Restrained Male and Female Occupants in Frontal Crashes: Are We Different?

Chantal S. Parenteau, David Zuby, Karin B. Brolin, Mats Y. Svensson,
Camilla Palmertz, Stewart C. Wang

Abstract The safety community is questioning the effect of gender on the performance and assessment of occupant protection systems. This study consists of: 1) an investigation of NASS-CDS data with belted occupants involved in frontal vehicle crashes and 2) a comparison of dummy responses in two matched frontal tests. Because of recent work on a 50th female dummy neck, focus was placed on neck responses. An assessment of cervical facet angles was also carried out from computed tomography (CT) scans of 423 adult patients.

The NASS-CDS data showed that the relative risk of being seriously injured was higher in females than in males for crash severities up to 65 km/h. Females had higher overall risks of serious injury in all body regions except for the head and the abdomen. In 25 to 65 km/h crashes, females were more at risk of spine injuries than males. In the matched tests, the normalized results showed overall higher biomechanical responses in the female than in the male dummy, in particular in the neck region. Airbag interaction with the head/neck complex was noted with the female dummy. The CT scan data indicated that the cervical facet angles increased with age, becoming more horizontal. The increase was greater in females than in males. The quantification of anatomical changes associated with gender is needed to improve physical and/or numerical tools used to assess occupant responses and to understand differences in injury patterns.

Keywords Cervical spine, crash tests, field data, gender, injury

I. INTRODUCTION

In 2007, NHTSA [1] found that the number of fatalities was lower in females than in males; females accounted for about one-third (32%) of all fatalities while males accounted for 68%. NHTSA also reported that the number of fatalities decreased by an average 0.7% per year in females and 0.8% in males. The corresponding increase in population was 1.1% and 1.3% per year. Despite lower fatality counts, the fatality risk was 22 ± 9% to 28 ± 3% greater for females than for males in the same impact [2-3]. Bose et al. [4] analyzed injury data and reported that, in a comparable crash, the odds for severe injury were 47% higher in lap-shoulder belted female drivers than in lap-shoulder belted male drivers. Why are females more at risk? Females have a higher seatbelt use rate than males in fatal crashes [5] and in injury crashes [6]. Females also have lower mean Body Mass Index (BMI) and drive newer cars [7]. The body geometry and composition may influence the injury outcome. Females are physically different than males. Kent et al. [8] analyzed anatomical measurements obtained from CT scans and reported that ribs were more horizontal in males than in females. Using mathematical models, the authors reported that rib angles that were more perpendicular to the spine increased the chest's effective stiffness. Parenteau et al. [9] found that fat distribution differs by gender; females had 1.22- to 1.50-times more subcutaneous fat than males, while males had 1.19- to 1.99-times more visceral fat than females. An increase in subcutaneous fat in the abdominal area should be helpful in distributing the loading forces by providing padding, absorbing energy and reducing the loading rate. Melochi [38] reported anatomical difference in the pelvis region by gender including cross section area at the superior pubic rami, and distance between the pelvis's iliac wing to the femur's greater trochanter. Carlsson et al. [10] showed that, since the 1960s, female occupants consistently have higher neck injury risks. Mordaka [11] identified the orientation of facet joint as an important contributor to cervical injury mechanisms. The anatomy of the cervical and thoracic spine has been characterized [12-15] from relatively small data samples. To the current authors' knowledge, the detailed quantification of the cervical spine is lacking as a function of gender and age using a large sample of CT scans.

Test data comparing 5th percentile female and 50th percentile male dummy responses have also shown higher injury values for female dummies. For example, in 1999, NHTSA [16] compared belted 5th percentile

Chantal Parenteau, PhD, and Stewart Wang, MD, PhD, International Center for Automotive Medicine, University of Michigan, USA, (parentea@med.umich.edu, ph: (734) 764-4380, fax: (734) 764-7173). David Zuby, Insurance Institute for Highway Safety, USA; Karin B. Brolin, PhD and Mats Y. Svensson, PhD, Chalmers University of Technology, Vehicle Safety Division, Safer Center, Sweden; Camilla Palmertz, Ampersand, Sweden.

female and 50th percentile male dummy responses in various frontal tests involving 1998-1999 model year vehicles. Appendix 1 lists the peak head, neck, chest and femur responses. It also shows the applicable injury assessment reference values (IARVs) from Mertz et al. [17]. Each peak response was normalized with the corresponding IARV. Table I shows the ratio between the female and male normalized responses in matched tests. Overall, the normalized responses were higher in the 5th percentile female dummy than in the 50th male dummy. In the 48 km/h oblique test, the ratio was 1.39 ± 0.41 for N_{ij}, 1.19 ± 0.20 and 1.11 ± 0.17 for femur loads. The ratio was, however, lower for HIC_{15} and chest g's. In the 60 km/h offset test, the ratio was consistently higher. It ranged from 1.03 ± 0.37 for chest g's to 3.98 ± 3.05 for HIC_{15}.

Digges and Dalmotas [18] compared frontal full-rigid barrier crash data in newer vehicles (model year 2005-2006) with the 5th percentile female dummy at 40 km/h and with the 50th percentile male dummy at 56 km/h. The authors assessed the injury risks associated with the chest deflection response and found that they were 1.77 times higher on average in female dummies in the driver seat and 1.30 times higher in females in the right-front passenger seat, despite the lower crash severity.

