Lower Limb Injuries and Female Vulnerability

Abstract from a 2023 ESV Paper 23-0323 by Kennerly Digges and Dainius Dalmotas

A 2023 ESV paper by Dalmotas shows that a major factor in male/female injury risk difference results from differences in their crash exposure. The female representation in well-defined two-vehicle collisions as a function of vehicle type/size classification is displayed in Figure 1 (Dalmotas, 2023). Because females are overrepresented in the smaller vehicles and underrepresented in the larger vehicles, their crash exposure differs from males. Males are more likely than females to be exposed to crashes while in heavier vans and pickup trucks. Females are more likely to be in smaller cars, and subjected to higher crash forces when a collision occurs with a heavier vehicle.

Figure 2 shows the distribution of AIS 2+ HARM by body region. The distributions in Figure 2 are for 2017-2020 CISS cases of belt restrained outboard occupants of passenger cars or LTV's in Well-Defined Frontal planar crashes with injuries AIS 1 to 9. The HARM factors are based on US costs of injuries as determined by Miller and shown in Table A1 (Miller, 1990), The female injury data is in Table A2. The HARM calculation uses the procedure developed by Mallaris (1982) and applied in a 1998 SAE Paper (Digges, 1998). The cost of an AIS 9 injury was assumed to equal an AIS 2 Injury.

It may be noted from Figure 2 that Lower Extremities are the greatest sources of AIS 2+ HARM to females and the largest male to female difference is the lower extremities. A further analysis of lower limb injuries is in the discussion section of this paper. In addition, chest injuries merit further analysis because they are a large source of HARM that is not being adequately addressed in current NCAP, as discussed in the introduction to this paper.

