Female Driver Lower Extremity Injury: Contributing Factors and Crash Test Relevance

Matthew L. Brumbelow

Abstract Despite improvements for both sexes, relative to males, female drivers are at elevated risk of lower extremity injury in front crashes of modern vehicles. Additional progress requires a targeted approach to identify and address factors unique to or more prominent for females. This study focused on front crashes involving drivers restrained by a seat belt and front airbag with low levels of toe pan intrusion. Two field crash datasets were analysed using logistic regression to model the odds of three different AIS≥2 outcomes: any lower extremity injury; non-ankle/foot injury; and right ankle/foot injury. Cases with event data recorder delta-V and precrash braking were used to identify crash- and occupant-related risk factors. Cases with representative Insurance Institute for Highway Safety moderate-overlap crash tests were studied to evaluate the effect of vehicle factors as measured with the Hybrid III 50th percentile male dummy. The risk of a female driver sustaining at least one of the three injury types increased with delta-V, precrash braking, age and body mass index, and decreased with knee airbag deployment. The principal component describing the largest amount of vehicle dummy measurement variation was a meaningful predictor of female driver injury outcome, especially for injuries of the right ankle/foot.

Keywords BMI, Hybrid III, lower extremities, females, front crashes.

I. INTRODUCTION

The risk of sustaining a fatal or serious injury in a frontal crash continues to decline in the newest vehicles. This has been demonstrated through studies using crash test scores from different evaluation programs over the past three decades [1-3]. As these improvements have been made, the relative importance of non-life-threatening injuries has increased, and lower extremity injuries are the most common type of injury with a severity of 2 or greater on the Abbreviated Injury Scale (AIS≥2) [4-5]. Here, too, there have been dramatic crashworthiness improvements. In frontal crashes involving a driver restrained by a seat belt and deployed airbag, Brumbelow and Jermakian [6] found that a good rating in the Insurance Institute for Highway Safety (IIHS) moderate overlap test was associated with a 60% reduction in AIS≥2 lower extremity injury risk. Despite this, and despite the fact that the risk reduction was similar for female and male drivers, they found that the odds of a female driver sustaining a lower extremity injury remained nearly three times that for a male driver (female odds ratio [OR]: 2.72; 95% confidence interval [CI]: 1.57–4.71). This contrasted with an essentially equal likelihood that a female and male driver would sustain an AIS≥3 non-extremity injury (female OR: 0.98; 95% CI: 0.56–1.70).

Other researchers comparing relative injury risk by body region also have reported that the increased risk of lower extremity injury for females is higher than the relative risk of injury to other body regions [5][7]. Potential explanations for this higher risk have included bone and ligament properties [5], stature [8-9], footwear [8], or foot placement and pedal use [8][10-11]. Some of these possibilities are best studied in laboratory environments with post-mortem human subjects (PMHS) or with computer modelling [12], but others can be at least partially evaluated using field crash data. For example, Brumbelow and Jermakian [6] concluded that stature and mass differences typical of female and male drivers did not explain the increased injury risk for females in the set of crashes they analysed. However, they did not assess whether "the effects of mass and height are similar for females and males" and identified this as an area for future research. This principle can be applied even more generally; it may be unnecessary to fully understand all the sources of the disparity in female and male injury risk prior to identifying factors that affect injury outcomes for females specifically.

M. L. Brumbelow (e-mail: mbrumbelow@iihs.org; tel: +1-434-985-4600) is a Senior Research Engineer at the Insurance Institute for Highway Safety in Virginia, USA.

A related question is whether existing crashworthiness evaluations are able to assess lower extremity risk for females. It is possible that the improved outcomes in good-rated vehicles primarily are a function of reduced toe pan intrusion, which others have identified as a main contributor to lower extremity injury [4][8][11][13]. When tested at the same severity, today's vehicle fleet typically has lower toe pan intrusion than prior designs (Fig. 1), but this trend has slowed in recent years. Requiring even lower values for the best ratings may be unrealistic, and many injuries already occur at lower crash severities. Instead, further protection improvements for females may require tools that can be used to evaluate injury risk in the absence of significant intrusion. Whether this can be done with existing dummies and test configurations has not been explicitly evaluated. IIHS has been conducting its moderate overlap (40%) test since 1995 using a Hybrid III 50th percentile male dummy (HIII-50M) in the driver seat. Measurements taken during these tests comprise the largest source of potential predictors of lower extremity injury risk for production vehicles in the USA, and the greatest opportunity to study the relationship with injury outcomes for female drivers. While others have used the IIHS test data to group vehicles by model year [4][10-11] or by rating [6], the effect of lower extremity test results on injury risk in matched vehicles has not been evaluated.

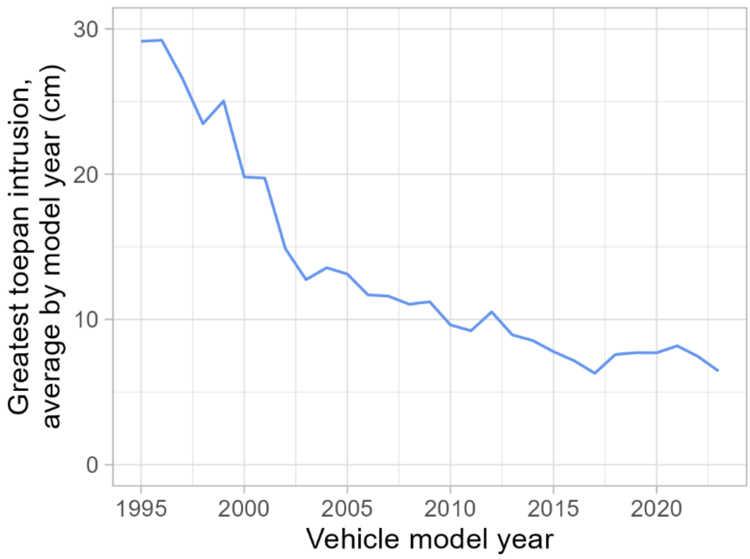

Fig. 1. Toe pan intrusion in IIHS moderate overlap test.