Table I.
Ratio of female to male percent of IARVs (peak responses normalized to the corresponding IARVs) in matched frontal tests with 1998-1999 model year vehicles (from NHTSA [16])

		Ratio of Female v Male Normalized Responses				
Vehicle	**Occ.**	**HIC_{15}**	**Nij**	**Chest g's**	**Chest Deflection**	**Max. Femur Load (N)**
	Frontal test	*48 km/h (30 mph) , +/-30 Degree Oblique, Belted Dummy*				
1998 Dodge Neon	Driver	0.59	1.68	0.92	1.05	0.98
1998 Ford Contour	Pass	1.01	1.10	0.84	1.33	1.23
	ave	0.80	1.39	0.88	1.19	1.11
	sd	0.30	0.41	0.06	0.20	0.17
	Frontal test	*60 Km/h (37.5 mph), ODB, 40% Overlap, Left, Belted Dummy*				
1998 Dodge Neon	Driver	1.43	1.26	0.95	1.16	0.85
1998 Ford Contour	Driver	0.99	5.51	0.88	1.14	1.03
1998 Chevy Venture	Driver	3.41	0.90	0.92	0.94	1.36
1998 Dodge Neon	Pass	8.22	0.62	1.76	0.68	1.91
1998 Ford Contour	Pass		1.20	0.93	1.57	0.50
1998 Chevy Venture	Pass	5.85	0.91	0.72	1.21	0.76
	ave	3.98	1.73	1.03	1.12	1.07
	sd	3.05	1.87	0.37	0.30	0.50

FMVSS 208 and NCAP were recently upgraded to include both a belted 50th percentile male and a 5th percentile female dummy in a 56 km/h full rigid barrier frontal test [19]. One of the objectives was to provide increased occupant protection in higher severity crashes. The protection may be accomplished through restraint and vehicle design changes. A 5th percentile female dummy is a scaled version of a 50th percentile male. Adding the 5th percentile female in the right-front passenger seat addresses small stature occupant protection in high speed crashes, but not necessarily female protection. A better understanding of injury tolerance, injury mechanisms and anatomical differences are needed to address female protection.

Chalmers University is currently conducting research for the development of a 50th percentile female neck dummy model. [32] The model was developed for rear impacts but a similar model could eventually be designed for frontal crashes. One of the objectives of this study was to assess male and female responses in frontal crashes with a focus on neck responses. Field accident data were first investigated to determine the risk of lap-shoulder belted male and female drivers involved in frontal impacts by crash severity and body region. Female and male dummy responses were then analyzed using crash test data. The 5th percentile female and the 50th percentile male Hybrid III dummy responses were evaluated in matched IIHS frontal crash tests with small overlap. Another objective of this study was to assess selected neck geometrical parameters by gender. For this purpose, cervical facet angles obtained from a large sample of CT scans were analyzed by gender. Age was also investigated since it has been shown to affect cervical geometry [42].

II. METHODS

NASS-CDS Data

NASS-CDS is a stratified sample of US crashes that are selected for in-depth investigation. Most of the vehicles are towed from the scene because of damage. The data include information based on crash investigation teams, vehicle registration, medical records, police reports and interviews. The data were extrapolated to US national estimates using weighting factors. In this study, NASS-CDS data for calendar years 1997-2011 were used to assess injuries in non-ejected, lap-shoulder belted occupants by gender.

This study included frontal crashes and light vehicles from model year (MY) 1997+. MY 1997 was included because more than 90% of new models in this year could be expected to be equipped with driver airbags. Frontal crashes were defined as vehicles involved in frontal impacts where the greatest damage was to the front (GAD1 = F). Collisions in which a rollover occurred were excluded from the sample (Rollover ≤0).

Belt use: Belt use was defined by the NASS-CDS investigator's variables MANUSE. Belted occupants were defined lap-shoulder belted (MANUSE=4).

Injury severity: Injury severity of the occupant was assessed using the Maximum Abbreviated Injury Scale (MAIS) and the "TREATMNT" variable. MAIS represents the assessment of life-threatening injuries at the time of first medical evaluation and not long-term consequences. It ranges from MAIS 0 to 9. MAIS 3-6 represents a serious-to-currently untreatable (usually unsurvivable) injury. Fatality was also used to determine if the occupant died of injuries in the accident. The variable "TREATMNT" was used to define fatality, which is TREATMNT = 1. Because fatalities can occur at any MAIS level, seriously injured occupants were defined as those with MAIS 3-6 or fatality. The shorthand notation for this is MAIS 3+F.

Occupants with injuries were classified as:

- MAIS 3+head: Number of occupants with serious (AIS 3-6) injuries to the head (region90 = 1).
- MAIS 3+thorax: Number of occupants with serious (AIS 3-6) injuries to the chest (region90 = 4).
- MAIS 3+ado: Number of occupants with serious (AIS 3-6) injuries to the abdomen (region90 = 5).
- MAIS 3+spine: Number of occupants with serious (AIS 3-6) injuries to the spine (region90 = 6).
    - AIS 3 fracture-dislocations were classified as serious (AIS 3-6) injuries to the spine (region90 = 6 and strutype = 5). The AIS 3+ fracture-dislocations were all AIS 3.
- MAIS 3+UX: Number of occupants with serious (AIS 3-6) injuries to the upper extremities (region90 = 7).
- MAIS 3+LX: Number of occupants with serious (AIS 3-6) injuries to the lower extremities (region90 = 8).

AIS 3+ by body region: The number of serious injuries was determined for the head, spine and thorax.

Crash tests

IIHS has conducted two small overlap frontal tests with the 5th percentile female (IIHS test CF11012) and the 50th percentile male (IIHS test CF11002) Hybrid III dummies with a 2008 Ford Fusion. These were the only tests available with the two dummies in the similar crash condition. The rigid barrier tests were at 64.4 ± 1 km/h with a 25 ± 1% overlap. The barrier used in both tests consisted of a rigid steel barrier with a 15 cm radius integral solid pole at the end. Figure 1 shows the test set-up. The crash test results were downloaded from the IIHS testing web site.

The dummies had instrumented lower legs and were positioned in the driver seat according to the "Guidelines for Using the UMTRI ATD Positioning Procedure for ATD and Seat Positioning (Version V)" [20]. A three-point lap-shoulder belt was used in the tests.

