Are Crash Test Dummies Representative of the Population?

A pre-study

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SAFER
VEHICLE AND TRAFFIC SAFETY CENTRE AT CHALMERS

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Summary

The overall aim of this study was to identify possible limitations in how well current crash test dummies represent the population through an inventory of available knowledge.

Vehicle safety has a strong focus on males, for several reasons. Males dominate in the number of fatalities due to higher exposure (i.e. distance travelled) as well as other risk factors (speed, seatbelt usage, alcohol, etc). However, another pattern appears when looking at vehicle safety from an injury risk perspective, given the same exposure. Published data revealed that the crash related injury risks are higher in females than males through the whole range of injury severity, from minor to fatal. There are several factors that may influence the injury outcome, for example geometry, stature, mass and mass distribution, age, anatomy, material properties of tissues, as well as hormones and pregnancy.

For both females and males, the injury risk is affected by the body stature and mass as well as age. Today, the adult population is represented by three different dummy sizes in regulatory and rating testing; the small sized female, the average sized male and the large sized male.

Most of the regulatory and rating testing is performed with average sized male dummies. Vehicle safety systems are thus being optimised to the dummies available, in particular the average male dummy. In order to ensure that safety systems give the best possible level of protection for both males and females, future safety evaluation must be performed with dummies that represent both sexes.

A few prototype dummies have been developed; a low speed rear impact average sized female, an obese male of average stature, and an elderly obese female of average stature. These dummy types are however not yet fully developed nor commercially available.

In future research it will be important to further explore and ensure potential injury reducing effects of restraint systems with regards to females and males, and to investigate the possibility of developing adaptive restraint systems that will adjust automatically to occupants of different sex, size and age. It is therefore important that data from injury statistics and/or testing is collected, analysed and reported for females and males separately in order to increase the understanding of the influence of sex in relation to other factors.

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A prerequisite for addressing age and size is that both sexes are represented as occupant models. Thus, occupant models representing both occupant sexes as well as different sizes and ages are needed. Furthermore, injury criteria and threshold values for different occupant sex, size and age need to be defined.

Keywords: Females, Males, Vehicle Safety, Biomechanics, Safety Systems, Injury Outcome, Injury Statistics, Anatomy

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Content

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Introduction

The overall aim of this study was to identify possible limitations in how well current crash test dummies represent the population through an inventory of available knowledge.

Vehicle safety has a strong focus on males, for several reasons. Males dominates in numbers of fatalities due to higher exposure (i.e. distance travelled) as well as other risk factors (speed, seatbelt usage, alcohol, etc). However, another pattern appears when looking at vehicle safety from an injury risk perspective, given the same exposure. Since the mid-sixties a number of studies have shown that females, in comparison to males, have a greater risk of crash related injury, ranging from minor to fatal (Narragon 1965; Kihlberg 1969; O'Neill et al. 1972; Thomas et al. 1982; Otremski et al. 1989; Maag et al. 1990; Morris & Thomas 1996; Dolinis 1997; Temming & Zobel 1998; Richter et al. 2000; Chapline et al. 2000; Evans 2000; Evans & Gerrish 2001; Bédard et al. 2002; Krafft et al. 2003; Jakobsson et al. 2004a; Storvik et al. 2009; Carstensen et al. 2011; Bose et al. 2011; Parenteau et al. 2013; Forman et al. 2019; Abrams & Bass 2020; Kullgren et al. 2020; Brumbelow & Jermakian 2021). Furthermore, elderly and obese occupants also pose a greater risk of injury (Rice & Zhu 2013; Kahane 2013). It is time to improve the vehicle safety for occupants deviating from the male norm in traffic safety contexts. This report is a first effort to summarise the current knowledge.

Future vehicles will likely include more advanced adaptive protective systems. In order to make full use of the potential of the adaptive technology it will be necessary to simulate and assess the new safety systems with occupant models that represent a variety of different occupant sizes and gender. It will then be beneficial to obtain a better understanding of female dynamic response and injury tolerance and how it differs in relation to the male population, if any. Additionally, it is of interest to further understand seated postures and behaviours during car riding, generally as well as gender specific.

Injury Severity

Injury severity has two meanings with regard to the consequences of an injury; a) *threat to life* and b) *risk of permanent impairment*. Since 1975, there is an international standard for grading injury severity according to the threat to life, the AIS system (Huelke 1975). The AIS system enables grading on an ordinal scale from 1 (minor injury) to 6 (life-threatening injury, currently untreatable).

Attempts have also been made to grade the risk of permanent impairment, based on the AIS system (Hirsch & Eppinger 1983, von Koch et al. 1994). So far, no standard has been established on how to estimate the risk of permanent impairment or costs for specific injuries, although some methods have been used (Gustafsson et al. 1985, Miller 1993, Malm et al. 2008, Gustafsson et al. 2015).

In addition, for many injuries, there is no relationship between the threat to life and the risk of permanent impairment. A major laceration of the spleen is life-threatening if not treated within a short time, but properly treated it will not cause any permanent impairment at all. On the other hand, a neck sprain is not life-threatening at all, but will cause significant permanent impairment in about ten percent of car occupants injured in rear-end impacts. There are many other examples of this discrepancy.

In order to evaluate the accuracy by which todays´ crash test dummies and simulation models estimate the injury risk in diverse accident scenarios for the whole population, it is necessary to consider the risk of death as well as the risk of permanent impairment. Many factors influence the risk of injury, let it be the fatality risk or the risk of permanent impairment. Age and gender are most obvious, but weight, stature, adiposity, and impact conditions also have significance.

In this report, the focus is to describe how well crash test dummies and simulation models mimic all kinds of people injured in traffic accidents, specifically on differences with regard to gender and age, and how the models should be improved. As the biomechanics of injury is not depending on the injury cause, such knowledge will promote the development of protection systems for all types of accident.

Accidents & Injuries: Females & Males

Male motor vehicle occupants are in general overrepresented in the number of crash related fatalities (***Figure 1***). In Sweden, 73% of car occupants who were fatally injured in vehicle crashes during 1996–2005 were males (***Figure 2a***) (Brude & Björketun 2007), and this ratio has remained at the same level, 74%, during 2006–2021 (personal communication with Khabat Amin, the Swedish Transport Agency). Similar proportions have been reported in Finland (Laapotti 2005), Australia (Ginpil & Atteway 1994), and USA (Bose et al. 2011; Ferguson & Braitman 2006, NHTSA 2007, Abrams & Bass 2020). The latter study stated that the "A*nnual vehicle occupant fatalities have decreased overall since 1975, yet fatalities among females have remained largely the same year-to-year*" (***Figure 1***, Abrams & Bass (2020). The excess road crash-related mortality and morbidity in males is especially relevant among young people (Twisk et al. 2013).

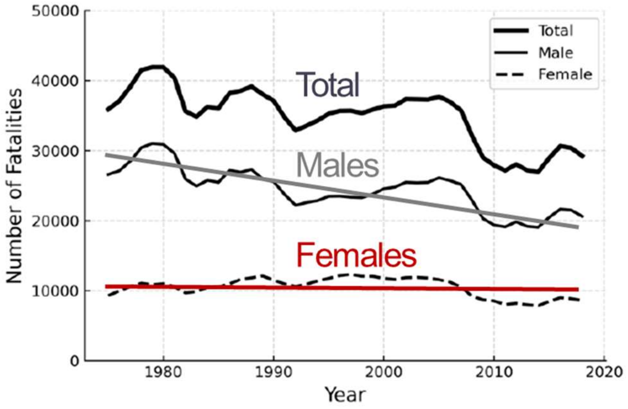


Figure 1. Annual vehicle occupant fatalities in USA. Graph from Abrams & Bass (2020). The straight lines indicate the overall trends for males (grey) and females (red).

Several factors may contribute to these differences in crash-related fatalities between males and females, such as exposure (the annual distance travelled by car), restraint usage, driver age, risk perception and driving behaviour, crash types and crash severity. For example, females are more seldom involved in single car crashes (23%) compared to males (43%) (***Figure 2b***, Brude & Björketun 2007), which may affect the injury distribution and injury outcome. Moreover, females generally travel shorter distances by car on a yearly basis (***Figure 2c***) (RVU 2021; Ginpil & Atteway 1994), have higher seatbelt usage rates (***Figure 2d***) (NTF 2021; Larsson et al. 2013; Glassbrenner 2004), and less often drive after drinking (***Figure 2e***) (SRA 2013; Ginpil & Atteway 1994). Furthermore, females tend to adopt a less risky driving behaviour (Ginpil & Atteway 1994). According to the study by Ginpil & Atteway (1994), deliberate risk taking (including alcohol, speeding and other risky actions) played a role in 30% of fatal car crashes caused by female drivers, while for males it was 53%. Car crashes with male occupants are more severe than with female occupants (Narragon 1965; Tavris et al. 2001; Martin & Lenguerrand 2008; McAndrews et al. 2013). After adjusting for demographics and driving exposure, Cullen et al. (2021) found that, in comparison with females, males had 1.25 times higher rates of being involved in a crash.

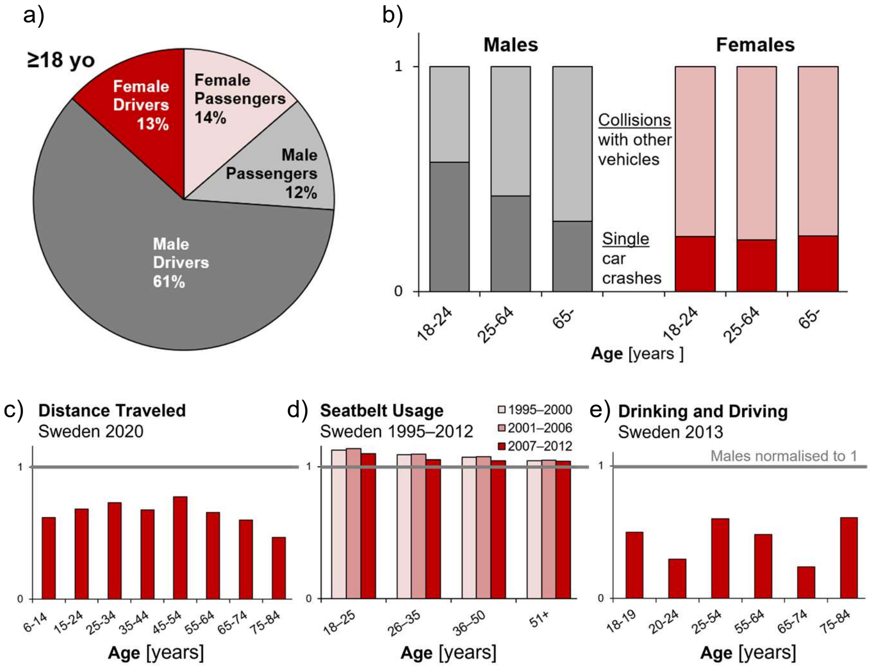


Figure 2. a) Fatal crashes among ≥18 years old female and male car drivers/ passengers and b) proportions of Single Car Crashes and Crashes Involving Other Vehicles among females and males during 1996–2005 (Brüde & Björketun 2007). Comparison between females and males of different age categories regarding c) the daily distance travelled by car during 2020 (RVU 2021), d) seatbelt usage during 1995–2012 (Larsson et al. 2013), and e) driving after drinking during 2013 (SRA 2013). All graphs are based on Swedish data.

However, when comparing the overall crash related injury outcome among drivers, relatively less of females are uninjured (47% compared to 64% among males, ***Figure 3***), i.e. females are more prone of receiving an injury than their male counterpart (Welsh & Lenard 2001). It can also be seen that the distribution of these injuries differs between the female and male drivers, with a greater proportion of slight injuries among females (49% compared to 31%). A more recent study reported that young females are at higher risk of crash related injury requiring hospitalisation (Cullen et al. 2021). Moreover, Berecki-Gisolf et al. (2012) showed that females over the age of 35 have a higher risk for work disability 6 months after sustaining musculoskeletal or orthopaedic injuries from a car crash.

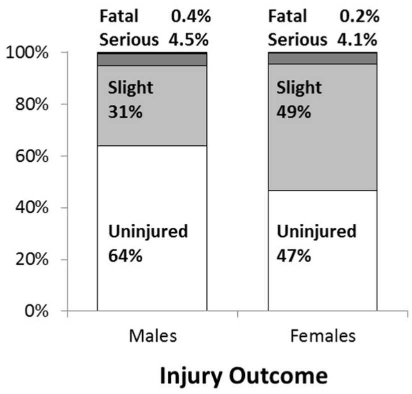


Figure 3. *Distribution of injury outcome by gender (based on Welsh & Lenard 2001). 'Slight' = medical treatment as an out-patient, 'serious' = admitted to hospital, 'fatal' = death within 30 days.*

During the mid-sixties, the first study (to the knowledge of the authors of this report) was published, analysing the difference in injury *risk* between females and males in car collisions, i.e. "*calculated as if males and females were exposed to an identical variety of accident situations*" (Narragon 1965). The risks for males and females were calculated as if both sexes 1) occupied seated positions in an identical manner, 2) had the same age distributions, 3) were involved in accidents of the same type, and 4) were involved in accidents of the same severity. The conclusion of the study was that females were injured 11% more often than males (Narragon 1965).

During the 1980s, Evans developed a statistical technique – *double-pair comparison* analysis – and applied it to the *Fatality Analysis Reporting System* (FARS) to quantify how fatality risk from the same crash situation increases with age and is different for males and females (Evans 1986, Kahane 2013). To identify specific non-fatal injuries, there are other databases that are more suitable, such as *the National Automotive Sampling System* (NASS) *Crashworthiness Data System* (CDS). With these databases and an additional statistical technique – *logistic regression* – the relationship between age, gender, and fatality or injury risk, or their variation by type of vehicle, impact, or injury can be investigated. Using these tools, a number of studies have found that the injury risks are higher for females than males when controlled for factors such as crash severity, restraint usage, and blood alcohol content (Evans 2000; Evans & Gerrish 2001; Bédard et al. 2002; Digges & Dalmotas 2007; Bose et al. 2011; Kahane 2013; Parenteau et al. 2013; Forman et al. 2019; Abrams & Bass 2020; Brumbelow & Jermakian 2021).

Fatal Injuries

The double-pair comparison method has been used in several studies to compare fatal injury risks for males and females (Evans 2000; Evans & Gerrish 2001; Kahane 2013; Abrams & Bass 2020). They all show a typical relationship between the female to male fatality risk, R, with regards to age (***Figure 4***). For example, in the study by Evans & Gerrish (2001) the fatality risk in the same car-to-car impact was found to be 22 ±9% greater for unbelted front seat female occupants in comparison to male ones; this difference cancels when the female's car becomes 4% heavier than the male's car. The annual increase in risk after the age of 20 was found to be greater for males (2.86 ±0.32%) than females (2.66 ±0.37%). Kahane (2013) reported that female vehicle occupants aged 20–35 years are 20–29% are more likely to die as a result of a fatal crash than males in the same age range. After the age of 35, females' added fatality risk diminishes sharply, and becomes similar/lower after the age of 60–65. The author concluded:

> *"Aging increases a person's fragility (likelihood of injury given a physical insult) and frailty (chance of dying from a specific injury). Young adult females are more fragile than males of the same age, but later in life women are less frail than their male contemporaries."*

Abrams & Bass (2020) found that female vehicle occupants aged 20–30 years are 20–25% more likely to die as a result of a fatal crash than males in the same age range. The risk to females and males becomes similar as age increases to 60. These trends hold when looking at subsets of crashes in either rural or urban areas, when looking at vehicles manufactured since 2010, and when isolating by single, two- or multiple-vehicle crashes. The authors conclude that this consistency of this age-dependent relative risk emphasises a need to further investigate sex differences in crash-related outcomes.

