Effects of BMI on the Risk and Frequency of AIS 3+ Injuries in Motor-Vehicle Crashes

Jonathan D. Rupp[1,2,3], Carol A.C. Flannagan[1], Andrew J. Leslie[1,4], Carrie N. Hoff[5], Matthew P. Reed[1] and Rebecca M. Cunningham[2,6]

Objective: Determine the effects of BMI on the risk of serious-to-fatal injury (Abbreviated Injury Scale $\geq$ 3 or AIS 3+) to different body regions for adults in frontal, nearside, farside, and rollover crashes.

Design and Methods: Multivariate logistic regression analysis was applied to a probability sample of adult occupants involved in crashes generated by combining the National Automotive Sampling System (NASS-CDS) with a pseudoweighted version of the Crash Injury Research and Engineering Network database. Logistic regression models were applied to weighted data to estimate the change in the number of occupants with AIS 3+ injuries if no occupants were obese.

Results: Increasing BMI increased risk of lower-extremity injury in frontal crashes, decreased risk of lower-extremity injury in nearside impacts, increased risk of upper-extremity injury in frontal and nearside crashes, and increased risk of spine injury in frontal crashes. Several of these findings were affected by interactions with gender and vehicle type. If no occupants in frontal crashes were obese, 7% fewer occupants would sustain AIS 3+ upper-extremity injuries, 8% fewer occupants would sustain AIS 3+ lower-extremity injuries, and 28% fewer occupants would sustain AIS 3+ spine injuries.

Conclusions: Results of this study have implications on the design and evaluation of vehicle safety systems.

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Introduction

In the United States, $\sim$72 million adults, or 34% of the adult population, are obese, based on a BMI $\geq$30 kg m^{-2} criterion (1,2). Obesity is a known contributor to four of the top five causes of death for adults in the U.S. and has been shown to decrease quality of life (3,4). Despite widespread efforts to address the obesity problem, the portion of the U.S. population that is obese has not decreased in recent years, and obesity is recognized as a public health problem that will need to be addressed for the foreseeable future (1,2).

One aspect of the obesity problem that has received attention in the past decade is the relationship between obesity on the risk of death in motor-vehicle crashes. Analyses of case databases consisting of occupants admitted to trauma centers demonstrate that obesity increases the risk of death for occupants who sustain injuries in motor-vehicle crashes that are severe enough to merit admission to a trauma center (5-9). However, analyses of these trauma-admission databases cannot provide insight on the effect of obesity on the risk of injury in motor-vehicle crashes since the cohorts being analyzed lack the necessary controls (uninjured occupants).

Analyses of crashes involving a vehicle occupant death in the fatality analysis reporting system, which is a census of crashes on public roadways where a fatality occurred, have found that obesity increases the risk of death for an occupant involved in a fatal crash and that the effects of obesity are affected by occupant sex and belt use (10-12). However, these analyses only apply to occupants involved in fatal crashes as neither study used techniques to control for the differing exposure of occupants in fatal crashes relative to occupants in crashes that did not result in fatality (13).

Analyses of the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS), which is a clustered stratified probability sample of tow-away motor vehicle crashes in the U.S. (14), support the finding that obesity increases the risk of death as a result

[1] University of Michigan Transportation Research Institute, Ann Arbor, MI 48109-2150, USA. Correspondence: Jonathan Rupp (jrupp@umich.edu)
[2] Department of Emergency Medicine, University of Michigan Injury Center, Ann Arbor, MI 48109, USA [3] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI 48109-2099, USA [4] Department of Radiology, University of Michigan, Ann Arbor, MI 48109, USA [5] Department of Health Behavior and Health Education, University of Michigan School of Public Health, Ann Arbor, MI 48109-2029, USA [6] Department of Statistics, University of Michigan, Ann Arbor, MI 48109-1107, USA

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of motor-vehicle crashes (15-17). Studies that have analyzed NASS-CDS have also reported that obesity increases the risks of injuries associated with a serious or greater threat-to-life on the Abbreviated Injury Scale (i.e., injuries with that have an abbreviated injury scale score that is three or greater). These same studies suggest this effect is modulated by gender (17-19). However, there is little agreement on the direction of the interaction between gender and obesity. For example, one study reports that obese female drivers are 2.19 times more likely to sustain serious injury than female drivers with normal BMI and that obese male drivers are 0.68 times as likely to sustain serious injury than normal BMI male drivers (17). Other studies report that obese male drivers are more likely to sustain serious injury than normal BMI male drivers and that BMI does not significantly affect injury risk for female drivers (18,19).

Previous studies demonstrate that obesity is a significant predictor of injury outcome in frontal crashes, but few studies have reported the effects of obesity on injury outcome to different body regions. Further, no studies have reported on the effects of obesity on injury outcome in different crash modes. These two shortcomings are particularly relevant as many injury prevention countermeasures (e.g., airbags) that could be used to more effectively protect obese occupants in crashes are crash-mode dependent (e.g., side impact airbags). Further, most injury prevention countermeasures are targeted toward preventing injury to specific body regions within a particular crash mode (e.g., frontal-impact airbags are intended to reduce the risk of head and thorax injuries, but do little to reduce the risk of lower extremity injury).

The analyses described in this paper address these shortcomings by developing statistical models that describe the effects of obesity on the risk of serious and more severe injury to different body regions across crash modes. In addition, the models adjust for other predictors of injury risk, such as the crash severity, age, and vehicle type. These models are then used in conjunction with the population-based sample of occupants in tow-away crashes provided by NASS-CDS to estimate the number of people who sustain injuries to different body regions because they are obese.

