crashes were selected from the CIREN database using the following criteria:

1. Case occupant must be in a single-event frontal crash (principal direction of force between 11 o'clock and 1 o'clock) involving a maximum of two vehicles.
2. Case vehicle must be equipped with the EDR system.
3. Case vehicle type to include only passenger cars, sport utility vehicles, light trucks and mini vans.

Table 1
Description of selected CIREN cases.

	Case 1	Case 2	Case 3
Crash type	Frontal	Frontal	Frontal
PDOF (deg)	340	350	350
Delta-V (km/h)	35	68	18
Opposing impactor	Vehicle	Vehicle	Concrete barrier
Airbag status	Deployed	Deployed	Deployed
Vehicle class	Compact car	Compact car	Compact car
Vehicle model year	1999	2002	2001
Vehicle curb weight (kg)	1315	1214	1188
Occupant role	Driver	Driver	Driver
Occupant sex	Female	Female	Female
Occupant age (years)	43	75	75
Occupant height (m)	1.61	1.75	1.68
Occupant weight (kg)	158	87	48
Seatbelt usage	Used	Used	Used
Whole body MAIS	3	4	3

PDOF and MAIS are abbreviations for Principal Direction of Force in the crash and the Maximum Abbreviated Injury Scale, respectively.

4. Case Occupant must be an adult (16 years or older) in the role of a driver during the crash.
5. Case occupant must be restrained by a 3-point safety belt during the crash and the airbag must have deployed as a result of the impact.

The search yielded 62 crash cases involving 29 different vehicle models (descriptive statistics listed in Appendix A). A compact-class vehicle model with highest frequency ($n = 11$) among the selected cases was chosen to represent the standard vehicle model. Further, three crash cases involving significantly different crash severities (range of barrier impact speed between 18–72 km/h) were chosen for the validation of injury prediction using the computational method. Details about the three selected CIREN cases are listed in Table 1.

2.2. Multibody crash simulation framework

2.2.1. Occupant model

A multibody representation of a 50th percentile adult male Hybrid-III dummy, available in the database of MADYMO™ (v6.3.2), was modified to represent the case occupants involved the CIREN crashes (TNO, 2006a). The multibody occupant model used in this study comprises of 37 ellipsoidal rigid bodies connected through non-linear joints. The non-linear joint properties, contact characteristics, and physiological range of motion have been derived through various component level validation tests (TNO, 2006b). The MADYMO™ model has been validated for multi-directional loading environment (frontal and lateral impacts) using biofidelic requirements for rating numerical models and mechanical test surrogates (de Lange et al., 2005).

A case specific occupant model was developed by scaling the anthropometric measures of the 50th percentile adult occupant model based on the principles of geometric scaling(Langhaar, 1951). The reference values for scaling the occupant stature (Occ_s) and mass (Occ_m), correspond to the stature and mass of a 50th percentile adult male and were obtained from an US-based, human anthropometric database (Gordon et al., 1988). Using mean (standard deviation) values of 1.757 m (σ = 0.071 m) and 77.99 kg (σ = 11.04 kg) for the normal distribution of population stature and mass, respectively, values of Occ_s and Occ_m for each occupant model were evaluated as a function of their percentile rank in the population. For geometric scaling of the occupant models to represent different percentile ranks of stature and mass, the length scaling factors in three directions and mass scaling factor were determined based on equivalent length scaling in the two non-axial directions (*x* and *y* directions in the model) and mass density were invariant across the population (Eq. (1)). Using the software MADYSCALE™, occupant models with different values of Occ_s and Occ_m were developed using the length and mass scaling factors estimated from the anthropometry database, and assuming that the length and mass scaling factors are uniformly applicable to all body regions of the adult human model. The adopted methodology for developing numerical human models based on the dimensional scaling principle has been previously reported by Rodarius et al. (2007).

$$\lambda_{lz} = \frac{Occ_s}{Occ_{sref}}; \quad \lambda_m = \frac{Occ_m}{Occ_{mref}}; \quad \lambda_{lx} = \lambda_{ly} = \sqrt{\frac{\lambda_{lx}}{\lambda_{lx}}} \tag{1}$$

2.2.2. Vehicle model

A simplified multibody model representing a compact passenger car developed by NHTSA was used as the baseline vehicle model in this study (Fig. 2). The front end of the vehicle model included a simplified rigid body representation of the front

