Age-Related Differences in AIS 3+ Crash Injury Risk, Types, Causation and Mechanisms

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Abstract Data from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) and the Crash Injury Research Engineering Network (CIREN) cases were analyzed to (1) define how occupant age affects crash exposure and the risk of AIS 3+ injury and (2) identify how age affects injury types and causation while considering comorbid factors and gender. Multivariate logistic regression models developed from NASS indicated that age significantly increases the risk of AIS 3+ injury to almost every body region in all crash modes. The largest age effect was observed for the thorax in frontal crashes and was modulated by gender such that older women were at significantly higher risk relative to younger women than were older men relative to younger men.

A subset of 1289 CIREN cases, analyzed for injury causation, found occupants under age 25 and over 65 years sustained greater proportions of head and thoracic injuries respectively. For frontal crashes, thoracic injury type changed from soft to bony tissue injury as age increased and comorbid factors were more common for the older occupants. Crash severity was consistently lower for the older age groups and outcomes were worse in the older occupants even for similar crash severity and injury.

Keywords: Older occupant, risk analysis, CIREN, injury codes, comorbidities

I. INTRODUCTION

The graying of world populations is well documented. In the United States, approximately 40 million people, or 13% of the US population, are over the age of 65. By 2030, 72 million people, approximately 19% of the US population, will be over age 65. Similar pronounced trends exist in other highly motorized regions. For example, in Europe, the proportion of the population over age 65 is forecast to grow by 67 million between 2010 and 2030 or from 16% to 22% [1]. These statistics suggest that any effects that occupant age has on injury outcome in motor-vehicle crashes in these regions will become more pronounced in coming years.

The effects of age on death and injury in motor-vehicle crashes have been studied in previous analyses. FARS analyses demonstrate that fatality rates per vehicle miles traveled (VMT) or per licensed driver are higher for the elderly than for all age groups except younger drivers [2]-[3]. Analyses of NASS-CDS demonstrate that occupant age is a significant predictor of whole body maximum abbreviated injury severity scale (MAIS) even when other significant predictors of injury outcome are controlled for [3]-[5].

A subset of these analyses and other studies of crash injury data report that the body region that is most affected by age-related increases in injury risk is the thorax and that the magnitude of the thoracic injury problem is greatest in frontal crashes [6]-[8]. As a result, there has been a large body of research on how age

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affects the risk of thoracic injury, and in particular, the most common type of thoracic injury—rib fractures [9]-[10]. This research demonstrates that the increased injury risk with age is from skeletal fragility and is primarily caused by changes in bone material properties [10] and in particular fracture toughness, regional changes in rib cross-sectional geometry [9]-[10] and calcification of the costal cartilage [11].

Relative to the amount of research that has been done on the effects of age on thoracic injury tolerance and impact response in frontal crashes, less has been done to study the effects of age on other body regions in frontal crashes. Examples of the work that has been done are analyses of crash-injury data that indicate that age affects the risk of head injury and knee-thigh-hip injury [6]-[7],[12]. Minimal biomechanical research has been done to study the effects of age on these body regions in frontal crashes, although risk curves for the knee-thigh-hip complex that are parametric with age have been developed based on an analysis of data from cadaver tests [12]-[13].

Compared to frontal impact, less has been done to study the effects of age on injury in side impact, despite the fact that older drivers are more likely to be involved in side impact crashes than other age groups [3],[14]. No analyses of crash-injury data report on the effects of age on the outcome of different types of injury in side impact while controlling for other significant predictors of injury outcome, like deltaV or belt use. Meta analyses of data from biomechanical studies have attempted to quantify the effects of age on injury to different body regions in side impact. Eppinger [15] analyzed whole body side impact tests in the NHTSA biomechanics database to develop the Thoracic Trauma Index (TTI), which uses spine acceleration and occupant age to predict the risk of thoracic injury in side impact. Kuppa et al. [16] analyzed a larger set of side impact cadaver tests in the NHTSA biomechanics database and found that age and chest deflection were the best predictors of AIS 3+ injury outcome. Petitjean et al. [17] reconstructed a series of cadaver tests with the WorldSID midsize male dummy and used dummy measurements from these tests along with the corresponding sets of cadaver injury information to generate WorldSID-specific risk curves for different body regions. An age effect was incorporated into these risk curves based on linear regression analysis of cadaver injury data and WorldSID response data from corresponding body regions across the reconstructed test conditions.

Prior to conducting testing to further characterize the effects of age on response and injury to different body regions in different crash modes, additional research on the effects of age on the risk of injury to different body regions in real-world crashes is needed to prioritize testing efforts. This manuscript contains an analysis of NASS-CDS and CIREN that quantifies the effects of aging on serious and more severe injuries to different body regions across crash modes and identifies possible contributing factors to the injuries and associated mechanisms.

II. METHODS

The methods used in this paper relied on two levels of crash field data analysis: (1) analyses of data from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) that define how occupant age affects crash exposure and the risk of AIS 3+ injury and (2) analyses of a subset of the Crash Injury Research Engineering Network (CIREN) CIREN cases that describe how age affects injury types, causation and mechanisms while considering comorbid factors and gender.

NASS Analysis

The effects of aging on the risk of serious and more severe injury in motor-vehicle crashes were estimated using a dataset consisting of NASS-CDS (2000-2010)[18]. For this analysis, serious and more severe injury was defined as an injury that had a score between three and six on the Abbreviated Injury Scale, 1998 revision[19] (denoted as AIS 3+, below).

<u>Inclusion Criteria</u>

The dataset was limited to

- Model year ≥2000, known vehicle type

- 3-point belted or unbelted
- Occupants in front outboard seating positions
- Non-pregnant adults and pregnant women in their first trimester (age ≥15)
- Occupants with known height, weight and age

Occupants of heavy trucks, buses and motorcycles were removed from the dataset, as were occupants with missing height or weight information. Occupants in rear impacts and occupants in frontal or side impacts that were missing crash severity were also removed from the combined dataset. For this analysis, crash severity was defined using deltaV, which is the change in the velocity of the occupant's vehicle estimated using standard crash reconstruction techniques.