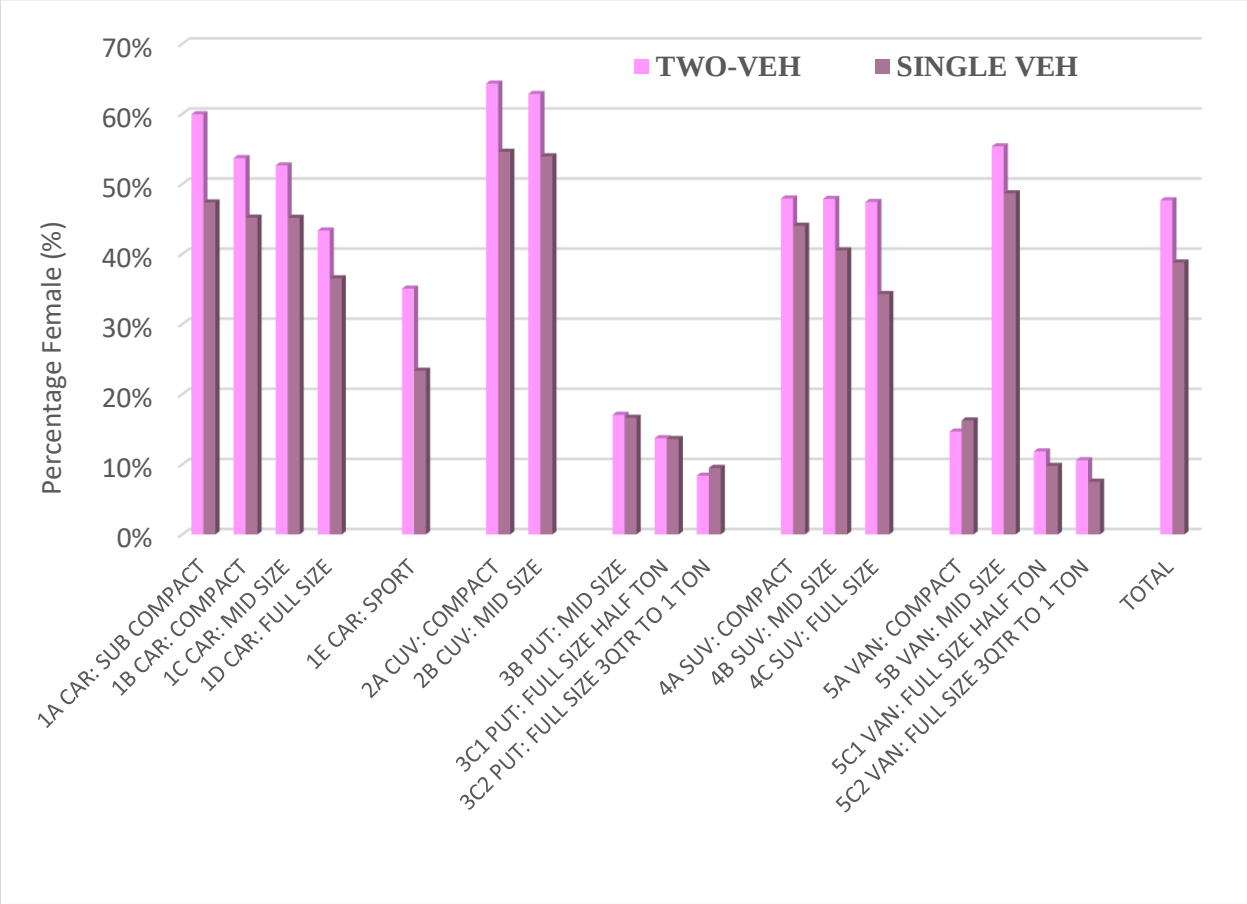

Figure 1. Female Representation in Well-Defined Collisions as a Function of Vehicle Type/Size Classification

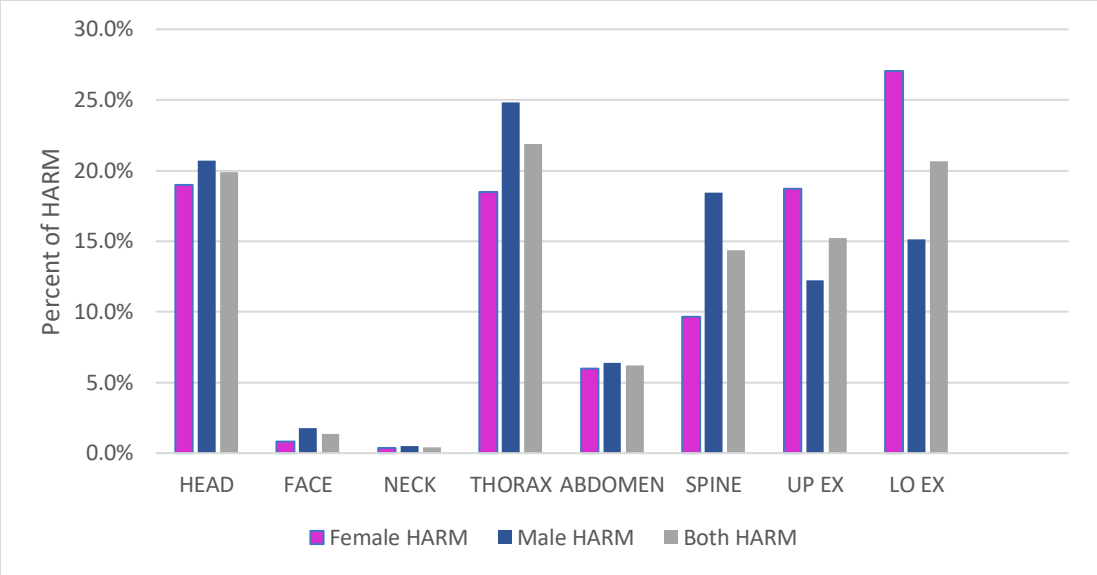

Figure 2. Occupant Injury Inventory, Distribution of AIS 2+ HARM by Body Region and Gender

A 2019 study by the University of Virginia showed that female gender was a high risk factor for Leg, Ankle and all lower extremities (Figure 3).

