INFLUENCE OF PRE-COLLISION OCCUPANT PROPERTIES ON THE INJURY RESPONSE DURING FRONTAL COLLISIONS

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ABSTRACT

Optimal performance of future adaptive restraint systems will require an accurate assessment of occupant characteristics including physical properties and pre-collision behavior of the occupant. This study is aimed at evaluating the sensitivity of frontal collision induced injuries to occupant state parameters: stature, mass, and pre-collision postural orientation. A numerically modeled restraint system was used to determine the potential benefits in injury mitigation by accounting for the occupant state parameters estimated during the pre-collision phase. The restraint system with properties optimized for varying sets of occupant anthropometries and posture states reported a reduction of 20-35% in the value of overall injuries. Restraint loading characteristics optimized for individual values of occupant parameters reported significant variation in the load-limiting threshold of the restraint system (4 kN to 8 kN). The influence of occupant state parameters on the overall injuries sustained in frontal collisions and the requirements on optimized restraint performance will provide a framework for developing restraint systems using accurate information regarding pre-collision occupant behavior.

Keywords: Adaptive restraint system, Occupants, seat belt, Multi-Body, posture.

FUTURE EFFORTS IN RESTRAINT DESIGN must be directed towards optimized restraint devices that account for specific occupant information involved in the collision. However, majority of the restraint systems are designed with an emphasis on fixed set of parameters dominated by the requirements of the federal regulations and New Car Assessment Program (NCAP) assessment tests, which represent a limited range of occupant population. For instance, the US Federal Motor Vehicle Safety Standard (FMVSS) 208 focuses on the performance of restraint system using anthropometric tests devices representative of the 50th percentile adult male and 5th percentile adult female only [NHTSA, 2004]. In addition to the anthropometric measures of the occupant, postural behavior such as seating position and postural orientation of the occupant is expected to influence the requirements on restraint system designed for specific occupant characteristics [Adomeit et al., 1997; Mackay, 1994; Miller, 1995]. Given the variations in the occupant characteristics observed in field studies [Bingley et al., 2005; Mackay et al., 1998], it is desirable to develop a framework for restraint system performances that accounts for occupant state parameters, including both time-independent properties such as stature and mass, and time-varying states, such as seating posture.

Given adaptability of the restraint systems to control the restraint properties, several studies have highlighted the importance of tuning the values of restraint properties to account for specific occupant state parameters. Miller & Maripudi, (1996) used a numerical model to evaluate the seat belt load-limiting value and the airbag vent size due to variation in three anthropometric sizes and three seating positions. The maximum variation in the values of injury metrics: Head Injury Criteria (HIC), chest acceleration (c_{accl}), and chest displacement (c_{disp}), estimated for occupants restrained using optimized properties were 141%, 140%, and 70%, respectively. Among the different occupant parameters evaluated in the study, maximum reduction in the value of the injury metrics using restraint optimization was reported for the extreme anthropometrics sizes, namely the 5th percentile adult female and the 95th percentile adult male. In a similar study, Adomeit et al., (1997) analyzed the sensitivity of thoracic loading-displacement characteristics as a function of occupant mass, stature, and seated position, using numerical methods. The results of the study reported high sensitivity of peak thoracic load to both occupant mass and seated position. While studies by Miller & Maripudi, (1996) and Adomeit et al., (1997), have evaluated potential reduction in injury risk in the upper-body region, the effect of the occupant state parameters on the overall risk of injuries is yet to be reported. To evaluate the sensitivity of overall injuries to individual occupant state parameters, an injury metric weighted to the severity and distribution of overall injuries in the body must be developed.

Driven by the significant reduction in the risk of injury achieved by adaptive restraint systems in numerical studies, advanced restraint systems capable of adjusting restraint properties to account for crash severity, occupant mass and positioning of the seat have been introduced in high-end vehicle models. The estimation of occupant state parameters in such advanced restraint systems involves hardware sensors such as pressure mats and seat-pan load cells for occupant classification and estimation of occupant mass [Pewinski et al., 2001; Sakai et al., 2004]. Although, current state of sensors are capable of estimating time-invariant properties, fewer studies have reported on the technology for estimating time-invariant states such as spatial imaging techniques to estimate postural orientation. [Krotosky & Trivedi, 2004; Stockman et al., 1997]. Limitations in robust evaluation of pre-collision dynamic postural properties of the occupant have prevented advanced restraint system to account for time-varying state information of the occupant.

To summarize, restraint systems that account for occupant characteristics require assessment of occupant states, referred to as occupant state parameters hereafter, including both time-invariant properties like stature and mass as well as time-invariant states such as the postural orientation and muscle bracing level. In order to develop a procedure for estimating the occupant state parameters, it is necessary to investigate the significance of the state parameters and determine the potential benefits for a restraint system, which accounts for these properties. The goal of the study, which is to evaluate the influence of the three occupant state parameters on the injury outcome of the occupant, was accomplished by performing two specific tasks (Fig. 1):

1. To evaluate the sensitivity of severity, and distribution of injuries sustained by an occupant in to values of occupant time-invariant and time-varying parameters.
2. To estimate the potential reduction in injury outcome using restraint properties optimized for specific occupant state parameters in frontal collisions.