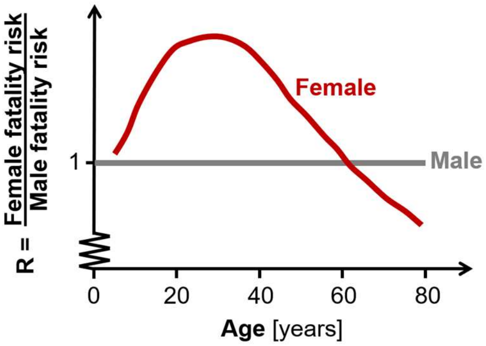


Figure 4. *Typical relationship between female to male fatality risk, R, with regards to age, in studies based on double-pair comparisons (Evans 2000; Evans & Gerrish 2001; Kahane 2013; Abrams & Bass 2020).*

Table 1 presents a summary of fatal injury risks for females relative to males in different studies, ranging from 1990 to 2020 (i.e. three decades). These studies show that females have a 20–54% greater fatal injury risk than males.

Table 1. *Summary of studies presenting fatal injury risks for females relative to males.*

Reference	**Parameters**	**Δv** [km/h]	**Age** [years]	**Injury Severity**	**Injury Risk Females rel Males**
Foret-Bruno (1990)	Accident Research Laboratory Thorax tolerances Belted casualties Cadaver tests	-	-	Fatal	+20%
Evans (2000)	FARS 1975–1996 (Different combinations), Double-pair comparison Single-vehicle crashes Front seat passengers	-	25	Fatal	+35%
Evans & Gerrish (2001)	FARS 1975–1998 Unbelted drivers Two-car crashes	-	25–45	Fatal	+22 ±9%
Bédard et al. (2002)	FARS 1975–1998 Drivers Single-vehicle crashes with fixed objects Un-adjusted OR Adjusted OR Multivariate logistic regression	-	-	Fatal	+54%
Kahane (2013)	FARS 1975-2010 FARS-MCOD NASS-CDS Double-pair comparison Vehicles containing a pair of occupants, at least one being killed		–30 “Later in life”	Fatal	+25–30% “Women less frail than males”
Abrams & Bass (2020)	FARS 1975-2018 Double-pair comparison Vehicles containing a pair of occupants, at least one being killed		20–30 >60	Fatal	+20–25% Similar risks

AIS 2+, 3+, 4+ Injuries

Several studies have reported that females, in comparison to males, have a greater risk of AIS 2+, 3+, and/or 4+ injuries (**Table 2**). Noteworthily, Digges & Dalmotas (2007) found that younger age (15–49) was associated with greater difference in MAIS 3+ injury risk between females and males, which is line with the results from double pair comparison studies of fatal injury risks (**Table 2**) (Evans 2000; Evans & Gerrish 2001; Kahane 2013; Abrams & Bass 2020).

Based on frontal crash data from USA, Parenteau et al. (2013) reported that the relative risk of serious-to-fatal injury (MAIS 3+F) was highest in crashes at the change of velocities (Δv) 25–45 km/h and 45–65 km/h, accounting for 64% and 60% higher risks for females. Bose et al. (2011) found that the odds for a belt-restrained female driver to sustain MAIS3+ injuries were 47% higher than those for a belt-restrained male driver involved in a comparable crash; for MAIS2+ injuries the odds were 71% higher for the females. Forman et al. (2019) found that belted female occupants have 73% greater odds of being seriously injured in frontal car crashes compared to belted males, after controlling for collision severity, occupant age, stature, body mass index and vehicle model year. Brumbelow & Jermakian (2021) reported that female drivers in front crashes had higher estimated overall risks of MAIS2+ and MAIS3+ injury before controlling for crash and vehicle differences. All ratios of injury odds for females relative to males were however reduced after accounting for such differences. Yet, females remained at higher risk of MAIS2+ injury. Kahane (2013) found that the estimated increase in injury risk for females relative to males of the same age does not share the aging effects’ pattern of growth as the injuries become more severe. The author concluded:

> *“The increased risk for older occupants and women may to a large extent be a consequence of intrinsic human anatomy and physiology. But a vehicle’s design and technology and the crash environment could also be influential. Specifically, safety technology that is even more effective for the elderly and women than it is for young males would shrink the relative risk increase for older occupants and women. However, another technology that is especially effective for young males would tend to augment the risk disparity – even if it is also effective to some extent for the older or female occupants, but just not as effective as for young males.”*

Table 2. *Summary of studies presenting AIS2+, AIS3+, and/or AIS4+ injury risks for females relative to males.*

Reference	Parameter	Δv [km/h]	Age [years]	Injury Severity	Injury Risk Females rel Males
Digges & Dalmotas (2007)	NASS-CDS 1995–2005 Belted, front seat occupants Cars/light trucks/vans Frontal crashes Rollovers excluded Available airbag	0–40	50–97	MAIS 3+	+4%
		0–40	15–49		+39%
		41–56	50–97		+63%
		41–56	15–49		+187%
Bose et al. (2011)	NASS-CDS 1998–2008 Belted, non-ejected drivers Cars/SUVs/light trucks/vans <15 yo, Multivariate logistic regression models	-	-	MAIS 3+	+47%
		-	-	MAIS 2+	+71%
Kahane (2013)	FARS 1975-2010 FARS-MCOD NASS-CDS Double-pair comparison Vehicles containing a pair of occupants, at least one being killed	-	-	AIS 4+	+29%
		-	-	AIS 3+	+37%
		-	-	AIS 2+	+29%
Parenteau et al. (2013)	NASS-CDS 1997–2011 Belted, non-ejected Front seat occupants Light vehicles Model year 1997+ Rollovers excluded	25–45		MAIS 3+F	+64%
		45–65	-	MAIS 3+F	+60%
Forman et al. (2019)	NASS-CDS 1998–2015 Belted car occupants frontal car collisions model year pre/post -09			MAIS 3+	+73%
				MAIS 2+	+142%
Brumbelow & Jermakian (2021)	NASS-CDS 1998–2015 Frontal/side car collision Rollovers excluded Compatible crashes Vehicle model year <10 yo in each calendar year Logistic regression Multiple imputation			MAIS 3+	+45% *(not significant OR 1.45 CI: 0.81–2.56)*
				MAIS 2+	+123%

Injured Body Parts

Female occupants have a greater risk of spine, thorax and extremity injuries (***Table 3***). For head and abdominal injuries most studies show that females are at greater risk, although some studies show that risks are at greater for males (***Table 3***). Bose et al. (2011) found that the odds of an effectively belted female driver to sustain a chest or spine AIS2+ injury was 38% and 67% greater, respectively, than those of a belted male driver in comparable crash conditions. Parenteau et al. (2013) found that females have greater overall risk than males for spine, thorax and extremity injuries, while they 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. Similar results were reported by Welsh & Lenard (2001), who found that female drivers had higher incidences of spine and leg injuries, while males sustained more head injuries in frontal crashes. In near-side side impacts a higher proportion of female than male drivers sustained head, face, or neck injuries (IIHS 2003). Kahane (2013) reported that females are susceptible to neck and abdominal injuries and, at lower severity levels, highly susceptible to arm and leg injuries. The estimated increase in fatal injury risk for females relative to males of the same age was much larger for neck (39.4 ± 9.4%) and abdominal (31.9 ± 8.3%) injuries than for the head (14.6 ± 3.1%) or chest (8.8 ± 4.6% greater risk). The same author stated that female drivers are especially vulnerable to leg fractures from toe-pan intrusion. Forman et al. (2019) found that females in comparison to males had an increased risk across most injury types, especially to the lower extremities.

Female occupants sustain injuries at lower velocity changes (Δv) in comparison to males (Mackay & Hassan 2000; Welsh & Lenard 2001). Based on frontal crash data from 1992–1994 in UK, Mackay & Hassan (2000) reported that restrained front seat female car occupants sustained head, thorax, and upper extremity AIS 2–6 injuries at less Δv than males. Welsh & Lenard (2001) found that females had a higher propensity for skeletal chest injuries at lower crash severities. In addition, female occupants show greater increase in thoracic injuries with increasing age in comparison to males (Ridella et al. 2012; Forman et al. 2019). Forman et al. (2019) found that the prevalence of skeletal thoracic injury increased significantly from the younger to the older age group, occurring almost 3 times as often as any other injury type in the older cohort.

Table 3. Summary of studies presenting injured body parts for females relative to males.

Body Part	Injury Type or Severity	Injury Risk Females rel Males		
Head	Fatal	+15%		1)
	AIS2+	+22%		1)
	AIS2+ skull fracture	-53%		2)
	AIS2+ any brain injury	+60%		2)
	MAIS3+	-38%	(Δv 25–45 km/h)	6)
	MAIS3+	+23%	(Δv 45–65 km/h)	6)
	MAIS3+	-8%	(overall)	6)
Neck	Fatal	+39%		1)
	AIS2+	+45%		1)
	AIS2+	+99%		2)
Spine	AIS2+	+67%		3)
	MAIS3+	+77%	(Δv 25–45 km/h)	6)
	MAIS3+	+94%	(Δv 45–65 km/h)	6)
	MAIS3+	+15%	(overall)	6)
Chest/ thorax	Fatal	+9%		1)
	AIS2+	+26%		1)
	AIS2+	+38%		3)
	AIS2+ rib fracture	+56%		2)
	AIS3+ rib fracture	+114%		2)
	MAIS3+	+80%	(Δv 25–45 km/h)	6)
	MAIS3+	+96%	(Δv 45–65 km/h)	6)
	MAIS3+	+39%	(overall)	6)
	MAIS3+ (15–49 yo)	+433%	(Δv 41–56 km/h)	7)
	MAIS3+ (50–97 yo)	+28%	(Δv 41–56 km/h)	7)
Abdomen	Fatal	+32%		1)
	AIS2+	+38%		1)
	AIS2+	+106%		2)
	AIS2+ hollow organs	No association observed for gender		4)
	MAIS3+	+24%	(Δv 25–45 km/h)	6)
	MAIS3+	+56%	(Δv 45–65 km/h)	6)
	MAIS3+	-13%	(overall)	6)
Upper extremities	AIS2+	+58%		1)
	MAIS2+	+95%		5)
	MAIS3+	+145%	(Δv 25–45 km/h)	6)
	MAIS3+	-29%	(Δv 45–65 km/h)	6)
	MAIS3+	+41%	(overall)	6)
Lower extremities	AIS2+	+80%		1)
	AIS2+ knee-thigh-hip	+89%		2)
	AIS2+ knee	+79%		2)
	AIS2+ leg	+129%		2)
	AIS2+ ankle	+280%		2)
	AIS2+	+205%		2)
	MAIS3+	+172%		5)
	MAIS3+	+47%	(Δv 25–45 km/h)	6)
	MAIS3+	+76%	(Δv 45–65 km/h)	6)
	MAIS3+	+11%	(overall)	6)

1) *Kahane 2013*
2) *Forman et al. 2019*
3) *Bose et al. 2011*
4) *Poplin et al. 2015*
5) *Brumbelow & Jermakian 2021*
6) *Parenteau et al. 2013*
7) *Digges & Dalmotas 2007*

Vehicles of more recent model years show great improvements in safety and injury outcome (Dischinger et al. 2016; Forman et al. 2019; Kullgren 2019; Kullgren 2020; Brumbelow & Jermakian 2021). Significant declines in ancle/foot injuries have been noted, especially for females, whose risks are now similar to those for males (***Figure 5***) (Dischinger et al. 2016). Yet, significant risk factors remain for each sex, primarily related to body size (BMI) and toepan intrusion. Age was a risk factor for foot injuries among females, for whom the foot pedals were more likely to be an injury source. Toepan intrusion remains a major factor for both men and women, but, with the exception of 30+ cm of intrusion, odds ratios were primarily much higher for men in each category of intrusion (Dischinger et al. 2016). Forman et al. 2019 found that vehicles of model year 2009+ generally carry less risk of AIS 2+ and AIS 3+ injury in frontal collisions with belted occupants compared to older model year vehicles (odds ratios 0.69 and 0.45, respectively). However, this risk reduction was not uniform across injury types. The greatest reductions were observed in skull fracture, knee–thigh–hip injury, and ankle injury. No statistically significant change in risk of AIS 3+ rib fracture or sternum injury was found. Brumbelow & Jermakian 2021 reported that a good rating in the Insurance Institute for Highway Safety (IIHS) moderate overlap frontal test was estimated to reduce the risk of every type of studied injury for all drivers, with the exception of MAIS 2+ upper extremity and MAIS 3+ thorax injuries. The estimated benefits of improved crashworthiness were similar or greater for females than for males for most injury outcomes.

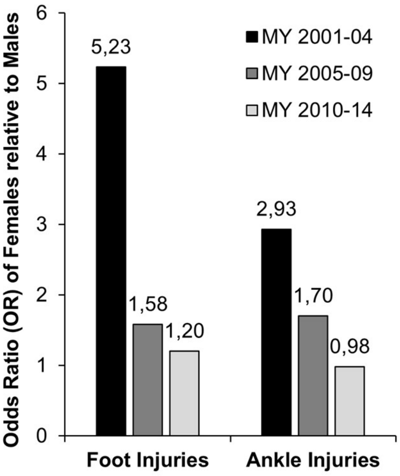


Figure 5. *Incidence of foot and ankle injuries in weighted NASS odds rations of females relative to males. Based on Dischinger et al. (2016).*

Permanent Medical Impairment (PMI)

When analysing the relative risk of sustaining an injury leading to *permanent medical impairment (PMI)*, it is revealed that 82% of severe impairments (PMI ≥10%) originate from *minor or moderate injuries (AIS 1–2)* (Gustafsson et al 2015). Furthermore, in cars of model years ranging from 1980 to 2018, neck injuries (whiplash injuries) stand out with regards to both risks and slow improvement rates (Kullgren 2019) (***Figure 6***). Relative injury risks were calculated using the pair comparison technique for two-car crashes. The method, initially developed by

Evans (as described above), has been further developed by Folksam for car-to-car collisions (Kullgren 2019; Hägg et al. 1992; Hägg et al. 2001).

For PMI ≥1% it can be noted that (***Figure 6a***):

- Neck injuries are associated with the highest risks, and only minor improvements can be seen with regards to car model year.
- Head, lower extremity and pelvis injuries show great improvements with regards to car model year.

For PMI ≥10% it can be noted that (***Figure 6b***):

- Neck injuries are associated with the highest risks from car model year 1995 and forward. Minor improvements can be seen with regards to car model year.
- Head (and lower extremity and pelvis) injuries show great improvement with regards to car model year.