This study was designed to identify lower extremity risk factors specific to female drivers in vehicles with modern levels of crash protection. Such factors include driver and crash variables, as well as crashworthiness metrics from the IIHS moderate overlap test. Some of these also may affect male driver risk, but males were included only where this could lead to more precise effect estimates for females. Particular emphasis was given to the right ankle/foot, as previous work [8][14-15] and preliminary analyses for this study indicated a higher risk of injury at this location.

II. METHODS

Two datasets were used to study the risk factors for female lower extremity injury in front crashes. First, factors specific to the driver and crash environment were analysed using cases from the Crashworthiness Investigation Sampling System (CISS) with event data recorder (EDR) information. On average, delta-V estimates derived from vehicle crush measurements in front crashes are lower than those reported by EDRs [16]. In addition, there is some evidence that the magnitude of this discrepancy varies by driver sex, likely because of systematic differences in the vehicle types that females and males drive [17]. To minimise the potential for these effects to confound the analyses of crash- and driver-based risk factors, CISS EDR cases were used. CISS also provides the most crash data for the most recent model years, which was an important focus of this study.

While CISS is the best data source of crashes involving the newest vehicles and has a relatively high rate of associated EDR data, it does not yet have a large sample of cases involving vehicles with a full complement of lower extremity dummy measurements from the IIHS moderate overlap crash test. In 2006, to support the development of new crashworthiness evaluations, IIHS began accepting moderate overlap test data submitted by vehicle manufacturers as part of its rating program. When manufacturers submit data, IIHS only retains peak values necessary for assigning ratings. Component-level moments and accelerations are not saved, and only the greater of the two resultant moment and index values recorded at the upper and lower tibias are kept. For vehicles with good overall and structure ratings, IIHS conducted 75% of tests up to model year 2009, but manufacturers have conducted 73% of tests since then. As a result, there are still many more cases from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS), the predecessor of CISS, involving vehicles with known values for all the lower extremity injury metrics, making it a better data source for evaluating the influence of vehicle-specific variables from matched crash tests. The two crash samples and the regression analysis procedure for each are described below.

CISS EDR Case Analysis

CISS is a survey-weighted database maintained by the National Highway Traffic Safety Administration (NHTSA) of police-reported tow-away crashes in the USA. The first full year of data collection was 2017. For this study, 2017–2021 cases were queried for those involving a driver restrained by a seat belt and deployed airbag who was involved in a frontal non-rollover crash. Both female and male drivers were included. Matching cases were restricted to those with associated EDR files. Pickups were excluded to avoid potential confounding with driver sex [17].

As discussed in the Introduction, it previously has been established that footwell intrusion increases lower extremity injury risk [8][13]. This study was focused on identifying risk factors in crashes that occur at or below severities evaluated in crash test programs. Since modern vehicles have lower intrusion levels than older vehicles tested at the same severity (Fig. 1), CISS cases were limited to those involving 2010 or later model years. In addition, cases were excluded if they had reported intrusion greater than 14 cm in the toe pan or greater than 7 cm at the instrument panel, A-pillar, or windshield. The toe pan, instrument panel and A-pillar values roughly correspond to the IIHS structural rating boundary between good and acceptable intrusion levels in the moderate overlap test [18].

Many CISS cases do not have a reported EDR delta-V despite a recorded delta-V time history curve that appears to have reached a value that would be close to its ultimate minimum (Fig. 2). In order to maximise the sample size, the following criteria were used to identify pulses from which the total longitudinal delta-V could be calculated: the minimum delta-V was between -5 and -120 km/h, the slope of the delta-V curve reached a value that was greater than -5 g, and there were non-zero delta-V values prior to the minimum delta-V.

Logistic regression was used to estimate the effect of various factors on the odds of lower extremity injury. Three different AIS≥2 lower extremity injury outcomes were considered: any injury; any non-ankle/foot injury; and any right ankle/foot injury. There were insufficient data to evaluate left ankle/foot injury separately. For the purposes of this study, "lower extremity" injuries exclude pelvic injuries. Covariates included in each regression model were longitudinal EDR delta-V, driver sex, driver age, driver BMI, braking status, and knee airbag (KAB) deployment. Braking status was determined from the EDR precrash data and was defined as any brake pedal application during the last 2 seconds preceding the crash. Interaction terms between driver sex and the other covariates were evaluated and retained if they were significant at the $\alpha = 0.05$ level.

While the CISS inclusion criteria meant all cases had matching EDR data, not all could be used to estimate a minimum longitudinal delta-V using the procedure outlined above. Other covariates also were missing for some cases. The R package "mice" was used to construct 30 multiply-imputed datasets and to pool regression model results [19]. Covariates with missing data were delta-V (8% of cases), driver age (0.1%), driver BMI (34%), and braking status (0.4%). For reasons possibly related to the COVID-19 pandemic, the proportion of CISS occupants missing height or weight information increased from 27% in 2017–2019 to 59% in 2020–2021. The R package "survey" was used to fit the models while accounting for CISS case weights [20]. Case weights were capped at the 99.5th percentile value.