Methods and procedures

Data sources and dataset development

The effects of obesity on the risk of serious and more severe injury in motor-vehicle crashes were estimated using a dataset developed by combining the NASS-CDS (1998-2008) dataset with observations from the crash injury research and engineering network (CIREN) dataset from the same years. For this analysis, a serious and more severe injury was defined as an injury that had a score between three and six on the Abbreviated Injury Scale (AIS) 1998 revision (denoted as AIS 3+, below). The AIS is a commonly used injury coding system that identifies the location and characteristics of types of traumatic injuries and ranks their injury severity between one and six based on mortality and other aspects of injury severity (20). For reference, AIS = 3 represents a serious injury (e.g., a displaced femur fracture) while AIS = 6 is a maximal injury (usually fatal).

NASS-CDS is a probability sample of ~5,000 crashes per year selected to produce national estimates of factors relating to vehicle crash performance and occupant injury. In contrast, CIREN is a case database that samples ~300 occupants of vehicles <8 years old at sampling who sustained AIS 3+ injury in a motor-vehicle crash and were treated at a participating Level-1 Trauma Center each year (21). As a result of these differences in sampling, combining NASS-CDS and CIREN is not as simple as pooling NASS and CIREN cases. In particular, combining NASS and CIREN in a manner that allows for analyses aimed at estimating risk requires calculating case weights for CIREN. The method for doing this is described by Elliot et al. (22) and summarized below. These weights are referred to as pseudoweights because, unlike NASS weights, they are estimated rather than measured.

A combined NASS-CDS/pseudoweighted CIREN dataset was used because combining CIREN and NASS-CDS increases the sample size of injured occupants, which is particularly important when analyzing the effects of injuries that are less common, such as serious injuries to the spine. Also, all CIREN cases contain height and weight measurements that are from investigator measurements and are therefore more likely to be accurate than height and weight measurements in NASS-CDS, which may either be from the medical record or self-reported if injury occurs and are exclusively self-reported when an occupant is not treated at a medical facility or is uninjured.

Pseudoweighting process

The process used to develop a pseudoweighted CIREN dataset involves modeling the case weights of cases meeting CIREN sampling criteria in NASS-CDS using predictors of the probability of sampling that are available in both databases (22). The resulting model is then applied to each CIREN case to establish a pseudoweight for that case. Sampling biases known to exist in CIREN (23) are corrected as part of the pseudoweighting process. In developing the pseudoweights and when combining pseudoweighted CIREN with NASS-CDS, only completed CIREN cases were used. The resulting pseudoweighted CIREN plus NASS-CDS dataset can be treated as a probability sample and analyzed in a similar manner as NASS-CDS.

Fusing and reweighting of data

When combining pseudoweighted CIREN with NASS-CDS, the case weights for the subset of NASS-CDS meeting CIREN inclusion criteria and the CIREN pseudoweights are adjusted so that the sum of these weights is equal to the sum of the weights for NASS cases meeting CIREN inclusion criteria. This assures that adding cases to the dataset do not change the estimate of the total number of injured occupants in tow-away crashes each year and that the sample can still be treated as population-based. The adjustment factor also alters the pseudoweights for CIREN and the subset of NASS-CDS meeting CIREN inclusion criteria so that the sum of the weights for each of these groups of cases is given leverage in proportion to the raw number of occupants meeting CIREN inclusion criteria in each dataset. NASS-CDS cases make up about 70% of occupants meeting CIREN inclusion criteria in the combined NASS-CDS plus pseudoweighted CIREN dataset, so weights for NASS-CDS cases meeting CIREN inclusion criteria in the combined dataset are adjusted so that these weights sum to ~70% of the weights for cases meeting CIREN inclusion criteria in the combined NASS/CIREN dataset.

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^{-1})	Continuous
Vehicle type	Passenger car (reference), light truck, utility vehicle, van
Belt use	Unbelted (reference), belted 3pt, belted other
Seat location	Driver (reference), passenger
Height (cm)	Continuous
Vehicle age (yr)	Continuous
Vehicle model year (yr)	Categorical (1992–1996, 1997–2000, 2001–2004, 2005–2008)
No. 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-/farside impacts only)	T-Type (reference), L-Type

Inclusion criteria

Once a combined NASS-CDS/CIREN dataset was generated, the dataset was limited to

- Vehicle model year ≥1992,
- Occupants in front outboard seating positions,
- Non-pregnant adults and pregnant women in their first trimester (age ≥16),
- Occupants with known height and weight, and
- Known vehicle type.

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

Modeling the effects of BMI on injury risk. Multivariate logistic regression was applied to the 1998-2008 NASS-CDS/pseudo-weighted CIREN dataset 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, farside, and rollover crashes. Equation 1 provides the relationship between the probability of AIS 3+ injury to a body region and predictors of injury produced by logistic regression.

$$p_i = \frac{1}{1 + \mathrm{Exp}[-(b_o + b_1 x_1 + \cdots + b_n x_n)} \quad (1)$$

where p_i is the probability of AIS 3+ injury to a body region, x_n are predictor variables (which can be continuous or binary) and b_n are regression coefficients (parameter estimates).

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 (24) for the most severe event associated with a particular vehicle. Rollovers were identified using the rollover variable in NASS-CDS/CIREN. Unless otherwise noted, all analyses used weighted data. Nearside and farside 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.

A backward 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. CIREN was treated as stratum and each CIREN center was treated as a principal sampling unit in accordance with methods developed by Elliot et al. (22). Second order effects were explored for BMI and age 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.