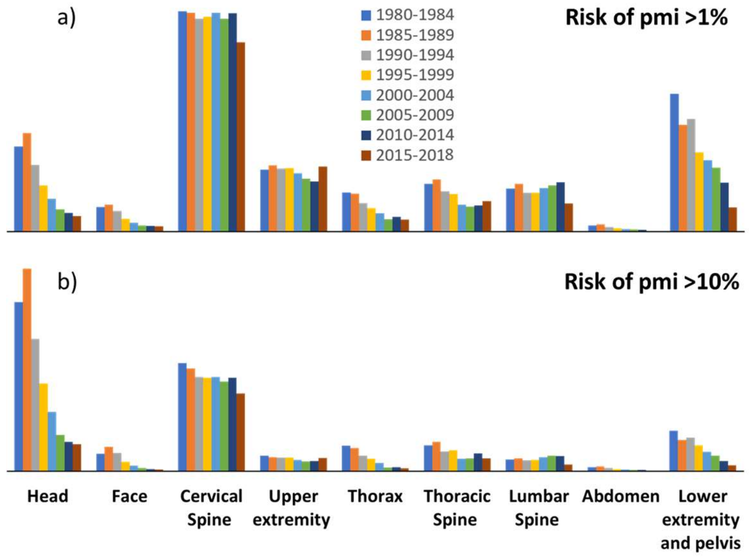


Figure 6. *The relative risk of sustaining an injury leading permanent medical impairment a) PMI ≥1% and b) PMI ≥10%, for cars of model years ranging from 1980 to 2018.* Based on Kullgren (2019).

The same method was used in Kullgren et al. (2020), separating data for females and males. Police-reported two-car crashes (irrespective of crash type) were used to calculate relative risk of any injury, fatal and serious injury and fatality. The data was then adjusted with regards to vehicle mass, and together with occupant injuries reported by Swedish emergency care centres, the risk for PMI ≥1% was assessed. The cars were categorised in ten-year periods according to year of introduction. When comparing car models introduced in 1980–1989 with models introduced in 2010–2019, it was found that the reductions in risk of an injury leading to PMI>1% differed depending on body region, gender and age.

In general females had higher risk for injuries leading to PMI, and especially regarding injuries to the cervical spine (***Figure 7***). Large improvements were found for injuries to the head, face, thorax, abdomen and lower extremities/pelvis, while no or small improvements were found for injuries to the cervical spine, upper extremities, thoracic spine and lumbar spine. Injuries to the head leading to PMI>1% were found to drop by approximately 70%, injuries to the face by approximately 60% and injuries to the thorax by approximately 50% for both males and females. For males, the risk of a cervical spine injury leading to PMI was found to increase by 7% when comparing car models introduced in 1980–1989 with models introduced in 2010–2019, while for females the risk decreased by 12%. Another body area where the risk differed was lumbar spine, which increased by 50% for males while no change in risk was seen for females. Injuries to the lower extremities and pelvis was reduced by 48% for males and by 38% for females (***Figure 7***).

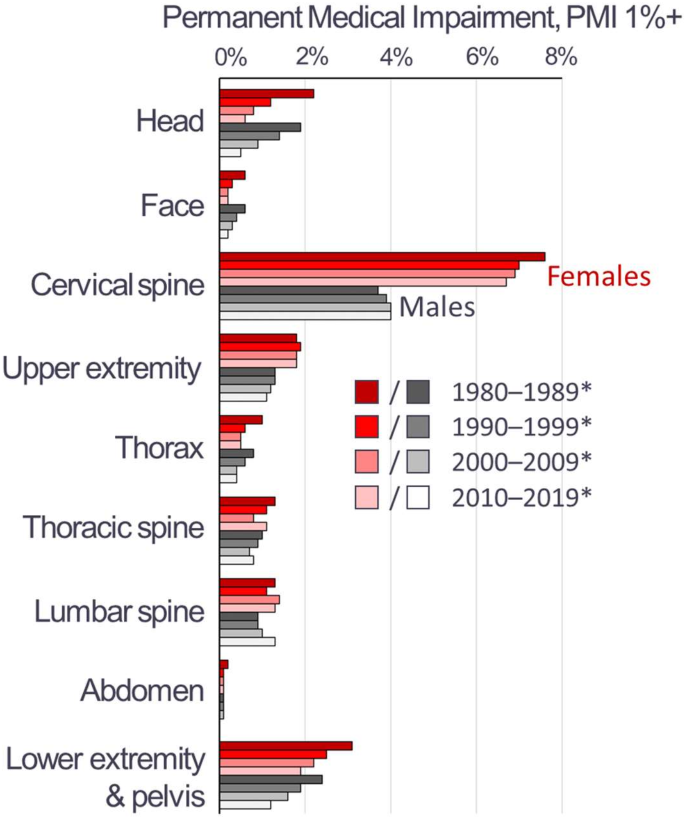


***Figure 7**.. Development of risk for PMI to different body regions for females and males for cars launched for the 10-year periods 1980–89 to 2010–19 (*Model Year (MY) of introduction). Based on Kullgren 2020.*

Since car manufacturers mainly focus on serious injuries (AIS 3+), the vast majority of injuries resulting in severe impairment are neglected (Gustafsson et al. 2015). Injury prevention must incorporate a long-term perspective and target minimising impairment among all vehicle occupants in a collision. Thus, minor and moderate injuries, that to a large extent lead to long-term consequences – in particular whiplash injuries – should also be taken into consideration in car safety development (Gustafsson et al. 2015; Tingvall et al. 2013; Bohman et al. 2014).

Whiplash Injuries

Whiplash injury is the single most common and costly vehicle accident-related disorder and deserves special attention. From a societal perspective these injuries are costly since they are frequent and can lead to long-lasting pain and medical impairment. In front seat occupants, whiplash injuries account for approximately 65% of all injuries leading to permanent medical impairment following a vehicle collision (personal communication with Anders Kullgren, Folksam Insurance Group, 2022-01-11, ***Figure 8***).

Figure 8. *Distribution of injuries leading to permanent medical impairment in front seat occupants (personal communication with Anders Kullgren, Folksam Insurance Group, 2022-01-11).*

Since the mid-1960´s, statistical data has shown that females generally have a higher risk of sustaining Whiplash Associated Disorders (WAD) – commonly denoted ‘whiplash injuries’– than males, even in similar crash conditions (***Figure 9***) (Narragon 1965; Kihlberg 1969; O’Neill et al. 1972; Thomas et al. 1982; Otremski et al. 1989; Maag et al. 1990; Morris & Thomas 1996; Dolinis 1997; Temming & Zobel 1998; Richter et al. 2000; Chapline et al. 2000; Krafft et al. 2003; Jakobsson et al. 2004a; Storvik et al. 2009; Carstensen et al. 2011, Kullgren et al. 2020). According to these studies, the whiplash injury risk is up to three times greater for females compared to males. This may (partly) explain the greater proportion of slight injuries among females in ***Figure 3*** (Welsh & Lenard 2001).

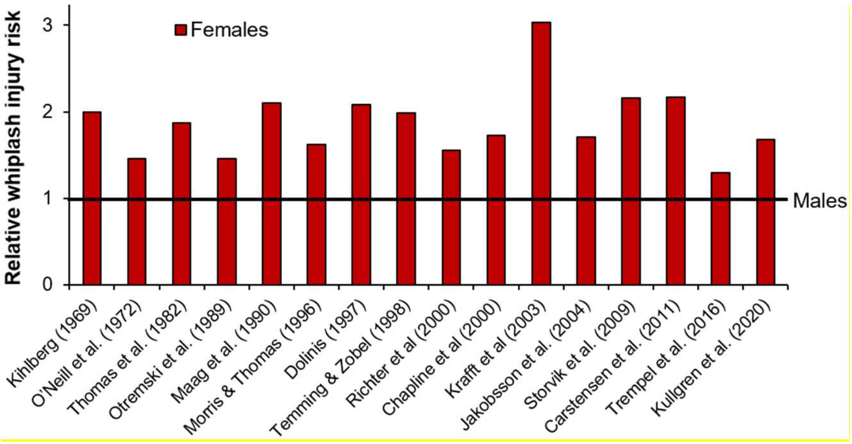


Figure 9. *The relative whiplash injury risk for females (shaded light grey) compared to males (normalised to 1) from a mix of studies representing different risk measures, crash directions and methodologies.*

Since 1997, there has been a decreasing trend of whiplash injuries resulting from rear and side impacts, while for frontal impacts the injuries appear to be more or less constant (Kullgren et al. 2013). Airbags in combination with seatbelt pretensioners was found to reduce the number of whiplash injuries by 41% ±15% in frontal impacts (Kullgren et al. 2000). In rear impacts, a small decrease in the long-term (symptoms lasting >4 weeks) whiplash injury risk (from 15.5% to 13.6%) was recorded in cars manufactured after 1997 and equipped with standard seats (i.e. no advanced whiplash protection systems) in comparison to cars manufactured before 1997 (Kullgren et al. 2007). Cars equipped with more advanced whiplash protection systems had approximately 50% lower risk of long-term whiplash injuries compared to cars manufactured after 1997 without whiplash protections systems installed (Kullgren et al. 2007). The most common whiplash protection concepts are to minimize the relative motion between head and torso, to control energy transfer between the seat and the human body, and to absorb energy in the seatback (Wiklund & Larsson 1998; Sekizuka 1998; Jakobsson 2004b). Overall data reveals that existing concepts are more effective for males than females, with 31% risk reduction of permanent medical impairment for females and 52% for males, according to insurance claims records (***Figure 10***) (Kullgren et al. 2013). Thus, the relative difference between females and males has increased since the introduction of whiplash protection systems, although the overall whiplash injury risk has decreased.

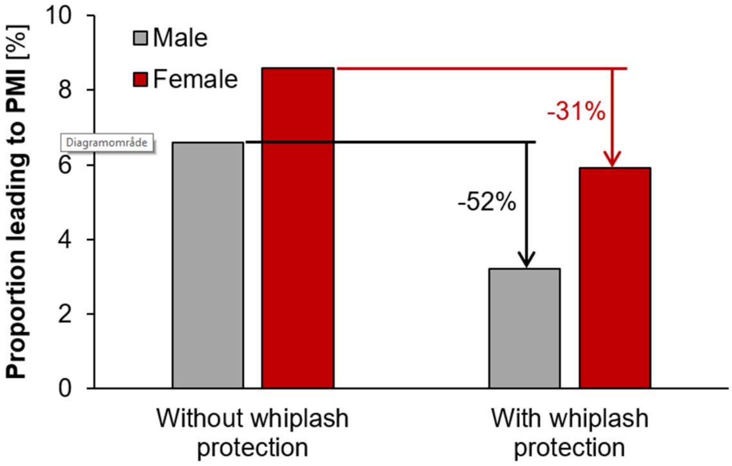


Figure 10. *Proportion of initial whiplash injuries, leading to permanent medical impairment (PMI) in seats of model year >1998 with and without whiplash protection, for females and males (based on Kullgren et al. 2013).*

However, substantial differences are found when analysing the different whiplash protection concepts separately (***Figure 11***) (Kullgren et al. 2013). Seats designed to absorb energy in the seatback (such as passive seats and Volvo WHIPS) had equal or even somewhat higher effectiveness for females compared to males (also shown in Jakobsson & Norin 2004), while seats with Reactive Head Restraints (RHR) showed very high reductions for males (approximately 70%) and no reduction for females.

Seatback yielding and/or seat track failure decreases the whiplash injury risk in rear impacts (Kihlberg 1969; States et al. 1969; O'Neill et al. 1972; Thomas et al. 1982; Foret-Bruno et al. 1991; Parkin et al 1995; Morris & Thomas 1996; Krafft et al. 2004; Jakobsson et al. 2004b, 2008); especially in females (Thomas et al. 1982; Jakobsson et al. 2004b, 2008). Yet, seatbacks have increased up to 5.5-fold in strength from the 1960´s to the 1990´s in order to increase the vehicle crashworthiness in high-speed rear impacts (Viano 2008). The increase in strength has resulted in greater seat stiffness. The boosted seat stiffness affects the interaction between the occupant and the seatback and may increase the forces on the neck. This is believed to be one of the reasons for the increase in whiplash injuries since the late 1960´s; especially in females (Morris & Thomas 1996; Hell et al. 1998; Viano 2003). Controlled seat yielding is one option to reduce occupant accelerations, and several technical solutions have been presented (Krafft et al. 2004; Jakobsson et al. 2000; Zellmer et al 2001; Schmitt el al. 2003). Krafft et al. (2004) obtained a substantial reduction of the whiplash injury risk when the forward acceleration of the occupant was reduced after the introduction of yielding of the seat front attachments to the floor (the only design change made to the vehicle).

Volvo's whiplash protection system (WhiPS) is based on controlled yielding of the seatback (Jakobsson et al. 2000) and the injury reducing effect has been reported to be in the range of 31 to 71% (Farmer et al. 2003; Jakobsson et al. 2008; Kullgren & Krafft 2010; Kullgren, et al. 2013). Studies have indicated that the injury reducing effect of the WhiPS may be somewhat greater for females compared to males (Jakobsson 2004b; Kullgren & Krafft 2010; Kullgren et al. 2013). By adapting the stiffness of the seats to account for smaller occupants as well, further reductions in the whiplash injury risk in females may thus be expected. A mechanical or computational model of the average female would be an important tool when evaluating the seat response with regards to the female properties. The RHR systems, focusing on geometric performance initially in the crash phase, appear to have a limited effect on women (***Figure 11***, Kullgren et al. 2013). This shows that there is a difference in protecting males and females against whiplash injury. Understanding these differences will probably be a key knowledge in improving future seat concepts.

More detailed information about whiplash injury with regards to females and males can be found in Carlsson (2012) and Stemper & Corner (2016).

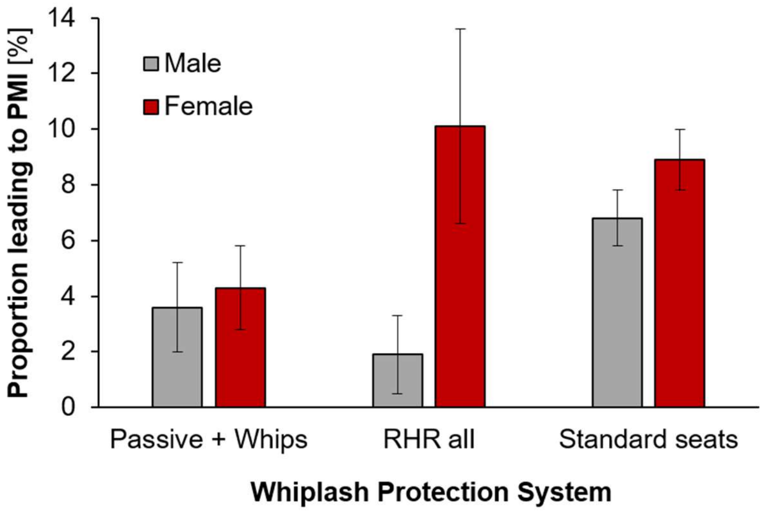


Figure 11. *Proportion of initial whiplash injuries leading to permanent medical impairment (PMI), in seats of model year >1998 with and without whiplash protection (Passive + WHIPS, Reactive Head Restraint (RHR) and Standard Seats), for females and males. Based on Kullgren et al. (2013).*

Variations in the Population

Females and males have different anthropometry (Schneider et al. 1983) and mass distribution (Carlsson et al. 2014; Young et al. 1983; McConville et al. 1980) (***Figure 12***), which may influence the seated posture and the interaction between the body and the seat as well as the inner vehicle structures and restraint systems (seatbelts, airbags, whiplash protection systems, etc).