Fig. 1. Overview photo of the small overlap test set up with the 2008 Ford Fusion (CF11012)

Dummy kinematics were assessed by reviewing the high-speed video. Contact of the dummy's head or knees with the vehicle interior was recorded in the test reports. Triaxial accelerometers at the head cg (center of gravity) were used to determine peak resultant head acceleration and HIC15. The spinal transducers measured neck forces (axial tension-compression, lateral and fore-aft shear) and moments (flexion-extension moment, lateral bending and head rotation). Accelerometers were also used to measure the chest resultant acceleration and 3 ms peak.

Morphomics

Standard medical computed tomography (CT) scans were used. The CTs were obtained from the University of Michigan Hospital and approved by the University of Michigan Internal Review Board (IRB HUM00041441). The scans were processed semi-automatically using custom algorithms written in MATLAB (The MathWorks, Natick, MA) following the methodology described by Wang et al. [21]. The patients were selected based on CT scan availability. Each CT was reviewed by a radiologist to ensure that that patient did not sustain a neck injury. There were 423 CT scans of the neck available for review with adult patients (18+ year old); 250 males and 173 females.

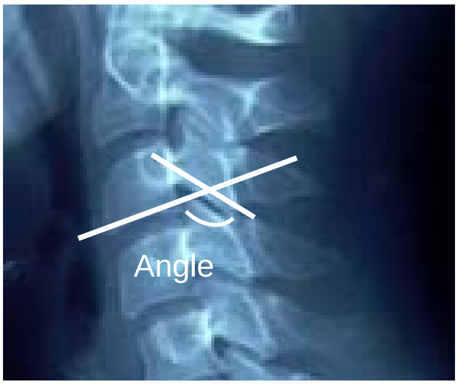

Fig 2. Facet angle measurement based on Milne et al. (1991).

The disc-facet angles were measured at each vertebra level from C2 to C6 in the cervical spine. To define the disc-facet angle, a plane was taken from the most anterior bony point in the spinal cavity to the anterior at the vertebral body at inferior intervertebral disc level. Since facet surfaces sit laterally to the spinal canal, they were projected medially onto a body-sagittal plane. The facet angle was then determined by the angle between disc plane and the projected inferior facet plane, as described by Wang et al. [21] and shown in Figure 2. The data were analyzed by gender groups (males, females) and by age groups (18-29, 30-44, 45-59 and 60+ years old).

III. RESULTS

NASS-CDS Data

Table II.

Annual incidence and risks of serious-to-fatal injury for belted, front-outboard occupants in frontal crashes by gender, injury location and crash severity.

	Delta V (km/h)				
	<25	25-45	45-65	65+	Total w/ Unk
Males	*Annual incidence*				
MAIS 0+F (n=)	134,048	40,440	3,814	573	300,918
	Frequency				
% MAIS 0+F	74.9%	22.6%	2.1%	0.32%	
% Airbag deploy	46.8%	81.6%	95.0%	97.0%	48.8%
	Risk per MAIS 0+F				
MAIS 3+F	0.45%	2.31%	15.97%	71.37%	1.30%
MAIS 3+ head	0.11%	0.27%	2.51%	6.09%	0.24%
MAIS 3+ spine	0.03%	0.14%	0.64%	8.97%	0.11%
MAIS 3+ thorax	0.10%	0.66%	5.98%	27.26%	0.45%
MAIS 3+ adomen	0.01%	0.15%	1.32%	15.75%	0.11%
MAIS 3+ UX	0.07%	0.47%	5.26%	8.49%	0.28%
MAIS 3+ LX	0.12%	0.96%	7.31%	41.37%	0.53%
Females	*Annual incidence*				
MAIS 0+F (n=)	148,280	41,558	2,758	559	317,316
	Frequency				
% MAIS 0+F	76.8%	21.5%	1.4%	0.29%	
% Airbag deploy	48.7%	82.2%	87.1%	99.7%	47.1%
	Risk per MAIS 0+F				
MAIS 3+F	0.48%	3.78%	25.51%	54.66%	1.55%
MAIS 3+ head	0.06%	0.17%	3.09%	8.39%	0.22%
MAIS 3+ spine	0.05%	0.25%	1.24%	1.94%	0.13%
MAIS 3+ thorax	0.09%	1.19%	11.74%	34.60%	0.62%
MAIS 3+ adomen	0.02%	0.18%	2.06%	8.77%	0.10%
MAIS 3+ UX	0.23%	1.15%	4.24%	4.95%	0.39%
MAIS 3+ LX	0.13%	1.41%	12.87%	25.01%	0.59%
Females/Males	*Relative Risk*				
MAIS 3+F	1.07	1.64	1.60	0.77	1.19
MAIS 3+ head	0.56	0.62	1.23	1.38	0.92
MAIS 3+ spine	1.35	1.77	1.94	0.22	1.15
MAIS 3+ thorax	0.92	1.80	1.96	1.27	1.39
MAIS 3+ abdomen	3.21	1.24	1.56	0.56	0.87
MAIS 3+ UX	3.50	2.45	0.81	0.58	1.41
MAIS 3+ LX	1.06	1.47	1.76	0.60	1.11

Table II shows the annual incidence of belted, non-ejected outboard front seat occupants in frontal crashes by crash severity based on 15 years of NASS-CDS data from 1997-2011. There was an average 300,918 male and 317,316 female occupants with known injury (MAIS 0+F) per year. The relative risk was assessed by taking the ratio between the risk of MAIS 3+F or MAIS 3+ by body region in females and in males. The risk for serious-to-fatal injury (MAIS 3+F) was 1.19 higher in females than in males (1.55% and 1.30%). Overall, males were more likely to be seriously injured in crashes above 65 km/h, while females had higher MAIS 3+F risk in crashes up to 65 km/h. The relative risk was highest in the 25-45 km/h and 45-65 km/h crashes, at 1.64 and 1.60 respectively. More than 81% of airbags deployed in the 25-45 km/h crashes and 95% in the 45-65 km/h crashes.

Table II also shows the risk of MAIS 3+ by body region. The results indicate that females have higher overall risk than males for spine, thorax and extremity injuries, ranging from 1.11 to 1.41. Females were less likely to sustain MAIS 3+ abdominal and head injuries. In 25-45 km/h crashes, females had higher risks for all body regions except for the head. Females had higher risk of spine, abdomen and lower extremity injuries than males in crashes up to 65+ km/h.