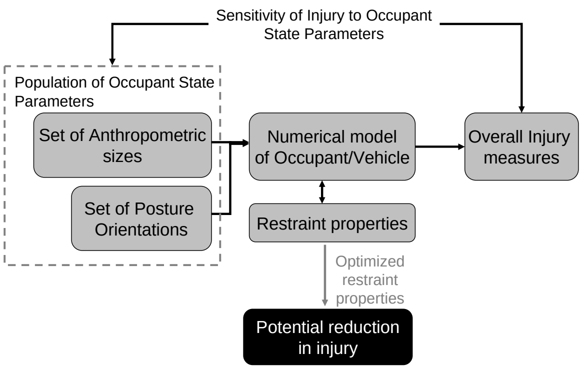

Fig. 1-Overview of the study objectives to evaluate the effect of occupant state parameters on injury outcome and in-vehicle sensor measurement data.

METHODS

Commercially available and extensively validated multi-body models of a human occupant and driver-side interior compartment of a mid-sized sedan car was used in this study to simulate occupant dynamics in a collision-loading environment. The occupant model was adapted to represent different sets of occupant state parameters using an anthropometric scaling procedure, in order to generate human models of varying sizes, while the initial joint positions were varied to obtain different postural orientations of the occupant model. A whole body injury metric (WBIM), developed as a combined function of injury severity and distribution, was used to evaluate the sensitivity of overall harm due to injuries to different values of pre-collision occupant state parameters. A detailed description of the numerical models, the analysis for determining the sensitivity of injury outcome to occupant state parameters, estimation of occupant state parameters, and evaluation of optimized restraint properties is presented in the following subsections.

NUMERICAL MODELS

Occupant model

A multi-body representation of a 50th percentile adult male, available in the database of MADYMO™ (v6.3.2), was used as the primary occupant model in the study [TNO, 2006]. The multi-body occupant model, commonly referred to as an occupant facet model, consists of rigid elliptical structures and representing the skeletal system and facet shell structure defining an accurate surface skin geometry for the human model (Fig. 2). The non-linear joint properties and contact characteristics were derived through various component level validation tests [TNO, 2006]. The MADYMO™ human occupant model has been validated for multi-directional loading environment (frontal and lateral impacts) using biofidelic requirements for rating numerical models and mechanical test surrogates [deLange et al., 2005].

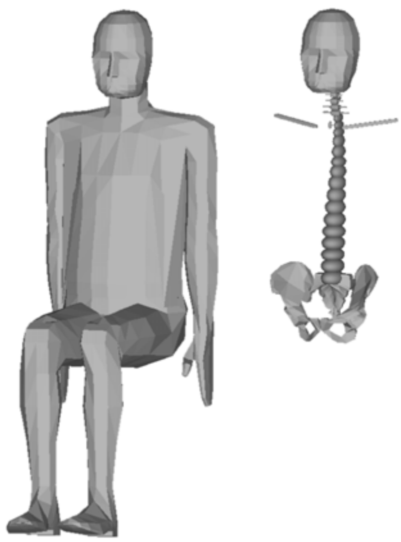

Fig. 2 - Multi-body model of a 50th percentile adult male occupant (MADYMO™ database). The figure on the right shows the representation of the spine and the pelvis using rigid elliptical bodies and FE structures, respectively.

To populate the design space of occupant time-invariant anthropometric properties (Fig. 1), the mid-sized adult male occupant model was scaled to obtain occupant models representative of varying anthropometric sizes. Occupant models corresponding to specific values of the stature (Occ_s) and the mass (Occ_m) variables were developed based on the principles of geometric scaling [Langhaar, 1951]. The reference values for scaling the Occ_s and the Occ_{m_ref}, correspond to the stature and mass of a 50th percentile adult male and were obtained from an U.S.-based, human anthropometric database [Gordon et al., 1988]. Using mean (standard deviation) values of 1.757m (σ = 0.071m) and 77.99kg (σ = 11.04kg) 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 [Gordon et al., 1988]. 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 was an invariant across the population (Eq. 1). Using the software sub-routines available in MADYMO™, 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; Untaroiu et al., 2008]. Thirteen occupant models, with a variation of 0.12m, 11.58kgs and 3.75kg/m^2, in stature, mass and body mass index (BMI), respectively, were developed to evaluate the influence of occupant anthropometric size on the overall injury outcome (Table 1).

$$\lambda_{lz} = \frac{Occ_s}{Occ_{s\_ref}}, \; \lambda_m = \frac{Occ_m}{Occ_{m\_ref}}, \; \lambda_{lx} = \lambda_{ly} = \sqrt{\frac{\lambda_m}{\lambda_{lz}}} \tag{1}$$

To develop a population of time-varying postures (Fig. 1), nominal driving posture and non-nominal postures were determined from field observation studies. The positioning of the occupant model in the nominal driving posture (POS_{nom}) was based on geometric dimensions and joint angles measured for preferred seating posture of adult drivers [Schneider et al., 1983]. To evaluate the effect of seating posture, alternate occupant postures were considered based on literature studies involving video-photography of real-world driving postures, survey of drivers to solicit opinions on posture usage, and laboratory experiments involving out-of-position risk to injury [Zhang et al., 2004]. Although, video-photography of real-world drivers provide limited information about the overall occupant posture, the results of the study suggest that the adopted postural configurations leads to substantial variation in the distance between the head and the steering column [Bingley et al., 2005]. To characterize the overall posture of the occupant, characteristics postures from a survey on preferred occupant postures was used to develop eight non-nominal occupant postures for the driver[Zhang et al., 2004]. The common postural traits used for the variation in the occupant postures were positioning of the lower extremities, proximity of the upper-body to the steering column, and sideways lateral bending (in the coronal plane) of the occupant. The details of joint configurations used to orient the occupant model in the nine occupant postures evaluated in this study (Fig. 3) are reported in Table 2.