Variables and Analytical Techniques

Univariate analysis was performed to characterize baseline risks of injury to different body regions and to characterize distributions of the predictor variables listed in Table 1 by age group. For univariate analyses, occupant age in years was categorized as either <25, 25-44, 45-64, 65-74, and ≥75. Multivariate logistic regression was used to model the effects of the predictors listed in Table 1 on AIS 3+ injury outcome to the head, face, spine, thorax, abdomen, lower extremities, and upper extremities in frontal, nearside, far-side and rollover crashes. Body regions with one or more AIS 3+ injuries were identified using the AIS code. Frontal and side impacts were identified using the area of deformation of the collision deformation code [20] for the most severe event associated with a particular vehicle. Rollovers were identified using the rollover variable in NASS-CDS. Unless otherwise noted, all analyses used weighted data. Nearside and far-side impacts were classified as T-Type if the collision deformation code (CDC) indicated damage to the occupant compartment (middle third of the vehicle) and as L-Type if damage only involved the front or rear thirds of the side of the vehicle. Crashes were characterized as multiple severe impacts if the occupant's vehicle sustained a secondary impact that was associated with a CDC code with an extent zone greater than two, or a greater than one quarter turn rollover.

Table 1. Predictors Used in Analyses

Predictor	Level
Age (yr), Age^2	Continuous
Gender	Male (reference), female
BMI (kg/m^2), BMI^2	Continuous
deltaV (km/h)	Continuous
Vehicle type	Passenger car (reference), light truck, utility vehicle, van
Belt use	Unbelted (reference), belted 3pt
Seat location	Driver (reference), passenger
Height (cm)	Continuous
Vehicle Age (yr)	Continuous
# of Quarter Turns (Rollover only)	Categorical (1-2, 3-6, 7-10, 11-13, >13)
Interrupted Rollover (Rollover only)	No (reference), Yes
Multiple Severe Impacts	No (reference), Yes
Position of occupant relative to direction of roll	Same side (reference), Opposite side.
L-Type/T-Type (Near-/Far-side Impacts)	T-Type (reference), L-Type

A backwards stepwise approach to model development was used where all predictors were initially included in a model for a particular body region and crash mode and then the least significant predictor was removed from the model until all remaining predictors were significant at a 0.05 level. Survey methods in SAS version 9.2 (SAS Institute, Cary NC) were used for model development. Second order effects were explored for age and BMI in all body regions where a first order effect was significant or where second order effects had been reported in previous studies. Interactions between age and gender, BMI and vehicle type, and BMI and gender were tested in the development of all models since these interactions have either been previously demonstrated or postulated.

CIREN Case Analysis

Beginning in June of 2005, an improved injury causation coding method, BioTab, was developed for CIREN crash and injury analysis. BioTab is a systematic process to derive injury causation and mechanisms based on objective analysis of crash characteristics and injury patterns [21]. A subset of 1289 cases, enrolled in CIREN from 2005-2011 that had an injury or injuries analyzed using BioTab, were selected for analysis and followed the inclusion criteria used in the NASS analysis. These 1289 cases were separated into five age groups: less than 25, 25-44, 45-64, 65-74, and ≥75 to facilitate a simple characterization of the cases based on age. Data analysis was conducted on increasingly specific conditions related to crash type, gender, age, injury type, involved physical component, injury mechanism and contributing factors. CIREN cases are uniquely qualified for this analysis as each case that was put through the BioTab process has the complete record for these variables with appropriate levels of certainty applied to the step in the injury mechanism analysis. Descriptive statistics were largely used for these data since sample sizes became small as the analysis proceeded and since CIREN is a convenience sample of severely injured occupants, no attempt was made to compare risks across or within groups.

III. RESULTS

NASS Dataset Characteristics

Applying the crash type, model year, occupant age and vehicle type to the NASS-CDS dataset resulted in a dataset consisting of 26,246 occupants. Removing occupants in frontal, nearside and far-side crashes that were missing deltaV from this dataset reduced the total number of occupants by 30% to 18,371 occupants (unweighted), which corresponds to 6,011,575 occupants after weighting factors are applied.

Table 2 lists the raw numbers of occupants with AIS 3+ injuries in the dataset used in this analysis by body region and crash mode. Because of the small number of occupants with AIS 3+ face and soft tissue neck injuries, statistical models of the probability of AIS 3+ injury to the neck and face body regions were not developed. Models predicting the risk of AIS 3+ injury to the abdomen, spine and upper extremities in farside and nearside impacts and the lower extremities in farside were not developed for similar reasons.

Table 2. Raw Counts of Occupants with AIS 3+ Injuries by Injured Body Region and Crash Mode (NASS-CDS, 2000-2010)

	Head	Face	Neck	Thorax	Abdomen	Spine	UpperEx	LowerEx
Frontal	172	22	5	344	78	103	195	453
Nearside	176	16	1	280	59	37	28	156
Far-side	95	5	0	112	24	25	28	31
Rollover*	423	38	8	459	94	160	124	194

*includes cases with missing deltaV

Figure 1 shows the risk of MAIS 3+ injury for different body regions by age group combined across crash modes. Risk of injury was highest for the age ≥75 group for all body regions. Injury risk also generally increased with age for the head, thorax, spine, and upper extremities.