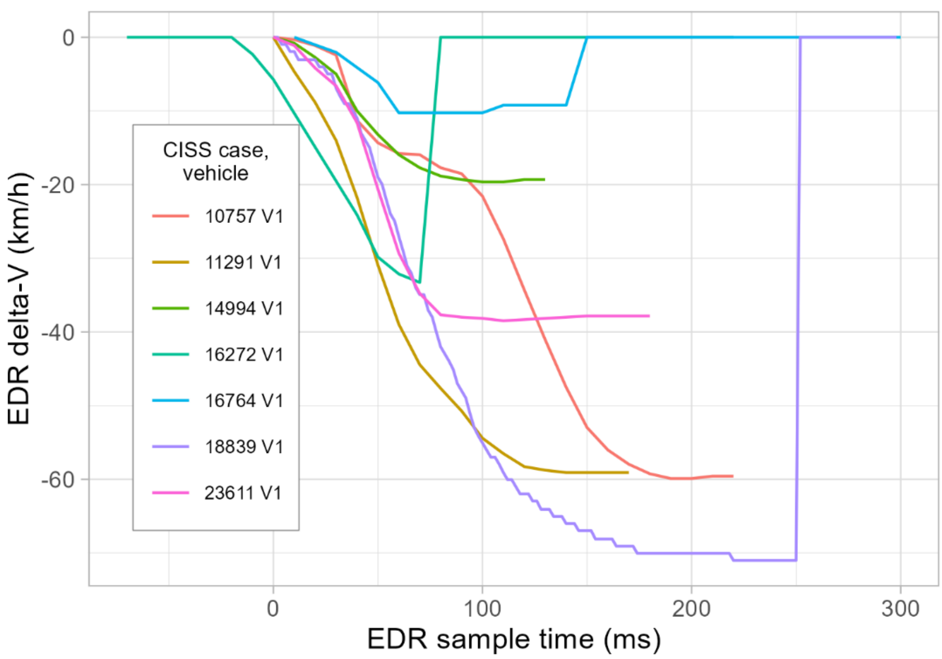

Fig. 2. Sample CISS EDR data for cases without reported EDR final delta-V.

TABLE I
HIII-50M LOWER EXTREMITY MEASUREMENTS IN IIHS MODERATE OVERLAP TEST

Femur axial force
Knee displacement
Tibia axial force
Tibia upper X moment
Tibia upper Y moment
Tibia upper resultant moment
Tibia upper index
Tibia lower X moment
Tibia lower Y moment
Tibia lower resultant moment
Tibia lower index
Foot X acceleration
Foot Z acceleration
Foot resultant acceleration

NASS-CDS Case Analysis

NASS-CDS is a survey-weighted database of police-reported tow-away crashes that occurred in the USA between 1988 and 2015. It was the direct predecessor of CISS and its sampling criteria were similar. While other algorithms were employed earlier, beginning in 2000 WinSMASH software was used to estimate delta-V based on vehicle damage. For this study, 2000–2015 NASS-CDS cases were queried for those involving a female driver restrained by a seat belt and deployed airbag who was involved in a frontal non-rollover crash with an associated WinSMASH delta-V estimate. Crashes with large trucks, buses, or other non-passenger-vehicle partners were excluded, as these may confound the relationship with crash test measurements. Subject vehicles required a matching moderate overlap test that was conducted by IIHS and produced good overall and structure ratings. As with the CISS sample, cases with coded intrusion above 14 cm in the toe pan or 7 cm at the instrument panel or windshield were excluded.

Logistic regression was used to estimate the effect of increased Hybrid III injury metrics on the risk of female drivers sustaining lower extremity injuries in the same make and model of the tested vehicles. The same three injury outcomes were considered as for the CISS case analysis: any injury; any non-ankle/foot injury; and any right ankle/foot injury. These were measured using the 2008 version of the AIS scale [21]. NASS-CDS cases that only contained injury codes on the 1995 scale were mapped to the newer scale. Where a single 1995 code could match multiple 2008 codes, case details were sufficient to determine the presence of an AIS≥2 injury on the 2008 scale, or else the driver sustained another confirmed injury to the same region as the ambiguous injury.

The covariates included in the regression models were driver age, driver BMI, WinSMASH delta-V, and one dummy metric from the moderate overlap test. In addition, an interaction term between delta-V and the version of WinSMASH was included, since others have shown that the 2008 software update that included vehicle-specific stiffness values produced a "step-change" in the resulting severity estimates [22]. Missing values for BMI (14% of cases) were imputed and case weights were capped at the 99.5th percentile value. The R package "mice" was used to construct 20 multiply-imputed datasets and pool results [19].

Including the left and right legs, there are 28 different lower-extremity injury measurements recorded in the IIHS moderate overlap test (Table I). Eighteen of these are measured directly and 10 are derived (resultant moments, resultant accelerations, and tibia indices). Fitting 28 separate logistical models to each of the three injury outcomes would increase the possibility of a Type I error, in which metrics correlated with injury outcome by chance are assumed to be risk factors. To mitigate this possibility, principal component analysis (PCA) was used for dimensionality reduction. PCA is a technique that creates new variables ("principal components" or PCs) from linear combinations of the existing variables, resulting in a lower dimension approximation of the full dataset. The PCA was based on all IIHS moderate overlap tests matching at least one crashed vehicle in the NASS-CDS dataset. Each PC represents the unique linear combination of all metrics that maximises the variance across the tested vehicles after controlling for any higher order PCs. For example, the first principal component (PC1) captures the largest amount of variation among test vehicles, while PC2 captures the most variation remaining after controlling for PC1. As peak values of the 10 derived metrics were already strongly correlated with linear combinations of two direct metrics (Appendix, Table A.I), these were not included in the PCA. To facilitate interpretation, peak measures with negative signs (e.g. axial compression) were converted to positive values prior to PCA. Each of the three lower-extremity injury outcomes was modelled using PC1 and PC2. Since PCs are orthogonal by definition they can be included in the same model without risk of confounding.