Table 1-Anthropometric details of occupant models evaluated in the study

Model	Height (m)	Height %^{ile}	Weight (kg)	Weight %^{ile}	BMI (kg/m^2)
H50_W50	1.758	50	77.99	50	25.2
H60_W50	1.776	60	77.99	50	24.7
H70_W50	1.795	70	77.99	50	24.2
H40_W50	1.740	40	77.99	50	25.8
H30_W50	1.721	30	77.99	50	26.3
H50_W60	1.758	50	8079	60	26.1
H50_W70	1.758	50	83.78	70	27.1
H50_W40	1.758	50	75.19	40	24.3
H50_W30	1.758	50	72.20	30	23.4
H60_W55	1.776	60	79.38	55	25.2
H80_W68	1.818	80	83.15	68	25.2
H40_W44	1.740	40	76.32	44	25.2
H20_W32	1.698	20	72.83	32	25.3

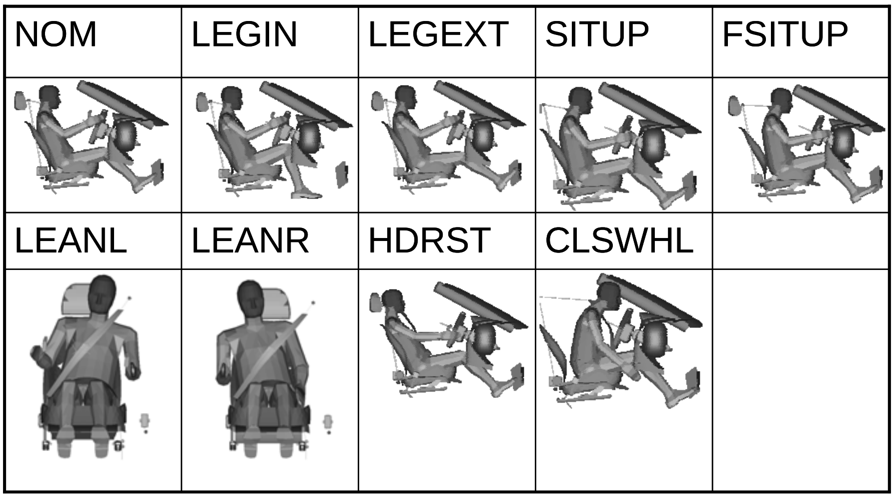

Fig. 3-The occupant model oriented in the nine driving postures evaluated in the study

Vehicle model

The vehicle model used in the study was a validated multi-body representation of the driver's side interior compartment of a mid-size sedan car (shared by TASS-Safe™, Delft, Netherlands). The model includes geometrically accurate FE structures representing the seat belt, retractor system, buckle system, airbag, seat structure, windshield, front panel and the knee bolster. A simplified representation, using planar and ellipsoid multi-bodies, were used to model the side door, side window, A-pillar, steering column structure and toe-pan (Fig. 4-Components of the multi-body model representing the driver-side interior compartment). The material properties for the structures interacting with the occupant model were defined as contact stiffness characteristics determined through experimental validation. The vehicle restraint system included a standard three-point belt system including a load-limiting retractor, an adjustable D-ring system, a buckle system, and pretensioners at the belt anchor points, and a dual airbag system (Fig. 4).

Table 2-Details of positioning and joint angle orientations used for determing non-nominal posture orientations. All values are relative to the corresponding values for the nominal posture. The position of the body is positive in the direction of vehicle movement, rotations for the lumbar, head, hip, knee and ankle are positive for flexion, and lateral bending of the body is positive towards the left of the body. Position, joint, lateral, rotation are shortened as pos., jnt., lat., rot., respectively.

Posture	Description	Body Pos	lumbar jnt rot	Lat. bend	Head rot.	Hip jnt rot.	Knee jnt rot.	Ankle jnt. rot.
		(mm)	(rad)	(rad)	(rad)	(rad)	(rad)	(rad)
POS_{legin}	From POS_{nom}, legs pulled in	0	0	0	0	-0.15	-0.55	0
POS_{legext}	From POS_{nom}, legs extended out	0	0	0	0	0	0.2	0.2
POS_{situp}	From POS_{nom}, upper body upright	0	0.198	0	0	0	0	0
POS_{fsitup}	From POS_{situp}, wholebody moved forward	0	0.198	0	0	0	-0.1	0
POS_{leanl}	From POS_{nom}, upper body leaning left	56	0	-0.25	0	0	0	0
POS_{leanr}	From POS_{nom}, upper body leaning right	0	0	0.25	0	0	0	0
POS_{hdrest}	From POS_{nom}, reclined back	0	-0.152	0	-0.05	0	0	0
POS_{clswhl}	From POS_{nom}, upper body close to steering column	56	0.398	0	0	0	-0.1	0

The positioning of the seat structure and the restraint system was adapted in the vehicle model to accommodate the anthropometry of individual occupants. The position of the seat-structure on the tracks relative to the steering column was determined using published regression equations describing occupant preferred seating position as a function of their stature and interior geometry of the vehicle [Flannagan et al., 1998]. The occupant model was oriented in the driver seat based on nominal driving posture reported in the literature [Schneider et al., 1983]. The initial positioning of the seat belt around the occupant body was performed by pretensioning the belt until the tensile force in the shoulder segment of the belt was set to a nominal value of 10N. A generic load-limiting value of 2000N and pretensioning stroke length of 120mm was used to model the restraint system, referred to as the standard restraint system in the study. To improve the efficiency of the numerical model in parametric evaluations and optimization routines, an optimal time-step for the model was chosen based on the sensitivity of time-step to computational time and convergence of measured occupant responses such as contact forces and kinematic characteristics. An optimal minimum time-step of 1.5 X 10^{-5}s and 5 X 10^{-6}s for rigid-body and FE parts, respectively, resulted in a computational time of 375s to simulate a 300ms event.