Characterizing the effects of BMI on numbers of occupants with injury. The logistic regression models developed using the methods detailed above describe the effect of BMI and other significant covariates on AIS 3+ injury, but do not consider exposure and therefore do not provide estimates of how being obese affects the frequency of AIS 3+ injuries in crashes. To estimate the effects of obesity on the total number of people experiencing AIS 3+ injury to different body regions in crashes, an approach was used that is conceptually similar to that described by Kent et al. (25).

For the current application, the effects of BMI on the frequency of injury to a body region for which a significant BMI effect was found were estimated using the following steps:

1. The crash, vehicle, and occupant information associated with each occupant in a NASS (2007-2008) dataset was applied to each of the logistic regression models to predict a risk for each occupant.
2. The risk predicted for each occupant was then multiplied by the associated case weight, and the results were summed to provide a baseline estimate of the sum of the weighted risks.
3. Next, the NASS 2007-2008 dataset was altered so that all occupants who have a BMI greater than a given cutoff had their BMI reset to that value (e.g., all occupants with a BMI greater than 45 kg m^{-2} have their BMI reset to 45 kg m^{-2}).

TABLE 2 Raw (unweighted) counts of occupants with AIS 3+ injuries by injured body region and crash mode for combined CIREN and NASS-CDS (1998–2008)

	Head	Face	Neck	Thorax	Abdomen	Spine	UpperEx	LowerEx
Frontal	616	95	17	1232	332	321	650	1665
Nearside	547	36	6	967	227	214	105	616
Farside	282	20	3	305	80	64	56	93
Rollover[a]	884	76	20	997	331	281	316	447

[a]Includes cases with missing deltaV.

4. Information from all occupants in the dataset was again applied to the regression models (some with new BMI) and the resulting risks were multiplied by the associated case weight, and the results were summed. The percent difference between the baseline sum of the weighted risk estimates and the sum of the weighted risk estimates produced when BMI was limited to a particular value was then calculated.
5. Steps 3 and 4 were repeated while varying levels at which BMI was limited at integer values between 24 and 45 kg m^{-2} to obtain estimates of the effect of BMI on the percentages of occupants with AIS 3+ injury to different body regions that are from varying degrees of being overweight or obese.

Estimates of the annual numbers of occupants with AIS 3+ injuries to different body regions that are due to varying degrees of being overweight or obese were obtained by multiplying the results of Step 5 for a particular body region by the corresponding estimate of the annual number of occupants with injury to that body region from NASS-CDS (2007-2008). This last step is necessary because the statistical models that described the effects of obesity on injury in crashes cannot be used on ~1/3 of the relevant crashes in the database because these crashes are missing predictors used in the models (most commonly deltaV).

Results

Dataset characteristics

Applying the crash type, model year, occupant age, and vehicle type to the NASS-CDS and pseudoweighted CIREN dataset resulted in a dataset consisting of 49,558 occupants. Removing occupants in frontal, nearside, and farside crashes who were missing deltaV from this dataset reduced the total number of occupants by 27% to 36,290 occupants (unweighted), which corresponds to occupants after weighting factors are applied. An additional 13 cases were removed for missing height or weight information, leaving a total of 36,277 occupants (unweighted) or 13,952,405 occupants (weighted) for use in the analysis.

Table 2 lists the raw numbers of occupants with AIS 3+ injuries in the combined dataset 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 impact were not developed for similar reasons.

The weighted BMI distribution for occupants involved in tow-away crashes changed also with crash year such that median BMI increased from 24.1 kg m^{-2} in 1998-1999 to 25.1 kg m^{-2} in 2007-2008. Between 1998-1999 and 2007-2008, the proportion of crash-involved population with BMI $\geq$ 30 kg m^{-2} increased from almost 14% to almost 21%.

Table 3 shows the proportions of the adult front-seat crash-involved occupant population that fall into five BMI groups for a subset of the predictor variables used in model development. For each predictor variable, a Rao-Scott Chi-Squared statistic and the associated P value are provided. This statistic accounts for the complex survey design of the combined NASS plus pseudoweighted CIREN dataset and indicates whether the independence model is violated. That is, the test measures whether the observed numbers of occupants in any BMI category varies as a function of the category of the predictor it is compared to (e.g., whether the BMI distribution differs between vehicle types).

Notable results in Table 3 include: (1) higher-BMI occupants tend to travel in larger vehicles, (2) lower and higher BMI crash-involved occupants are more likely to be female, while occupants with BMI between 25 and 35 are more often male. However, BMI is not associated with significant differences in restraint use or crash severity (deltaV).

BMI effects analysis

BMI and/or interactions between BMI and vehicle type, or gender were significant predictors of the risks of AIS 3+ injury to the spine, upper extremities, and lower extremities in frontal crashes and the upper and lower extremities in nearside crashes. BMI was not a significant predictor of the AIS 3+ injury for any body regions in rollover or farside impacts. Table 4 lists the parameter estimates and associated 95% confidence intervals for models in which BMI and its interactions were significant.

Figures 1 and 2 show plots of models describing the relationship between BMI and risk of AIS 3+ injury for frontal and nearside impact crashes, respectively. Plots include only significant BMI main effects or interactions. In generating Figures 1 and 2, other significant predictors of injury were held constant so that curves in these figures apply to male drivers who are 35 years old and involved in crashes with a 53 km h^{-1} deltaV for frontals and a 27 km h^{-1} deltaV for nearside impacts. The crash severities (deltaV) associated with Figures 1 and 2 are in the ~98th and 90th percentiles for frontal and side impacts, respectively, and were selected because they are typical of the deltaV values associated with common crash tests. The occupant age used to generate Figures 1 and 2 was the median age of the NASS/CIREN sample.