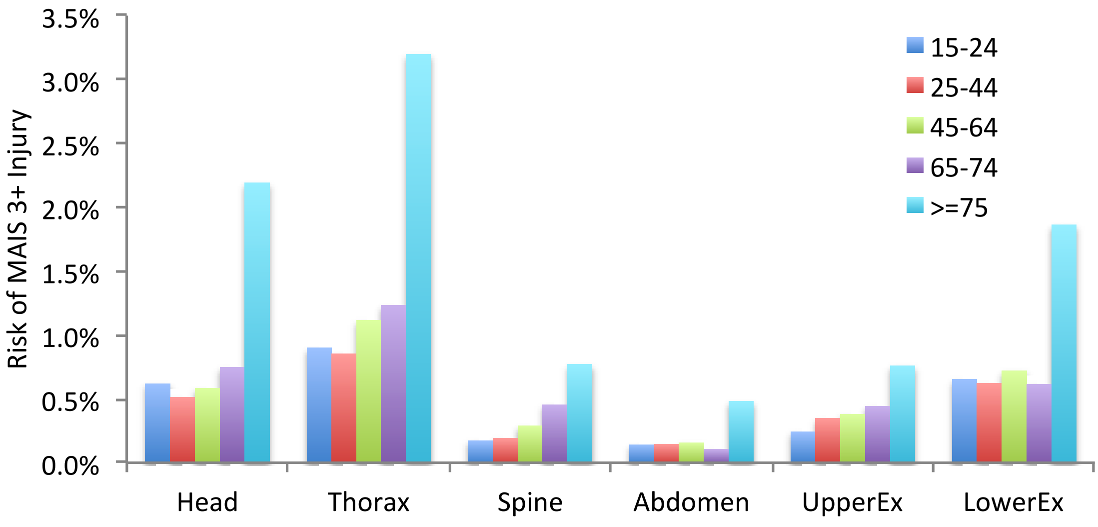

Figure 1. Risk of MAIS 3+ injury for different body regions by age group combined across crash modes.

Table 3 shows the distributions of key predictor variables for NASS crash-involved occupants by age group. Differences between younger and older age groups include that the two oldest age groups are significantly more likely to be 3-point belted and less likely to be in crashes involving multiple severe events than occupants in the youngest (15-24 year-old) age group. Both occupants in the youngest and oldest age groups were significantly more likely to be in passenger cars than other vehicle types. Occupants in the oldest age group were also significantly less likely to be in utility vehicles than other age groups while younger occupants were significantly less likely to be in vans. Occupants in the youngest age group were significantly more likely to have BMI in the normal (18-24 kg/m^2) and or underweight (BMI<18 kg/m^2) ranges than other age groups while occupants in the youngest and oldest age groups were significantly less likely to be obese (30<BMI≤35 and BMI>35 kg/m^2) than occupants in the middle age groups.

Occupants in the oldest age group were also significantly more likely to be in nearside and farside impacts than occupants in the youngest age group. Greater proportions of occupants in the youngest and oldest age groups were in higher deltaV nearside impacts. However, there was not a meaningful difference in the deltaV distributions for younger and older age groups in farside impacts.

Age Effects Analysis

Table 4 lists adjusted odds ratios for the age effect for all body region and crash mode combinations for which age was a significant predictor of AIS 3+ injury risk. Separate odds ratios were calculated for men and women for body region and crash mode combinations for which an age*gender interaction was significant. All odds ratios in Table 4 are associated with a 10-year increase in age. As shown in Table 4, age significantly increased the risk of injury to all body regions for which sufficient sample size existed in frontal crashes and significantly increased risk of head and thorax injury in every crash mode. The largest age effect was for thoracic injury to females in frontal crashes.

The odds ratios in Table 4 describe the relative size of the age effect, but do not provide insight on the magnitude of the increase in injury risk with age for each body region and crash mode combination. Figures 2 through 5 show the predicted effects of age on injury risk for different body regions for frontal, nearside, far-side and rollover crashes, respectively when controlling for other significant predictors of injury. The models used to generate Figures 2-5 are provided as supplementary material in the appendix.

Table 3. Distribution of Predictor Variables by Age Group

		Age Group (yrs.)					
		15-24	25-44	45-64	65-74	≥75	
Sex	Female	48%	48%	51%	47%	43%	$\chi^2(4)=4.8$, p=0.32
	Male	52%	52%	49%	53%	57%	
deltaV (kph), Frontal Impacts	ΔV <15	26%	28%	36%	37%	37%	$\chi^2(12)=16.2$, p=0.18
	15≤ ΔV <30	56%	56%	51%	44%	51%	
	30≤ ΔV <45	15%	14%	11%	17%	8%	
	ΔV > 45	3%	2%	2%	2%	3%	
deltaV (kph), Nearside Impacts	ΔV <15	38%	54%	60%	45%	38%	$\chi^2(12)=32.3$, p=0.001
	15≤ ΔV <30	45%	39%	35%	50%	50%	
	30≤ ΔV <45	14%	5%	4%	4%	7%	
	ΔV > 45	2%	1%	1%	1%	5%	
deltaV (kph), Far-side Impacts	ΔV <15	43%	46%	66%	38%	36%	$\chi^2(12)=36.8$, p=0.0002
	15≤ ΔV <30	46%	43%	30%	49%	50%	
	30≤ ΔV <45	9%	10%	4%	12%	9%	
	ΔV > 45	2%	1%	1%	0%	4%	
N Quarter Turns (Rollover only)	1-2	54%	51%	60%	44%	35%	No significance tests performed due to low n in higher N qt turns groups
	3-6	42%	44%	34%	53%	60%	
	7-10	4%	5%	6%	3%	6%	
	11-13	0%	0%	0%	0%	0%	
	>13	0%	0%	0%	0%	0%	
BMI (kg/m^2)	BMI < 18.5	4%	1%	1%	0%	1%	$\chi^2(16)=216.7$, p<0.0001
	18.5≤BMI<25	50%	32%	27%	24%	28%	
	25<BMI≤30	35%	46%	44%	51%	60%	
	30<BMI≤35	7%	13%	19%	17%	8%	
	BMI>35	4%	8%	8%	8%	3%	
Belt Use	3-point	87%	90%	92%	95%	94%	$\chi^2(4)=30.6$, p<0.0001
	None	13%	10%	8%	5%	6%	
Seat Location	Driver	79%	86%	84%	81%	80%	$\chi^2(4)=15.6$, p=0.007
	Passenger	21%	14%	16%	19%	20%	
Multiple Severe Impacts	No	96%	97%	97%	98%	98%	$\chi^2(4)=9.8$, p=0.044
	Yes	4%	3%	3%	2%	2%	
Vehicle Type	Car	71%	53%	51%	59%	75%	$\chi^2(12)=143.0$, p<0.0001
	Pickup	10%	17%	19%	9%	6%	
	Utility	16%	22%	20%	21%	9%	
	Van	2%	9%	10%	11%	10%	
Crash Mode	Farside	11%	13%	15%	18%	16%	$\chi^2(16)=35.4$, p=0.0009
	Frontal	60%	61%	60%	59%	57%	
	Nearside	12%	13%	17%	18%	18%	
	Rollover	17%	13%	8%	6%	9%	