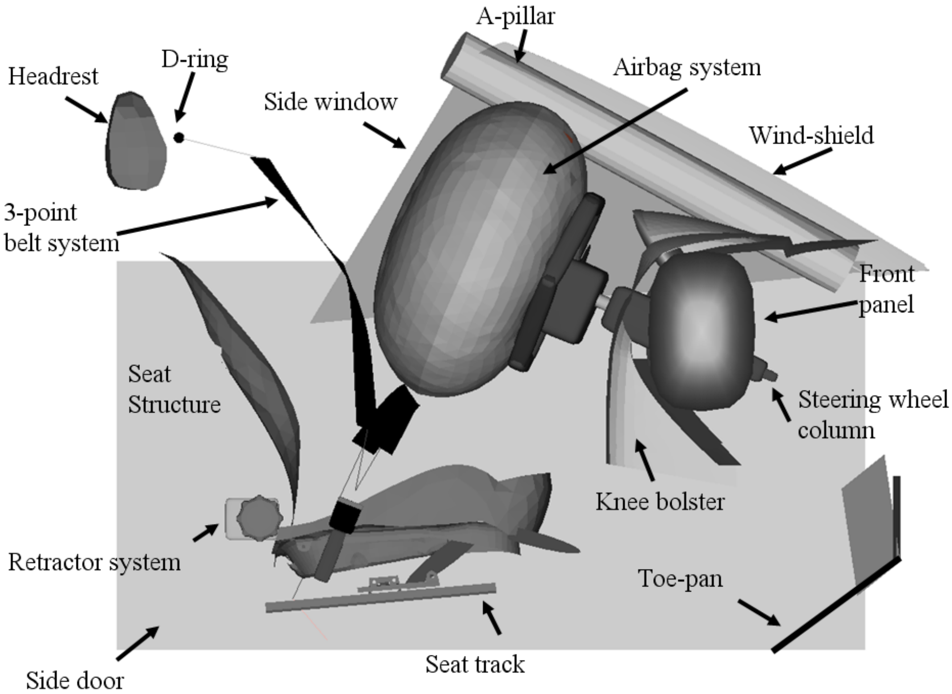

Fig. 4-Components of the multi-body model representing the driver-side interior compartment

SENSITIVITY OF OVERALL INJURIES TO OCCUPANT STATE PARAMETERS

Formulation of a Whole Body Injury Metric (WBIM)

The WBIM used in the study is a normalized representation of medical related cost and cost associated with lost quality of life due to the injuries. The WBIM relates the standard injury metrics estimated by an anthropometric tests device or a numerical human model to the overall harm associated with the injuries. While the WBIM provides a convenient means of assessing the total cost associated with the injuries, it should be noted that alternative whole body injury estimates could be utilized. The procedure for estimating the WBIM is outlined below.

Step 1: The occupant model was developed for numerically estimating the values of five standard injury metrics: head injury criterion (HIC), neck injury criterion (N_{ij}), chest deflection (C_{disp}), femur load (Fem_l) and tibial load (Tib_l), during a collision pulse simulation. Since injury risk functions exist only for the 50th percentile adult male, the estimated injury metrics were scaled based on the principles of dimensional scaling to account for differences in the anthropometry of the occupant models [Mertz & Irwin, 2003]. The scaling factors, λ_{HIC}, λ_{Force}, λ_{Moment}, λ_{disp},were used to scale the HIC values, force measures, moment measures, and displacement measures, respectively, from the mid-size adult male anthropometry (Eq. 2).

$$\lambda_{HIC} = \lambda_{lz}^{-1.5}, \lambda_{Force} = \lambda_{lx}^{2}, \lambda_{Moment} = \lambda_{lx}^{3}, \lambda_{disp} = \lambda_{lx} \quad (2)$$

Step 2: The probabilities of injuries at different severity levels and body regions were estimated using injury risk curves reported in the literature [Eppinger, 1999; Funk et al., 2001; Ryan et al., 1998] Using the values of injury metrics estimated in Step 1 and the corresponding injury risk curve for that body region, the probability of injuries in each severity category (Abbreviated Injury Scale (AIS) rating 1 to 6) were determined for the head, neck, chest, thigh and foot region.

Step 3: The medical and quality of life associated costs of injuries as a function of their severity and affected body region were determined using data reported in studies aimed at evaluating the social cost of motor vehicle collisions[Zaloshnja et al., 2004]. The formulation for estimating the whole body injury cost (WIC) is shown in Eq. 2, where P(AIS_{mn}) is the probability of AIS level *n* injury in the body region *m,* determined in step 2, and MC_{mn} and QL_{mn} are the medical and quality of life associated costs for an victim with maximum AIS (MAIS) level *n* injury in the body region *m,* determined from Zaloshnja et al., (2004).

$$WIC = \sum_{m}\sum_{n}[P(AIS_{mn}) \times (MC_{mn} + QL_{mn})] \tag{3}$$

Step 4: Since Zaloshnja et al., (2004) investigation examined MAIS associated costs for an injury within a body region, summation of injuries such as that in Eq. 3 overestimates the WIC. Therefore, the WIC derived in Step 3 was normalized to represent an objective injury metric, WBIM, rather than an accurate cost estimate.