UVa 2019 Traffic Injury Prevention Paper on Injuries to Belted Occupants in Frontal Collisions

Table 1. Imputed multivariate logistic regression model results (all frontal crashes; odds ratios) for various injury outcomes.[a]

Model	Delta-V (km/h)	Female	Age (years)	Height (cm)	BMI (kg/m^2)	2009+ MY
AIS 2+	1.09**	2.42**	1.02**	1.00	1.05**	0.69*
AIS 3+	1.11**	1.73**	1.04**	1.00	1.03**	0.45**
Skull fracture	1.07**	0.47*	1.01	1.01	1.01	0.37*
Brain, moderate	1.07**	1.76*	1.00	1.01	1.01	1.47
Brain, severe	1.07**	0.44	1.03**	0.98	1.03*	0.45
Brain, any	1.07**	1.60*	1.00	1.01	1.01	1.41
C-spine	1.02**	1.99**	1.00	1.00	1.03*	0.70*
Abdomen	1.06**	2.06**	1.01**	0.99	1.06**	0.71*
Knee–thigh–hip	1.08**	1.89*	1.00	0.99	1.07**	0.44*
Knee	1.06**	1.79*	1.00	0.98	1.06**	0.36**
Leg	1.09**	2.29**	1.03**	1.00	1.07**	0.65
Ankle	1.08**	3.80**	1.01**	1.03*	1.08**	0.40**
LEx[b]	1.07**	3.05**	1.00	1.02**	1.06**	0.60*
Sternum	1.08**	1.57	1.07**	1.01	0.98	1.03
Rib fracture	1.08**	1.56*	1.04**	0.98	1.01	0.49*
Rib fractures, 3+	1.10**	2.14*	1.08**	1.00	1.04*	0.67

[a] $N = 31,254$ (weighted = 14,532,617); AIS 2+ unless otherwise noted. See Appendix C, Table C2 for confidence intervals.
[b] LEx = general lower extremity (encompassing KTH, leg, ankle, and all other lower extremity codes).
* $P < .05$.
** $P < .001$.

Figure 3. UVa 2019 Study of Injury Risks by Body Region

Figures 4a, 4b and 4c provide plots for lower limb injury data. The distribution of female AIS 2+ injuries by body region is shown in Tables A3. Table A4 shows AIS 2+ Thorax and Lower Extremity injuries by age and gender for two DeltaV groups.

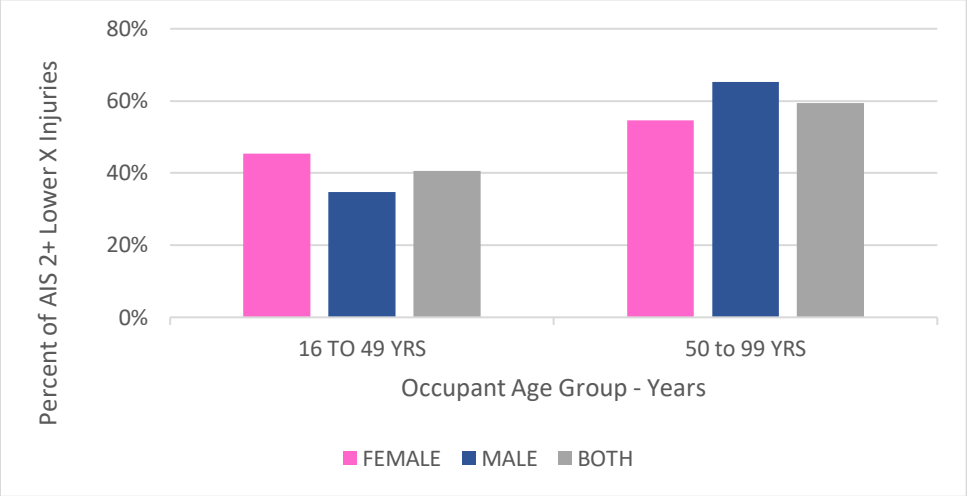

Figure 4a. AIS 2-6 Lower X Injuries in Well-defined Frontal Crashes by Gender and Age