Table 4. Adjusted Odds Ratios (and 95% CIs) for AIS 3+ Injury to Different Body Regions Associated with a Decade Increase in Age (Selected Gender Differences Cited)

	Head	Thorax	Abdomen	Spine	Upper Extremity	Lower Extremity
Frontal	1.29*** (1.21,1.37)	*M:* 1.37 (1.14,1.64) *F:*1.77 (1.31,2.39)	1.45* (1.10,1.90)	1.55*** (1.34,1.80)	*M:*1.46 (1.23,1.74) *F:* 1.09 (0.81,1.46)	1.22* (1.03,1.44)
Nearside	1.68* (1.14,2.48)	1.28*** (1.15,1.42)	NS	-	-	NS
Far-side	1.41** (1.15,1.73)	1.60** (1.23,2.07)	-	-	-	-
Rollover	1.17* (1.00,1.38)	1.23*** (1.12,1.34)	-	M:1.12 (0.88,1.42) F:1.51 (1.04, 2.18)	1.36*** (1.17,1.57)	NS

NS=Not Significant, M=Male, F=Female, *p<0.05, **p<0.001, ***p<0.0001

In constructing Figures 2-5 values for covariates were set to levels associated with US regulatory compliance tests. Specifically, seat position was set to driver, belt use was set to three-point belt, vehicle type was set to passenger car and BMI and stature were set to the BMI and stature specification of the Hybrid III midsize male ATD (25 kg/m^2 and 176 cm). For rollover crashes, where no full-vehicle dynamic regulatory compliance testing is performed in the US, covariate levels were arbitrarily set to a belted driver in a 7-10 quarter turn roll. For cases where gender interacted with other predictor variables, separate plot responses are provided for each gender.

Several notable trends exist in Figures 2-5. In frontal crashes, the interaction between age and gender results in the increase in risk in thoracic injury with age being significantly higher for women than men. Similar effects exist for head injuries in nearside crashes and thoracic injuries in far-side crashes and spine injuries in rollover crashes.

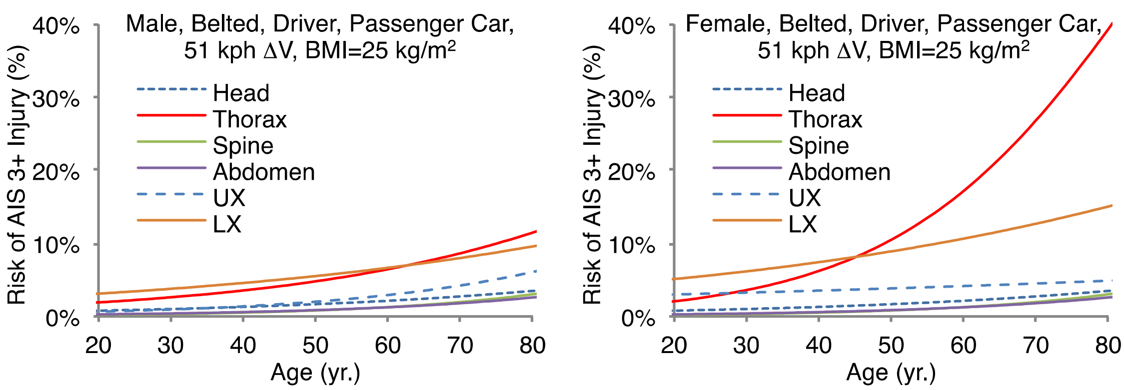

Figure 2. Effects of varying age from 20 to 80 years on AIS 3+ injury risk in *frontal* crashes by body region for males (left) and females (right) when controlling for other significant predictors of AIS 3+ injury.

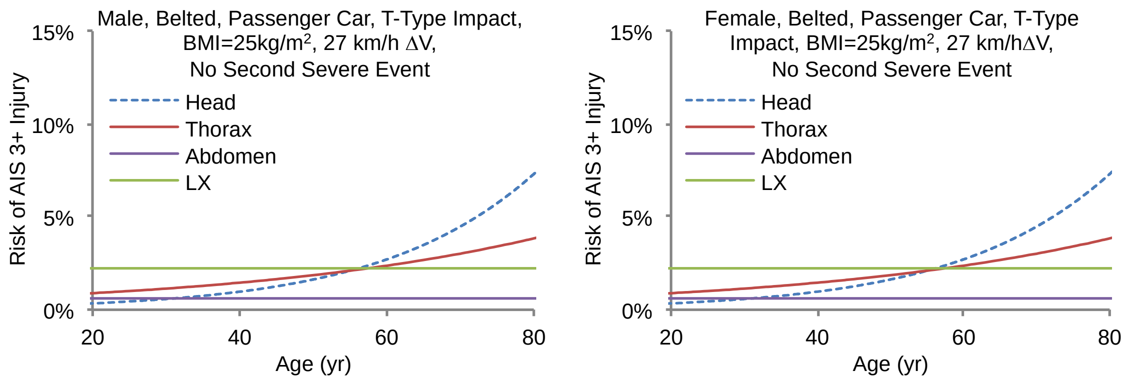

Figure 3. Effects of varying age from 20 to 80 years on AIS 3+ injury risk in *nearside* crashes by body region for males (left) and females (right) when controlling for other significant predictors of AIS 3+ injury.