III. Results

Driver and Crash Factors

There were 1,631 2017–2021 CISS cases with EDR data that met the inclusion criteria, of which 57% had a female driver. Fifty-two drivers sustained at least one AIS2+ lower extremity injury, and 30 sustained an AIS2+ right ankle/foot injury. Summary statistics and case counts are shown in Table II. Preliminary regression models indicated that driver sex interaction terms with age (p = 0.59), EDR delta-V (p = 0.64), precrash braking (p = 0.65), and knee airbag (KAB) deployment (p = 0.53) were not significant predictors of lower extremity injury at the α = 0.05 level; these were not retained in the final regression models.

TABLE II
CISS EDR CASE SUMMARY (UNWEIGHTED VALUES)

	AIS≥2 Lower extremity injury	
	None	Any
Cases	1,579	52
Females	895 (57%)	35 (67%)
KAB deployed	761 (48%)	19 (37%)
Braking	1,071 (68%)	34 (65%)
Median age	38	44.5
Median BMI (kg/m^2)	26.9	31.3
Median delta-V (km/h)	25	58.5

The final models included driver sex, driver age, driver BMI, EDR delta-V, precrash braking, KAB deployment, and an interaction term between driver sex and BMI. Results of these models for each of the three lower extremity injury outcomes are shown in Table III. The estimated effects of delta-V and driver age were significant at α = 0.05 for all three injury outcomes, while the estimated effects of precrash braking, KAB deployment and BMI for female drivers were significant for at least one of the injury outcomes. The results are presented graphically as odds ratios in Fig. 3, with each effect scaled to one standard deviation of the associated metric. As the effect of sex was estimated to vary by BMI, no overall odds ratio for sex is displayed in Fig. 3. Instead, Fig. 4 illustrates the estimated risk of injury by BMI for drivers of each sex. Estimated differences between females and males were small at lower BMI, but increased for drivers with higher BMI. Figure A1 in the Appendix shows the BMI distribution by driver sex.

TABLE III
RESULTS OF LOGISTIC REGRESSION MODELS FOR DIFFERENT LOWER EXTREMITY INJURY OUTCOMES IN CISS

	Any lower extremity			Non-ankle/foot			Right ankle/foot		
Term	Estimate	SE	p value	Estimate	SE	p value	Estimate	SE	p value
Intercept	−14.368	1.989	-	−16.173	2.455	-	−13.176	2.382	-
Delta-V (+1 km/h)	**0.117**	**0.015**	**<0.001**	**0.118**	**0.017**	**<0.001**	**0.101**	**0.011**	**<0.001**
Age (+1 year)	**0.039**	**0.014**	**0.005**	**0.052**	**0.015**	**<0.001**	**0.037**	**0.017**	**0.03**
BMI (+1 kg/m^2; females)	**0.118**	**0.041**	**0.004**	**0.138**	**0.045**	**0.002**	0.061	0.054	0.26
Precrash braking (ref: none)	0.949	0.584	0.10	0.251	0.735	0.73	**1.386**	**0.635**	**0.03**
Deployed KAB (ref: none)	**−1.617**	**0.543**	**0.003**	**−1.670**	**0.696**	**0.02**	−0.998	0.605	0.10
Male (ref: female)	2.703	2.239	0.23	**6.191**	**2.914**	**0.03**	0.379	2.747	0.89
Male: BMI interaction	−0.129	0.070	0.07	**−0.258**	**0.093**	**0.01**	−0.041	0.079	0.61