Parametric Test Matrix for WBIM Sensitivity

The effect of occupant state parameters on the overall injuries was analyzed using the multi-body models of occupant and vehicle system and the formulation of WBIM. The effect of occupant anthropometry and occupant postural on the overall injury was evaluated separately using the 13 scaled human occupant models (Table 1) oriented in the nominal driving posture and the mid-size occupant model (model H50_W50 in Table 1) oriented in the 9 driving postures (Table 2). The occupant model of a specific anthropometry and specific initially orientation was subjected to a representative frontal collision deceleration pulse (57 km/h, U.S. New Car Assessment Program (NCAP) frontal collision pulse). A full-width impact configuration was chosen in the study since the high decelerations developed in this configuration is appropriate for analyzing the restraint performance. To analyze the effect of occupant state parameters on injury as a function of collision speed, frontal collision pulses representative of different impact speeds were derived from the 57km/hr NCAP deceleration pulse. Assuming that the total duration of crash pulse is constant at all impact speeds [Warner et al., 2007], the ordinates of the standard frontal collision pulse was scaled (scaling factors from 0.5 to 1.5) to develop deceleration pulses corresponding to different impact speeds (delta-v from 29km/h to 88km/h).

INJURY REDUCTION THROUGH OPTIMIZED RESTRAINTS

The potential benefits in injury mitigation through adaptable restraint systems were evaluated by optimizing the restraint properties to different values of occupant state parameters. Five sets of occupant state parameters, each being a pair of occupant anthropometry and occupant posture value, were used to determine optimized restraint properties for each of the parameter sets. The values of occupant anthropometry and occupant posture chosen represent maximum variation in the anthropometric size among all the occupant models and variation in the proximity of the occupant upper-body to the steering column (Table 4). The purpose of choosing the five occupant state parameter sets is to evaluate requirements on optimized restraint properties to account for anthropometric size and postures representing upper-body orientations in the sagittal plane. The evaluation of optimized restraint properties applicable for all paired-values of occupant anthropometry and posture considered in the study was beyond the scope of this study.

Four restraint properties, seat belt load-limiting value, pretensioner firing time, airbag firing time, and airbag vent discharge coefficient, were chosen as the design variables of the optimization routine based on studies involving numerical analysis of adaptive restraint systems [Hesseling et al., 2006; Hou et al., 1995; Sieveka et al., 2001]. The choice of restraint properties was made such that the initiation and peak characteristics of the belt and airbag restraint force-profile could be adjusted for individual values of occupant anthropometry and posture. The low simulation run-time of the occupant-vehicle model and parametric modeling of the restraint components allowed for efficient optimization of the restraint design variables. The model parameters for the occupant-vehicle model and kinematic boundary conditions used for evaluating the restraint performance were identical to the conditions used while evaluating the sensitivity of WBIM to occupant state parameters.

A direct search optimization algorithm was implemented using the multi-objective optimization software, modeFRONTIER™ (v4, ESTECO s.r.l., Trieste, Italy), to iteratively evaluate the values of the restraint properties resulting in the minimum value of WBIM for each set of occupant state parameters. An initial range of values for the restraint properties was chosen based on values reported in the literature[Sieveka et al., 2001]. A Sobol design of experiment (DOE) sequence was used to uniformly populate the values of restraint properties in the chosen design space. The objective function of the optimization routine was formulated as minimization of WBIM, evaluated using Eq. 2 and standard injury metrics estimated by the occupant model. A standard multi-objective genetic algorithm, MOGA-II, was used to adapt the initial design populations over successive generations, and to determine optimal values for the restraint properties [Anderson, 2001]. The convergence to a uni-modal solution for four design variables and one objective function required an initial population of 20 designs sets adapted over 30 generations. The accuracy of the optimized design variables was improved by iteratively updating the range of restraint properties based on their sensitivity to WBIM.

The effect of the occupant state parameters on the optimization of restraint systems was evaluated by comparing the optimized values of restraint properties for the five sets of occupant state parameters. Further requirements on the belt restraint system were analyzed by comparing the restraint force-time history, optimized for individual occupant state parameters. The potential reduction in the values of standard injury metrics and WBIM using occupant state parameter specific restraint system was evaluated for different values of occupant state parameters. To emphasize the increased risk of injuries under all conditions while using a restraint system optimized for a mid-sized occupant in nominal posture, the effect of occupant state parameters on the injury measures for a standard restraint system was compared to the same when the restraint system was optimized for a fixed set of occupant state parameters.

RESULTS

SENSITIVITY OF OVERALL INJURIES TO OCCUPANT STATE PARAMETERS

The variation in the values for standard injury metrics and WBIM for an occupant, restrained by the standard restraint model to a 56 km/h frontal collision pulse, was evaluated as a function of occupant anthropometry and postures (Fig. 5, Fig. 6 & Fig. 7). In addition to WBIM, individual harm to the body regions evaluated as relative proportion of the WBIM was reported as a function of the occupant state parameters (Fig. 5, Fig. 6 & Fig. 7). Among the occupant postures, the minimum value of WBIM was estimated for POS_{leanl} and POS_{situp} with relatively lower risk of injuries to the head and thorax region. Maximum value of WBIM was estimated for POS_{leanr} and POS_{clswhl} with relatively higher risk of injury to the head region compared to other postures. While the risk of injuries to the upper body regions increased significantly for postures with upper body close to the steering column (e.g., POS_{clswhl}), the risk of lower extremity injuries reduced with the decrease in the excursion distance of the upper body.