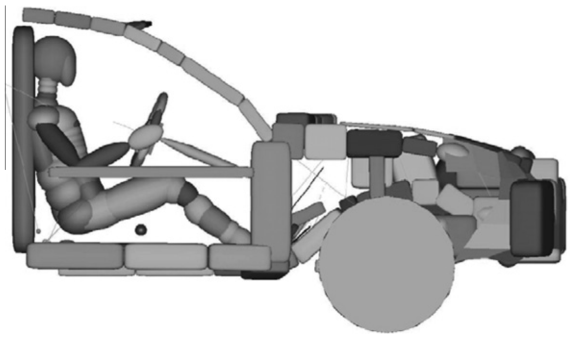

Fig. 2. Multibody model of the occupant–vehicle system.

bumper, front wheel and axle system, hood and the critical components of the engine compartment. The driver compartment consisted of the windshield, A-pillar, B-pillar, steering column and wheel, instrumentation panel, firewall, toe-pan, knee bolster, and seat structure. The occupant safety system was modeled using a finite element (FE) model of the driver-side frontal airbag and a force-limited retractor and a 3-point FE belt system. The properties of the restraint system were obtained from standard values as provided in the MADYMO™ database and further optimized during vehicle model validation. The modeling of the vehicle is designed to provide reasonable crash kinematics to the occupant compartment in moderate to severe frontal crashes.

To reconstruct each of the crash cases, the baseline vehicle model was modified to represent the unique compact-class vehicle model. The modification included matching the geometrical dimensions of the driver compartment in the baseline model to an exemplar vehicle model. The geometrical dimensions adjusted in the vehicle model included the A-pillar curvature, windshield angle, steering column angle, and steering wheel geometry. The geometrical dimensions were obtained from a US NCAP report describing frontal barrier crash tests involving the specific compact-class vehicle model.

Besides geometrical dimensions certain parameters of the vehicle model were critical for the accuracy of the simulated crash dynamics but were unknown for the model used in this study. The injury predictability of the unknown explanatory variables was determined based on stepwise regression of the multivariate model. The predictor variables with significant effect on the injury outcome ($p < 0.05$) included airbag trigger time and friction, belt friction and stiffness, seat friction, belt load-limiting value, knee bolster stiffness and friction and shoe friction. The results of the US NCAP dynamic tests were used to optimize the values of the parameters in the vehicle model. To accomplish this, a parametric simulation was set up using the vehicle model and the 50th percentile Hybrid-III male dummy model to simulate a 56km/h frontal barrier impact test.

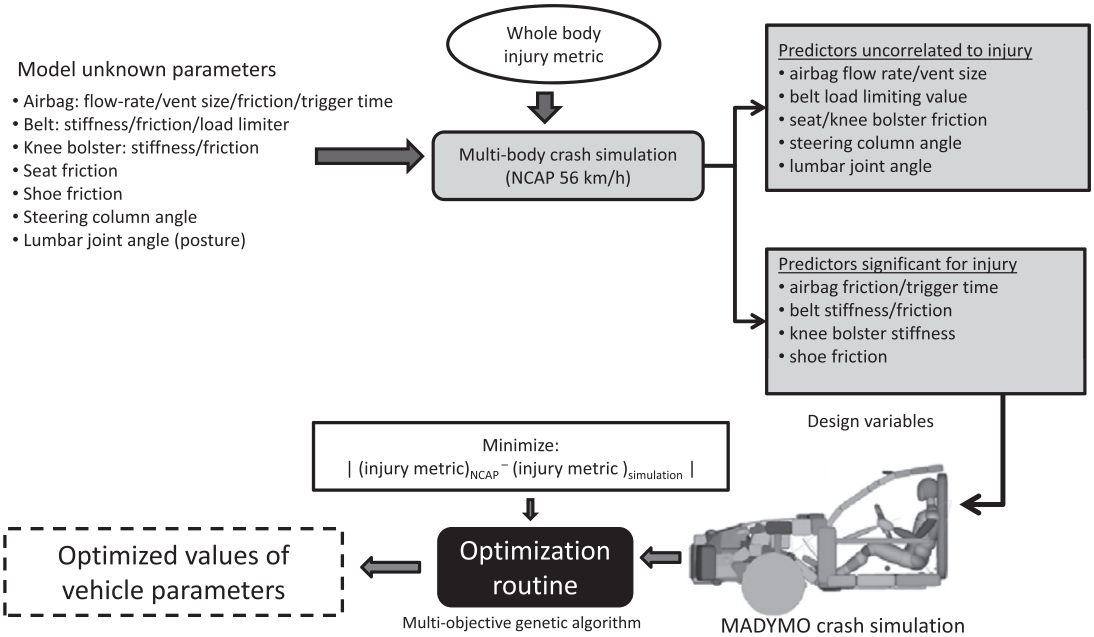

Fig. 3. Methodology to optimize unknown parameters of the vehicle model.