TABLE 3 BMI (kg m^{-2}) distribution by predictor variables from NASS/CIREN (1998–2008)

		BMI < 18.5	18.5 ≤ BMI < 25	25 < BMI ≤ 30	30 < BMI ≤ 35	BMI > 35	Rao-Scott χ^2 and associated *P* value
Sex	Female	82%	55%	35%	43%	58%	$\chi^2(4) = 102.2$, $P < 0.0001$
	Male	18%	45%	65%	57%	42%	
DeltaV (km h^{-1})	<15	37%	34%	32%	36%	28%	$\chi^2(16) = 19.9$, $P = 0.22$
	15≤ΔV<30	53%	54%	54%	52%	52%	
	30≤ΔV<45	9%	11%	11%	11%	18%	
	45≤ΔV<60	1%	2%	2%	1%	1%	
	≥60	0%	0%	1%	0%	0%	
Age group (yr)	15–29	77%	55%	36%	28%	37%	$\chi^2(16) = 312.5$, $P < 0.0001$
	30–44	14%	22%	30%	30%	35%	
	45–59	4%	13%	20%	27%	19%	
	60–74	3%	5%	9%	12%	7%	
	75–89	3%	4%	5%	3%	2%	
Belt use	3-point	88%	87%	87%	87%	84%	$\chi^2(8) = 7.7$, $P = 0.46$
	No	10%	12%	11%	13%	15%	
	belted other	2%	1%	2%	0%	2%	
Seat location	Driver	75%	80%	84%	86%	86%	$\chi^2(4) = 23.3$, $P < 0.0001$
	Passenger	25%	20%	16%	14%	14%	
Multiple severe impacts	No	97%	97%	97%	97%	96%	$\chi^2(4) = 1.56$, $P = 0.81$
	Yes	3%	3%	3%	3%	4%	
Vehicle type	Car	76%	68%	61%	60%	63%	$\chi^2(12) = 68.0$, $P < 0.0001$
	Pickup	8%	11%	15%	15%	12%	
	Utility	10%	15%	16%	15%	13%	
	Van	5%	5%	8%	9%	12%	
Crash mode	Farside	15%	14%	12%	14%	11%	$\chi^2(12) = 24.0$, $P = 0.02$
	Frontal	58%	62%	60%	61%	61%	
	Nearside	11%	13%	15%	17%	18%	
	Rollover	16%	11%	13%	8%	10%	

Figures 1 and 2 illustrate that the effect of BMI on AIS 3+ injury is complex, and for some body regions, interacts with gender and vehicle type. For the lower extremities, increasing BMI increased the risk of AIS 3+ injury in frontal crashes, but decreased the risks of injury in nearside impacts. Upper extremity injuries in frontal crashes showed a gender interaction such that men had a greater increase in the risk of AIS 3+ injury with BMI than women. The effect of BMI on spine injury in frontal crashes was independently modulated by both gender and vehicle type such that the effect of increasing BMI on AIS 3+ injury risk was greater for male occupants of passenger cars than for occupants of other vehicles. In addition, the increase in risk of AIS 3+ spine injury with BMI in frontal crashes was greater for men than women. The effect of BMI on upper extremity injuries in nearside impact was also interacted with vehicle type such that the increase in injury risk with BMI was greater for utility vehicle occupants than it was for occupants of other vehicle types.

Effects of obesity on the frequency of serious injuries to different body regions

Figure 3 shows the percent and overall change in the numbers of AIS 3+ injuries to the upper extremities, spine, and lower extremities in frontal crashes predicted to occur if the maximum BMI of the crash-involved population were limited to values between 24 and 45 kg m^{-2}. Figure 4 shows a similar analysis for upper and lower extremity injuries in nearside crashes.

Interesting findings in Figure 3 include that if no motor-vehicle occupants were obese, i.e., all occupants who had BMI ≥ 30 had a BMI of 30 kg m^{-2}, then ~600 occupants would not sustain AIS 3+ injury to the upper extremities, 1,200 occupants would not sustain AIS 3+ lower extremity injuries, and 1,200 occupants would not sustain AIS 3+ spine injuries. As shown on the left side of Figure 3, these values represent 7% of occupants with AIS 3+ upper extremity injuries, 8% of occupants with AIS 3+ lower extremity injuries, and 28% of occupants with AIS 3+ spine injuries.

Figure 4 indicates that if all occupants with a BMI ≥ 30 had a BMI of 30 kg m^{-2}, then ~3% or 200 more occupants would experience AIS 3+ injury to the lower extremities in nearside crashes while ~12% or 140 fewer occupants would experience AIS 3+ upper extremity injury. Larger changes in the numbers of occupants with AIS 3+ injury are predicted to occur if BMI is limited so that none of the crash-involved population has a BMI > 25 kg m^{-2}.