Note: SE = standard error. Estimates with p ≤0.05 are shown in **bold.**

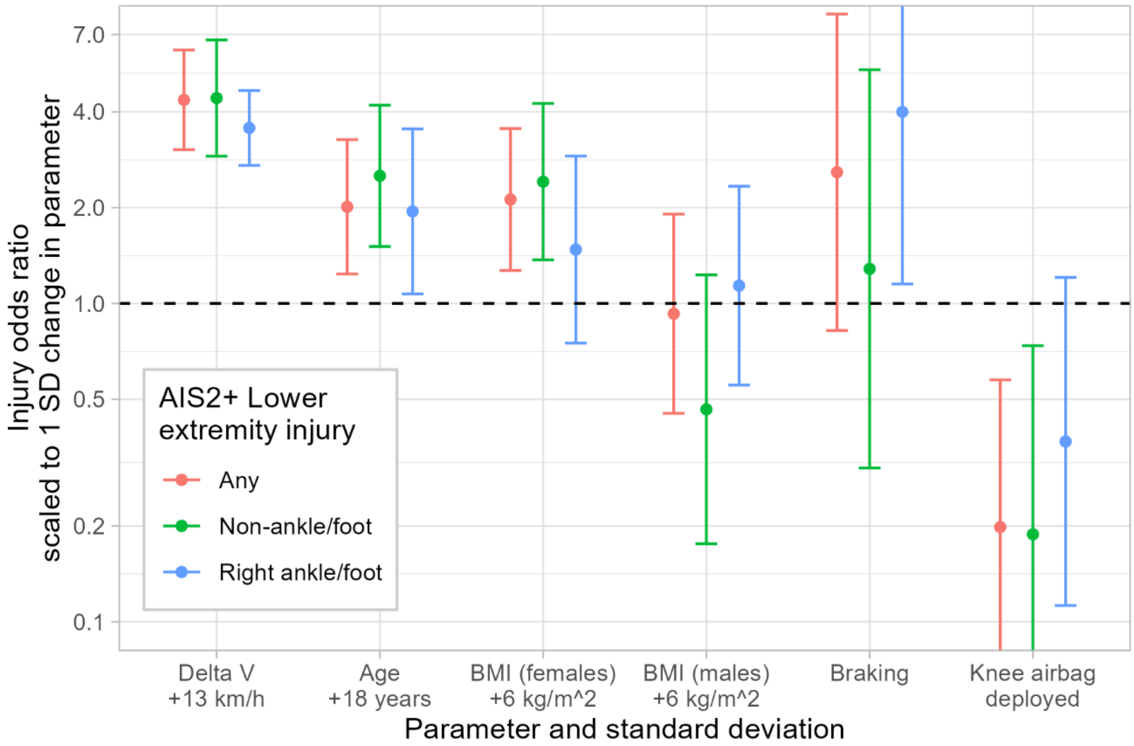

Fig. 3. Estimated injury odds ratios for different crash and occupant factors in CISS EDR dataset. SD = standard deviation.

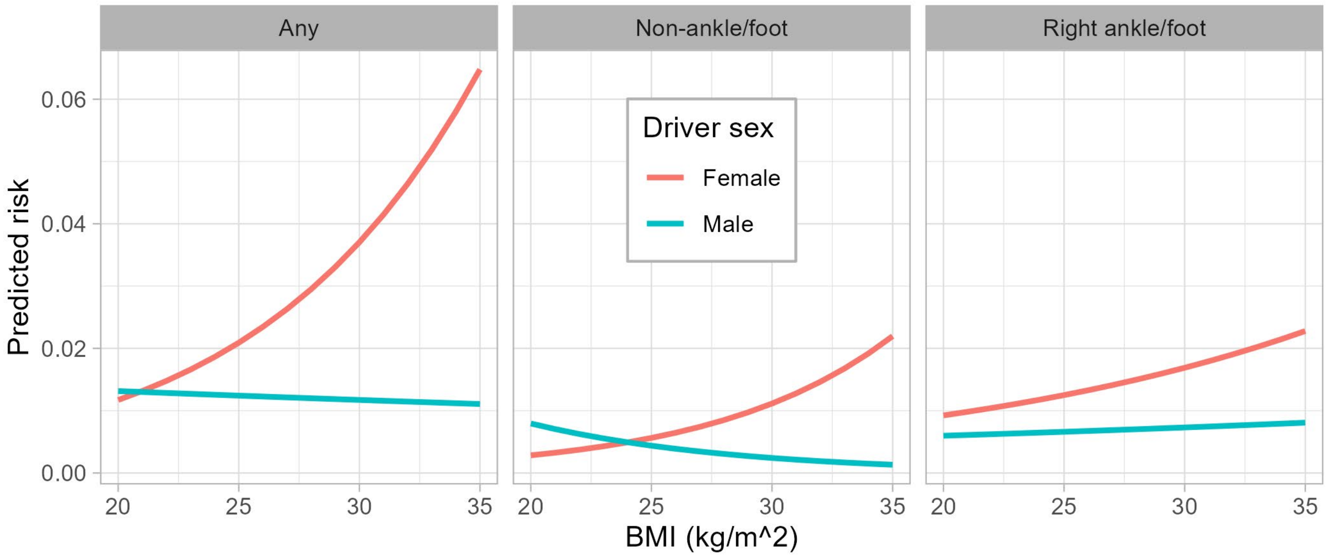

Fig. 4. Predicted AIS≥2 lower extremity injury risks for a 50-year-old driver in a 40 km/h crash by sex and BMI.

Vehicle Crashworthiness Factors

There were 1,355 NASS-CDS cases from 2000 to 2015 with a female driver that met all inclusion criteria. One-hundred and three drivers sustained at least one AIS2+ lower extremity injury, 56 had a non-ankle/foot injury, and 57 sustained a right ankle/foot injury. Crashworthiness data came from 162 matching IIHS moderate overlap tests. Summary values are shown in Table IV.

Figure A2 in the Appendix shows the proportion of total variance among the lower extremity measures recorded in the vehicle tests that was accounted for by the first 10 PCs. PC1 and PC2 accounted for 24% and 13%, respectively, of the total variance, and there was less difference among the proportions explained by subsequent PCs. PC1 and PC2 were included in regression models, and the loadings for these PCs are shown in Fig. 5. The loadings are the values which are multiplied by each test metric (scaled to the number of standard deviations from the mean) during the linear combination that forms each PC. Metrics with high-loading magnitudes contribute more to a PC than those with low magnitudes, while the sign of the loading indicates whether higher or lower values of each metric increase the PC score. PC1 represented a linear combination of a wide range of dummy metrics. All the loadings were positive, indicating that the greatest variance among test vehicles was captured by characterising the overall dummy response from both legs. While the highest loadings had similar magnitudes, the greatest contributions to PC1 came from foot accelerations and right leg forces and moments. PC2 described the degree to which a vehicle combined high values of right leg metrics (specifically tibia X moments and axial force) with low left-leg metrics (knee displacement, femur force, and upper tibia Y moment).