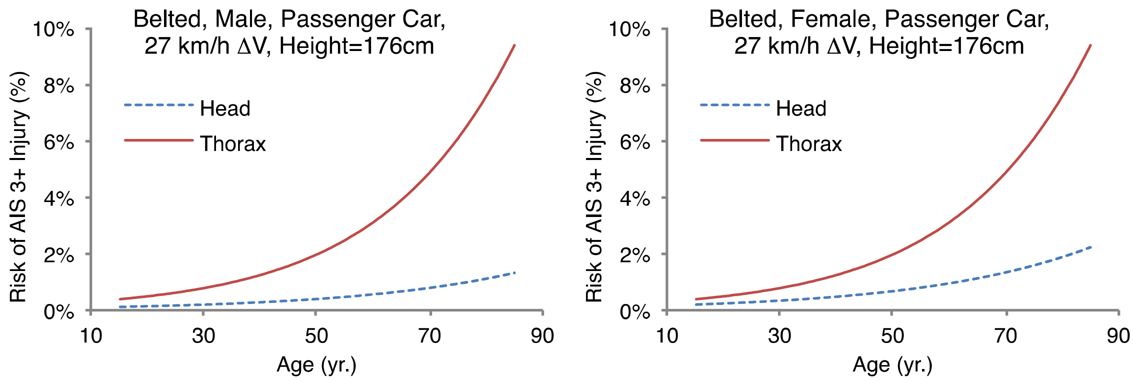

Figure 4. Effects of varying age from 20 to 80 years on AIS 3+ injury risk in *far-side* crashes by body region for males (left) and females (right) when controlling for other significant predictors of AIS 3+ injury.

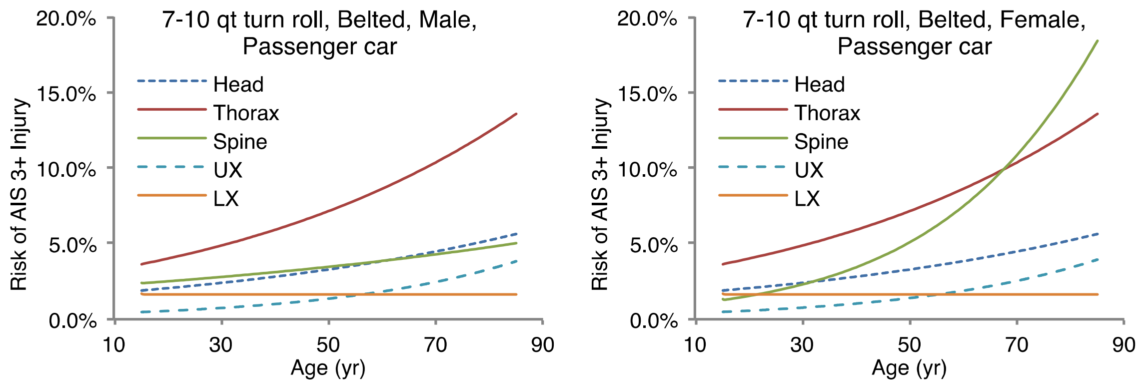

Figure 5. Effects of varying age from 20 to 80 years on AIS 3+ injury risk in *rollover* crashes by body region for males (left) and females (right) when controlling for other significant predictors of AIS 3+ injury.

CIREN Case Analysis

The injuries from the 1289 CIREN cases that had undergone the BioTab analysis were analyzed in a manner similar to the NASS cases. It was important to know if there were sufficient numbers of older occupants in the BioTab dataset. Of these BioTab cases, 103 (8%) involved occupants aged 65 to 74 years old and another 114 cases (9%) involved occupants 75 years old or older. Injuries were distributed by crash mode, age and gender for each body region and then normalized by the total injuries for each specific age group and crash type and gender. Figure 6 shows the percent of injuries by body region in frontal impact for each age group. It is evident immediately that both thoracic and spinal injuries increase with age and lower extremity and head injuries, as a percent of the total injuries experienced in each age group, decrease as age increases. For example, of the 244 injuries from frontal impact in the ≥75 age group, 102 or about 41% of the injuries (AIS 2+) were thoracic injuries while 58 of the 322 (18%) injuries in the under 25 age group were thoracic injuries. There were no gender differences in these trends in the CIREN dataset that was found in the NASS data so analysis was continued only on thoracic injuries in frontal impact CIREN cases without stratifying for gender.

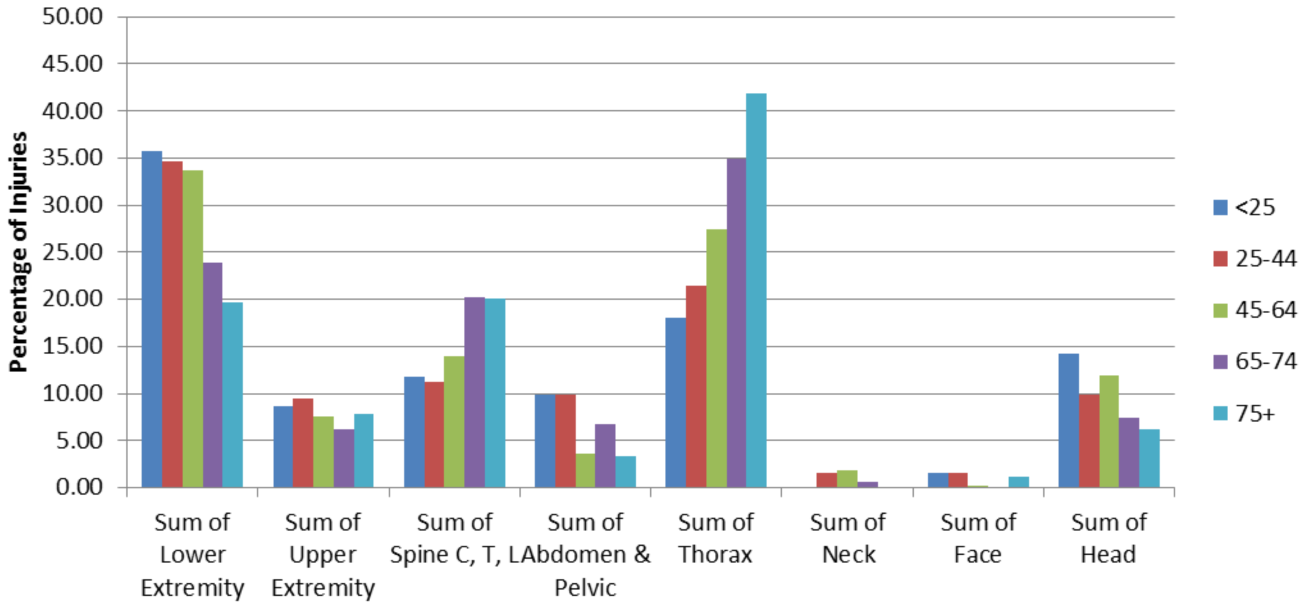

Figure 6. Percent of Injuries from Frontal Impact by Age Group (N = 2018 CIREN BioTab injuries)

Table 5 indicates the top 3 thoracic AIS codes for frontal crashes by age group with the total number of injuries in parentheses for each cell. Thoracic injury is the dominant coded injury in each age group, however, the nature of the injury changes as age increases. The dominant injury changes from a soft tissue injury (lung contusion) to bony injuries (sternal fracture) and an increasing amount of rib fractures. The 65-74 year old age group only had bony injuries as their top 3 coded injuries.