The unknown variables to be determined through the optimization routine included the vehicle parameters described previously. The objective defined for the optimization routine was to minimize the difference between the aggregated injury metrics measured during the US NCAP test and the same values predicted in the simulation. The aggregated injury metrics was the sum of measured head injury criteria, neck injury criteria, chest deflection and femur force. A multi-objective genetic algorithm was used in the optimization routine which included a initial randomized set of 20 designs mutated over 30 generations (a total of 600 simulations). The overview of the optimization routine is shown in Fig. 3.

2.3. Injury prediction

Using the validated multibody vehicle model, case-specific occupant model, and the barrier impact speed as reported in the CIREN database, a frontal crash simulation was performed in MADYMO™ for each of the three CIREN cases. In the standard run, the posture of the occupant model was oriented in a standard posture as described in the US NCAP procedures. Using post-simulation results the injury metrics in the five body regions-head, neck, chest, thigh and leg-were estimated and converted to injury risk using functions described in Appendix B. The injury risk estimation was blinded to the actual injuries observed in the CIREN cases. In addition to the standard, two additional simulation runs were done with varying impact speeds and two others with varying initial posture of the occupant. The variation in the impact speed included two additional barrier impact speeds, 10% of the originally estimated speed. For postural orientation, two additional postures-one leaning forward and second reclined back-were used to simulate each of the cases. The simulations were performed on a standard personal computer (Intel Core 2 Duo™ 3Ghz processor).

3. Results

3.1. Injury risk prediction

Simulation results for each crash case provided reasonable estimates for overall occupant kinematics and interaction with the restraint systems (Fig. 4). The evidence-based occupant contact data, available in the CIREN data, were matched to corroborate the simulation kinematics. Region-specific injury risks predicted by the computation methodology and comparisons with actual values of maximum AIS recorded in that body region are shown in Fig. 5. In CIREN case 1, three AIS 2+ injuries were noted on the right lower extremity with probable causation attributable to toe-pan intrusion (injury details listed in Appendix C). Although not accounting for realistic toe-pan intrusion, the simulation results indicated loading of the leg/foot complex by the floor structure. Consistent with the clinical findings, the simulation results indicated a 100% probability of AIS 2+ injury to the leg/foot region. Low severity injuries to the head, neck and chest region were suggested by a lower than 30% probability for the risk of AIS 2+ and AIS 3+ injuries in these regions.

Case 2 was a high crash severity case (Δv 68 km/h). The most severely injured body region for this case was the thorax which sustained two AIS 4 injuries: rib fractures as well as several AIS 3 injuries to the extremities. Case documents lead to the conclusion that occupant contact with the steering wheel rim, seat belt webbing/buckle, knee bolster/instrumentation panel and portions of the floor was responsible for most of the significant injuries. By comparison simulation results predicted a high risk for head, chest and lower extremity injuries, which is in agreement with the observed injuries.

Case 3 was a low velocity crash case (Δv 18 km/h) in which occupant sustained severe upper extremity, fibula fracture and the lumbar spine injuries. Unfortunately, none of the five injury metrics targeted the upper extremity or the lumbar spine region and therefore, the risk or probability of injury predicted by the computational methodology was relatively low (less than 30% for either region).

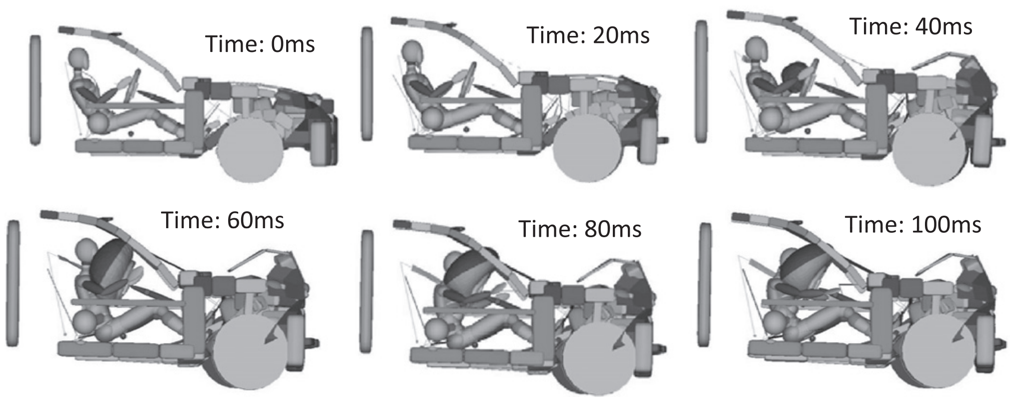

Fig. 4. Simulation snap-shots at 20 ms interval.