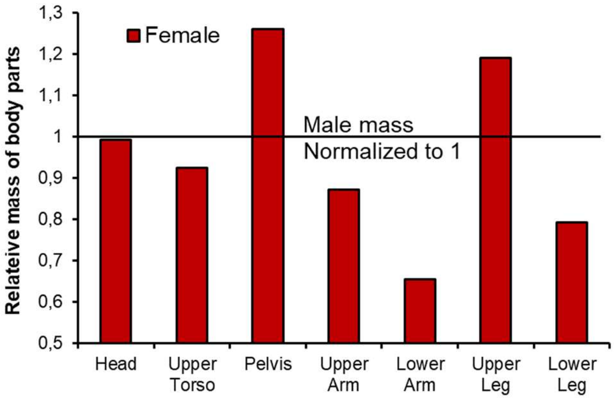


Figure 12. *The mass distribution body parts of the 50th percentile female relative to the 50th percentile male (normalised to 1 as indicated by the black solid line). Based on Carlsson et al. 2014; Young et al. 1983; McConville et al. 1980.*

Size, seated posture & geometry

Differences in seated postures in males and females are illustrated in ***Figure 13***, showing an up-scaled 5th percentile female, aligned with a 50th percentile male and a down-scaled 95th percentile male (based on a sample of 25 persons of each size, Schneider et al. 1983). Several studies have reported a shorter head-to-head restraint distance (backset) for females compared to males (Jonsson et al. 2007; Linder et al. 2008; Carlsson et al. 2011; Minton et al. 1997; Schick et al. 2008; Carlsson et al. 2014). This may (partly) be due to a tendency among females to sit more upright and have a seatback angle that is 3˚ lesser than males (Jonsson et al. 2008a). The backset is also affected by whether the hands are positioned on the steering wheel (“driver position”), or on the lap (“front seat passenger position”). Jonsson et al. (2007) reported that females [males] had 27 mm [37 mm] greater backset when both hands were positioned on the steering wheel (in a 10 and 2 o’clock position) as compared to the lap, in static conditions. In driving conditions, the mean backset increased 40 mm for both sexes, as compared to static conditions (Jonsson et al. 2008b). In addition, in order to reach the pedals, female drivers tend to sit closer to the steering wheel (Parkin et al. 1995; McFadden 1998;

Bingley et al. 2005; Malczyk et al. 2013), which may influence the position of the arms holding the steering wheel (***Figure 13***). Malczyk et al. (2013) found that, in comparison to average sized male volunteers, average sized female volunteers were sitting 6.2 cm closer to the upper steering wheel rim (measured from the nose); 7.8 cm closer to the lower steering wheel rim (measured from the abdomen) and 2.5 cm closer to the lower instrument panel (measured from the knees). While the short stature drivers positioned their thighs at distinctly smaller angles than taller drivers, the lower leg angles did not differ significantly between the two groups. Parkin (1995) found that 50th percentile females are considerably closer than 50th percentile males to the steering wheel by 6.2 cm. The 5th percentile female is 21.5 cm closer than the 95th percentile male, at 38.5 cm from the centre of the steering wheel. For females and males of similar statures, McFadden (1998) reported a similar distance from the steering wheel, suggesting that the seating distance from the steering wheel is a function of the driver's stature rather than the driver's sex. Nonetheless, photos taken of motor vehicle drivers on a public road showed significant difference between the sexes in left- and right-hand position (Jonsson 2011).

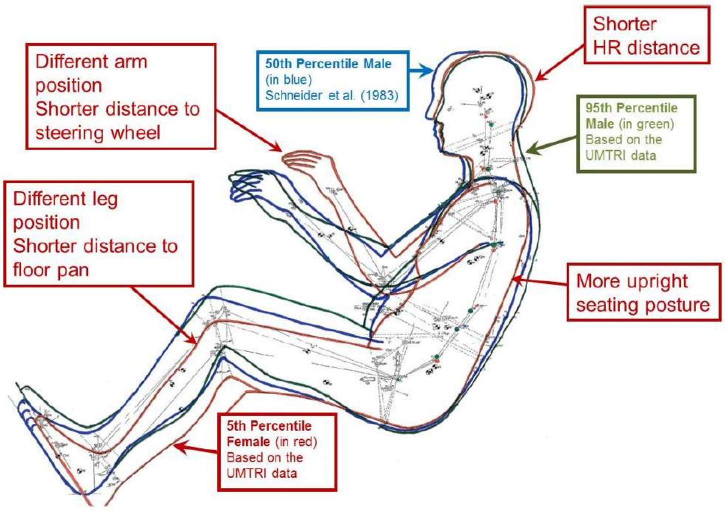


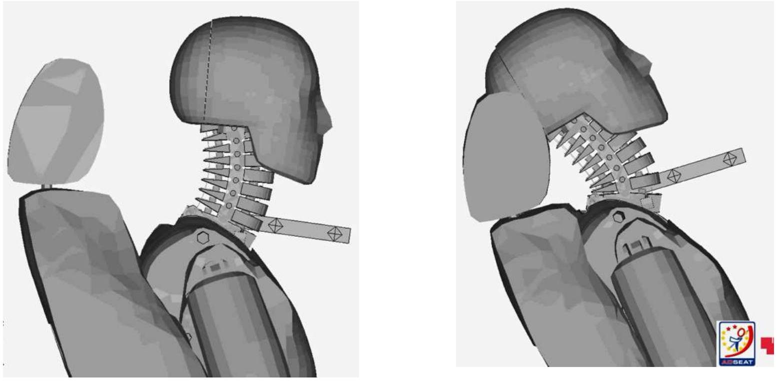
Figure 13. *An up-scaled 5th percentile female, aligned with a 50th percentile male and a down-scaled 95th percentile male. Based on Schneider et al. 1983.*

In rear impacts, the deflection of the seat frame, seatback padding, and springs may depend on the mass and/or the centre of mass of the upper body with respect to the lever about the seatback hinge (***Figure 14***). The deflection of the structures of the seatback affects the plastic deformation, energy absorption, and the dynamic head-to-head restraint distance, as well as the rebound of the torso (Svensson et al. 1993; Croft 2002; Viano 2003). The motion of the head relative to the head restraint may be affected by seated height in relation to the head restraint geometry.

Traditionally, there is a focus on the head restraint being positioned too low (***Figure 14ab***). A low head restraint may increase the whiplash effect by acting as a fulcrum, whereas more support of the head improves performance (Berton 1968; Severy et al. 1967, 1968). However, no major concern has been raised in case the head restraint being positioned too high, which may be the case for short persons (typically small females or children) (***Figure 14cd***). In this situation the head may be exposed to a combined downward and forward directed loading. This may in turn exacerbate the loading in the neck structures and increase the neck injury risk. Farmer et al. (1999) concluded that "*Not only are women more likely than men to suffer neck injuries in rear impacts, but they are more affected by changes in head restraint positioning*".

Average sized male model relative to head restraint in lowest position

a) Normal seated posture: b) Rear impact:



Average sized female relative to head restraint in highest position

c) Normal seated posture: d) Rear impact:

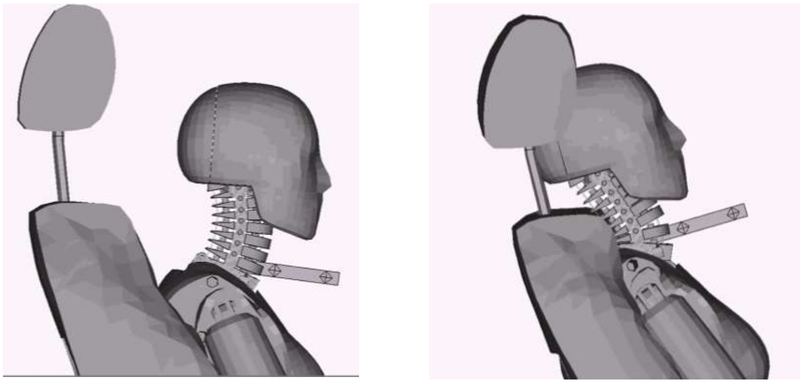


Figure 14. *Examples of head restraint geometries for average sized males (head restraint in high position) in and females (head restraint in low position). Pictures from www.adseat.eu*

A recent study found that a large majority of Saab 9-3 drivers adjust the head restraint to a (very) high position (89% in any of the three uppermost positions and 59% in the top position); the distributions were similar for both males and females (Carlsson et al. 2017). This is probably due to the technical configuration of the locking mechanism, because it is easier to move the head restraint upwards (one-hand operation) and more complicated to adjust it downward (two-hand operation). However, in older cars the head restraint was generally not lockable and just as easy to move upwards as downwards. This may explain the results of earlier studies, reporting that drivers frequently adjust their head restraint too low (Garret & Morris 1972; Kahane 1982; Viano & Gargan 1996; Young et al. 2005). Thus, due to improved locking mechanisms in recent-year cars, adjustable head restraints are probably more likely positioned at higher positions compared to older models. Carlsson et al. (2017) also noted that neither the position of the head restraint nor the position of the steering wheel was adjusted between individuals using the same car. Finite Element Method (LS-Dyna) was used to virtually investigate the behaviour of male and female vehicle occupants during a whiplash. Based on the results of the 50th percentile male BioRID II simulation, two setups with the 50th percentile female EvaRID model and different seat adjustments (head restraint (HR) in 'high' and 'low' positions) were compared.

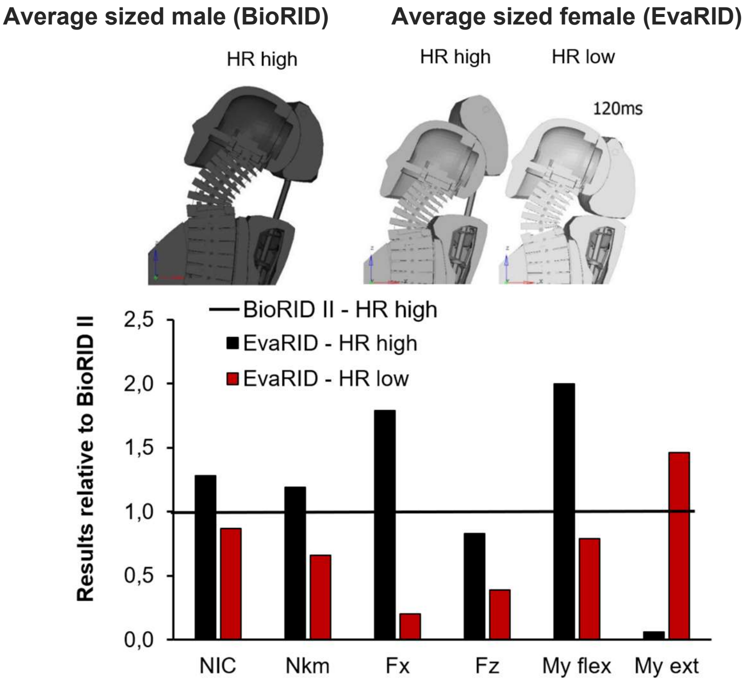


__Figure 15.__ Comparison of the cervical kinematics in the BioRID II and the EvaRID models at two different head restraint (HR) positions in a rear impact. HR high: the same HR position for BioRID II and EvaRID; HR low: lowest HR position for EvaRID. b) Load parameters of the EvaRID compared with the BioRID results. Pictures from Gutsche et al. (2012).

In rear impact volunteer tests, It has been reported that females have a somewhat different dynamic response, such as greater head forward acceleration, greater (or similar) T1 forward acceleration and a more pronounced rebound than males (***Figure 16***) (Szabo et al. 1994; Siegmund et al. 1997; Hell et al. 1999; Welcher & Szabo 2001; Croft et al. 2002; Mordaka & Gentle 2003; Viano 2003; Ono et al. 2006; Linder et al. 2008; Schick et al. 2008, Carlsson et al. 2011, Carlsson et al. 2012).

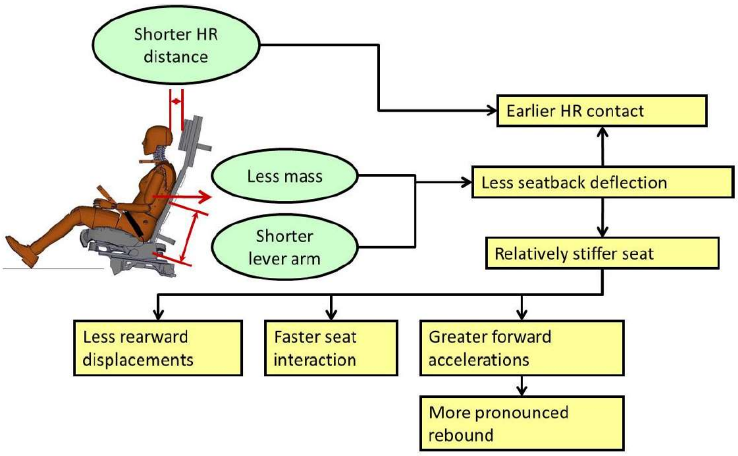


Figure 16. *The effect of smaller size in rear impacts.*

In frontal impacts, a greater risk for lower extremity fractures was found for small sized drivers compared to large sized drivers, and in female drivers as compared to male drivers (***Figure 17***) (Dischinger et al. 1995). Pedals can affect the injury outcome according to several studies (Forssell et al. 1996; Thomas & Bradford 1995; Portier et al. 1993). As small sized drivers trying to reach the pedals, they may experience more immediate contact and higher peak deceleration following intrusion of a dashboard, pedal, or toe pan (Wilson et al. 2001). Moreover, small sized driver´s feet tend to be more plantar flexed during braking than taller drivers, and they tend to lift their feet off the floor pan when changing position of the foot from the accelerator pedal to the brake pedal (Crandall et al. 1996; Palmertz et al. 1998). Another influencing factor may be the types of shoes females sometimes wear; that is, high heels could affect foot and ankle stability and thereby increase the risk of lower limb injuries (Crandall et al. 1996).