Table III.
Annual incidence of serious-to-critical injury for head, spine and thorax by injury source frequency, crash severity and gender.

	Delta V (km/h)				
	<25	**25-45**	**45-65**	**65+**	**Total w/ Unk**
Males	*Annual incidence and injury source distribution (%)*				
Head AIS 3+(n=)	172	189	182	50	1,499
Steering wheel	0%	10%	18%	71%	14%
A-pillar	3%	13%	26%	0%	13%
Roof/siderail	59%	1%	5%	17%	16%
Other/unk	38%	76%	51%	13%	56%
Spine AIS 3+(n=)	7	59	57	100	380
Seat	68%	2%	71%	0%	22%
Belt	0%	29%	2%	0%	12%
Steering wheel	7%	0%	5%	100%	26%
Non-contact	0%	41%	6%	0%	23%
Otherr/unk	25%	27%	16%	0%	17%
Thorax AIS 3+(n=)	148	333	287	277	1,917
Steering wheel	41%	34%	61%	76%	47%
Belt	47%	38%	25%	11%	22%
Side interior	11%	17%	2%	2%	19%
Other/unk	1%	12%	12%	10%	12%
Females	*Annual incidence and injury source distribution (%)*				
Head AIS 3+(n=)	101	126	192	112	1,174
Steering wheel	14%	13%	65%	58%	45%
Roof/side rail	12%	4%	0%	30%	6%
Non-contact	7%	19%	6%	10%	8%
Other/unk	67%	65%	29%	2%	41%
Spine AIS 3+(n=)	26	91	88	54	376
Seat	15%	35%	26%	0%	19%
Belt	38%	10%	11%	0%	11%
Steering wheel	15%	35%	26%	0%	19%
Non-contact	8%	41%	22%	25%	54%
Otherr/unk	39%	14%	40%	75%	16%
Thorax AIS 3+(n=)	164	594	450	279	2,434
Steering wheel	3%	12%	24%	27%	18%
Belt	46%	66%	40%	54%	59%
Side interior	17%	6%	7%	1%	7%
Other/unk	33%	16%	28%	17%	16%

Table III shows the annual incidence of head, spine and thoracic AIS 3+ injuries in belted, non-ejected outboard front seat occupants in frontal crashes by injury source distribution. Males had 1,499 head injuries per year and females had 1,174. Contacts with the steering wheel were more significant in females than in males, accounting for 45% of serious head injuries in females and 14% in males. Heads in male occupants were more frequently injured from contact with the roof/side rail than in females (16% v. 6%). There were 380 spine injuries per year in males and 376 in females. Steering wheel contacts were the most frequent injury source in males, and non-contact in females. Non-contact injuries are injuries can be result from inertial forces, for example. Belt and seat contacts were significant injury sources in both genders. Though not shown, airbag injuries were more frequent in females than in males, in particular in crashes <25 km/h where airbags accounted for 22.6% of the injury sources in females and 10.2% in males. More than 91% of AIS 3+ spine injuries involved a fracture or dislocation in females, and 82% in males. There were 1,917 thoracic injuries in males and 2,434 in females, most occurred from seatbelt loading.

Crash tests

Two matched IIHS frontal tests with small overlap were compared; one was with a 5th percentile female (IIHS CF11012) and the other with 50th percentile male (IIHS CF11002) dummy. Both were carried out with the 2008 Ford Fusion and lap-shoulder belted dummies with front and side airbag deployments. In addition to crushing the front ends of both vehicles, the small overlap configuration caused the vehicles to slide sideways (rightward) and rotate (counterclockwise) away from the barrier leaving them with some of their pre-impact kinetic energy. The longitudinal delta Vs of the centers of gravity were 39.6 and 45 km/h for the cars with the 50th percentile male and 5th percentile female, respectively. This lateral sliding and rotation also influenced the dummy's movements within each car.

Fig 3. 5th percentile female Hybrid III dummy kinematics in IIHS test CF11012 with a 2008 Ford Fusion.

Figure 3 shows the kinematics of the 5th percentile female dummy in the test. The dummy initially moved forward during the barrier impact. The steering column moved about 13 cm inboard with lateral intrusion. The dummy moved forward and outboard relative to the vehicle interior. The pre-tensioners and the frontal airbag deployed at 58 ms. The side-curtain and thorax airbags deployed at 64 ms. The head of the dummy contacted the unfurling frontal airbag on the outboard side and was pushed to the left as the airbag became taut with pressure. The head acceleration peaked at 86 ms. The head moved toward the A-pillar but did not make contact. It contacted the left forearm at 134 ms. The dummy then rebounded rearward. The head contacted the curtain airbag.

Figure 4 shows the kinematics of the 50th percentile male dummy in the IIHS small overall test with a rigid pole (CF11002). The driver moved forward at impact. The pre-tensioners, frontal, curtain and thorax airbags deployed at 58 ms. The steering column moved inboard with intrusion. The dummy moved forward and outboard. The head of the dummy did not contact the frontal airbag. It contacted the curtain airbag at about 80 ms and the left hand at about 120 ms. The dummy then rebounded rearward.

Appendix 2 shows the peak biomechanical responses. The data were normalized with the Injury Assessment Reference Values (IARV) also provided in Appendix 2. The trend for all of the biomechanical responses was higher with the 5th percentile female than with the 50th percentile male Hybrid III dummy; there were a few exceptions. Figure 5 shows the ratio between selected 5th percentile female and 50th percentile male normalized responses. The head response was 2.35 times higher in the 5th percentile female than in the 50th percentile male dummy, the neck response was up to 5 times higher and the chest was up to 1.63 times higher.