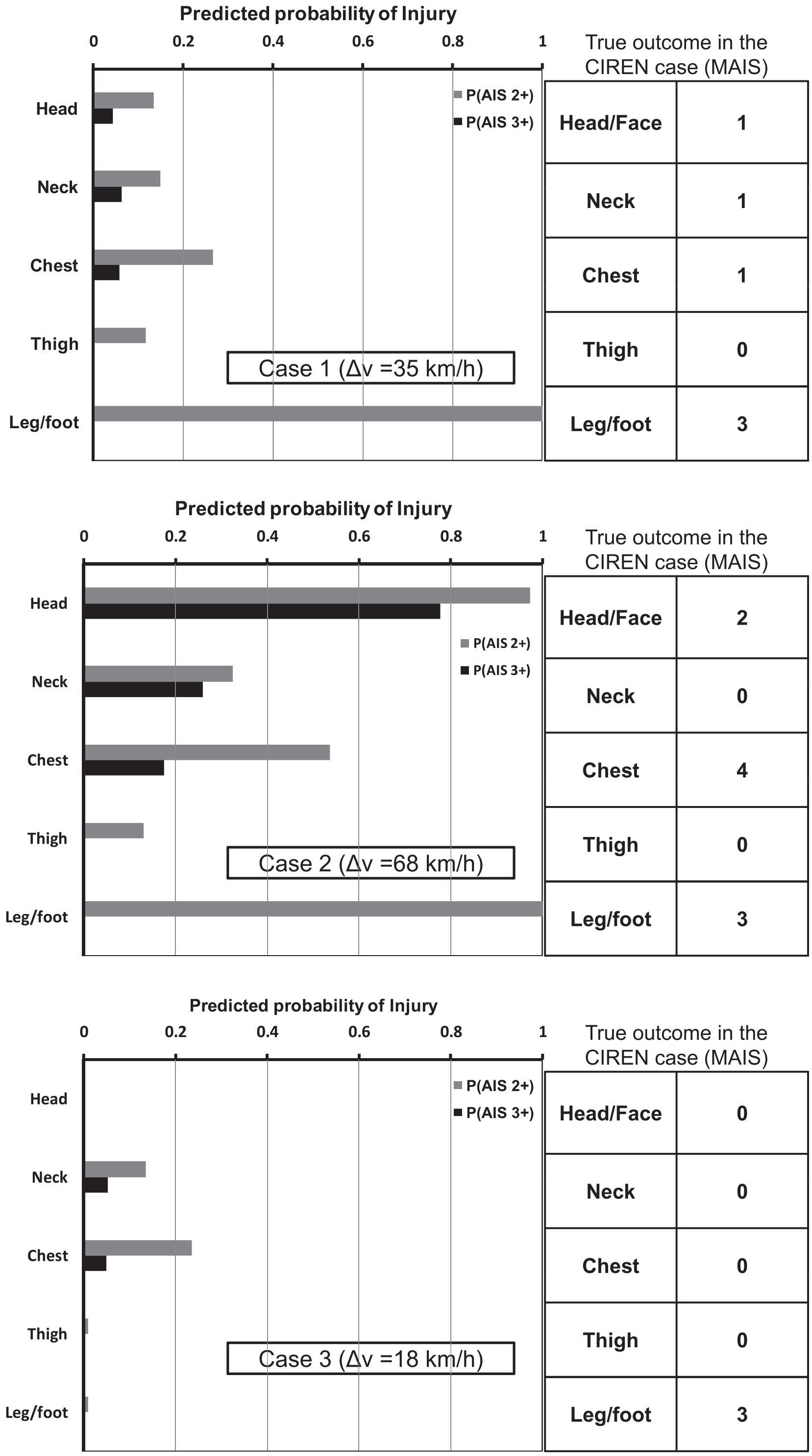

Fig. 5. Injury risks for the CIREN cases predicted by the computational methodology.