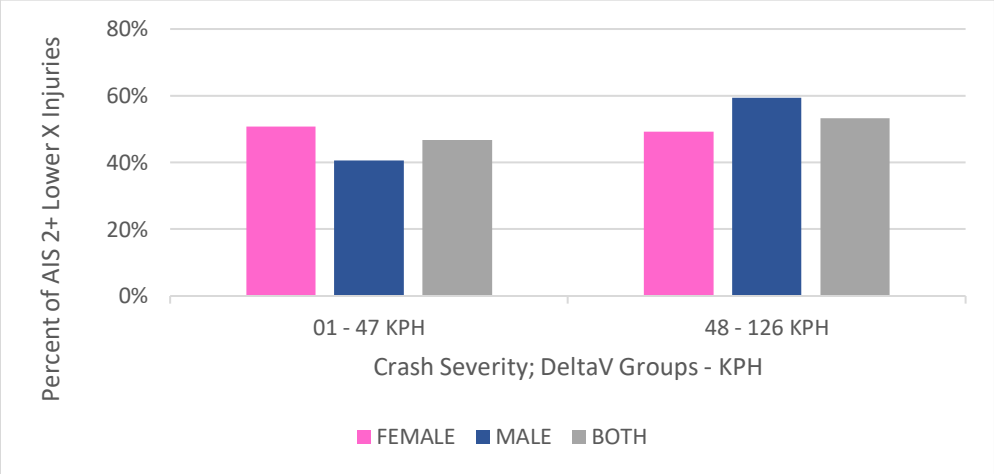

Figure 4b. AIS 2-6 Lower X Injuries in Well-defined Frontal Crashes by Gender and Crash Severity

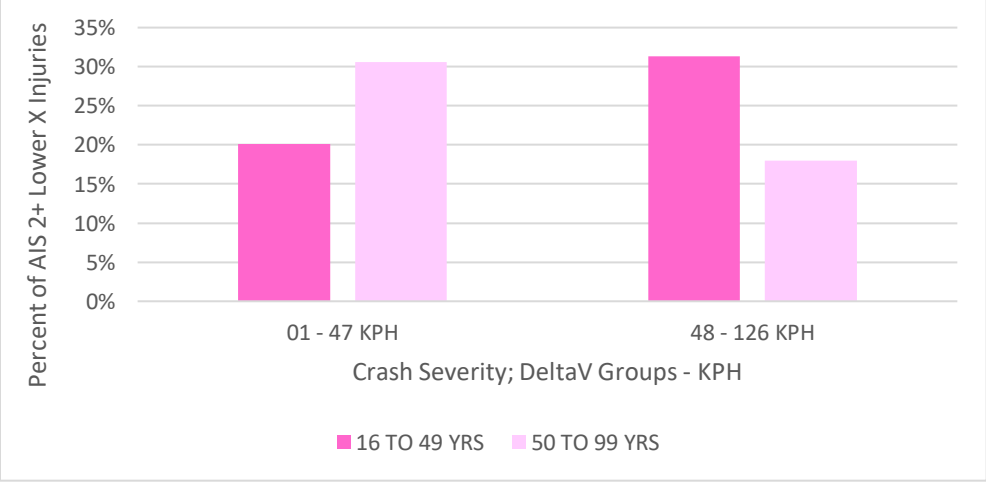

Figure 4c. AIS 2-6 FEMALE Lower X Injuries in Frontal Crashes by Age and Crash Severity