TABLE IV
NASS-CDS CASE SUMMARY (UNWEIGHTED VALUES)

	AIS≥2 Lower extremity injury	
	None	Any
Cases	1,252	103
Median age	37	50
Median BMI (kg/m^2)	24.8	28.0
Median DV (<2008; km/h)	20	33
Median DV (≥2008; km/h)	23	34
Mean PC1	0.07	0.08
Mean PC2	0.07	-0.15

Results of logistic regression models for the NASS-CDS dataset are shown in Table V. These models estimated the effects of PC1 and PC2 on lower extremity injury risk while controlling for the WinSMASH delta-V, the WinSMASH version, driver age, and driver BMI. The estimated effect of PC1 on the risk of any lower extremity injury and on the risk of a right ankle/foot injury was significant at $\alpha = 0.05$. The estimated effect of PC1 on non-ankle/foot injuries ($p = 0.11$) and all the estimated effects for PC2 ($p \geq 0.48$) were not significant at this level. The estimates for delta-V, the difference in delta-V by WinSMASH version and driver BMI were statistically significant for all three outcomes.

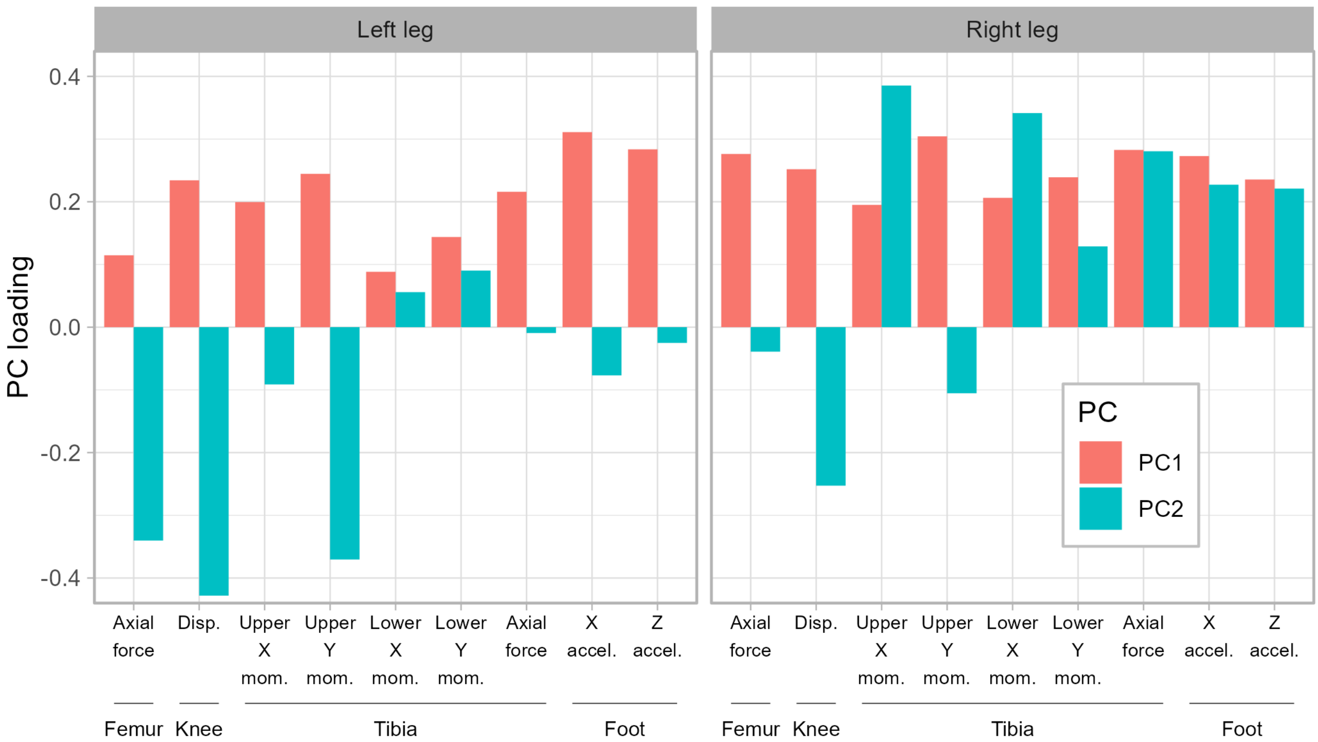

Fig. 5. Crash test metric loadings for the first and second principal components.
Note: Disp. = displacement; mom. = moment; accel. = acceleration; PC = principal component.

TABLE V
RESULTS OF LOGISTIC REGRESSION MODELS FOR DIFFERENT LOWER EXTREMITY INJURY OUTCOMES IN NASS-CDS

	Any			Non-ankle/foot			Right ankle/foot		
Term	Estimate	SE	*p* value	Estimate	SE	*p* value	Estimate	SE	*p* value
Intercept	−9.262	1.282	-	−8.969	1.026	-	−8.801	1.238	-
Delta-V (+1 km/h)	**0.110**	**0.016**	**<0.001**	**0.112**	**0.021**	**<0.001**	**0.110**	**0.014**	**<0.001**
Age (+1 year)	0.018	0.010	0.08	0.016	0.012	0.18	0.007	0.011	0.52
BMI (+1 kg/m^2)	**0.085**	**0.033**	**0.01**	**0.046**	**0.021**	**0.03**	**0.067**	**0.031**	**0.03**
PC1 (+1 unit)	**0.179**	**0.080**	**0.03**	0.123	0.077	0.11	**0.230**	**0.088**	**0.01**
PC2 (+1 unit)	−0.084	0.118	0.48	−0.068	0.133	0.61	−0.072	0.153	0.64
WinSMASH≥2008: Delta V interaction	**−0.037**	**0.012**	**0.003**	**−0.044**	**0.012**	**<0.001**	**−0.034**	**0.015**	**0.03**

Note: SE = standard error. Estimates with $p \leq 0.05$ are shown in **bold.**

IV. DISCUSSION

In front crashes with low levels of intrusion, female driver lower extremity injury risk factors include age, BMI, crash delta-V, precrash braking and vehicle crashworthiness, as assessed with the IIHS moderate overlap test. Evidence that the BMI effect is unique to females is somewhat consistent with findings by Dischinger *et al*. [11], who reported that male risk increased only for the extremely obese while female risk was higher even for overweight drivers. When considering lower extremity injury risk overall, the sex disparity reported most recently by Forman *et al*. [5] and Brumbelow and Jermakian [6] may primarily be driven by a difference at higher BMI levels (Fig. 4).