3.2. Sensitivity to posture and impact speed

The effect of impact speed and initial driving posture on the region specific injury risk is shown in Fig. 6. For impact at 35 km/h, the risk of injury to all body regions except the chest was greater for occupants who were reclining or leaning

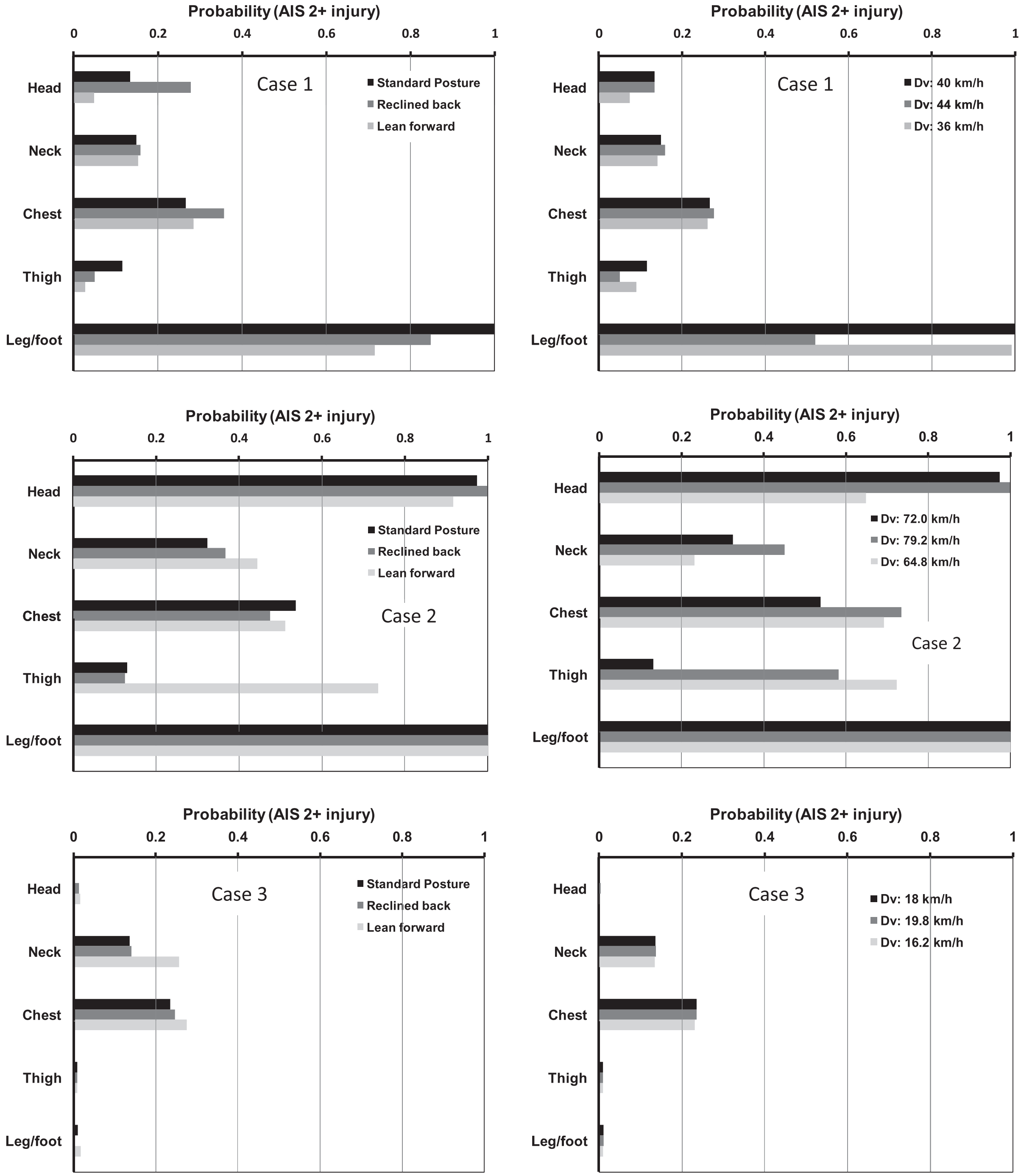

Fig. 6. Sensitivity of injury risks to initial posture and impact speed.

forward. This finding tends to confirm an overall impression that seat belt-airbag systems perform optimally when the occupant is in the standard driving posture. In general the reclined posture posed a higher threat for the head/neck region while occupants leaning forward at the moment of the impact were at increased risk for lower extremity injuries. A ten percent variation in impact speed was associated with a marginal effect on the risk of upper body injuries. For example, in Case 2 (high impact speed) postural variation yielded results similar to a crash of moderate severity, although the probability of lower extremity injuries increased to 100%. In low impact speed conditions (Case 3) the variation in injury risk was minimal when initial posture or impact speed was varied by 10%. The exception was a marginally higher risk of chest and neck injuries if the occupant was leaning forward when compared to an occupant in a standard or reclining posture.