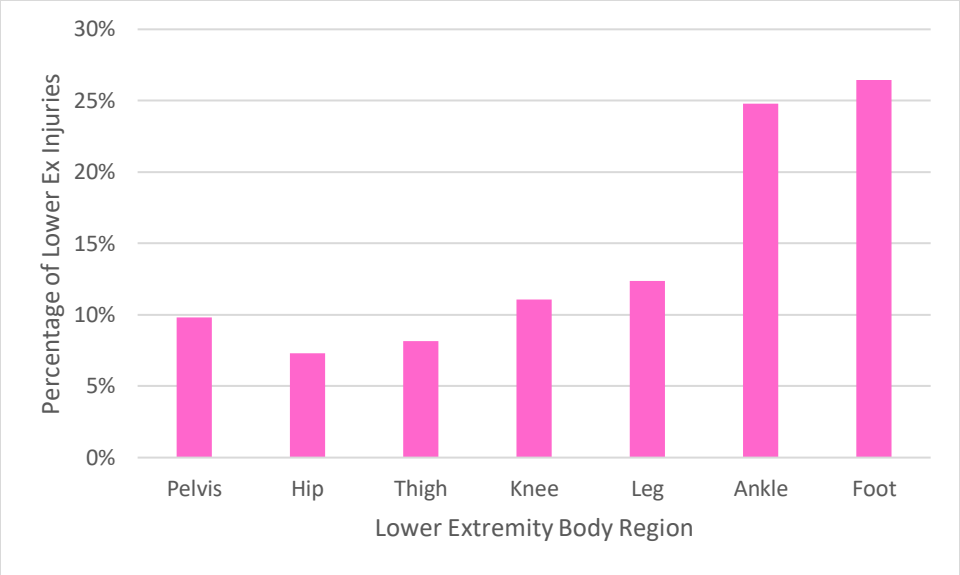

Figure 5. Distribution of Pelvic and Lower Extremity AIS 2-4 Injuries to Females in CISS 2017-2020 Well-Defined Frontal Crashes

The distribution of CISS Lower Extremity AIS 2+ injuries sustained by females in Well-Defined Frontal crashes is shown in Figure 5. A further disaggregation of foot and ankle injury data by left and right lower extremity is contained in Table 1. Table 1 shows the unweighted and weighted injury counts and percentage distributions for the foot and ankle injuries.

Table 1
Number and Distribution of Unweighted and Weighted AIS 2-3 Foot and Ankle Injuries to Front Seat Females in CISS 2017-2020 Well-defined Frontal Crashes

Body Region	Unweighted Number	Weighted Number	Unweighted Distribution	Weighted Distribution
Ankle Left	36	6,789	24%	33%
Ankle Right	38	3,291	25%	16%
Foot Left	19	2,990	13%	14%
Foot Right	59	7,749	39%	37%
Total	152	20,819	100%	100%

An examination of the Event Data Recorder data for the Single Vehicle Well-Defined Frontal cases found that braking was present when 79% of the 48 AIS 2+ injuries to the lower limbs. The body regions included in this Lower Limb category were foot, ankle, leg and knee. Table 2 shows the number of female driver foot and ankle AIS2+ injuries that occurred when the driver was braking. The table shows that the right foot injuries were predominately to the foot (66.6%) rather than the ankle. Braking was indicated by the EDR data for 79% of the female lower limb injuries and 88% of the foot/ankle injuries. The percentage of female all AIS 2+ foot/ankle injuries that occurred to the right foot/ankle was 64% unweighted and 53% weighted. During braking, the percentage was 70% (unweighted), as shown in Table 2.

Table 2.

CISS Documented Injuries to the Foot and Ankle During Braking

FEMALE BRAKING	Foot/Ankle	Foot/Ankle	Percent
Lower Limb Region	AIS 2-6	Percent	On Brake
Foot Left	5	17%	
Ankle Left	4	13%	
Foot Right	14	47%	
Ankle Right	7	23%	70%
All	30	100%	

.0 Sec .06 Sec .15 Sec

Figure 6a. Brake Pedal Motion in Test 9335; 5 mm Recorded Brake Pedal Intrusion

.0 Sec .06 Sec .15 Sec

Figure 6b. Brake Pedal Motion in Test 9336 – 110 mm Recorded Brake Pedal Intrusion

In their vehicle database, NHTSA has a series of NCAP like frontal crash tests with the 50% Male THOR Dummy in the Driver position. These tests also positioned a camera to record the motion of the brake pedal. Figures 6a and 6b show comparative motion from two different tests. The ankle inversion/eversion angles for the Figures 6a and 6b images are plotted in Figure 7.

Analysis of NHTSA crash test database provides insights into injury mechanisms and possible countermeasures for lower limb injuries. Figure 8 shows a comparison of Driver and Right Front Passenger Foot Accelerations that is typical of the NCAP like frontal tests conducted by NHTSA to evaluate the 50% male THOR Dummy in the driver position. The right front passenger was a 5% Female HIII dummy. Since the foot position 5% Female HIII is further away from the toepan than the 50% Male THOR, a more severe impact occurs and a higher acceleration results.