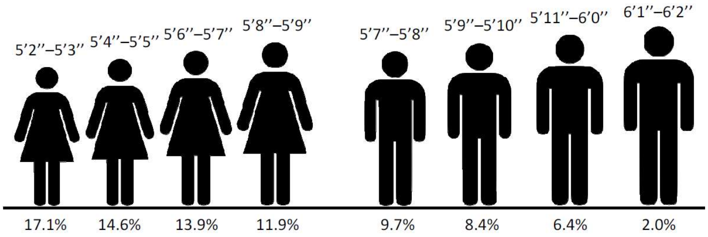


Figure 17. *Ankle/tarsal injuries in women and men – incidence by stature. Based on Dischinger et al. (1995).*

Moreover, in order to reach the pedals, female drivers tend to sit closer to the steering wheel (Parkin et al. 1995; McFadden 1998; Bingley et al. 2005; Malczyk et al. 2013), which makes them more vulnerable during hard braking or evasive maneuvers – especially in combination with improperly adjusted seatbelts – putting them on top of or extremely close to airbags when they deploy (as discussed by Ferguson & Braitman 2006). Pareteau et al. (2013) reported that contacts with the steering wheel were more significant among belted, non-ejected, outboard front seat female occupants than in males, accounting for 45% of serious (AIS 3+) head injuries in females and 14% in males; it is unclear whether the airbags were activated or not, or if they bottomed out. Head in male occupants were more frequently injured from contact with the roof/side rail (16%) compared to female occupants (6%).

In rollovers, *unbelted* females are at 33.3 ± 9.2 higher risk of being fatally injured compared to unbelted males (Kahane 2013). Furthermore, it was found that unbelted females are more likely to be ejected from the vehicles than unbelted males. The authors suggested that females, being smaller on the average than males, can pass more easily through ejection portals such as the side-window area. However, in another study regarding ejections of unrestrained vehicle occupants no statistically significant correlation was found between risks of being ejected and body size (Atkinson et al. 2010). In contrast, Funk et al. (2012) found that larger size was associated with greater risk of *belted* occupants being *partially* ejected.

Obese drivers involved in crashes are significantly more likely to be fatally injured than drivers of normal Body Mass Index (BMI) (Viano et al. 2008; Rice & Zhu 2013). The study by Rice & Zhu (2013) was based on 41,283 fatal crashes, recorded in the National Highway Traffic Safety Administration's Fatality Analysis Reporting System (FARS). Drivers involved in these crashes were categorised by their BMI, which was derived from the height and weight recorded on their licenses. The World Health Organization (WHO) defines normal BMI as falling between 18.5 and 24.9 (WHO – BMI). Researchers looked at incidents without any significant differences in the size of the vehicles involved. They also accounted for data such as seat belt use, time of day, air bag deployment, type of collision, gender, and alcohol use. Drivers with a BMI that fell into WHO's three classes of obesity were significantly more likely to be fatally injured in a crash. A BMI of 30 to 34.9 (Class I) were linked to a 21% increase in the risk of death. A BMI of 35 to 39.9 (Class II) increased the risk of a fatality by 51%, while a BMI above 40 (Class III) were 81% more likely than drivers with a normal BMI to die in a crash. In addition, obese women were more at risk of death than obese men. In contrast, underweight males were more at risk of death than underweight females (***Figure 18***). Rupp et al. (2013) found that 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. In a recent review study by (Hoebee et al. 2021) it was demonstrated that there is an increased risk of fatality and injury for obese occupants in motor vehicle accidents, specifically lower extremity and neck injuries. Overall, obese occupants were 58% more likely to sustain any injury in comparison to normal weight occupants. The risk of neck injury increased by 338% in obese occupants, while for lower extremity injury the risk increased by 44%. Overall fatality risk was increased by 51% for obese occupants in motor vehicle accidents with Class I, Class II, and Class III showing an 8%, 20%, and 49% increased risk of fatality, respectively.

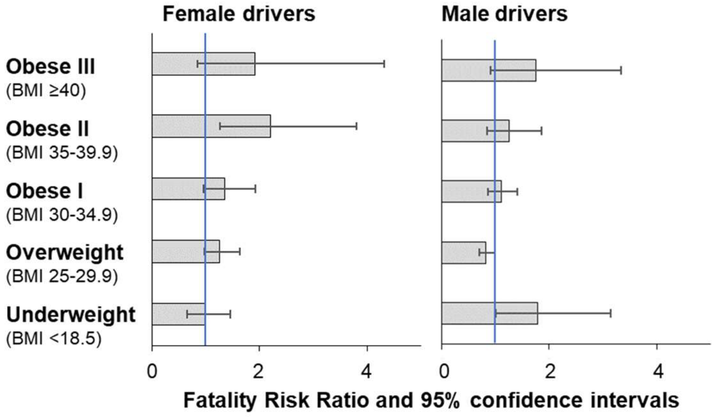


Figure 18. *Body Mass Index (BMI), fatality risk ratios and 95% confidence intervals. Based on Rice & Zhu (2014).*

BMI is the most important factor influencing lap belt fit and is associated with lengthier webbing regardless of seat position or height (Reed et al. 2012). An increase of BMI in 20 kg/m^2 was associated with the lap belt being placed 102 mm further forward and 94 mm higher, relative to the pelvis, and increases in lap and shoulder belt webbing length of 276 and 258 mm, respectively (Reed et al. 2013). Increased BMI influenced shoulder belt fit, independent of age (***Figure 19***, Bohman et al. 2019). Reed et al. (2012) concluded that “obesity effectively introduces slack in the seat belt system by routing the belt further away from the skeleton. Particularly in frontal crashes, but also in rollovers and other scenarios, this slack will result in increased excursions and an increased likelihood and severity of contacts with the interior. The higher routing of the lap belt with respect to the pelvis also increases the likelihood of submarining in frontal crashes”. Furthermore, normal BMI drivers are 67% more likely than morbidly obese drivers to wear a seat belt (Jehle et al. 2014). Reasons may be that the seatbelt isn’t long enough to fit obese drivers.

Figure 19. *Left: Shoulder belt on mid-shoulder and low shoulder belt position on abdomen. Right: Shoulder belt against the neck and high shoulder belt position on the abdomen. Pictures from Bohman et al. (2019).*

Age

For older adults, changes in posture and fat distribution can lead to difficulties with belt fit (Bohman et al. 2019). An increase in age from 20 to 80 years resulted in the lap belt positioned 18 mm further forward relative to the pelvis, 26 mm greater lap belt webbing length, and 19 mm greater shoulder belt length (Reed et al. 2013). Ageing is associated with more pronounced thoracic kyphosis (forward head posture) (Katzman et al. 2010; Quek et al. 2013), and a redistribution of fat tissue to the abdomen region (***Figure 20***). Males more commonly develop kyphosis than females (Bartynski et al. 2005). The forward head posture can be assessed by the carniovertebral angle (CVA), i.e. the angle between the horizontal line passing through C7 and a line extending from the tragus of the ear (the angle α in ***Figure 20***). Older adults were more likely to have the lower part of the shoulder belt higher up on the abdomen compared to younger participants (Bohman et al. 2019). Furthermore, a decreased CVA resulted in a "*shorter distance between the suprasternal notch and the shoulder belt, possibly due to the increased curvature of the thorax pushing the upper torso forward, which pushes the shoulder belt closer to the neck*". This trend in shoulder belt fit may thus be common among older adults with a developed kyphosis (Bohman et al. 2019). The same study also found that older adults seemed less

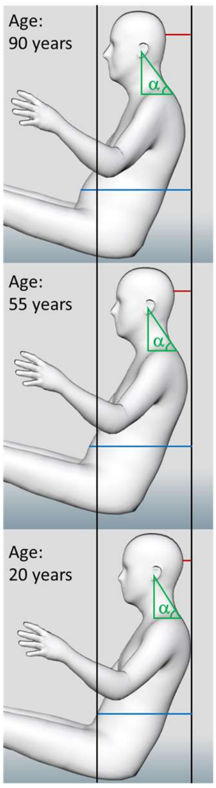


Figure 20. *Body shape changes with increasing age (male 175 cm and BMI 22). Based on:* http://adultshape.org.

aware of safety related to belt fit. In addition, older adults prefer to sit higher up to achieve a better field of vision compared to younger adults (Bohman et al. 2019). Osvalder et al. (2019) found that 16% of the older adults brought an accessory when going for a ride, including pillows to improve sitting height and support the lumbar spine or neck.

Aging increases a person's fragility (likelihood of injury given a physical insult) and frailty (chance of dying from a specific injury) (Kahane 2013). Elderly drivers have more injuries and fatalities per distance travelled compared to younger drivers (Augenstein et al. 2005; Braver & Trempel 2004; Li et al. 2003; SARTRE 3 Consortium 2004). On the order of half of the injured or killed are so as a result of decreased tolerance due to aging (Kent et al. 2009). Senior adults in rear-seats were associated with a significantly higher rate of sustaining fatal (6%) and severe injuries (16% for MAIS 3+ injuries) in comparison to the younger cohorts (Bose et al. 2011). Furthermore, older adult occupants are 2–3 times as likely as younger occupants to be seriously injured in similar crashes (Evans 2001, ***Table 4****. Comparison of number of fatalities in two populations of drivers identical in numbers and crash rates (Evans 2001).*; Welsh et al. 2006). This is mainly due to greater vulnerability for the elderly and impaired ability to drive due to slower responsiveness and poorer vision (Kent et al. 2005, 2009; Li et al. 2003; Meuleners et al. 2006).

Table 4. *Comparison of number of fatalities in two populations of drivers identical in numbers and crash rates (Evans 2001).*

Driver Population A	Driver Population B	Fatality Comparison
Males: 70-year-old	Males: 20-year-old	253% more in Population A
Females: 70-year-old	Females: 20-year-old	194% more in Population A
Females: 70-year-old	Males: 20-year-old	286% more in Population A

Based on data from crash pulse recorders, it was found that elderly occupants (>60 years of age) have >60% greater risk of sustaining serious (MAIS 2+) injuries in comparison to other occupants (Ydenius 2010). In addition, older occupants tend to sustain greater injury for a given crash severity (Morris et al. 2003; Kent et al. 2005). For both males and females, older age is also associated with a higher risk of Permanent Medical Impairment (PMI) (Gustafsson et al. 2015). Bédard et al. (2002) concluded that "*the importance of age and gender suggests that the specific safety needs of older drivers and female drivers may need to be addressed separately from those of men and younger drivers*".

All of the major occupant protection technologies in vehicles of recent model years have displayed at least some benefit for adults of all age groups and of either gender; none of them are harmful for a particular age group or gender (Kahane 2013). Seatbelts have historically been somewhat less effective for older occupants and female passengers, although more effective for female drivers. Frontal airbags are virtually equally effective across all ages; side air bags may be even more effective for older occupants than for young adults. Airbags and other non-belt protection technologies are helping females just as much and quite possibly even more than they protect males; this may have contributed to reducing the historical increase in risk for females relative to males of the same age (Kahane 2013).

Biological Perspective

This study has (among others) reviewed differences in injury risk between males and females in car accidents. The increased risk for females involved in car accidents, in comparison to males, has been noted in several studies. Notable, the whiplash injury risk is approximately twice as high for females as for males of equal size (Kihlberg 1969; Temming & Zobel 1998; Lundell et al. 1998; Jakobsson et al. 2000), which may be due to physiological differences. More research is required in order to understand how these differences between females and males may influence the injury risk. This short summary concerns less obvious biological differences that may influence how males and females react and tolerate being involved in a car accident. See Stemper et al. (2012) for more details.

Spine

The cervical spine has been investigated more than the lumbar and thoracic spines. Any differences in biomechanical properties may be due to structural and material gender differences of the spine as well as the muscles. The differences in dimension and shape of the segments of the three different spinal sections in males and females consequently means that in comparison, the weight of the head will be heavier to support for the slighter female neck, than for the more substantial male neck (Vasavada et al. 2008; Stemper et al. 2012). Due to more pronounced trunk muscle differences than first concluded (Marras et al. 2001), body mass scaling is not as accurate as would be necessary (Stemper et al. 2012). Jorgensen et al. (2001) reported that males should have significantly larger torques for a majority of muscles and at a majority of spinal levels. Essentially, injury risk during dynamic loading is elevated for females due to their body size generally being smaller, muscle volumes and lever arms, as well as the capacity of the female neck of supporting the comparatively heavier head (Stemper et al. 2012). Various factors influence spinal canal dimensions, including gender (Hukuda & Kojima 2002;

Pettersson et al. 1995; Sasaki et al. 1998; Lim & Wong 2004; Tatarek 2005; Ulbricht et al. 2014). To date, intervertebral gender differences of the foramina have not been established. The curvature of the cervical and lumbar spine is lordotic (bends backwards) and kyphotic (bends forward) in the thoracic region. The lordotic angle in females is 40% greater than in males (Bergenudd et al. 1989; Youdas et al. 1996; Youdas et al. 2000; Norton et al. 2004; Janssen et al. 2009) which may be to offset abdominal mass during pregnancy (Whitcome et al. 2007).

Again, with regard to range of motion of the spine, the cervical spine has been investigated more thoroughly than the lumbar and thoracic spines. Three studies found no significant gender differences for active flexion–extension, lateral bending, or axial rotation (Trott et al. 1996; Castro et al. 2000; Lansade et al. 2009). A larger study found greater range of movement in women for extension, lateral bending, and axial rotation (Youdas et al. 1992). Two other studies reported similar results for extension (Mayer et al. 1993; Malmström et al. 2006), axial rotation (Malmström et al. 2006), and coupled lateral bending during axial rotation (Malmström et al. 2006). In most of these studies, females had greater cervical spinal ranges of motion than males. Some studies on the passive angular range-of-motion have reported similar gender differences for the cervical spine (Dvorak et al. 1992; McClure et al. 1998) and the lumbar spine (McGill et al. 1994). In addition to reporting gender differences in total angular range of motion, passive angular motion studies have also reported greater flexibility of the female cervical spine compared with males. On the contrary, linear motion of the head/neck has been found to be less in females (Hanten et al. 1991; Hanten et al. 2000). Neck injury risk in rear impact may be negatively influenced due to these issues (Stemper et al. 2011).

Despite plentiful research (mostly on PMHSs), spinal soft tissue studies are contradictory, and establishing whether any strength/elasticity gender differences is due to greater dimensions of vertebral components in men rather than stress/strain characteristics gender differences, is challenging (Osakabe et al. 2001; Brown et al. 2002; Masharawi et al. 2005; Nightingale et al. 2007; Stemper et al. 2010). How gender influences spinal biomechanics is a complex issue, and any differences in flexibility (males stiffer/females more flexible) may be due to size rather than gender (Masharawi et al. 2005). Further investigation is recommended.

Chest

The rib angle is flatter and the rib cage depth/width is greater in males than in females of similar stature, irrespective of stature (Shi et al. 2014). The angle decreased, while depth/width/height increased with stature, and the rib cross sectional area was greater in males than females in each rib, which diminished with age in both genders. Due to considerable differences in ribs and rib location between males and females, exact values have not been established.

The lower extremities

The shape of the male and female pelvis differ considerably (***Figure 21***) which may, although conclusive data is lacking, put females at increased risk of injury in frontal collisions due to greater anteversion of the acetabulum (directed more ventrally) (Wang et al. 2004; O´Connor 2006; Traina et al 2009; Tohtz et al. 2010; Nakahara et al. 2011; Stemper et al. 2012).