Table 2
Comparison of injury risk outcomes as predicted by NHTSA Urgency algorithm, body-region regression algorithm, computation methodology, and the true injury outcome recorded in CIREN database.

Body region	CIREN injury	Urgency	Body-region regression	Computation method	
	MAIS	P(MAIS 3+)	P(MAIS 3+)	P(MAIS 2+)	P(MAIS 3+)
Case 1					
Whole body	3	0.22	0.10	–	–
Head/face	1	–	0.01	0.13	0.04
Neck	1	–	–	0.15	0.06
Chest	1	–	0.00	0.27	0.06
Thigh	0	–	0.05	0.12	–
Leg/foot	3	–	0.05	1.00	–
Case 2					
Whole body	4	0.96	0.87	–	–
Head/face	2	–	0.86	1.00	1.00
Neck	0	–	–	0.37	0.32
Chest	4	–	0.01	0.48	0.14
Thigh	0	–	0.03	0.13	–
Leg/foot	3	–	0.03	1.00	–
Case 3					
Whole body	3	0.16	0.16	–	–
Head/face	0	–	0.88	0.01	0.01
Neck	0	–	–	0.14	0.06
Chest	0	–	0.00	0.25	0.05
Thigh	0	–	0.00	0.01	–
Leg/foot	3	–	0.00	0.00	–

The injury risk is expressed in terms of probabilities denoted by P().

3.3. Comparison with regression model results

A comparison of estimated injury risk based on statistical models with injury risk based on computational methodology is presented in Table 2. The NHTSA Urgency Algorithm as evaluated in this study has shown better predictive accuracy for high impact speed crashes then for low speed crashes. While the body-region regression model showed consistent results for *whole body risk estimates*, it provided comparatively poor estimates for region-specific injury risk. Compared to the two statistical approaches, the estimates obtained from the multibody model appear more consistent with the actual injury data.

4. Discussion

While advances in AACN technology provide opportunities for improving both the quality of emergency medical care as well as clinical outcomes of motor vehicle crash victims, there is also enormous potential for improving the existing framework of immediate injury assessment and identification of life threatening conditions. Towards that goal, this study focuses on the development and validation of a computational methodology for post-crash injury risk assessment Compared to existing statistical regression techniques, the computational algorithm for stochastic injury prediction provided greater specificity regarding pre-crash conditions (e.g., occupant posture) as well as better information about the vehicle kinematics evolving during the crash. Validation results involving three real-world frontal crashes indicated better injury prediction by the computational methodology when compared to existing algorithms, such as the Urgency Algorithm.

For example, in the frontal crash loading environment, the study compared occupant interaction with vehicle components between the simulation results and physical contact evidence reflected in the CIREN data. It must be noted that the intrusion of the vehicle interior components was not simulated accurately due to lack of sufficient modeling details. Additional modeling efforts are needed to accurately represent vehicle intrusions which may contribute to increase the injury-risk being analyzed. However, the data confirmed that physical contact evidence as well as the gross kinematics of the driver were simulated appropriately with the methodology. Subsequently, the computational methodology based algorithm was able to identify the risk of injuries in regions of the head, chest and the lower extremities that were frequently contacted.

The modeling approach as evaluated in this study provides a stochastic estimate of the injury outcome taking into account the variability in the estimates of the crash properties. The conceptual framework for an AACN system assumes that specific vehicle properties and restraint usage are known apriori to the crash; however, crash kinematics and occupant characteristics may only be determined with lesser degree of certainty as probabilistic estimates. It is hypothesized that with real-time monitoring of sensor data during the progression of the crash, the error in the final estimates of the crash and occupant properties may be reduced but their variance is important for the injury risk prediction. A stochastic estimation approach allows to incorporate the variance in the input parameters and determine the sensitivity of the injury outcome to such parameters. To demonstrate this, the sensitivity of injury risk to initial posture and impact speeds was evaluated using parametric simulations. Results indicated that both parameters, initial posture and crash speed, had a substantial effect on the region-specific risk of injury for the given crash test conditions.