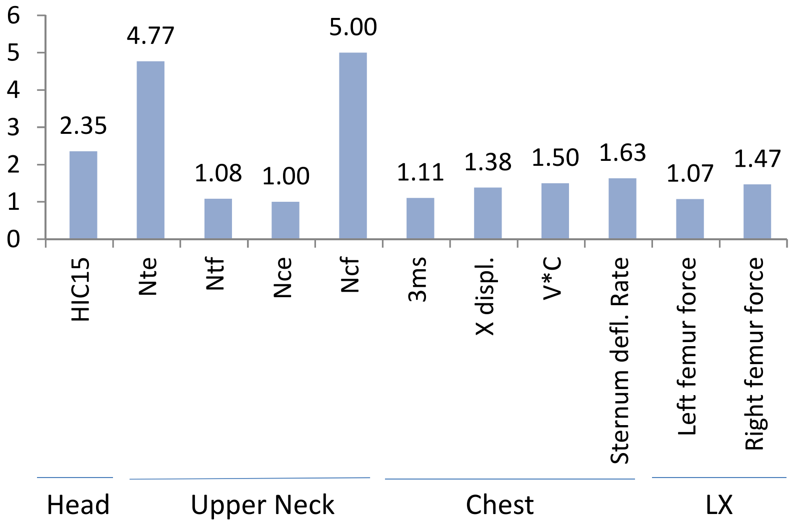

Fig 5. Ratio between selected 5th percentile female and 50th percentile male Hybrid III percent of IARVs in IIHS small overlap test with a 2008 Ford Fusion.

Neck measurements

Table IV.
Average cervical facet angle by vertebra location and gender.

		Facet Angle (deg)											
		Vertebra Level						Vertebra Level					
		C2	C3	C4	C5	C6	C7	C2	C3	C4	C5	C6	C7
Age groups		*Females*						*Males*					
Adults	ave	126.5	127.0	128.4	128.0	120.9	124.2	122.1	124.1	129.0	129.3	124.5	125.4
	sd	14.0	11.4	11.5	11.3	11.9	14.4	12.3	9.1	8.8	10.3	9.3	11.4
	n	173	167	166	166	162	151	249	249	250	248	242	232
18-29	ave	119.2	118.2	121.6	121.5	114.8	120.6	119.4	120.3	126.3	126.7	121.6	125.0
	sd	13.1	5.7	7.8	8.0	8.9	9.4	8.8	8.0	7.4	9.1	8.5	11.0
	n	34	34	34	34	33	32	75	75	75	75	73	71
30-44	ave	126.5	123.5	125.3	122.8	117.1	120.6	120.9	122.5	127.5	129.0	124.3	123.9
	sd	13.5	8.6	8.3	7.7	8.4	8.5	12.8	6.4	7.2	10.6	7.4	13.2
	n	32	32	32	32	32	29	63	63	63	62	61	59
45-59	ave	124.1	127.9	126.8	126.9	119.1	122.8	121.8	126.0	128.5	129.1	125.1	127.3
	sd	13.4	10.5	7.8	11.0	11.5	13.0	12.2	9.2	7.7	7.8	9.0	8.3
	n	43	43	42	41	42	37	59	59	59	59	59	55
60+	ave	132.1	133.4	135.3	135.3	128.0	129.4	127.8	129.2	135.5	133.9	128.3	125.9
	sd	13.0	12.0	13.6	10.8	12.1	18.6	14.5	10.4	10.5	12.5	11.6	12.6
	n	64	58	58	59	55	53	52	52	53	52	49	47

Table IV summarizes the average facet angle by vertebral level, gender and age groups. It also shows the average and standard deviation. There were 423 scans available. Overall, females had generally larger facet angles than males at C2-C3 level ($p < 0.001$ at C2 & $p < 0.01$ at C3) and lower angles at C6-C7 ($p < 0.01$ at C6). In the 18-29 group, however, males had up to 1.06 times larger facet angles than females. The facet angles increased with age in both males and females. In the 60+ age group, the facet angles ranged from 125.9 ± 12.6

to 135.5 ± 10.5 deg for males and from 128.0 ± 12.1 to 135.3 ± 13.6 deg for females. The facet angle increase with age is more significant in females (7%-11%) than in males (6-7%), in particular in the upper spine. Figure 6 illustrates the average facet angles by vertebral level, gender and age.

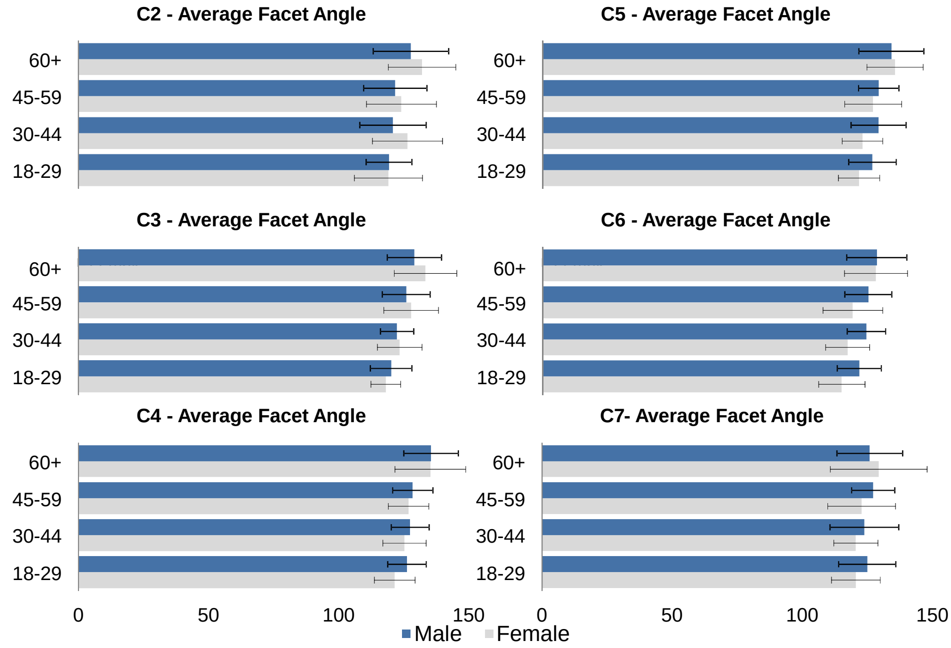

Fig. 6. Average cervical facet angle by vertebra location and gender.