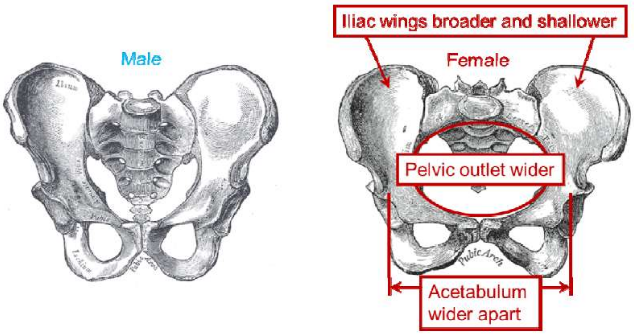


Figure 21. *Pelvic bone differences between males and females. Pictures from Wikimedia Commons.*

Similarly, inherent gender differences are also seen in the anatomy of the proximal femur (Nakahara et al. 2011; Crabtree et al. 2002; Stemper et al. 2012). The anteversion in the femoral neck being greater in females (25.2 ±9.8˚ in females and 20.3 ±9.9˚ in males, Nakahara et al. 2011), although the female femoral neck being slighter. Differences in pelvis shape produces differences in the knees in males and females (Chao et al. 1994; Hsu et al. 1990; Varadarajan et al. 2009; Stemper et al. 2012). Although gender differences in femoral alignment and knee angulation influences joint reconstruction, no studies have been found that show different impact tolerances of the skeletal structures of the femur and knee in men and women (Stemper et al. 2012).

Females present with greater rotation and knee laxity than males, which may be due to anatomical factors or related to mechanical properties of the ligaments in the knee (Wojtys et al. 2003; Sbriccoli et al 2005; Chandrashekar et al. 2006; Park et al. 2008; Cammarata & Dhaher 2010; Stemper et al. 2012). Muscle spasm and attenuated muscle function have also been found to be more pronounced in females (Sbriccoli et al 2005).

Tissue properties differ consistently between males (femur stronger) and females (femur weaker) based on the size of different anatomical structures. Predominantly, mechanical properties were alike and previous assumptions with regard to gender differences appear ambiguous. Compact bone and elastic modulus thereof, as well as ultimate angle of twist/strain of long bones and vertebrae do not present any gender differences, although differences have been found in torsion of compact bone specimens and maximum angle of twist, which are less in females than in males (the ultimate distortion being 85% of male compact bone). Tensile strength and compression do not differ, and ultimate torsional strength and maximum angle of twist presented less in females than in males. Data on tissue properties is collected from Yamada (1970).

Ligaments, tendons and muscles

Females are exposed to an increased risk of knee ligament injury in sports, which is influenced by various factors, many of which are not related to the mechanical properties of ligament tissue (Wild et al. 2012). Anterior cruciate ligament studies are plentiful (Chandrashekar et al. 2006; Lipps et al. 2012) while studies into other ligaments are scarce, and any statistical differences have yet to be established. Differences have been ascribed to smaller cross-sectional areas of the ligament and a greater lateral tibial slope in female specimens (Lipps et al. 2012). Some differences have been found in the cranio-cervical ligaments and failure force of the transverse ligament and posterior atlanto-occipital membrane (Mattucci et al. 2013), however, further investigation is required to confirm. Ultimate strength in skeletal muscle have not presented any gender differences (Yamada 1970).

Hormones

Exposure to football injuries influenced by phases of the menstrual cycle has both been reported and contradicted. The ovulation and luteal phases in relation to the follicular phase have shown to increase knee laxity in some studies, although that does not influence injury risk (Zazulak et al. 2006). In fact, the knee is stiffer in the pre-ovulatory phase which suggests that females are exposed to an increased risk of injury at this time in the menstrual cycle. Although confounding factors have been found for a number of factors such as knee alignment, hamstring muscle force and neuromuscular activation, further investigation is required (Wild et al. 2012).

Ageing

Ageing refers to progressive changes within the tissues of the body associated with the passage of time. The rate of degeneration within specific tissues associated with loading history, genetics, and a number of other factors. A considerable body of clinical and experimental literature exist on different degenerative conditions affecting with regard to the majority of tissues within the human body. Please refer to Stemper et al. (2012) regarding biomechanical changes associated with degeneration from tissue level to body segment level.

Crash Test Dummies

Crash test dummies are used as human substitutes in crash testing at force levels most probably injurious for living humans. The dummies are used in sled tests as well as in full scale vehicle tests. The dummy should be sensitive to parameters resembling an injury or an injury mechanism and have a good repeatability. Furthermore, it should be human-like in terms of size, mass and mass distribution, as well as in dynamic response during a crash. The validation of a mechanical dummy model is usually based on volunteer tests and/or PostMortem Human Subject (PMHS) tests. Volunteer tests needs to be carried out at very low, non-harmful velocities and accelerations, while PMHS tests can be performed at higher, injury inducing velocities and accelerations. However, the lack of muscle tone, internal pressure, and other changes in the PMHS due to the time lapse after death, makes the results less representative.

The first crash test dummy, Sierra Sam, was developed in the late 1940s by Samuel W Alderson at Alderson Research Labs (ARL) and Sierra Engineering Co. The size corresponded to a 95th percentile (large) male. The dummy was primarily used for aircraft related testing (ejection seats, helmets and pilot restraint harnesses). In the early 1950s, Alderson and Grumman produced a dummy which was used to conduct crash tests in both motor vehicles and aircraft.

Existing adult dummy sizes

Frontal impact dummies

The *Hybrid III* dummy family was developed for high-speed frontal crash testing and for evaluation of early automotive safety restraint systems. Reports covering the development process are collected in Backaitis & Mertz (1994). The anthropometry of the dummy family is in line with the University of Michigan Transportation Research Institute (UMTRI) study (Schneider et al. 1983, Robbins et al. 1983ab). Initially, the family consisted of four dummy members; the 5th and 50th percentile females, and the 50th and 95th percentile males (***Table 5***).

Table 5. *The stature, mass, and seated height of the four-member dummy family in the UMTRI study (Schneider et al. 1983).*

Sex	Dummy Size	Per-centile	Stature [cm]	Mass [kg]	Seated Height [cm]
Female	Small	5th	151.1	47.3	78.1
Female	**Average**	**50th**	**161.8**	**62.3**	**84.4**
Male	Average	50th	175.3	77.3	90.1
Male	Large	95th	186.9	102.3	96.6

In the first part of the UMTRI study, data was collected and analysed for all four dummy members. The stature, mass and seated height, were defined based on the National Health and Nutrition Examination Survey (HANES) of 1971–1974 by Abraham et al. (1979ab). This data was collected on 13,645 individuals representing the 128 million persons aged 18–74 in the US population. It was later decided, though, that the 50th percentile female dummy member should be dropped since the level of funding would not allow completion of the study for all four dummy members (***Figure 22***).

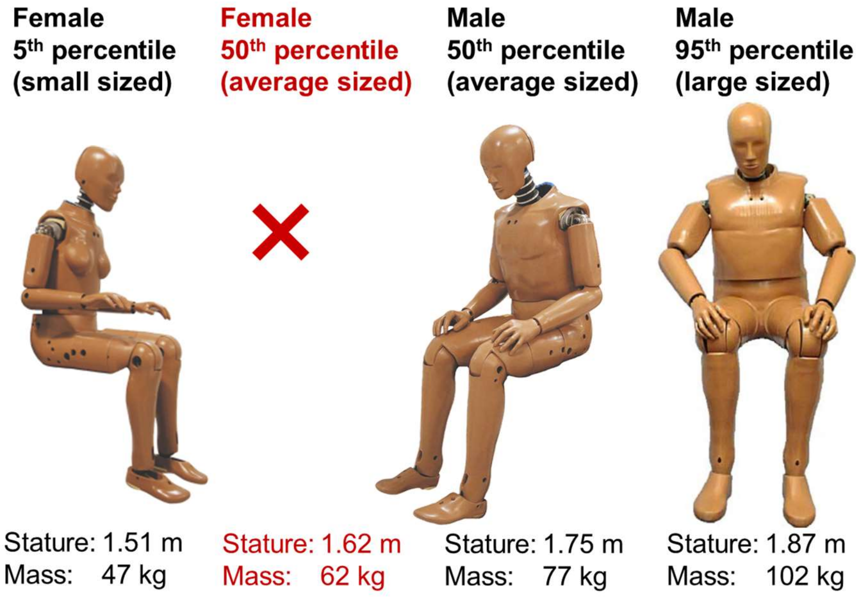


Figure 22. *Existing crash test dummy sizes (adults). The picture shows the Hybrid III dummy family from Humanetics.*

- The 50th percentile (average sized) male Hybrid III dummy (***Figure 22***) is the most widely used crash test dummy in the world for the evaluation of automotive safety restraint systems in frontal crash testing. Originally developed by General Motors, the design is now maintained and developed by Humanetics in conjunction with the Society of Automotive Engineers' (SAE) Biomechanics Committees and the National Highway Transport and Safety Administration (NHTSA) (Hybrid III 50M): *"It is considered to have excellent biofidelity and instrumentation capability. Recent revisions have improved the biofidelity in the femur range of motion and the ankle and foot."*
- The 5th percentile (small) female Hybrid III dummy (***Figure 22***) was developed by First Technology Safety Systems (FTSS) and the Society of Automotive Engineers (SAE) Biomechanics Subcommittees, Center for Disease Control (CDC) and Ohio State University. The dummy represents the smallest segment of the adult population based on USA anthropometry studies (Schneider et al. 1983, Robbins et al. 1983b, ***Table 5***) (Hybrid III 5F): It was "*derived from scaled data from the Hybrid III 50th Dummy. Originally developed in 1988, the dummy was upgraded in 1991 to evaluate seat belt submarining. It was upgraded again in 1997 to improve the dummy's ability to evaluate airbag aggressiveness, particularly for the car driver close to the steering wheel in the "Out Of Position" (OOP) test condition."*
- The 95th percentile (large) male Hybrid III dummy (***Figure 22***) was originally developed by FTSS (now Humanetics) and the SAE Biomechanics Subcommittees, CDC and Ohio State University. The dummy represents the largest segment of the adult population and is based on USA anthropometry studies (Schneider et al. 1983, Robbins et al. 1983b) (Hybrid III 95M): *"The biomechanical impact responses are derived from scaling functions applied to the Hybrid III 50th Dummy. Originally developed in 1988, the dummy is used worldwide for the evaluation of automotive and military safety restraints and particularly for seat belt integrity testing."*
- The 50th percentile (average sized) male THOR (**T**est device for **H**uman **O**ccupant **R**estraint) dummy is an advanced dummy for frontal impact testing (THOR 50M, ***Figure 23a***): *"THOR incorporates enhanced biofidelic features and significantly expanded instrumentation"* compared to the Hybrid III. Euro NCAP is considering the usage of the 50th percentile THOR for in future tests.
- The 5th percentile (small sized) female THOR dummy has more humanlike biofidelity and a greater range of sensors for advanced injury detection than the Hybrid III (THOR 5F, ***Figure 23b***): *"A NHTSA scaled version of the THOR-50M dummy was used as a basic for the mechanical blueprint with the skeleton and flesh geometry redesigned to match the UMTRI AMVO 5F landmarks and surface geometry."*

- The 50th percentile (average sized) male Hybrid II is the predecessor of the 50th percentile male Hybrid III dummy (Hybrid II 50M, ***Figure 23c***): ”*This dummy was capable of generating test data with sufficient biofidelity to be used for automotive crashworthiness testing. In 1973, the dummy was mandated by NHTSA for use in testing automotive restraint systems to meet Federal Motor Vehicle Safety StandardNo.208 (FMVSS 208).”*

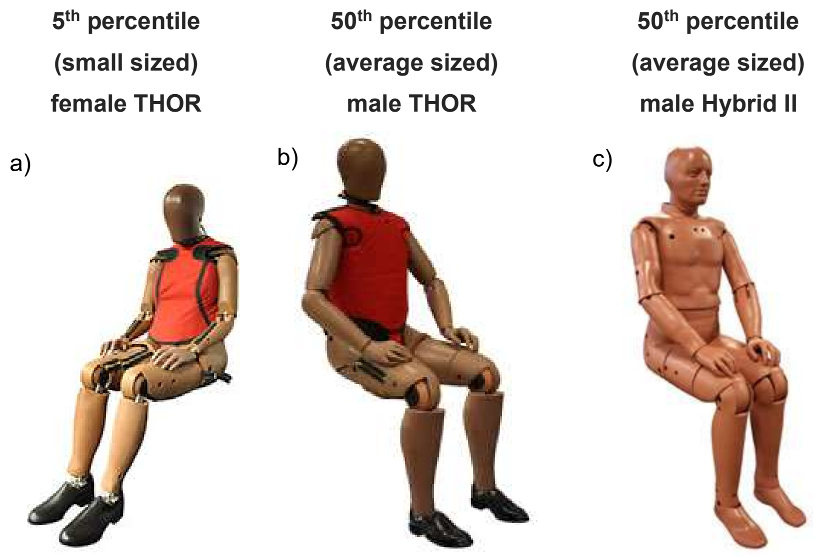


***Figure 23.** The a) 5th percentile female and b) 50th percentile male THOR, and c) 50th percentile male Hybrid II dummies from Humanetics.*

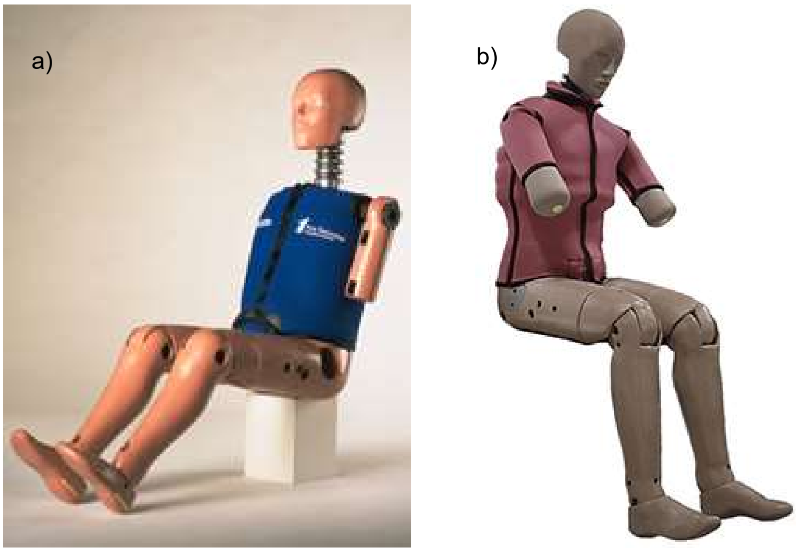
- The ECE R16 Manikin is used for seat belt testing in accordance to the UN Regulation No. 16 (R16). The manikin is a simplified 50th percentile (average sized) male crash test dummy and used as a loading device. The forward motions of the chest and pelvis, relative to the seat, are measured with a string potentiometer.

***Figure 24.** The ECE R16 (TNO-10) Manikin from Humanetics.*

Side impact dummies

The first 50th percentile (average sized) male *Side Impact Dummy (SID)* was developed in the late 1970s at the University of Michigan. The dummy was based on the predecessor of the 50th percentile male Hybrid III dummy (the Hybrid II), with an adapted thorax but without arms (Schmitt et al. 2014). The dummy primarily measures head, chest and pelvis injury risks.