Sex-related differences in the type, percentage and distribution of body fat for the same BMI are well established. For example, Jackson *et al*. [23] found that for the same BMI, the percent body fat for females was 10% higher on average than for males. A literature review by Karastergiou *et al*. [24] explained how sex differences in fat distribution put women at lower risk of cardiometabolic disorders than men. Females have more subcutaneous adipose tissue in the abdominal and gluteofemoral areas, while men have more intra-abdominal visceral fat.

How these differences affect driver kinematics in ways that relate to lower extremity injury is being studied by others. Jones *et al*. [25] investigated seat-belt fit for obese female and male drivers. They found that at the same BMI and stature, body shape differences meant that females used more belt webbing than males and that the lap belt was higher and less forward relative to the ASIS. While the first two of these differences are likely to increase excursion and submarining risk, they did not speculate how the third difference may affect these risks in aggregate. Boyle *et al*. [26] studied the effect of restraint system differences on midsize and obese female and male human body models in simulated 56 km/h crashes. Positioning the obese female model appropriately relative to the steering wheel and foot pedals required greater knee angles than those for the midsize female and male models. They found that this posture increased knee-thigh-hip (KTH) loading from the toe pan and indicated that tibia loads could be measured in future studies. Additional research is needed to determine whether the female BMI effect is due to belt fit issues, leg- and foot-positioning differences, or a combination of these and other factors. Countermeasures could include improved belt and seat geometry, lap-belt pretensioning, or pelvic restraint cushions (PRCs). Many vehicles are equipped with lap-belt pretensioners, but it is unknown whether typical belt geometry limits effectiveness for females with elevated BMI. “Dynamic anchor repositioning”, which has been proposed as an anti-submarining countermeasure for reclined seating positions in autonomous vehicles [27], may be beneficial in many current scenarios. PRCs reduced pelvic excursion for female PMHS in sled tests [28], but all of the subjects had low BMI (≤23.4).

Precrash braking increased right ankle/foot injury risk for both sexes. The effect was equivalent to a delta-V increase of nearly 14 km/h, especially high given the weighted median delta-V of 23 km/h. Assal *et al*. [14] reported an increased risk associated with braking, and Dischinger *et al*. [11] found that female injuries were attributed to foot pedal contact more often than male injuries. Both of those studies relied on contact codes reported by investigators. While the CISS EDR dataset is still limited in size and analyses should be updated as more cases become available, precrash-braking rates were similar for females (71%) and males (69%).

The magnitude of the estimated benefit of knee airbag (KAB) deployment on lower extremity injury risk was greater than might be expected from prior research, but the associated confidence intervals were wide given the small case count. The largest study that has quantified the effect of KABs on lower extremity injury was conducted by McMurry *et al*. [29]. They reported KABs were associated with a reduction in AIS≥2 KTH injuries and AIS≥3 injuries to body regions other than the lower extremities, but also with a possible lower magnitude increase in AIS≥2 below-knee injuries. While there were too few CISS EDR cases in this study to group injuries in this way, the estimated KAB benefit was smaller for right foot injuries than for lower extremity injuries in general. It is also possible that the KAB benefit is greater in the low-intrusion cases that were the focus of this study. As with the braking effect, it will be important to review this finding with additional CISS years.

Several studies have compared the lower extremity response of the HIII-50M with PMHS. In whole-body sled tests with the right foot placed on the brake pedal, Rudd *et al*. [30] reported lower tibia loads for PMHS than HIII. The following year, Rudd *et al*. [31] reported on component-level test results that demonstrated the THOR lower extremity was more biofidelic than the HIII. More recently, Parent *et al*. [32] reached the same conclusion, although they pointed out that HIII comparison data are lacking for several of the matched PMHS test conditions used to evaluate THOR. The general finding that HIII response is stiffer than the PMHS may be somewhat mitigated by the inability to simulate the muscle tensing or other bracing that would be exhibited by many human drivers during precrash braking.

Despite the known shortcomings of the HIII-50M lower extremities, and despite the anthropometric differences between the dummy and human female drivers, this study shows that the overall characterisation of lower extremity crashworthiness using the dummy is a strong predictor of real-world injury for female drivers. It is especially notable that this relationship was found using the first principal component (PC1) identified by PCA. The PCA was completely independent of any field crash data; PC1 describes the unique linear combination of test data that describes the largest amount of variance among the test vehicles. While each dummy metric has limitations, the overall effect of higher PC1 values was a higher risk of female lower extremity injury. It is possible that testing this set of vehicles using THOR or another surrogate, or at a severity that more closely matched the field cases (Table II), would provide an even better assessment of risk. Evaluating these possibilities was outside the scope of this study.