IV. DISCUSSION

In this study, the risk of serious-to-fatal injury was higher in belted females than belted males when involved in a frontal crash. The risk of injury increased with crash severity. The relative risk between females and males varied with severity. Differences in injury patterns were also observed. The risk of MAIS 3+F was 1.47 times greater in females than in males (3.48% v. 5.13%) in the 25-65 km/h delta V crashes. This is concerning since crashes with a 25-65 km/h represent the regulated test conditions for which restraint systems are optimized. Females had higher overall risks of chest, spine and extremity injuries than males. The risk for serious spine injury was 1.77 to 1.94 higher in females than in males in 25-65 km/h crashes. Correspondingly, the risk for serious chest injury was 1.80 to 1.96. In this study, the effect of age was not analyzed. Digges and Dalmotas [18] analyzed chest injuries using 1997-2005 NASS-CDS data by gender and age groups and reported that the risk was 5.33 times higher for 15-49 year-old females and 1.18 times higher for 50-97 year-old females than males in the same age group in 40-56 km/h delta V crashes. In this study, NASS-CDS data were analyzed for calendar years 1997 to 2011 using 1997+ model year vehicles. The effect of model year was not analyzed but the sample includes more recent vehicles than the one used by Digges and Dalmotas. Injury patterns may vary in more recent vehicles with more crashworthy designs.

Female occupant protection is a safety priority. Currently, it is assessed in frontal crashes with the 5th percentile female and a 50th percentile Hybrid III dummy. In 2006, NHTSA [19] upgraded NCAP and FMVSS 208 tests by adding a belted 5th percentile female dummy in a 56 km/h full rigid barrier frontal test. The 5th percentile female and the 50th percentile male are used to attain a wider coverage of body sizes. The size of a 50th percentile male dummy is somewhat representative of a 95th percentile female [10, 22]. The 5th percentile female dummy measures 1.51 m and weighs 46.7 kg [23]. According to CDC [24], the average weight of a 5th percentile female is 50.2 kg and the average height is 1.51 m. The height of the 5th percentile dummy is thus consistent with newer literature data. However, she is 3.5 kg lighter. The average height and weight of a 50th percentile female is 1.62 m and 71.3 kg [25]. Thus, if good protection is achieved with both a 5th percentile female and a 50th percentile male dummy, most sizes of occupants should be well protected.

The accident data and the IIHS test analysis indicated the females have different interactions with the vehicle interior and airbags than males. However, it is not clear that the difference between the 5th percentile female and 50th percentile male dummy responses in crash tests reflects the difference in injury risk for women compared to men. The test data were based only on one test series. Furthermore, the test with 5th female had more 30% energy than the test with the 50th male dummy. The largest differences in injury risk for women compared to men in the accident data were for injuries to the upper extremities and the thorax, whereas the largest difference in indicated risk from the crash tests was for the neck and head. The upper extremities of the crash test dummies were not instrumented so the crash tests cannot show this risk. After thorax, the neck had the third largest difference between men and women in the accident data and this risk is reflected by the dummy injury measures.

In the IIHS crash tests, the male dummy did not contact the driver airbag because the intruding steering column moved rightward before any potential airbag contact, exposing the dummy's head to a risk of contacting the intruding roof rail or windshield header (Figure 8). This risk was not reflected in the recorded HIC because the dummy's head did not impact either structure. Nevertheless, the dummy's motion did reflect the accident data observation that men's heads are at most risk from these structures. The 5th percentile female dummy's high neck forces resulted from interaction with the deploying airbag (Figure 7), whereas the accident data suggest that women's necks are more likely to be injured in non-contact events. This difference between the crash test results and accident data probably reflects two facts. Firstly in accident investigations, it can be difficult to identify the airbag as the source of a driver's injuries. Secondly, the 5th percentile female dummy by definition is smaller than the average woman and therefore sits closer to the steering wheel [25].

Fig 7. 5th percentile female Hybrid III dummy neck and airbag interaction in IIHS test (CF11012).

Fig 8. 50th percentile male Hybrid III dummy neck and airbag interaction in IIHS test (CF11002).

The high neck responses for the 5th percentile female dummy in the IIHS tests may have been exaggerated compared to what a human would have experienced. Researchers have questioned the dummy head and neck interactions with airbags in frontal crashes [26]. The issue is that the smaller neck diameters in dummies compared to humans [27] combined with the shape of the dummy's chin allows the airbag fabric to get caught between the neck and a hollow behind the dummy's chin; a location that does not have a human analog. Neck shields were developed and the vinyl covering of the dummy's head was modified to address these issues. Neck shields were used in the two IIHS tests with the 2008 Ford Fusion. Furthermore, a detailed analysis of the test films did not indicate any non-biofidelic interaction.