- The 5th percentile (small sized) female SID-IIs is a new generation crash test dummy to specifically evaluate advanced automotive side impact protection systems, particularly side airbags (SID II-s, ***Figure 25***a). The dummy was developed during 1994–1995 within a cooperation between First Technology Safety Systems (FTSS) and the Occupant Safety Research Partnership (OSRP), in the USCAR program. The anthropometry was based on the 5th female Hybrid III dummy and *“also closely matches size and weight of the 12–13 year old child”* (SID II-s).
- The 50th percentile (average sized) male EuroSID (ES-2/ES-2re) is used in Europe to ensure compliance with safety standards (***Figure 25***b).
- The 50th percentile (average sized) male BioSID is a more sophisticated version of SID and EuroSID but is not used in a regulatory capacity.


5th percentile (small sized) female SID-IIs

50th percentile (average sized) male ES-2 / ES-2re

Figure 25. *The a) 5th percentile female SID-IIs and b) 50th percentile male ES-2 / ES-2re side impact dummies from Humanetics.*

- The 5th percentile female and 50th percentile male WorldSID is a project to develop a harmonised new generation of dummy by a worldwide consortium under the umbrella of the International Standardisation Organisation (ISO) (Schmitt et al. 2014, ***Figure 26***).

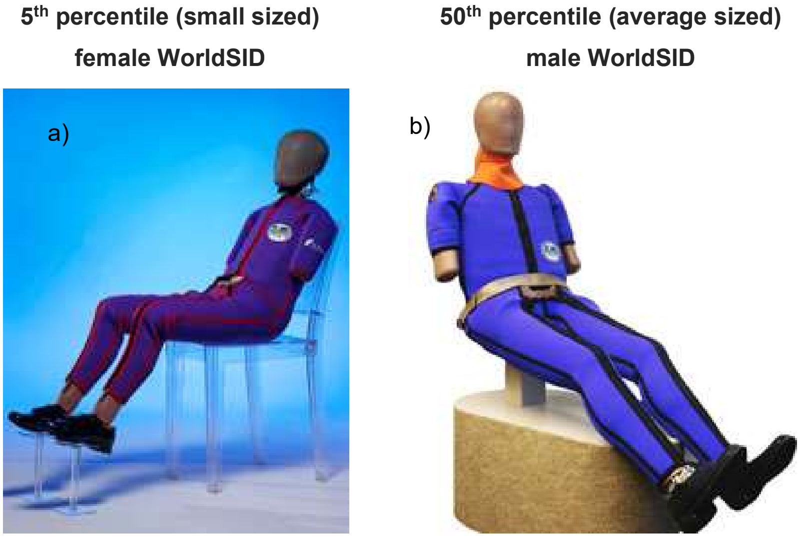


Figure 26. *The a) 5th percentile female and b) 50th percentile male WorldSID side impact dummies from Humanetics.*

Rear impact dummies

It has been established that the dynamic response of the Hybrid III is not human-like in low-speed rear impact tests (Cappon et al. 2000; Scott et al. 1993, among others). A new dummy, the Biofidelic Rear Impact Dummy (BioRID), was therefore developed during the late 1990´s, in a cooperation between Autoliv, Chalmers, Saab and Volvo.

- The 50th percentile (average sized) male BioRID dummy is more sophisticated in its spinal construction in comparison to the Hybrid III. The spine consists of the same number of vertebrae as the human spine, including lordosis of the neck and kyphosis of the thoracic spine (***Figure 27***). The motion is restricted to the sagittal plane. Furthermore, the dummy has a human-like mass distribution of the torso. The BioRID has been evaluated against data from volunteer tests (Davidsson et al. 1999ab) and PMHS test (Linder et al. 1999).

Figure 27. *The BioRID dummy.*

A further low-speed rear impact test dummy, the Rear Impact Dummy version 3D (RID3D) was developed during the late 1990´s. The RID3D is a modification kit (flexible spine and neck construction, a more realistic back shape, and the application of the ribcage design of the THOR dummy) for the 50th percentile Hybrid III male dummy (Cappon et al. 2000).

Both the BioRID and the RID3D have been shown to be more biofidelic in low speed rear impact tests than the Hybrid III dummy (Davidsson et al. 1999ab; Siegmund et al. 2001; Philippens et al. 2002).

Pedestrian dummies

Vulnerable road users (VRUs) are defined in the Intelligent Transport Systems (ITS) Directive (2010) as "*non-motorised road users, such as pedestrians and cyclists as well as motor-cyclists and persons with disabilities or reduced mobility and orientation*" (p. 4). According to the European Commission (2017), VRU transport accounts for the same proportion of road fatalities as cars (46%). VRUs, such as pedestrians, for whom efforts at enhancing traffic safety are still facing major challenges, have steadily been attracting more attention (World Health Organization 2009, 2015). Pedestrian injury protection can be evaluated by pedestrian dummies or with impactor forms (Simms & Wood 2009):

- The 50th percentile (average sized) male POLAR III is an advanced pedestrian test dummy developed by Honda (Akiyama et al. 2001). The dummy is used to study how pedestrians are injured or killed when hit by motorized vehicles. POLAR III has instruments to measure the level of injury throughout the body (POLAR III, ***Figure 28a***).
- The 5th percentile female, 50th and 95th percentile male Hybrid III Pedestrian dummies are Hybrid III dummies modified in the lower torso and knee regions for automotive-pedestrian impact testing (5th percentile female, 50th percentile and 95 percentile male Hybrid III Pedestrian; ***Figure 28b-c***). Non-automotive applications for this test dummy include equipment and injury potential studies of recreation vehicles, wheelchairs, medical equipment and sports gear.
- Pedestrian subsystem impactor tests include only specific parts of the body being struck to a car, for instance head form to bonnet, upper leg form to bonnet leading edge and leg form to bumper (***Figure 28***d). These tests do not take into consideration the relative motion of different parts of the body. They are mainly used for legislations.

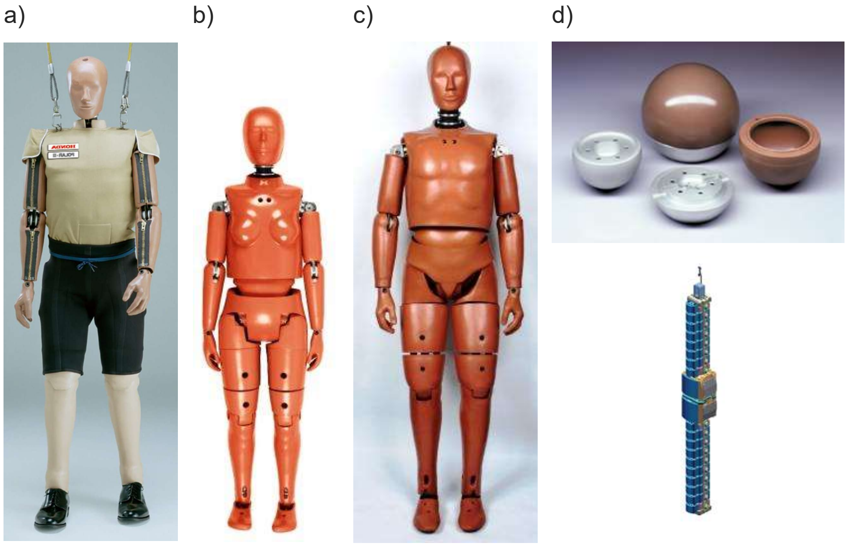


Figure 28. *a) The POLAR III pedestrian dummy from Honda (POLAR III) b) the 5th percentile female and c) 50th percentile male Hybrid III pedestrian dummies and d) pedestrian headform and flexible legform impactor from Humanetics.*

An overview of the crash test dummies currently for sale (Humanetics; Cellbond) is provided in ***Table 6***. More information about crash test dummies in general can be found on Humanetics webpage (Humanetics).

Table 6. *Crash test dummies, currently for sale (Humanetics; Cellbond)*

	Impact Direction	Dummy Type	Dummy Size			
			Female		Male	
			Small	Average	Average	Large
Humanetics	Frontal	THOR	×		×	
		HIII	×		×	×
		HII			×	
	Side	SID-IIs	×			
		ES-2			×	
		ES-2re			×	
		WorldSID	×		×	
	Rear	BioRID-II			×	
Cellbond	Frontal	THOR			×	
		HIII	×1)		×1)	×

1) Parts of the dummy

How representative are existing dummies of females?

Overall, the size of the 50th percentile (average) female varies around the world, with statures/masses ranging from 154.6 cm/52.5 kg (Thailand) to 167.3 cm/72 kg (The Netherlands; ISO/TR 2012). The corresponding numbers for the 50th percentile males are 166.3 cm/63.8 kg (Thailand) and 180.6 cm/83 kg (The Netherlands; ISO/TR 2012). Moss et al. (2000) concluded that the size of a world-harmonized 50th percentile adult male at that time would correspond well with the size of the 50th percentile adult male as defined by the UMTRI project (Robbins 1983a,b; Schneider et al. 1983). It was found reasonable to make the same conclusion regarding the 50th percentile adult female (i.e. stature 161.8 cm, mass 62.3 kg; ***Table 5***).

The 50th percentile male dummies roughly correspond to a 90th–95th percentile (large) female in terms of stature and mass (Welsh & Lenard 2001), but not in terms of mass distribution ***Figure 29***) and dynamic response. Only the extremes of the female population are accounted for by either the 50th and 95th percentile male dummies or the 5th percentile female dummy assessing adult occupant safety in regulatory and/or rating tests.

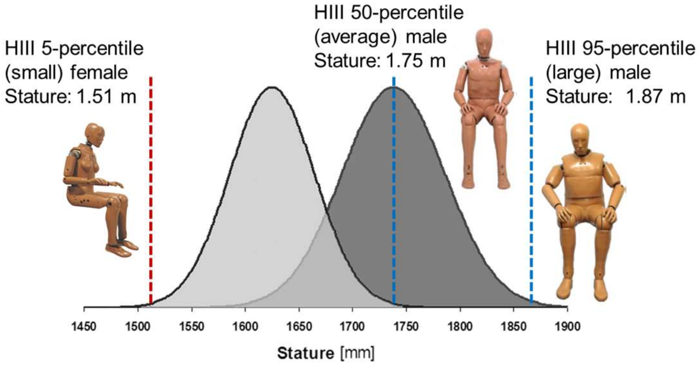


Figure 29. *Existing (adult) crash test dummy sizes in comparison to the distribution of statures for males and females (based on Pheasant & Haslegrave 2006).*

Mordaka & Gentle (2003) developed a biomechanical FE model of the 50th and 5th percentile female cervical spine, respectively, based on a male model. The objective of the study was to distinguish if females actually responded as scaled-down versions of males in rear impacts. It was found that detailed responses varied significantly between the genders and thus it was evident that female models based on scaled-down males would not suffice. The study substantiated the necessity for separate male and female biomechanical models. Mordaka & Gentle (2003) also stated that the need to revise car testing programmes and regulations, currently based on the average male, is evident.

Dummies in regulatory & consumer information tests

The 50th percentile male dummy is the most commonly used size during the development process of new safety concepts for frontal (***Table 7***), side (***Table 8***) and rear (***Table 9***) impacts. Consequently, it is unclear whether the safety is as good for an average sized female or persons of other sizes/ages (Welsh & Lenard 2001; Linder & Svensson 2019).

Table 7. *Overview of dummies used in regulatory (grey) and rating (white) test assessing adult occupant safety in frontal impacts. The table is based on public information from CARHS (www.carhs.de/en).*

			Frontal Impact Dummies			
			Female		Male	
			Small	Average	Average	Large
Europe	UN R16	R16 Manikin			×	
	UN R94	HIII			×	
	UN R137	HIII	×		×	
	EuroNCAP	HIII THOR	×		× ×	(×)
USA	FMVSS 208	HIII	×		×	
	US NCAP	HIII THOR	×		× ×1)	
	IIHS	HIII			×	
	Latin NCAP	HIII			×	
Asia	Japan Regulations	HIII			×	
	China Standards	HIII			×	
	KNVSS 102	HIII			×	
	India AIS (frontal, side)	HIII			×	
	JNCAP	HIII	×		×	
	C-NCAP	HIII	×		×	
	KNCAP	HIII THOR	×		× ×2)	
	Bharat NCAP	HIII			×1)	
	ASEAN NCAP	HIII			×	
AUS	ADR (frontal, side)	HIII			×	
	ANCAP	HIII THOR	×		× ×	(×)

1) *Planned (no date specified)*
2) *2022*

Table 8. *Overview of dummies used in regulatory (grey) and rating (white) test assessing adult occupant safety in side impacts. The table is based on public information from CARHS (www.carhs.de/en).*

			Side Impact Dummies			
			Female		**Male**	
			Small	**Average**	**Average**	**Large**
Europe	UN R95	ES-2			×	
	UN R135	World-SID			×	
	EuroNCAP	World-SID			×	
USA	FMVSS 214	ES-2re			×	
		SID-IIs	×			
		World-SID			×1)	
	US NCAP	ES-2re			×	
		SID-IIs	×			
		World-SID			×1)	
	IIHS	SID-IIs	×			
	Latin NCAP	ES-2			×	
Asia	Japan Regulations	ES-2			×	
		World-SID			×	
	China Standards	ES-2			×	
	KNVSS 102	ES-1			×	
		ES-2			×	
	India AIS (frontal, side)	ES-1			×	
		ES-2			×	
	JNCAP	World-SID			×	
	C-NCAP	SID-IIs	×			
		World-SID			×	
	KNCAP	World-SID			×	
	Bharat NCAP	ES-2			×1)	
AUS	ADR (frontal, side)	ES-2			×	
		World-SID			×	
	ANCAP	World-SID			×	
GTR2)	GTR 14 (Pole Side Impact)	World-SID			×	

1) Planned (no date specified)
2) Global Technical Regulation

Table 9. *Overview of dummies used in regulatory (grey) and rating (white) test assessing adult occupant safety in rear impacts. The table is based on public information from CARHS (www.carhs.de/en).*

			Rear Impact Dummies			
			Female		**Male**	
			Small	**Average**	**Average**	**Large**
Europe	EuroNCAP	BioRID II			×	
USA	FMVSS 202a	HIII			×	
	IIHS	BioRID II			×	
Asia	JNCAP	BioRID II			×	
	C-NCAP	BioRID II			×	
	KNCAP	BioRID II			×	
AUS	ANCAP	BioRID II			×	
GTR¹⁾	GTR 7 (head restraints)	BioRID II			×	

1) Global Technical Regulation

For example, the BioRID II dummy is not representative of the female population with the greatest frequency of whiplash injury (***Figure 30***). Data from Sweden, Switzerland and USA shows that the stature and mass distributions of females with whiplash injury correspond to that of the general population (Kihlberg 1969; Carlsson et al. 2014). Based on the assumption that this is applicable for any population in the world, the 50th percentile female dummy would correlate in size to the females who are most frequently injured in rear impacts. This may partly explain the differences found in seats equipped with RHR in protecting males and females against whiplash injury (***Figure 11***, Kullgren et al. 2013).