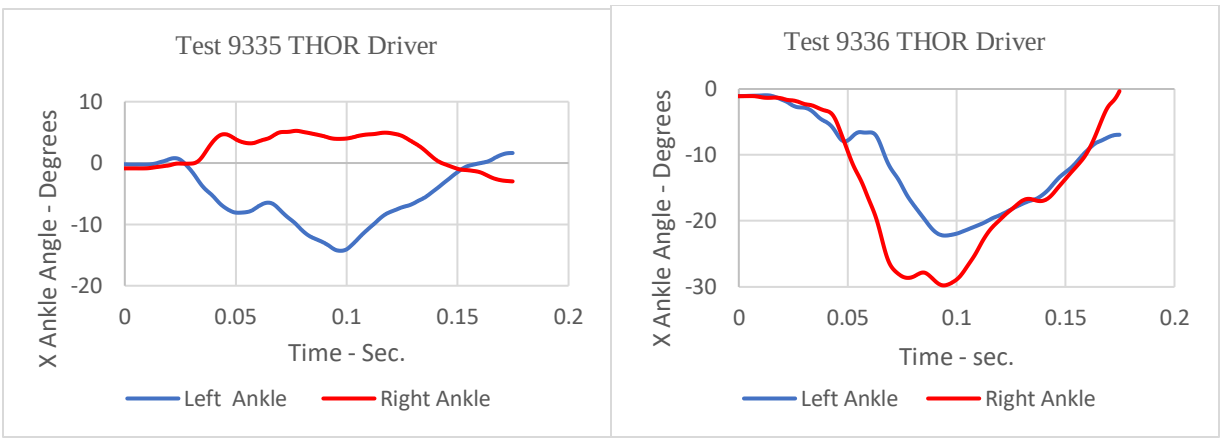

Figure 7. Ankle Inversion/Eversion Angle of 50% Male THOR Driver in NCAP Like Frontal Tests 9335 and 9336

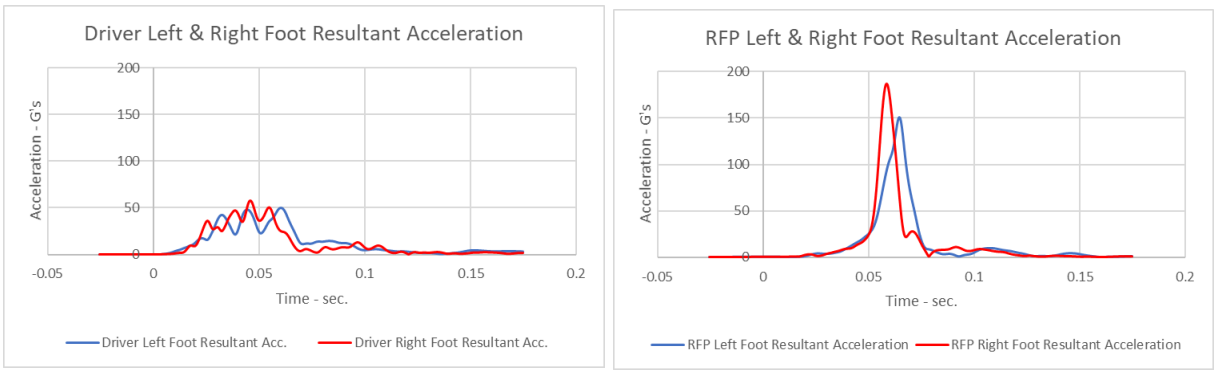

Figure 8. Foot Accelerations of 50% Male THOR Driver and 5% Female HIII in NCAP Like Frontal Test 9336

NHTSA's research testing of the Moving Deformable Barrier Evaluation of Small Overlap/Oblique Crashes clearly demonstrate a crash environment conducive to ankle eversion/inversion injuries (Saunders, 2012, 2015, 2021; Hu, 2019). The test condition was an impact by a moving deformable barrier traveling at 90 kph at an angle of 15 degrees and 35% offset. Ankle motion typical of this test mode is shown in Figure 9. Figure 9 shows the actual ankle position at three time periods. Figure 10 shows the plot of the THOR ankle eversion/inversion angles. The left ankle undergoes eversion and the right inversion. Note that the sign convention for eversion/inversion reverses from left to right foot. The longitudinal and lateral accelerations for the tested vehicle are shown in Figure 11.