Another issue associated with the use of the 5th percentile female dummy to understand female injury risk is that the IARVs for this dummy are based on size scaling under the assumption that the tissues and shapes of larger and smaller individuals are essentially the same [17]. However, recent morphomics data analyses indicate that other differences between men and women may also play a role in determining injury risk and injury patterns in vehicle crashes [8-9, 28-29]. Anatomical differences likely influence the loading patterns in a vehicle crash. In this study, females had higher risks of spine injuries than males in crashes lower than 65 km/h. Spine fractures and/or dislocations accounted for a larger distribution of AIS 3+ spine injuries in females than in males. The morphomic data analysis indicated that females had generally larger average facet angles than males at C2 and C3 level. Angle differences between the facet surface and the vertebral end plates may partially explain the increased relative risk of female versus male for MAIS 3+ spine injuries in frontal crashes or whiplash injuries in rear crashes [30]. However, the results in this study also indicate that males had larger facet angles in the lower cervical spine. These results are consistent with a study by Boyle [13] who found a slightly larger facet joint angle for males than females at C6 and C7. The study, based on 51 subjects of unknown age, highlighted a need to characterize spine measurements by age. The facet angles measured in this study were derived from a relatively large sample of 423 patients. Facet angles increased with age, more significantly in females than in males. The results obtained in this study indicated that age and gender influence the average facet angles. Larger facet angles correspond to more horizontal facets, implying differences in loading distribution and possibly higher risk for subluxation injuries [31], in particular for older occupants. Carlson [32] reported that sitting postures differ between males and females. In this study, the neck morphomic data were extracted for supine patients. The effect of sitting posture on facet angles could not be assessed and thus merit additional analysis. Further investigation into other morphomic variables assessed by gender is needed, using similar techniques as those used in this study. These variables include the spinal canal dimensions, the relative coverage of the spinal cord in the spinal canal, the articular joint angles in the upper cervical spine, the vertebral dimension, the neck circumference in relation to head size and the neck muscle mass relative to the vertebral column depth. Some of these variables have been studied but with relatively small samples, such as vertebral height [33-34), spinal canal dimensions [35], and vertebral depth and width [28].

There is however an astonishing lack of studies on the gender differences for material properties of tissues and injury criteria. Kubo et al [36] reported that the stiffness and hysteresis of tendons were significantly lower for females than males, implying that viscoelastic material properties may be gender dependent. Adachi et al [37] showed a significant correlation between ligament injury risks in females and the menstrual cycle phase, indicating that hormones may play an important role in failure thresholds. A similar hypothesis was reported by Melocchi et al. [38] who found that females of child-bearing age had the highest risk for hip injuries in side impacts. For bone fractures, there is a correlation between bone mineral density and fracture risk, and females have lower bone mineral density at all ages [9, 39]. Wu et al [40] showed that the viscoelastic properties of cortical bone depend on gender, and as bone has rate-dependent failure properties, this suggests that gender-specific injury criteria may be needed. These few examples highlight the need for in-depth studies on the dependence of material properties and injury criteria on gender.

The present study uses field accident data to give an overview of differences in injury risk between female and male vehicle occupants. Females are clearly at higher risk than males in identical accident situations. Differences in crash dummy responses between female and male dummy sizes in frontal collision tests provide examples of how current protective systems cause different loading to females and males respectively, for instance in the spine. Morphomics results give an example of differences in spinal properties between the genders that may explain the higher vulnerability in females. Based on the results obtained in this study, it would be worthwhile to develop and implement a physical and/or numerical model of a 50th percentile female occupant, with initial focus on chest and spine. A 50th percentile female dummy model has already been developed to assess neck responses in low speed rear impacts [10, 41]. The dummy model, called “EvaRID,” was developed based on literature data and volunteer tests comparing male and female occupants. With the combination of morphomic data discussed previously, a similar approach could potentially be applied to improve EvaRID or other models for multiple impact configurations. The models could eventually be used in various crash conditions, such as the IIHS small overlap test, to assess why females have higher injury risks than males.

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VII. APPENDIX

Appendix 1: Peak occupant responses in NHTSA frontal tests with a 5th percentile female and a 50th percentile male dummy (NHTSA 1999).

Occ	**Vehicle**	**Occupant**	**HIC_{15}**	**Nij**	**Chest g's**	**Chest Deflection (mm)**	**Max. Femur Load (N)**
	IARV	50th %ile Male	700	1	60	42	9070
		5th % ile Female	779	1	73	34	6160
	Crash type	**48 km/h (30 mph) , +/-30 Degree Oblique, Belted Dummy**					
Driver	1999 Dodge Intrepid	50th %ile Male	171	0.31	34.46	24.19	6376
		5th % ile Female	113	0.52	38.45	20.62	4256
Pass.	1999 Dodge Intrepid	50th %ile Male	117	0.3	35.57	21.53	3268
		5th % ile Female	132	0.33	36.29	23.2	2729
	Crash type	**60 Km/h (37.5 mph), ODB, 40% Overlap, Left, Belted Dummy**					
Driver	1998 Dodge Neon	50th %ile Male	182	0.54	38	31	7266
		5th % ile Female	290	0.68	44	29	4170
Driver	1998 Ford Contour	50th %ile Male	133	0.43	27	27	3087
		5th % ile Female	147	2.37	29	25	2161
Driver	1998 Chevy Venture	50th %ile Male	210	1.48	42	21	6067
		5th % ile Female	798	1.33	47	16	5586
Pass.	1998 Dodge Neon	50th %ile Male	21	0.5	36	31	4074
		5th % ile Female	192	0.45	49	22	2876
Pass.	1998 Ford Contour	50th %ile Male	117	0.41	29	33	3223
		5th % ile Female	ND	0.49	34	18	1885
Pass.	1998 Chevy Venture	50th %ile Male	93	0.26	28	26	3754
		5th % ile Female	605	1.24	32	17	3647
		% IARV					
	Crash type	**48 km/h (30 mph) , +/-30 Degree Oblique, Belted Dummy**					
Driver	1999 Dodge Intrepid	50th %ile Male	24.4%	31.0%	57.4%	57.6%	70.3%
		5th % ile Female	14.5%	52.0%	52.7%	60.6%	69.1%
Pass.	1999 Dodge Intrepid	50th %ile Male	16.7%	30.0%	59.3%	51.3%	36.0%
		5th % ile Female	16.9%	33.0%	49.7%	68.2%	44.3%
	Crash type	**60 Km/h (37.5 mph), ODB, 40% Overlap, Left, Belted Dummy**					
Driver	1998 Dodge Neon	50th %ile Male	26.0%	54.0%	63.3%	73.8%	80.1%
		5th % ile Female	37.2%	68.0%	60.3%	85.3%	67.7%
Driver	1998 Ford Contour	50th %ile Male	19.0%	43.0%	45.0%	64.3%	34.0%
		5th % ile Female	18.9%	237.0%	39.7%	73.5%	35.1%
Driver	1998 Chevy Venture	50th %ile Male	30.0%	148.0%	70.0%	50.0%	66.9%
		5th % ile Female	102.4%	133.0%	64.4%	47.1%	90.7%
Pass.	1998 Dodge Neon	50th %ile Male	3.0%	50.0%	60.0%	73.8%	44.9%
		5th % ile Female	24.6%	45.0%	67.1%	64.7%	46.7%
Pass.	1998 Ford Contour	50th %ile Male	16.7%	41.0%	48.3%	78.6%	35.5%
		5th % ile Female	NA	49.0%	46.6%	52.9%	30.6%
Pass.	1998 Chevy Venture	50th %ile Male	13.3%	26.0%	46.7%	61.9%	41.4%
		5th % ile Female	77.7%	124.0%	43.8%	50.0%	59.2%