The variation in WBIM as a function of occupant stature reported a positive trend ($r = 0.86$), whereas, the same when estimated as a function of occupant mass reported a negative trend ($r= -0.88$) (Fig. 6 & Fig. 7). In terms of statistical dispersion of WBIM expressed by coefficient of variation (c_v), the postural states reported a high degree of variation (0.36) compared to the anthropometric states (< 0.1). The interaction between the occupant state parameters and WBIM was further analyzed by stratifying the estimated WBIM for individual occupant state parameters into upper and lower effect groups and performing a t-test to evaluate the null hypothesis that the two effect groups have equal samples means. The t-test for the posture state variable was omitted due to lack of parameterization of the discrete states. Although a high level of significance was reported for rejecting the null hypotheses in the case of occupant stature ($p < 0.01$), the null hypothesis in the case of occupant mass ($p = 0.20$) could not be rejected at 95% confidence interval.

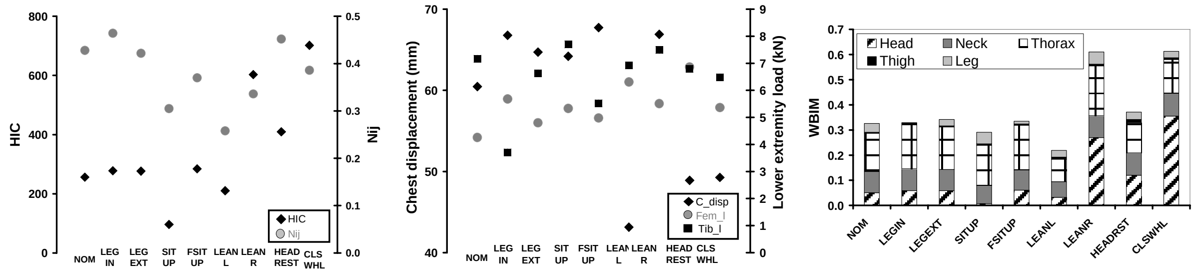

Fig. 5-Estimated values of standard injury metrics (left and middle figure), WBIM, and the relative contribution of the five body regions to the WBIM (right figure), plotted againts the initial posture of the occupant involved in a standard frontal collision.

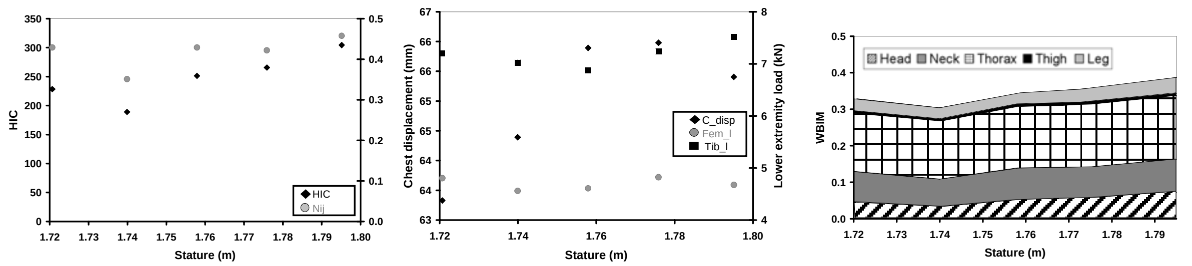

Fig. 6-Estimated values of standard injury metrics (left and middle figure), WBIM, and the relative contribution of the five body regions to the WBIM (right figure), plotted agianst the stature of the occupant involved in a standard frontal collision.

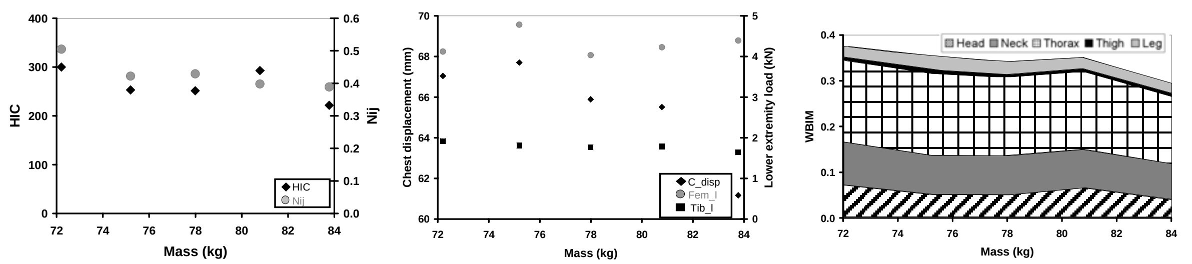

Fig. 7-Estimated values of standard injury metrics (left and middle figure), WBIM, and the relative contribution of the five body regions to the WBIM (right figure), plotted agianst the mass of the occupant involved in a standard frontal collision.

INJURY REDUCTION THROUGH OPTIMIZED RESTRAINTS

Using the direct search optimization routine described earlier, optimized values for the restraint properties for the five given sets of occupant state parameters were determined (Table 3). The results indicated that the load limiting value and the pretensioner firing time to be the two most important factors to affect the WBIM ($p < 0.015$). The optimized restraint properties yielded in approximately 22% to 35% reduction in WBIM compared to the WBIM estimated with the standard load limiting restraint system. The characteristics of restraint loading profile optimized for individual occupant state parameters were analyzed by comparing the belt tension time history for the five sets of optimized restraints (Fig. 8). The non-nominal occupant postures, especially with forward leaning of the upper body, significantly affected the peak restraint load limit, whereas, the differences in the occupant anthropometry altered both the timing of onset and the peak value of the restraint load profile. The importance of accurate estimation of occupant state parameters was highlighted by evaluating the injury measures as a function of occupant state parameters, first, when the occupant was restrained by the standard restraint system, and secondly when the occupant was restraint by a restraint system with properties optimized to protect a mid-sized occupant in nominal seating posture (Table 4).