The computational methodology developed in the study has been demonstrated as a *proof of concept* using a limited number of crash cases. However, one of the major short comings was the inability of the simplified modeling approach to accurately estimate the risk of injury in certain real-world conditions. The injury metrics and the injury risk functions used in the methodology are based on metrics applicable in dummy tests. Additionally, the injury metrics in the present form covers only five body regions and are representative of injury mechanisms typically associated with frontal crash loading. Further, the occupant model used in the methodology has been specifically validated for high-speed (around 56 km/h) frontal impact test conditions and is unable to represent a broader spectrum of injuries due to biofidelic limitations. Thus, the occupant model and the injury risk estimation technique is not applicable for all crash conditions, representing only a small portion of overall real world crash scenarios. For example, to evaluate injury risk in a rollover crash at a similar level of accuracy will require: (1) significant changes to the occupant model that incorporate substantially increased focus on the vertebral column; along with (2) a precise definition of injury metrics and injury risk functions specific to spinal injuries. Other limitations of the computational methodology include its current inability to incorporate important occupant characteristics properties such as age, sex, pre-crash driving behavior including but not limited to muscle bracing. Additionally, because of the simplifications incorporated in the vehicle model, kinematics of the crash evaluated in a 2-D plane, and other forms of variability related to real world crash conditions have not been captured by this simulation approach.

Overall, an AACN framework with the capacity to identify life threatening injuries occurring in different body regions as well as occult, soft tissue injuries requires precise understanding of crash loading and its interaction with the occupant in all body regions. Clearly, both statistical regression and computational methodology have their relative merits as well as their inherent limitations. From the results derived in this study, it is speculated that a computational methodology may have a greater potential for developing injury risk estimation algorithms most suitable for AACN applications. Anticipated advances in sensor technology involving occupant-adaptive restraints and stability control devices leads credence to the belief that the accuracy of information required for injury prediction will be significantly improved in the near future. For example, an optical scanning technique to estimate pre-crash occupant head position for optimal restraint and minimized injury is already under research. Data provided by such sensors will greater improve the accuracy of simulation predictions for head contact and associated injury risk.

5. Conclusion

A computational methodology for predicting the risk of crash-related injuries was developed and validated. A significant improvement in predicting the risk of real-world frontal crash injuries compared to existing algorithms was demonstrated in the study. Admittedly, the scope of the validated computational methodology is presently limited to specific crash orientations and severity; however, advanced biofidelity of human models coupled with real-time computational strategies may soon realize the potential of AACN-based applications in real-world motor vehicle crashes.

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Table A.1
Description summary of 62 CIREN crash cases filtered through the selection criteria defined in Section 2.1.

Variables	Units	Count	Mean/median[1]	Stdev.
Occupant age	Year	–	43	14
Occupant sex	(Male)	31	–	–
Occupant stature	m	–	1.68	0.19
Occupant mass	kg	–	85.3	35.6
Seating position	(Driver)	43	–	–
	(Front pass.)	16	–	–
Vehicle model year*	Year	–	2001	–
Vehicle type	(Car)	42	–	–
	(SUV)	8	–	–
	(Pick-up truck)	7	–	–
	(Mini van)	4	–	–
Vehicle curb mass	kg	–	1522	313
Crash delta-v	km/h	–	48.1	17.5
MAIS	(3)	45	–	–
MAIS	(4)	14	–	–
MAIS	(5)	3	–	–

Standard Deviation, front passenger, Sports Utility Vehicle, Maximum Abbreviated Injury Score, are abbreviated as Stdev., Front pass., SUV, MAIS, respectively.

[1] For binary variables, *Count* gives the sample size corresponding to the value noted in parenthesis under *Units*.

Appendix A. Descriptive statistics for CIREN cases

See Table A.1.

Appendix B. Injury risk prediction

To provide probabilistic estimates of region-specific injury risk as a function of their severities, NHTSA has published injury criteria based on statistical regression models (Eppinger et al., 1999). The statistical regression models define the relationship between variables measured by the injury metrics (e.g., force, acceleration, deflection) during an experimental test and the severity of concomitant post-test injuries, frequently classified for severity according to the Abbreviated Injury Scale (AIS) nomenclature (AAAM, 1990). The analytical closed form expression for the injury risk functions applicable to the five standard injury metrics are summarized below. To obtain the probability of sustaining an injury for a specific AIS level, the probabilities of sustaining injuries for two successive levels of injury and higher were subtracted.