Appendix 2: Peak occupant responses in IIHS small overlap frontal tests with a 5th percentile female and a 50th percentile male dummy in a 2008 Ford Fusion (CF11012 and CF11002).

	Frontal Flat 150, 25% overlap, 64.4 km/h	**Peak**		**IARV**		**% IARV**		**Ratio**
Vehicle	2008 Ford Fusion	5th	50th	5th	50th	5th	50th	**F/M**
	Test date:	07/21/11	01/21/11					
	Test #	CF11012	CF11002					
	Actual Test Impact Speed (km/h):	64.4	64.3					
Head	Resultant acceleration (g)	48	27		80			
	Resultant acceleration (3ms clip, g)	43	26		80			
	HIC	175	104		1000			
	HIC15	131	50	779	700	16.8%	7.1%	2.35
Neck	A-P shear force (kN)	-0.5	-0.9	-2.1	-3.1	23.8%	29.0%	0.82
	Axial compression (kN)	0.1	0.1	2.5	4	4.0%	2.5%	1.60
	Axial tension (kN)	1.2	0.9	2.1	3.3	57.1%	27.3%	2.10
	Flexion moment (Nm)	16	47					
	Extension moment (Nm)	29	9					
	Nij - Tension-Extension	0.62	0.13	1	1	62.0%	13.0%	4.77
	Nij - Tension-Flexion	0.26	0.24	1	1	26.0%	24.0%	1.08
	Nij - Compression-Extension	0.04	0.04	1	1	4.0%	4.0%	1.00
	Nij - Compression-Flexion	0.05	0.01	1	1	5.0%	1.0%	5.00
Chest	Resultant acceleration (3ms clip, g)	39	29	73	60	53.4%	48.3%	1.11
	X displacement (mm)	-26	-23	-41	-50	63.4%	46.0%	1.38
	V*C (m/s)	0.3	0.2	1	1	30.0%	20.0%	1.50
	Sternum deflection rate (m/s)	-3.1	-1.9	-8.2	-8.2	37.8%	23.2%	1.63
Left Leg	Left femur maximum force (kN)	-4.1	-5.6	-6.2	-9.1	66.1%	61.5%	1.07
	Left femur impulse (Ns)	99.6	110.3					
	Left knee displacement (mm)	-8	-7	-12	-15	66.7%	46.7%	1.43
	Left upper tibia L-M moment (Nm)	-113	-208	-115	-225	98.3%	92.4%	1.06
	Left upper tibia A-P moment (Nm)	57	-111	115	-225	49.6%	49.3%	1.00
	Left upper tibia resultant moment (Nm)	114	228	115	225	99.1%	101.3%	0.98
	Left upper tibia index	1.05	1.11	1	1	105.0%	111.0%	0.95
	Left lower tibia L-M moment (Nm)	-131	-330	-115	-225	113.9%	146.7%	0.78
	Left lower tibia A-P moment (Nm)	-34	-181	-115	-225	29.6%	80.4%	0.37
	Left lower tibia resultant moment (Nm)	132	373	115	225	114.8%	165.8%	0.69
	Left lower tibia axial force (kN)	-2.6	-3.3	-5.1	-8	51.0%	41.3%	1.24
	Left lower tibia index	1.21	1.74	1	1	121.0%	174.0%	0.70
	Left foot A-P acceleration (g)	89	-71					
	Left foot I-S acceleration (g)	-78	93					
	Left foot resultant acceleration (g)	97	116	150	150	64.7%	77.3%	0.84
Right Leg	Right femur maximum force (kN)	-1	-1	-6.2	-9.1	16.1%	11.0%	1.47
	Right femur impulse (Ns)	11.8	19.5					
	Right knee displacement (mm)	0	0	-12	-15	0.0%	0.0%	
	Right upper tibia L-M moment (Nm)	-28	-83	-115	-225	24.3%	36.9%	0.66
	Right upper tibia A-P moment (Nm)	-45	-59	-115	-225	39.1%	26.2%	1.49
	Right upper tibia resultant moment (Nm)	46	84	115	225	40.0%	37.3%	1.07
	Right upper tibia index	0.43	0.44	1	1	43.0%	44.0%	0.98
	Right lower tibia L-M moment (Nm)	-27	-97	-115	-225	23.5%	43.1%	0.54
	Right lower tibia A-P moment (Nm)	-125	-77	-115	-225	108.7%	34.2%	3.18
	Right lower tibia resultant moment (Nm)	125	109	115	225	108.7%	48.4%	2.24
	Right lower tibia axial force (kN)	-1.9	-2.8	-5.1	-8	37.3%	35.0%	1.06
	Right lower tibia index	1.12	0.54	1	1	112.0%	54.0%	2.07
	Right foot A-P acceleration (g)	71	-31					
	Right foot I-S acceleration (g)	-66	-56					
	Right foot resultant acceleration (g)	72	57	150	150	48.0%	38.0%	1.26
Vehicle	Resultant acc. (g)	56	44					
	Longitudinal acceleration (g)	-25	-25					
	Lateral acceleration (g)	12	10					
	Vertical acceleration (g)	-55	-43					