Table 3-Optimized values of restraint properties used in the standard and the five optimized restraint models. The second and third column list the occupant state parameters for which the restraint properties were optimized. The restraint properties of the standard restraint model were determined from literature studies. The airbag and pretensioner firing time is relative to the onset of the crash pulse. The value in paratheses indicates the standard deviation in the estimated value of the design variable in the final optimization iteration.

Restraint Name	Anthropometric model used in optimization	Posture orientation used in optimization	Load-limiting value in N (σ)	Airbag vent discharge (σ)	Pretensioner firing time in ms (σ)	Airbag firing time in ms (σ)
Standard model	N.A.	N.A.	2000	0.6	15	10
Opt_H50_W50_NOM	H50_W50	POS_{nom}	3952 (28)	0.90 (0.04)	25 (0)	28 (1)
Opt_H50_W50_FWD	H50_W50	POS_{fsitup}	7857 (398)	0.62 (0.09)	3 (2)	0 (0)
Opt_H50_W50_RCL	H50_W50	$POS_{headrest}$	3845 (27)	0.98 (0.03)	27 (1)	33 (1)
Opt_H20_W32_NOM	H20_W32	POS_{nom}	3554 (30)	0.79 (0.03)	37 (3)	26 (0)
Opt_H80_W68_NOM	H80_W68	POS_{nom}	4124 (32)	0.99 (0.04)	40 (0)	27 (0)

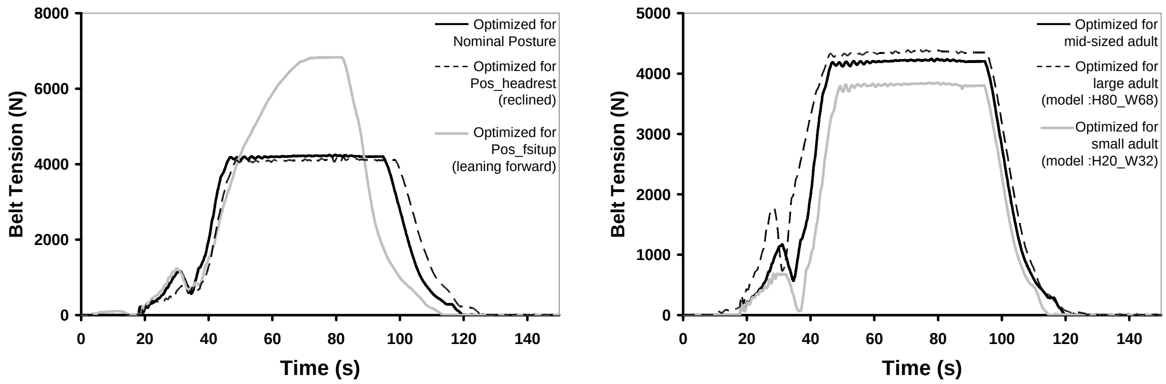

Fig. 8-Restraint belt tension time histories optimized for diffirent values of occupant postures (left) and anthropometries (right).

Table 4 Comparison of WBIM and standard injury metrics estimated for five sets of occupant state parameters with the occupant restraint by the standard restraint model and the restraint system with properties optimized for a mid-sized occupant seated in nominal driving posture.

Occupant Anthropometry	Occupant Posture	Standard Restraint Model						Optimized Restraint Model: Opt_H50_W50_NOM					
		WBIM	HIC	N_{ij}	C_{disp} (mm)	Fem_l (kN)	Tib_l (kN)	WBIM	HIC	N_{ij}	C_{disp} (mm)	Fem_l (kN)	Tib_l (kN)
H50_W50	POS_{nom}	0.329	228	0.429	63	4.805	7.202	0.263	129	0.366	59	5.567	6.967
H50_W50	POS_{fsitup}	0.335	285	0.37	68	4.979	5.522	4.365	2661	0.529	61	5.053	6.328
H50_W50	$POS_{headrest}$	0.371	409	0.452	49	6.863	6.798	0.361	343	0.449	54	8.538	6.563
H20_W32	POS_{nom}	0.324	240	0.442	64	4.737	6.619	0.295	140	0.373	59	6.410	7.767
H80_W68	POS_{nom}	0.407	363	0.424	63	4.975	7.469	0.269	172	0.401	51	4.853	7.800

DISCUSSION

Occupant characterization for adaptive restraint control has primarily focused on overall physical properties such as anthropometry (c.f. Happee *et al.*, 1998), and detailed material properties such as bone mineral density. However, relatively fewer research studies have emphasized on the importance of reflexive occupant behavior such as postural orientation. Factors that have limited this consideration include the lack of means to characterize the time-varying states, high degree of variability in the occupant responses, and significantly less biomechanical data available to provide insight into such effects. Although ignored in the restraint designs, the variability in the postural state is well reported in studies involving traffic observations, driving simulator studies involving driver response to emergency maneuvers (c.f. Bingley *et al.,* 2005).