TABLE 4 Parameter estimates and 95% CIs from logistic regression models of the risk of AIS 3+ injury for body regions associated with significant BMI effects (NASS/CIREN 1998–2008)

Parameter		Parameter estimates and 95% CIs				
		Frontal crashes			Nearside impacts	
		Spine	Upper Ex	Lower Ex	Upper Ex	Lower Ex
Intercept		−14.67*** (−17.21, −12.12)	−9.05*** (−10.57, −7.53)	−8.92*** (−9.66, −8.18)	−10.11*** (−10.85, −9.36)	−7.05*** (−8.71, −5.40)
Belt use (vs. unbelted)	3pt	−1.08*** (−1.62, −0.54)	−1.08*** (−1.62, −0.54)	−1.65*** (−1.85, −1.44)	–	–
	Other belt	−2.13* (−4.06, −0.21)	−2.13* (−4.06,−0.21)	0.06 (−1.68,1.79)	–	–
Vehicle type (vs. passenger car)	Lt truck	3.87* (0.29, 7.44)	–	–	−2.50 (−5.43,0.43)	−0.45 (−1.38,0.48)
	Utility	2.50* (0.39, 4.62)	–	–	−4.04** (−6.17, −1.91)	−1.29* (−2.37, −0.20)
	Van	−0.31 (−6.53,5.90)	–	–	−3.87 (−8.55,0.81)	0.47 (−1.50,2.44)
Age (yr.)		0.03*** (0.02,0.04)	0.02** (0.01,0.03)	0.02*** (0.01,0.03)	0.03*** (0.02,0.04)	0.02 (0.00,0.04)
BMI (kg m^{-2})		0.21*** (0.15,0.27)	0.08** (0.04,0.13)	0.06*** (0.04,0.08)	0.04* (0.01,0.06)	−0.04* (−0.08,0.00)
deltaV (km h^{-1})		0.08*** (0.06,0.09)	0.07*** (0.06,0.08)	0.10*** (0.09,0.11)	0.09*** (0.07,0.11)	0.13*** (0.12,0.15)
BMI × gender (vs. M)		−0.17*** (−0.22, −0.13)	−0.07** (−0.10, −0.03)	–	–	–
Gender (vs. M)		5.10*** (3.53,6.67)	2.63*** (1.64,3.62)	0.54* (0.18,0.90)	0.81* (0.22,1.40)	0.68* (0.13,1.23)
Seat position (vs. driver)		–	−0.70* (−1.32, −0.08)	–	–	–
BMI × vehicle type (vs. passenger car)	Lt truck	−0.15* (−0.28, −0.01)	–	–	0.10 (0.00,0.20)	–
	Utility	−0.10* (−0.16, −0.04)	–	–	0.13*** (0.07,0.19)	–
	Van	−0.03 (−0.20,0.14)	–	–	0.09 (−0.05,0.23)	–
Multiple severe impacts (vs. none)		–	–	–	–	1.44* (0.29,2.59)

*$P < 0.05$,
**$P < 0.001$,
***$P < 0.0001$.

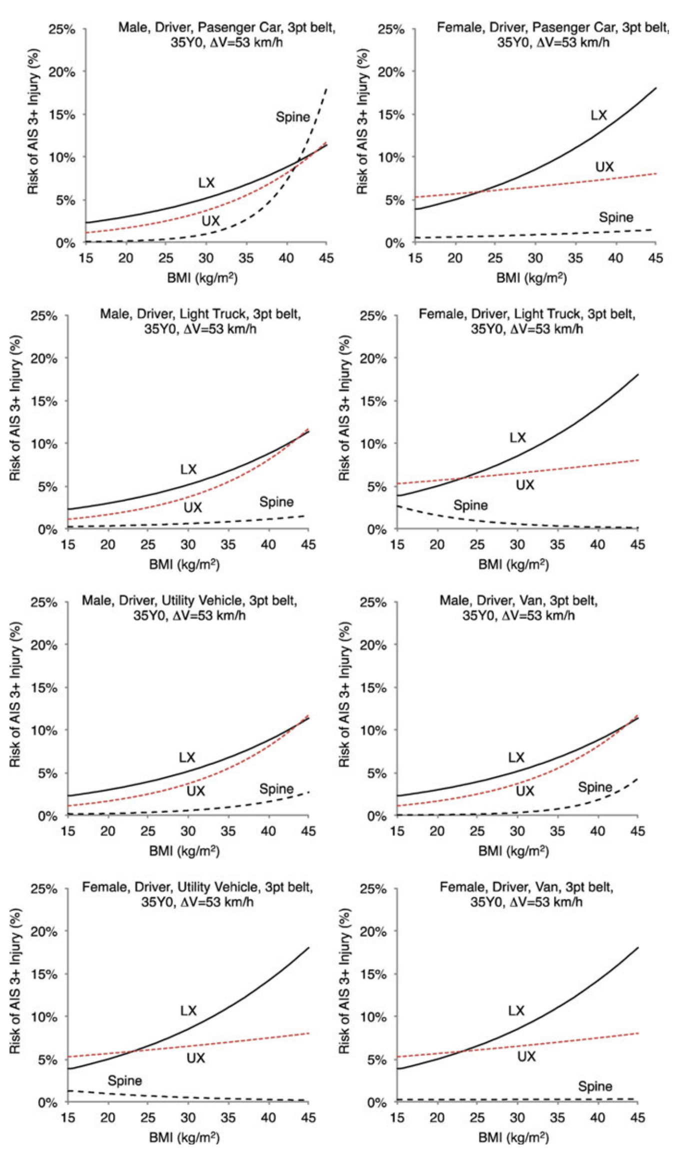

FIGURE 1 Effects of varying BMI from 15 to 45 kg m^{-2} on AIS 3+ injury risk in frontal crashes for body regions for which BMI was a significant predictor of AIS 3+ injury when controlling for other significant predictors (three-point belted, age = 35 years, deltaV= 53 km h^{-1}, seat position=driver). Abbreviations: lower extremities (LX), upper extremities (UX).

Discussion

This paper provides the first estimates of the effects of obesity on the risks of injury to different body regions for different crash types. These data are particularly important because engineering countermeasures used to prevent injury in crashes are generally targeted to a particular crash type and body region. This study also provides the first estimates of how BMI affects the numbers of occupants with AIS 3+ injury in crashes that consider the effects of other significant predictors of injury.