Table 5. Most Frequent Thoracic AIS Code Description by Age in Frontal CIREN BioTab Cases (n)

Age Group	Most Frequent AIS Code Description	Second Most Frequent AIS	Third Most Frequent AIS
<25	Unilateral lung contusion w/wo hemo-/pneumothorax (20)	Bilateral lung contusion w/wo hemo-/pneumothorax (8)	2-3 Rib fractures and Sternum fracture (6)
25-44	Unilateral lung contusion w/wo hemo-/pneumothorax (22)	>3 Rib fractures on one side and <=3 on the other with hemo-/pneumothorax (19)	Sternum fracture (18)
45-64	Sternum fracture (32)	>3 Rib fractures on one side and <=3 on the other (31)	Unilateral lung contusion w/wo hemo-/pneumothorax (21)
65-74	Sternum fracture (15)	>3 Rib fractures on one side and <=3 on the other (11)	2-3 Rib fractures (6)
≥75	Sternum fracture (25)	>3 Rib fractures on one side and <=3 on the other (17)	Unilateral lung contusion w/wo hemo-/pneumothorax (11)

The most frequent thoracic AIS code in each age group for frontal crash was further analyzed based on BioTab information in terms of crash severity and components of the vehicle that were involved in the injury mechanism. It is apparent that mean crash severity (deltaV) decreases steadily as age increases (Table 6). Also, it is noted how the contribution of the airbag and steering wheel decreases and the seat belt begins to play a larger role in injury causation for the oldest age groups. When the mortality associated with the most frequent AIS code by age was analyzed, it was found that none of the younger adults who had a lung contusion as their most severe injury died but that 7 of 25 died in the oldest age group who had a sternal fracture as their most severe injury. The time duration from crash to death date was determined from EMS and hospital records for the fatally injured occupants in Table 6. Of the two occupants in the 25-44 age group, one died on scene and one died nine days after the crash. They were both severely obese with BMIs over 35 and had multiple severe injuries. Of the eight older fatalities, three died on the scene or within one hour of the crash, however, the other five died between 4 and 25 days (avg. duration was 15 days) after the crash. In five of the eight fatalities in the groups age 65 and over, the sternal fracture and associated rib fractures and thoracic injuries were the only severe injuries observed in these occupants.

Table 6. Crash Characteristics and Mortality Associated with Most Frequent Thoracic AIS code in Frontal CIREN BioTab Cases by Age

	Most Frequent AIS Code for Frontal Crash from Table 5			
Age	N	Mean DeltaV (kph)	Involved Physical Component	Fatal: Non-fatal
<25	20	66	Steering Wheel , Seat Belt, Air Bag	0:20
25-44	22	43	Seat Belt, Steering Wheel, Instrument Panel	2:20
45-64	32	52	Seat Belt, Steering Wheel	0:32
65-74	15	46	Seat Belt	1:14
≥75	25	37	Seat Belt	7:18

Table 7 gives further insights into the factors that may have contributed to the occurrence of top 3 AIS injuries in frontal crashes for each age group. For younger adults, intrusion is the most common contributing factor to the injury, whereas for the older occupants, just being older (BioTab coded as “elderly”) was the top contributing factor. High crash severity was also a contributing factor for the youngest group. Also, note that some of the occupants are unbelted. To be included in CIREN, an occupant in a frontal crash must be restrained, but this restraint can come from an airbag with an unbuckled seat belt.

Table 7 also lists the comorbidities that were most frequently coded as affecting the occurrence or severity of one of the three most frequent thoracic injuries. For those younger than 25, no co-morbidities were assigned. For occupants in the 25-44 and 45-64 age groups obesity was the most contributing factor, followed by osteoporosis/osteopenia in the 45-64 year-old age group. In the 65-74 and ≥75 age groups osteoporosis was the most common contributing factor followed by obesity.

IV. DISCUSSION

This paper gives a thorough treatment for analyzing the risk of serious injury as a function of age for several crash modes as well as the exposure characteristics by age for crash-involved occupants. It also identifies the most frequent serious injuries suffered by the occupants in each age group and provides further information for injury causation and mechanism analysis, contributing factors and outcome of those injuries across the age groups. The NASS analysis with more recent model year vehicles (>2000) confirmed previous studies such as Newgard [4] who found that the probability of serious injury increased with increasing age and saw an increase in the slope of the risk curve at both age 50 and again at age 70 (Figures 2-5). Age was the most consistent predictor of injury for all body regions and crash modes in this study.