Using frontal collision simulation results determined for an extensive design space of the occupant state parameters (13 anthropometric models and 9 driving postures), the sensitivity of injury outcome to occupant state parameters was evaluated. The influence of the individual occupant state parameters on the injury outcome, represented by WBIM, was determined by using standard statistical measures. The use of WBIM for whole-body injury assessment is a considerable improvement over previously existing version of injury metrics which either use simplistic measures like exposure rate to weigh the injury metrics (Viano & Arepally, 1990), or use linear models of injury metrics (Miller & Maripudi, 1996), to assess the risk of injuries. Previous studies involving numerical occupant models (Adomeit *et al.,* 1997; Miller & Maripudi, 1996), have reported on the influence of occupant anthropometry and seating position on the injury metrics in the head and chest region. The estimated values for injury metrics for three anthropometric sizes (5^{th} percentile female, 50^{th} percentile male and 95^{th} percentile female) and three seating position (full forward, mid-position and full rear) reported by (Miller & Maripudi, 1996), showed consistent trends as evaluated in this dissertation. The occupant anthropometry, which was varied from 80^{th} percentile to 20^{th} percentile of the adult population, reported a range of +19% and -13% variation in the values of WBIM when compared against the mid-sized adult anthropometry. As hypothesized by (Miller, 1995), the overall injury to an occupant was dependent on the occupant stature, and relatively independent of the occupant inertial properties. Injury metrics with higher weighing factors in the determination of WBIM such as HIC, N_{ij} and c_{disp}, reported higher sensitivity and positive correlation to occupant anthropometry compared to lower extremity injury metrics. A t-test performed to evaluate the sensitivity of the anthropometric state parameters on the injury outcome reported significant influence for occupant stature on WBIM, while occupant mass was a statistically insignificant predictor of the WBIM.

The injury outcome reported relatively higher sensitivity to the posture states evaluated in the dissertation, with a range of +88% and -33% variations in the values of WBIM when compared against the nominal driving posture. The high range of WBIM reported for the 9 discrete posture cases is attributed to the high degree in variability among the posture representations. The variability in the posture orientations not only affect the available excursion distance for occupant ride down, but also affect the restraint effectiveness specially for postures with lateral bending. The posture orientations evaluated in the dissertation were representative of true postures seen in traffic studies and volunteer preferences. It could be reasonably concluded that compared to a representative range of occupant anthropometries in the driver population, the representative variation in the driver posture has a more significant affect on the injury outcome during a collision. Among the different occupant postures with variation in the orientation of the upper-body in the sagittal plane, POS_{fsitup} and POS_{clswhl} reported minimum and maximum value of WBIM, respectively, primarily attributed to the severity of the head and thorax injuries. The value of HIC was low for the nominal orientation of the upper-body, however, for postures with higher excursion distance ($POS_{headrst}$) and for postures with the head initially within the deployed volume of the airbag (POS_{clswhl}), significantly higher values of HIC was evaluated. For thoracic injuries, the risk of injuries increased with the decrease in the excursion distance of the upper-body. The restraining effectiveness of the seat belt was affected in the postures involving lateral bending, especially in the case of rightward bending where significantly higher values of HIC and c_{disp} were reported compared to the bending in the leftward direction.

The requirements on the restraint system to account for occupant state parameters were analyzed by determining optimum values of restraint properties for five sets of occupant state parameters representing maximum variation in anthropometric size and postural orientation (Table 3). Compared to injury reduction percentages reported in studies involving restraint system optimization (e.g., Hou et al., (1995) reported 33% reduction in overall injury using numerical optimization), the current study reported approximately 25% reduction in the value of WBIM by optimizing restraint properties for the mid-sized occupant in nominal seating posture. It should be noted that the objective function used in this study for defining the injury metric takes into account both distribution and severity of whole body injuries, which leads to lower values of injury reduction efficiency but improves the accuracy of the injury metric to represent realistic occupant injuries. As anticipated from results published in the literature [Adomeit et al., 1997; Miller & Maripudi, 1996], the restraint requirements for an occupant with anthropometry smaller than the mid-sized adult involved a lower value of load-limiting and vice-versa for an occupant with larger anthropometry (Fig. 8). For postural orientation with the upper-body too close to the steering column (POS_{fsitup}), a high value of restraining force (7857 N) was required to reduce the overall injuries. As the value of belt restraining force increased with the optimization of restraint properties, the performance of the restraint system improved for all values of occupant state parameters except for the postural orientation POS_{clswhl} (Table 4). Interpolating the results for reduction in WBIM evaluated for the five sets of occupant state parameters, it is anticipated that 20% to 51% reduction in overall injury could be achieved by using a restraint system that optimizes its properties to account for individual occupant state parameters in the design space considered in this study.

To realize the delimitations of the study it is important to note that the scope of occupant state parameters and crash characteristics considered in this study is not comprehensive and representative of the complete occupant and collision population. Additional occupant properties such as age, gender, and pathology were ignored in the current representation of the occupant state. The configuration of the occupant is restricted to a mid-sized belt-restraint driver subjected to a frontal collision loading with only a limited range of crash severities and types. The injury metric, WBIM, although serves the purpose of a weighted objective function for overall injuries, the accuracy of the metric to represent true injury associated cost is questionable since MAIS based costs overestimate the actual cost of multiple injuries sustained by an occupant. Additionally, the sensitivity of sensor measurements to occupant state parameters in the pre-collision phase was determined using a numerical model not verified for biofidelity in low-decelerations conditions. With future efforts in developing numerical models with stabilized response in non-collision conditions and accurate injury response in crash conditions, the framework for estimating pre-collision occupant state parameters could be significantly improved.

CONCLUSION

The results of the study provide insight into the effect of occupant anthropometry and pre-collision postural orientation on the injury outcome during a frontal collision. While the variability in posture state resulted in maximum statistical dispersion in overall injury, occupant stature proved to be a more significant predictor of injury compared to occupant mass. In addition to the physical properties of the occupant, the study also emphasized the role of reflexive occupant states, such as postural orientation, in predicting collision-induced injuries. The results from restraint optimization reported that upto 35% reduction in overall injuries could be achieved by tailoring restraint properties to individual values of occupant state parameters. In summary, the study investigates the casual relationship between the occupant state parameters and the injury outcome during frontal collisions and further highlights the importance of accounting such occupant properties in developing a framework for future adaptive restraint systems.

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