Dataset characteristics

Approximately 21% of the crash-involved population had a BMI $\geq$ 30 kg m^{-2} for the 2007-2008 calendar years, based on height and weight data that were primarily self-reported. In contrast, based on self-reported height and weight in the CDC's behavioral risk factors surveillance survey (BRFSS), 26.5% of the U.S. population had a BMI $\geq$ 30 kg m^{-2} for this same period (26). The differences between these two rates do not indicate that having BMI $\geq$ 30 kg m^{-2} is associated with less exposure to crashes. Rather, these differences result from younger and older occupants having lower BMI than middle-aged occupants but being exposed to crashes at higher rates than middle-aged occupants (27).

The rate of seat belt use for occupants with BMI $\geq$ 35 kg m^{-2} was ~84% while belt use rates were between 87 and 88% for lower BMI groups. Consistent with increases in national seatbelt use rates, rates of seatbelt use for different BMI groups in the current study were higher than those reported in earlier analyses (e.g., 6,28).

Several notable trends were observed in analyses of distributions of predictor variables including that occupants with higher BMI travel in larger vehicles and that occupants with lower and higher BMI tended to be female. While neither of these observations is surprising, both support the need to include interactions between BMI and vehicle type and BMI and gender in multivariate analyses.

Effects of BMI on injury risk

Increasing BMI was associated with an increase in the risk of AIS 3+ lower extremity injury in frontal crashes, but a decrease in the risk of lower extremity injury in nearside crashes. The reasons for these opposite BMI effects most likely arise from differences in the loading scenarios that cause lower extremity injuries in frontal and nearside impacts. Specifically, lower extremity injuries in frontal crashes occur from the knees impacting the lower instrument panel (called the knee bolster) and the feet loading the toepan. The increased mass associated with higher BMI results in higher knee impact forces, which are associated with an increased risk of knee-thigh-hip fracture and below-knee injury (29). The increased abdominal fat associated with higher BMI also results in increased knee excursion (30,31) because the lap belt must deflect a greater amount of soft tissue before it can begin to load the bony pelvis. This increased excursion and delayed belt engagement also increases knee impact forces and the risk of lower extremity injury. These findings suggest that engineering countermeasures like knee airbags, which reduce the force that needs to be applied to the knees to decelerate the lower body by applying restraint to the knees earlier in the crash event than traditional knee bolsters, may have a greater benefit for people with higher BMI.

In contrast to frontal crashes, the occupant in a nearside impact has little or no initial velocity along the direction of impact and is accelerated by contact with intruding door and later by acceleration of the occupant's vehicle. As a result of this, coupled with the fact that almost all lower extremity injuries in nearside impact are to the hip and pelvis, the decrease in lower extremity injury risk with increasing BMI is thought to be from increased padding provided by increased fat over the iliac wing and trochanter. This hypothesis is consistent with results of a series of lateral impacts to the trochanters of female pelves, which indicated that the force required to fracture the pelvis increased with the thickness of the tissue over the trochanter (32). These findings indicate it may possible to tune side airbags to apply higher forces to the pelves of obese occupants in nearside impacts without increasing the risk of pelvic fracture.

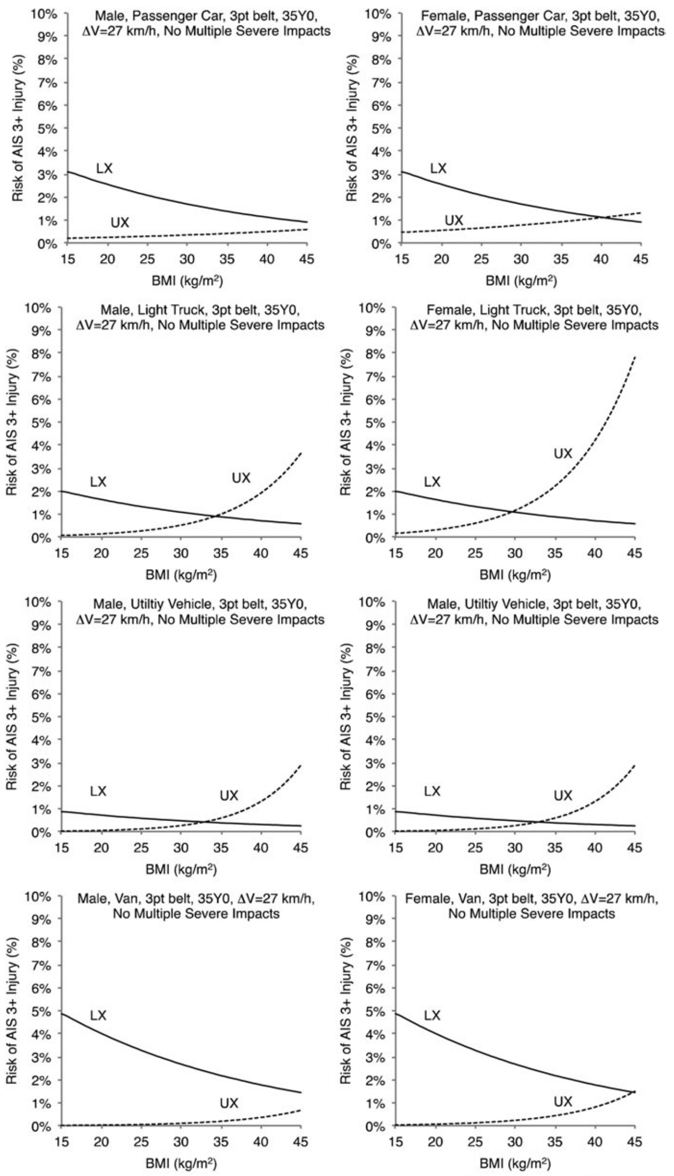

FIGURE 2 Effects of varying BMI from 15 to 45 kg m^{-2} on AIS 3+ injury risk in nearside crashes for body regions for which BMI was a significant predictor of AIS 3+ injury when controlling for other significant predictors (three-point belted, age = 35 years, deltaV= 27 km h^{-1}, no multiple severe impacts). Abbreviations: lower extremities (LX), upper extremities (UX).