Table 7. CIREN BioTab Contributing Factors (top 3) and Comorbidities Associated with All Injuries in Frontal Crashes (n)

	Front			Comorbidity 1	Comorbidity 2
Age	1	2	3		
<25	Intrusion (90)	High DeltaV (83)	Unbelted (72)	n/a	n/a
25-44	Intrusion (156)	Unbelted (112)	Comorbidity (68)	Obesity (37)	not significant sample size
45-64	Intrusion (124)	comorbidity (102)	Unbelted (72)	Obesity (48)	Osteoporosis/ Osteopenia (10)
65-74	Elderly (41)	Comorbidity (38)	Intrusion (24)	Osteoporosis/ osteopenia (20)	Obesity (7)
≥75	Elderly (126)	Comorbidity (58)	Unbelted (17)	Osteoporosis/ osteopenia (44)	Obesity (12)

In particular, the multi-variate models shown in Figures 2-5 and the odds ratios in Table 4 indicate that the effect of age on AIS 3+ injury risk is largest for the thorax body region for women in frontal crashes. This result is similar to Rhule [22] who compared injury risk in occupants over 60 years old to younger occupants and found women in the older occupant group had a significantly greater injury risk than younger women as well as men in the same older age group. In nearside impacts, the largest age effect was for the head, followed by the thorax, while the opposite trend was observed for far-side crashes. For rollovers, largest age effect was for spine for women. The NASS analysis also shed light on the effects of crash severity, belt use, and Body Mass Index (BMI) on AIS 3+ injury risk.

The NASS analysis indicated that serious head injury risk was second only to thoracic injury risk for the >75 age group. Mallory's [23] analysis of head injuries reported in NASS-CDS indicated higher risk for bleeding type head injuries in older occupants and they occurred at lower crash severities for the older occupants. She indicated that tolerance and mechanisms of these injuries may be age specific. For thoracic injuries, both the NASS and CIREN analyses found that thoracic injuries dominate for the oldest occupants which is consistent with Hanna and Hershman [24] who found that incidence of serious rib fractures increased with age especially after age 75 for frontal and near side crashes. The CIREN case analysis also showed how thoracic injury type changed from soft to bony tissue injuries as age increases. The multiple rib fractures and sternal fractures experienced by the oldest CIREN occupants also proved to have increased mortality and their time of death post-crash averaged over two weeks. This finding is consistent with results reported by Kent et al. [25] who analyzed the patients involved in motor-vehicle crashes in the National Trauma Databank (NTDB) and found that as age increased, the probability of rib injury as the maximum AIS increased as did the probability of death as a result of rib fracture.

The additional information from the CIREN BioTab cases confirms previous studies but also sheds light as to what factors are associated with aging and injury. The lower crash severity associated with the most severe injuries in the older occupant age groups indicates additional protection will be needed at lower crash speeds for older occupants. The NASS analysis in this study also indicated the same trend for lower speed frontal crashes for older occupants but did not find the same trend for side impact crash severity demonstrated by Rhule [22]. Rhule's analysis only included occupants with a thoracic injury while this study looked at all crash-involved occupants. Welsh [26] found that for similar crash characteristics, older occupants (65 years and older) have a significantly higher rate of fatality in frontal (and near-side) lateral impacts than younger occupants. Limiting crash severity or decreasing the severity for older occupants through pre-crash interventions may help to reduce the injury and increased mortality in these occupants.

The contributing factors and co-morbidities associated with the most common injuries also point to interventions that could benefit the older occupant. Adaptive restraint systems that lower the loads on the poorer quality bones of older occupants could help reduce incidence of rib injuries. Newer technologies such as 4-point belt systems and inflatable seat belts also help to reduce or distribute chest loading.

Limitations

Neither the NASS-CDS nor the CIREN analyses control for the effects of intrusion of structures into the occupant compartment in frontal or side impact, although controlling for intrusion is unlikely to alter the effect of age on injury. Controlling for intrusion may, however, reduce the effects of covariates that are related to intrusion, like deltaV and vehicle type. This NASS analysis also did not control for airbag deployment, which has been shown to be a cause of some upper extremity injuries. However, the NASS analysis did control for deltaV, which is a surrogate for airbag deployment in frontal, nearside and far-side crashes.

Approximately 30% of the frontal, nearside and far-side crashes in NASS that otherwise met the study inclusion criteria were missing deltaV estimates. Further, crashes in which deltaV is missing tend to result in more severe injuries, more often involve multiple impacts and are more likely to involve trucks than other vehicle types [25]. However, this bias is not likely to affect the relationships between AIS 3+ injury risk to different body regions and predictors of risk, such as age [27].

Finally, because information on comorbidities associated with age was not available for both the injured and uninjured in the NASS analysis, it was not possible to account for the comorbid conditions when modeling age effects in NASS. As suggested by the results of the CIREN analysis, the age effects documented in the NASS analysis could be in part, from comorbidities associated with increasing age rather than age itself. It is also possible that there are other factors involved in the injury process. CIREN attempts to document as much as possible regarding the occupant's physiological condition, however, for consistency in data reporting, the program has a finite list of comorbidities to associate with the injury causation scenario.

V. CONCLUSIONS

The main conclusions from this study indicate:

- Construction of multivariate risk models from more recent NASS (and vehicle) data give insight that age continues to play a significant factor in the risk of injury to all body regions and that the effect of age is different for women and men in some body region and crash mode combinations.

- The risk models also show that thorax, head, and lower extremity injuries are the most common injuries in frontal and near side impacts for older occupants.

- CIREN provided additional data on contributing factors that will help researchers better understand how to protect older adults in crashes. As one ages, the factors related to the injury change from high-speed crashes and intrusion into the passenger compartment to factors such as bone quality and obesity. The overall lower crash severity that still resulted in serious injury for an older occupant gives researchers opportunities to assess restraint effectiveness and crashworthiness at lower crash speeds.