Of the three different injury outcomes studied, PC1 had the strongest estimated effect on the risk of right ankle/foot injury. According to the IIHS test protocol [33], the right foot of the dummy is placed on the accelerator pedal, which is inconsistent with the EDR results showing a 71% precrash-braking rate for female drivers. While it is impossible to know whether dummy metrics would have an even stronger predictive value with a different right foot position, the contributions of the left foot acceleration components (X and Z) to PC1 were among the highest, and even exceeded those of the right foot accelerations (Fig. 5). Again, this does not imply that left foot accelerations are better correlated to injury risk than those from the right foot, but it does mean they help distinguish between vehicle designs in a way that predicts injury overall.

The results of this study suggest the IIHS moderate-overlap evaluation program could be modified to provide improved consumer information on lower extremity injuries for female drivers. One approach would be to adjust some or all of the current boundaries for the leg and foot to require lower magnitudes for the best ratings. While this may be the most straightforward option once new thresholds are established, selecting appropriate boundaries could be challenging. Some of the existing boundaries already have minimal supporting biofidelity data (e.g. foot acceleration [34]), while others are so much higher than values recorded in tests of modern vehicles that they would need to be reduced to a small fraction of their current levels to ever produce downgrades (e.g. femur force). More fundamentally, there are no evaluations of HIII-50M lower extremity biofidelity for female drivers. An alternative approach to upgrading the IIHS evaluation would be application of the PC1 calculation directly to the crash test data, combining all the lower extremity metrics into a single overall value. This would have the benefit of a known relationship to female injury outcomes without requiring additional HIII biofidelity testing. The drawback of this rating method would be its esotericism and lack of connection to specific injury mechanisms. The latter is also a limitation of the current study; even in EDR cases where precrash braking can be determined, there are many unknown variables that have the potential to affect loading and injury mechanisms. In addition, there were insufficient data to study more specific injury outcomes that might indirectly suggest prevalent loading types. This may be possible in the future, especially given NHTSA's plan to expand the number of CISS data-collection sites from 32 to 56 [35].

V. CONCLUSIONS

Efforts to reduce female lower extremity injuries in front crashes should consider the higher risk associated with BMI, which is unique to females, and precrash braking, which is not. Novel countermeasures may be required to address these issues but, in combination with knee airbags, could provide a meaningful crashworthiness improvement. Despite its limitations in representing the female driver population, measurements taken with the Hybrid III 50M dummy in the IIHS moderate overlap test predict female lower extremity injury outcomes in low-intrusion crashes. Adjusting the IIHS rating program may encourage designs that reduce injury risk for female drivers.

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VII. Appendix

TABLE A.I
CORRELATION BETWEEN DERIVED AND LINEAR COMBINATION
OF TWO DIRECT HIII-50M LOWER EXTREMITY METRICS

Region	Derived metric	Direct metrics	R^2
Left foot	Resultant acceleration	X acceleration + Z acceleration	0.95
Right foot	Resultant acceleration	X acceleration + Z acceleration	0.93
Left tibia	Lower index	Lower X moment + Lower Y moment	0.91
	Lower resultant moment	Lower X moment + Lower Y moment	0.92
	Upper index	Upper X moment + Upper Y moment	0.95
	Upper resultant moment	Upper X moment + Upper Y moment	0.96
Right tibia	Lower index	Lower X moment + Lower Y moment	0.91
	Lower resultant moment	Lower X moment + Lower Y moment	0.95
	Upper index	Upper X moment + Upper Y moment	0.90
	Upper resultant moment	Upper X moment + Upper Y moment	0.93

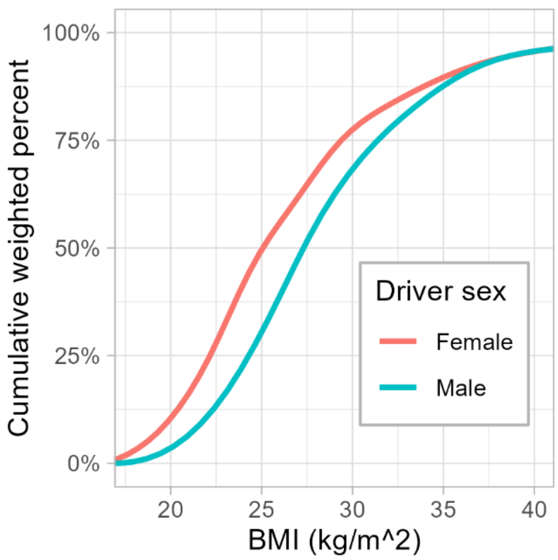

Fig. A1. Weighted distribution of BMI by driver sex in CISS EDR dataset.

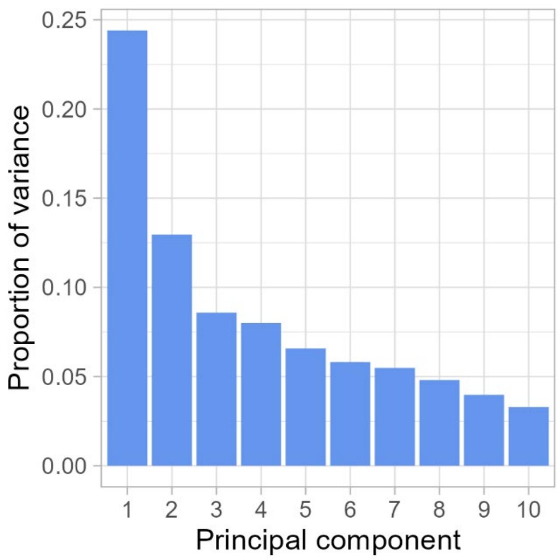

Fig. A2. Contribution of first 10 principal components to total crash test variance.