Further, applying higher force to the pelvis would allow forces applied to other body regions (and the resulting likelihood of injury to these body regions) to be reduced.

Increasing BMI was associated with an increase in the risk of AIS 3+ upper extremity injury in frontal and nearside crashes such that increasing BMI resulted in a greater increase in injury risk for men than women in frontal crashes and a greater increase in risk for women than men in nearside impacts. The reason for these trends is unknown but may be related to size and shape differences between men and women and the tendency of women to sit closer to the instrument panel than men. Further research is needed to help to elucidate the reasons for these trends.

Increasing BMI was also associated with a greater increase in the risk of AIS 3+ spine injury for men and occupants of passenger cars than for women and occupants of other vehicle types. AIS 3+ spine injuries caused by head contact may be more likely for taller occupants in vehicles with less head-to-roof clearance (i.e., men in passenger cars), and compression of the spine caused by either head contact or loading of the pelvis into the metal supporting structure of the seat cushion is likely to be greater for occupants with higher mass (i.e., men with higher BMI).

Previous studies have suggested that obese crash test dummies should be developed as tools to help automakers design vehicles that better protect obese occupants in crashes (e.g., 12,17). The findings in the current study suggest that if obese crash test dummies were to be developed, they should be designed for use in frontal crashes and should have sizes and shapes associated with higher BMI males rather than females because the increase in risk with BMI is greater in frontal crashes and is greater for men than women. However, if an obese crash test dummy is developed, steps should be taken to ensure that crash testing with this dummy does not result in restraint system design changes, like stiffer and more aggressive airbag or seat belts with higher load-limits that could reduce protection for other vehicle occupant populations (e.g., the elderly).

Comparisons to previous work

Previous studies have reported widely varying effects of obesity on the probability of serious injury to different body regions in motor-vehicle crashes, with some studies reporting that obesity is protective and other studies reporting that obesity increases injury risk in men and not women, women and not men, or both sexes (17,18,33). The reasons for the disagreement between different studies are primarily differences in the databases analyzed and differences in analysis methods, particularly the inclusion of different predictor variables. The current study helps to resolve this disagreement by including the predictor variables that were significant in previous analyses as well as several new predictor variables, like the presence of multiple severe impacts, and interactions between predictor variables like age and gender and vehicle type and BMI. Further, the current study includes information on the effects of BMI on the risk of serious injury in nearside impact crashes, which have not been previously reported in analyses of population-based samples of crashes. The current study is also the first analysis of BMI effects to combine crash- and injury-based data to provide the information on how the risk of serious injury varies with body region that is needed to focus the development of new vehicle restraint system technologies that better protect occupants with higher BMI.

In contrast to the current study, previous work found that increasing BMI was associated with an increase in risk to the head and thorax in frontal crashes (18). Our study found no significant BMI effects (or BMI interactions) for these body regions. Previous work has also indicated that having high or low BMI increases the risk of AIS 3+ injury to the abdomen (18). In contrast, the current study found that the probability of abdomen injury was not affected by BMI or BMI^2. Multiple studies have reported that increasing BMI increases the risk of lower extremity injuries and some studies have reported that the effect of BMI is greater for men than women (17,18).

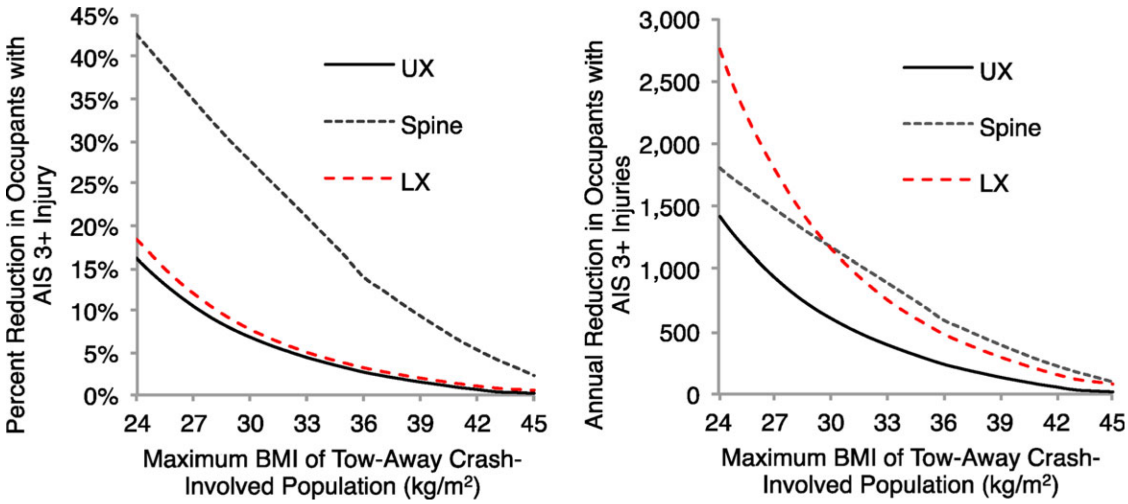

FIGURE 3 Predicted effects of limiting the maximum BMI of the crash-involved population on annual numbers of occupants with AIS 3+ lower extremity injury, occupants with AIS 3+ upper extremity injury, and occupants with AIS 3+ spine injury in frontal crashes. Abbreviations: lower extremities (LX), upper extremities (UX).