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VIII. APPENDIX

Table A1. Frontal models

Parameter		Parameter Estimates					
		Head	Thorax	Spine	Abdomen	Upper Ex	Lower Ex
Intercept		-7.745*** (-8.52,-6.97)	-8.276*** (-10.4,-6.19)	-8.729*** (-9.8,-7.63)	-9.708*** (-11.3,-8.14)	-7.771** (-12.1,-3.48)	-8.741*** (-9.91,-7.57)
Belt Use (vs. unbelted)		-7.745*** (-8.52,-6.97)	-1.482* (-2.45,-0.51)	-1.14* (-1.83,0.44)	-1.574* (-2.61,-0.53)	-1.340* (-2.57,-0.11)	-1.784*** (-2.26,-1.30)
Vehicle Type (vs. passen ger car)	Lt truck					3.195* (0.40,5.99)	
	Utility					-2.822 (-7.18,1.54)	
	Van					-2.509 (-5.88,0.86)	
Age (yr.)		0.025*** (0.02,0.03)	0.031** (0.01,0.05)	0.044*** (0.03,0.06)	0.037* (0.01,0.06)	0.038*** (0.02,0.06)	0.020* (0.00,0.04)
BMI (kg/m^2)						0.015 (-0.09,0.12)	0.061** (0.03,0.09)
deltaV (kph)		0.114*** (0.09,0.14)	0.163*** (0.13,0.19)	0.090*** (0.07,0.11)	0.147*** (0.11,0.18)	0.126*** (0.10,0.15)	0.162*** (0.15,0.17)
Gender (vs. M)			-0.438 (-1.88,1.01)			2.143*** (1.19,3.10)	0.513*** (0.30,0.72)
BMI*Gender (vs. M)							
Age*Gender (vs. M)			0.026* (0.00,0.05)			-0.030* (-0.05,-0.01)	
Seat Position (vs. Driver)						-1.065*** (-1.50,-0.63)	
BMI* Vehicle Type (vs. passen ger car)	Lt truck					-0.107 (-0.22,0.00)	
	Utility					0.058 (-0.08,0.19)	
	Van					0.101 (-0.01,0.21)	
Multiple Severe Impacts (vs. none)		1.751* (0.64,2.87)					

*p<0.05, **p<0.001, ***p<0.0001

Table A2. Nearside models.

Parameter		Parameter Estimates			
		Head	Thorax	Abdomen	Lower Ex
Intercept		-8.639*** (-10.54,-6.74)	-7.929*** (-9.17,-6.69)	-7.303*** (-8.00,-6.60)	-7.929*** (-9.17,-6.69)
Belt Use (vs. unbelted)		-1.254** (-1.95,-0.56)	-0.881 (-1.81,0.04)		-0.881 (-1.81,0.04)
Vehicle Type (vs. passenger car)	Lt truck		-0.087 (-0.95,0.77)		
	Utility		-0.470 (-1.35,0.41)		
	Van		-1.923* (-3.39,-0.45)		
Age (yr.)		0.052* (0.01,0.09)	0.025*** (0.01,0.04)		
BMI (kg/m^2)		0.029 (-0.03,0.09)	0.040* (0.01,0.07)		
deltaV (kph)		0.145*** (0.09,0.19)	0.212*** (0.16,0.26)	0.123*** (0.09,0.15)	0.025*** (0.01,0.04)
Gender (vs. M)		2.849* (0.12,5.58)			
BMI*Gender (vs. M)		-0.090* (-0.17,-0.01)			
Multiple Severe Impacts (vs. none)		1.099* (0.34,1.86)		1.672* (0.42,2.92)	
L-/T-Type (vs. T-Type)				-16.067*** (-16.74,-15.39)	0.040* (0.01,0.07)

*p<0.05, **p<0.001, ***p<0.0001

Table A3. Far-side Models

Parameter		Parameter Estimates	
		Head	Thorax
Intercept		-15.446*** (-22.12,-8.78)	-17.944*** (-23.11,-12.78)
Belt Use (vs. unbelted)		-2.279** (-3.48,-1.08)	
Vehicle Type (vs. passenger car)	Lt truck	-2.619* (-4.53,-0.71)	-1.124* (-1.92,-0.33)
	Utility	-0.742 (-1.76,0.28)	-0.629 (-1.80,0.54)
	Van	-2.756* (-4.76,-0.75)	-1.155 (-2.87,0.56)
Age (yr.)		0.035** (0.01,0.05)	0.047** (0.02,0.07)
deltaV (kph)		0.196*** (0.15,0.24)	0.164*** (0.14,0.19)
Gender (vs. M)		1.643* (0.60,2.69)	
Height (cm)		0.041* (0.00,0.08)	0.050** (0.02,0.08)

*p<0.05, **p<0.001, ***p<0.0001

Table A4. Rollover Models

Parameter		Parameter Estimates				
		Head	Thorax	Spine	Upper Ex	Lower Ex
Intercept		-3.703*** (-4.42,-2.99)	-8.972*** (-10.23,-7.72)	-8.778*** (-9.98,-7.57)	-8.806*** (-10.16,-7.45)	-8.897*** (-9.81,-7.98)
Belt Use (vs. unbelted)		-2.057*** (-2.40,-1.71)	-2.499*** (-3.10,-1.90)	-1.738*** (-2.57,-0.91)	-1.435*** (-1.81,-1.06)	-3.462*** (-3.96,-2.97)
Vehicle Type (vs. passenger car)	Lt truck			-0.373 (-0.97,0.23)		
	Utility			-0.755* (-1.35,-0.16)		
	Van			-0.102 (-1.06,0.86)		
Age (yr.)		0.733*** (0.45,1.01)	0.020*** (0.01,0.03)	0.011 (-0.01,0.04)	0.030*** (0.02,0.05)	
Gender (vs. M)				-1.100 (-2.47,0.27)	0.811* (0.16,1.46)	
BMI*Gender (vs. M)						
Age*Gender (vs. M)				0.011 (-0.01,0.04)		
Multiple Severe Impacts (vs. none)		0.733*** (0.45,1.01)				
Number Quarter Turns (vs <2)	3-6	0.475 (-0.08,1.03)	3.941*** (2.45,5.43)	0.614* (0.09,1.14)	0.811* (0.16,1.46)	0.336 (-1.87,2.54)
	7-10	1.573*** (1.00,2.14)	2.156*** (1.31,3.00)	1.555* (0.07,3.05)	3.351** (1.53,5.18)	0.185 (-0.30,0.67)
	11-13	2.894*** (2.00,3.79)	3.941*** (2.45,5.43)	2.206*** (1.55,2.87)	0.811* (0.16,1.46)	0.336 (-1.87,2.54)
	>13	-8.972*** (-10.23,-7.72)	2.156*** (1.31,3.00)	-8.806*** (-10.16,-7.45)	-8.897*** (-9.81,-7.98)	1.683** (0.75,2.62)
First impact over occupant seat position				0.564* (0.09,1.04		

*p<0.05, **p<0.001, ***p<0.0001