- Head injury risk function as a function of HIC NHTSA (1997)

$$P(AIS \geqslant 1)_{head} = \frac{1}{1 + e^{(1.54 + \frac{200}{HIC}) - 0.0065 HIC}} \tag{B.1}$$

$$P(AIS \geqslant 2)_{head} = \frac{1}{1 + e^{(2.49 + \frac{200}{HIC}) - 0.0048 HIC}} \tag{B.2}$$

$$P(AIS \geqslant 3)_{head} = \frac{1}{1 + e^{(3.39 + \frac{200}{HIC}) - 0.0037 HIC}} \tag{B.3}$$

$$P(AIS \geqslant 4)_{head} = \frac{1}{1 + e^{(4.90 + \frac{200}{HIC}) - 0.0035 HIC}} \tag{B.4}$$

$$P(AIS \geqslant 5)_{head} = \frac{1}{1 + e^{(7.82 + \frac{200}{HIC}) - 0.0043 HIC}} \tag{B.5}$$

$$P(AIS \geqslant 6)_{head} = \frac{1}{1 + e^{(12.24 + \frac{200}{HIC}) - 0.0057 HIC}} \tag{B.6}$$

- Neck injury risk function as a function of Nij Eppinger et al. (1999)

$$P(AIS \geqslant 2)_{neck} = \frac{1}{1 + e^{(2.054 - 1.195 Nij)}} \tag{B.7}$$

$$P(AIS \geqslant 3)_{neck} = \frac{1}{1 + e^{(3.227 - 1.969 Nij)}} \tag{B.8}$$

$$P(AIS \geqslant 4)_{neck} = \frac{1}{1 + e^{(2.693 - 1.195 Nij)}} \tag{B.9}$$

$$P(AIS \geqslant 5)_{neck} = \frac{1}{1 + e^{(3.817 - 1.195 Nij)}} \tag{B.10}$$

- Thorax injury risk function as a function of chest displacement Eppinger et al. (1999)

$$P(AIS \geqslant 2)_{thorax} = \frac{1}{1 + e^{(1.87 - 0.044 cdisp)}} \tag{B.11}$$

$$P(AIS \geqslant 3)_{thorax} = \frac{1}{1 + e^{(3.71 - 0.047 cdisp)}} \tag{B.12}$$

$$P(AIS \geqslant 4)_{thorax} = \frac{1}{1 + e^{(5.09 - 0.047 cdisp)}} \tag{B.13}$$

$$P(AIS \geqslant 5)_{thorax} = \frac{1}{1 + e^{(8.83 - 0.046 cdisp)}} \tag{B.14}$$

- Upper leg injury risk function (Eppinger et al., 1999)

$$P(AIS \geqslant 2)_{upperleg} = \frac{1}{1 + e^{(5.79 - 0.519 femurforce)}} \tag{B.15}$$

- Lower leg/ankle injury risk function (Funk et al., 2002)

$$P(AIS \geqslant 2)_{lowerleg} = e^{-e^{4.99 ln(tibiaforce) - 45.412}} \tag{B.16}$$

Appendix C. Injury Details for Selected CIREN cases

See Table C.1.

Table C.1
Description of injuries sustained by the case occupant in the three CIREN cases.

	Case 1	Case 2	Case 3
Head	None	Scalp cont.(1)	None
Face	Skin abrsn.(1)	Orbit fx.(2) Orbit fx.(2)	None
Neck	Skin abrsn.(1)	None	None
Thorax	Skin abrsnn.(1)	Bilat. lung cont.(4) Rib fx.(4) Diaphragm lac.(3) Sternum fx.(2)	None
Abdomen	Skin abrsn.(1)	Spleen lac.(2) Skin cont.(1)	None
Spine	None	Lumbar spine fx.(2)	Lumbar spine fx.(3)
Upper extremity	Skin cont.(1)	Radius fx.(3) Ulna fx.(3)	Radius fx.(3) Metacarpus fx.(3)
Lower extremity	Tibia fx.(3) Fibula fx.(2) Ankle disloc.(2) Skin cont.(1)	Pubic symphysis sep.(3) Sacroilium fx.(3) Tibia fx.(3) Pelvis fx.(2) Fibula fx.(2) Calcaneus fx.(2)	Fibula fx.(3)

The number in parenthesis indicates AIS level. Abrasion, contusion, dislocation, bilateral, laceration, seperation and fracture are abbreviated as abrsn., cont., disloc., bilat., lac., sep. and fx., respectively.

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