Results of the current study indicate that increasing BMI increases the risk of AIS 3+ injury for the lower extremities, but did not demonstrate an interaction between sex and BMI.

Limitations

This study did not control for intrusion of structures into the occupant compartment in frontal or side impact, although controlling for intrusion is unlikely to alter the effect of BMI on injury. Controlling for intrusion may, however, reduce the effects of covariates that are related to intrusion, like deltaV and vehicle type. This analysis also did not control for airbag deployment, which has been shown to be a cause of some upper extremity injuries (34). However, the analysis did control for deltaV, which is a surrogate for airbag deployment in almost all frontal crashes included in this analysis. Not controlling for airbag deployment may be problematic for analyses of side impact crashes in this study because only a portion of vehicles studied were side airbag equipped.

This analysis categorized crash types as frontal, nearside, farside, or rollover. It did not consider effects of crash direction within a crash type or the effects of subtypes of crashes, like small overlap frontal impacts or narrow object frontal or side impacts. Within these subtypes of crashes there may be different relationships between predictor variables (like BMI) and the occurrence of injury. Models describing the relationship between predictor variables and the occurrence of AIS 3+ injury could not be developed for crash subtypes because of small sample size issues.

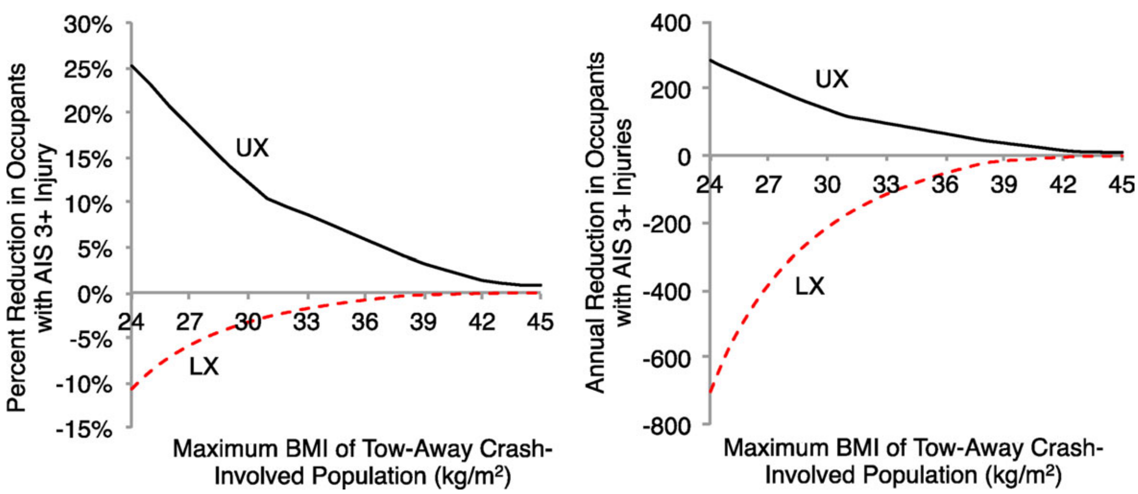

FIGURE 4 Predicted effects of limiting the maximum BMI of the crash-involved population on annual numbers of occupants with AIS 3+ lower extremity injury, and occupants with AIS 3+ upper extremity injury in nearside crashes. Abbreviations: lower extremities (LX), upper extremities (UX).

Another limitation of this analysis is that it uses data from NASS-CDS for which occupant height and weight data can be self-reported. This is particularly true for the uninjured population where there is not likely to be a medical record or other available document that contains accurate information on occupant height and weight. Because of this, height and weight data for uninjured occupants are likely to be biased such that these data will indicate that uninjured occupants (and particularly injured women) are taller and lighter than they are (35). This reporting bias, coupled with the fact that height and weight data for the injured population are more likely to be accurate, suggests that when BMI is shown to increase risk, the effect may be overestimated, and when BMI is shown to decrease risk, the effect may be underestimated.

Approximately 30% of the frontal, nearside, and farside crashes analyzed in this study 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 (36). While this bias likely affects the intercept parameter of the logistic regression, it should not affect the relationships between AIS 3+ injury risk to different body regions and predictors of risk, such as BMI (37). For this reason, the bias likely affects estimates of the numbers of occupants who sustain injuries to different body regions.

The methods used to estimate the number of occupants who sustain injury to particular body regions as a result of having BMI greater than a particular value vary the BMI of the population without varying factors that are covariates of BMI, like vehicle type. If these factors were accounted for, estimates of the change in numbers of occupants with injury to particular body regions would be different. Further, the estimates of the effects of BMI are based on a model of a population and may not apply to individual occupants. Additional research, including crash test simulations using computational models that have normal and high BMI, is needed to obtain insight into the effects of decreasing BMI on injury risk on individual occupants.

Finally, because information on comorbidities associated with obesity was not available for both the injured and uninjured groups, it was not possible to account for the comorbid conditions when modeling BMI effects. As a result, the BMI effects reported in this study could be, in part, from comorbidities associated with increasing BMI rather than BMI itself. O

Acknowledgments

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