.0 Sec .05 Sec .07 Sec

Figure 9. Foot and Ankle Motion Test 9500

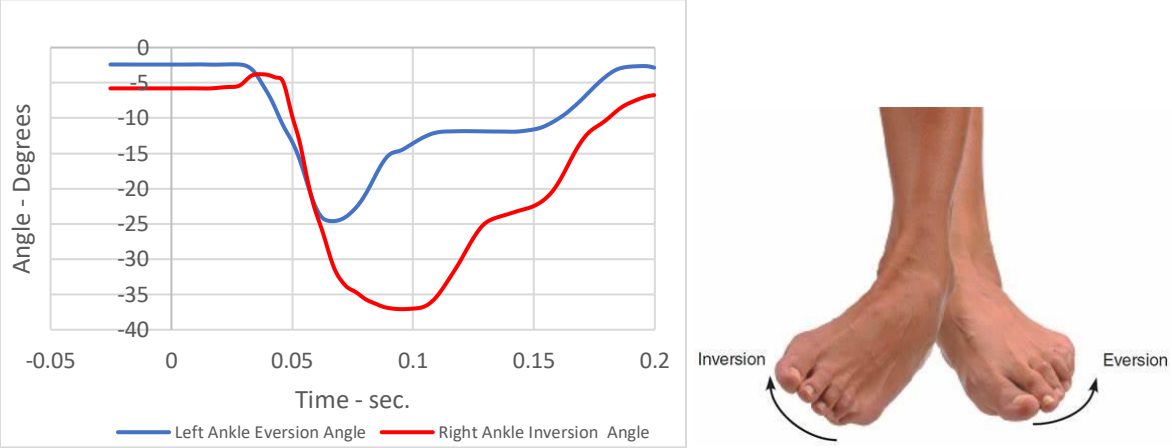

Figure 10. Foot and Ankle Eversion/Inversion Angle Test 9500

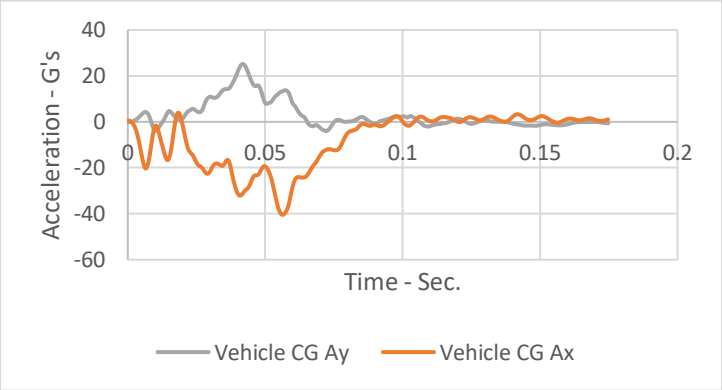

Figure 11. Vehicle Longitudinal and Lateral Accelerations in NHTSA Oblique/Offset Test 9500 (2015 Mazda CX5)

References

Dalmotas, D., Digges, K., and Prasad, P., "How Gender Preferences for Vehicle Size/Class Influence Fatality Outcomes," ESV Paper 23-0337, April 2023.

Digges K., Dalmotas D., "An NCAP Rating for Females," ESV Paper 23-0323, April 2023.

Foreman, J., Poplin, G., Shaw, G., McMurry, L., Schmidt, K., Ash, J and Sunnevang, C., "Automobile Injury Trends in The Contemporary Fleet: Belted Occupants in Frontal Collisions," Traffic Injury Prevention, 2019.

Ishikawa, H., Digges, K., Ennis, J., "Vehicle Collision Force in Offset Barrier and Car to Car Offset Tests", 1996 International Conference on the Biomechanics of Impact", p. 189-200, September 1996.

Digges, K., Bedewi, P., and Ishikawa, H., "Ankle Injury Mechanisms in Offset Crashes",1997 International Conference on the Biomechanics of Impact", p.87-98, September 1997.