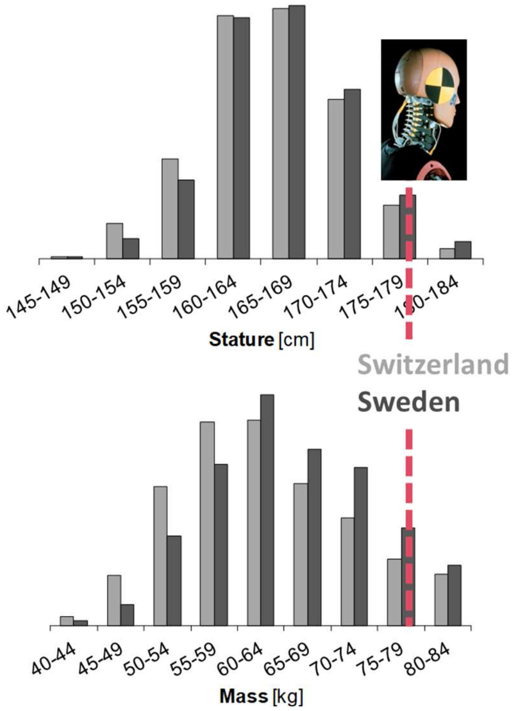


Figure 30. *a) Stature and b) mass distributions of female car occupants who sustained WAD in Sweden (from the Folksam database, light grey) and Switzerland (from the AGU Zurich database, dark grey) (Carlsson et al. 2014). The red line indicates the size of the average male dummy.*

Recent projects aiming at new types of dummies

50th percentile female rear impact dummy models – ADSEAT

A European research effort was initiated under the Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants (ADSEAT) project (Linder et al. 2013). The overall objective of ADSEAT was to provide guidance on how to evaluate the protective performance, for both females and males, of vehicle seat designs aiming to reduce the incidence of whiplash injuries. The project aimed at establishing the properties of an average female to be implemented into a finite element (FE) model in order to provide an improved tool for the development and evaluation of adaptive systems, with special focus son whiplash injuries protection. The anthropometry of a rear impact crash dummy model of the 50th percentile female was established based on data found in the scientific published literature. The FE model was named EvaRID (Eva = female; RID = Rear Impact Dummy) and details of its specification can be found in Carlsson et al. (2014). It was also shown that using a loading device, BioRID50F, resembling a 50th percentile female results in differences in kinematics and seat performance, compared to tests using a BioRID II (Carlsson

2012; Schmitt et al. 2012, Carlsson et al. 2021). With respect to female injury criteria it was concluded from the tests that using NIC (with a lower threshold value of 12 m^2/s^2) and N_{km} (with reduced intercept values of 29 Nm for extension moment, 53 Nm for flexion moment and 507 N for shear force) for females to be a suitable starting point.

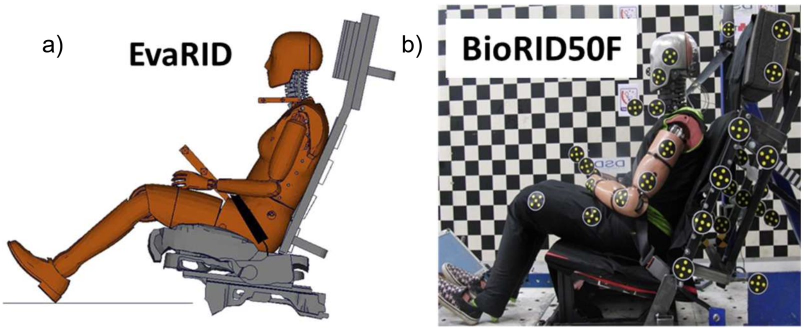


Figure 31. *The 50th percentile female rear impact a) FE model, EvaRID, and b) loading device, BioRID50F, developed within the ADSEAT project (Carlsson 2012; Linder et al. 2013; Carlsson et al. 2021).*

Obese 50th percentile male frontal impact dummy

As the obesity rate is growing worldwide, and injury statistics confirming that obese drivers are significantly more likely to die in an automobile crash, Humanetics has introduced an *Obese Crash Test Dummy* to help automotive suppliers improve safety for these larger sized occupants (Obese 50M). The prototype dummy was designed using a THOR-M platform and a 35 kg/m^2 BMI target. Additional mass was added to the upper and lower torso and upper legs, making it anatomically relevant to the obese driving population. In addition, new flesh material options were also explored. The preliminary analysis confirms that the obese dummy's seated posture translates further forward on the seat compared to a non-obese occupant and changes the seat belt positioning, thereby creating new challenges for effective restraint countermeasures and knee impact protection (Forman et al. 2009; Joodaki et a. 2015).

Figure 32. *The obese 50th percentile male prototype dummy from Humanetics.*

Elderly Anthropometric Test Device (EATD)

__Figure 33.__ The elderly, obese 50th percentile female prototype dummy from Humanetics.

A new elderly prototype anthropometric crash test dummy was developed in the EU SENIOR project, addressing questions regarding elderly people and what type of additional injury measures are needed as compared to current dummies (Beebe et al. 2017). Based on the ICAM's database, the anthropometry requirements for the EATD was determined to be a 70 years old female with a body mass of 73 kg and a stature of 1.61 meters. This represents occupants who are most likely to be injured. The UMTRI statistical body model (http://adultshape.org) was used for establishing the external shape of the dummy, while the internal organ shapes and positions from the ICAM's magnetic resonance imaging (MRI) scans provided guidance with the design of the internal organ shapes and positions. The experience designing and testing the obese 50th percentile male dummy (Obese 50M) was also used to review kinematic and flesh stiffness requirements for the EATD.

Virtual models

Validated mathematical models are used in crash simulations as a complement to the mechanical crash test dummies. There are two main types of mathematical simulation methods; Multi Body System (MBS) and the Finite Element (FE) method. An MBS simulates a system of rigid bodies connected by kinematic joints, as described in Schmitt et al. (2014). The motion of the system is analysed by exposing the system to external loading. The main advantage of MBS modelling is a better prediction of whole-body kinematics. The FE method approximates a solution to a boundary value problem by dividing the model geometry into smaller elements. This method allows the user to obtain the deformations and stresses in each part of the body. Contact interaction with the interior and restraints are preferably simulated using the FE method.

***Table 10.** Available crash test dummy models (Humanetics).*

	Impact Direction	Dummy Type	Dummy Size			
			Female		Male	
			Small	Average	Average	Large
Humanetics	Frontal	THOR	×		×	
		HIII	×		×	×
		HII			×	
	Side	SID-IIs	×			
		ES-2			×	
		ES-2re			×	
		WorldSID	×		×	
	Rear	BioRID-II			×	
Cellbond	Frontal	THOR			×	
		HIII	×1)		×1)	×

2) Parts of the dummy

So called Human Body Models (HBMs) have been developed during the latest decades. They are computational models of the human body, primarily developed in FE code. Until recently there were only average size male HBMs available (Kleinbach 2019). The EU-project VIRTUAL (https://projectvirtual.eu/) however, uses the average size female HBM "Viva" as a starting point. The project will develop a set of open-source HBMs representing both female and male road users. The long-term goal is to make these two, male and female, models "scalable" in such a way that they can be "morphed" into any adult size and age. The project will also demonstrate so called "virtual testing", meaning that physical dummy tests will be used as a verification and complemented with a range of crash simulations using the HBMs to assess the crash safety systems under varying conditions. In these simulations one may for instance vary the size and posture of the female and male models in order to ensure that the safety systems are robust and give good protection under varying conditions. Virtual testing is expected to become particularly important in the future when advanced adaptive restraint systems are expected to become more widely used. This type of system adapts automatically to the individual occupant as well as to the collision conditions of a given accident.

A review of Larsson (2020) gives an overview of how Finite Element (FE) Human Body Models (HBMs) are becoming more common as occupant substitutes in vehicle crash simulations. HBMs aim to be more realistic representations of human occupants than the FE-crash test dummy models as they model the actual human anatomy. In other words, HBMs intend to model the human occupant, as opposed to a virtual crash test dummy model, which models the corresponding physical crash test dummy.

In contrast to crash test dummy models, HBMs have the potential to evaluate injury risk at the individual organ or tissue level. They evaluate localized loading, for example pressure, stress or strain in the anatomical structures. HBMs also have the potential to be omni-directional occupant substitutes, representing human kinematics and injury risk in all impact directions.

To investigate vehicle occupant injury risk, detailed whole-body HBMs have been developed, such as the *Global Human Body Models Consortium (GHBMC)* (Gayzik et al. 2012; ***Figure 34***), *Total Human Model for Safety (THUMS)* (Shigeta et al. 2009; ***Figure 35***), *SAFER HBM* (Iraeus & Pipkorn 2019; ***Figure 36***), and *VIVA+ family of Open source HBMs* (John et al. 2021; ***Figure 37***). These HBMs are intended for predicting the whole-body occupant interaction with the vehicle and safety systems and the resulting organ blunt trauma injury risk.

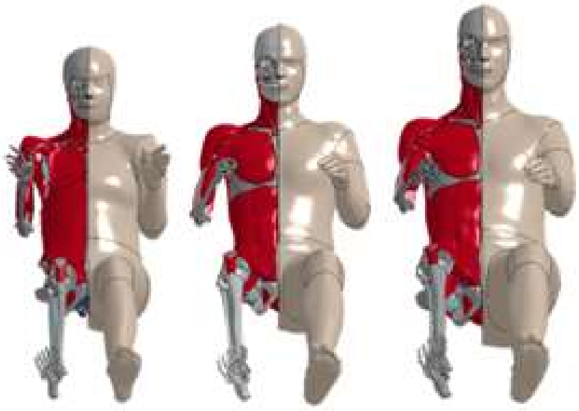


Figure 34. *The current official GHBMC family of HBMs (www.ghbmc.com; 2021). It is available in three adult sizes: the 5th percentile female [F05]; the 50th percentile male [M50]; and the 95th percentile male [M95]. Each of the three sizes are available in two versions: Simplified; Detailed. The simplified version is also available as a standing pedestrian.*

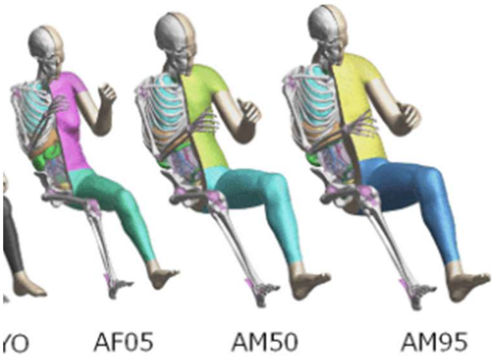


***Figure* 35.** *Current official THUMS family of HBMs (www.toyota.co.jp/thums/about; 2021). It is available in three adult sizes: the 5th percentile female [AF05]; the 50th percentile male [AM50]; and the 95th percentile male [AM95].*

***Figure 36.** The current SAFER HBM, in the middle the average size male M50 and on its sides two morphed versions (Larsson et al. 2021).*

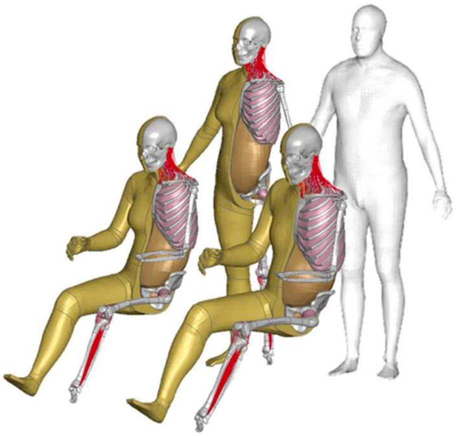


***Figure 37.** Current VIVA+ family of Open source HBMs. Based on one and the same mesh the VIVA+ can be morphed to both female and male, of various sizes, and ages. The picture shows the current female 50F and male 50M average sizes, 50 years of age, in both seated and standing postures (John et al. 2021).*

One main goal of HBM initiatives such as the SAFER HBM and the VIRTUAL project are to define the general workflow of a “*virtual test procedure*” that starts with a physical test that works as a reference for validation of the virtual simulation. The virtual simulation set-up is then compared to the physical test set-up by replicating the physical test conditions, to verify the validity of the virtual simulation test set-up. As an example, VIRTUAL uses the virtual dummy models to validate the FE environment of the simulation. Later the dummy model is replaced by the HBM and new simulations are performed. The virtual simulation test set-up will then be employed to study a range of parameter variations, for example occupant posture, sex and size as well as crash conditions including speed change and impact direction. This enlarged virtual evaluation matrix will enable a far more robust assessment taking the real-world variability into account.

When the virtual simulation set-up is validated this could then be used in rating tests, e.g. NCAP, and maybe later on even in regulations. It goes very well in line with the goal of developing the rating and regulation tests to be more robust, i.e. ensuring that safety systems address all occupant sizes, ages and genders. Today only one test configuration is tested for each crash scenario, since physical testing and dummy availability is limiting. When validated HBM and vehicle models are available, a large matrix of test speeds, impact angles and occupant variations can be assessed, but also e.g. varying seating or restraint positions. HBMs also enable new injury criteria that are based on actual injury in a human, rather than loads on a dummy to estimate injury outcome indirectly which is often limited to what injuries can be predicted. One such example is brain injury, but also organ injuries and detailed rib fractures are other but not the only examples, this list can almost be unlimited. We have also seen lately a rapid development in pre-crash sensing and also occupant detection sensing is under-way. If you combine this new possibility of advanced occupant simulations with knowledge that an inevitable crash is about to happen and how the occupant is positioned, body size etc, fascinating developments can then be foreseen in restraint systems that can be adaptive to be optimized in each individual crash. This could have a significant potential in reducing fatalities and severely injured, especially in the groups of occupants/crashes that today fall outside the crash test standards used.

Conclusions

- The crash related injury risks are higher in females than males through the whole range of injury severity, from minor to fatal.
- Female and male elderly drivers have more injuries and fatalities per distance travelled compared to younger drivers.
- Female and male obese drivers involved in crashes are significantly more likely to be fatally injured than drivers of normal Body Mass Index (BMI).
- Female occupants are poorly represented by existing dummies.
- Elderly and obese, female and male occupants are poorly represented by existing dummies.
- Human body models of females and males are being developed to enable simulations of variations in size, age, seated posture etc. These tools are expected to provide a powerful extension to the crash test dummies in future virtual test procedures.

Future Needs

- There is a need to further develop crash test dummies and occupant models, which represent both men and women. These need to be available in different sizes and ages. This is important to enable robust assessment of the injury reducing effects of restraint systems in all impact directions/crash scenarios.
- It is recommended that information about body size (stature and mass) is included in traffic injury databases (such as STRADA) in order to assess differences in injury risks between existing occupant categories.
- Data need to be collected, analysed and reported from injury statistics and testing (volunteers, PMHS, etc.) for females and males separately in order to increase the understanding and knowledge of the influence of gender in relation to other factors.
- The development of new automated vehicles drives the development of new advanced sensor systems. This leads to new possibilities to develop restraint systems that adapt to occupants of different size, age and gender. This development will require access to occupant models that represent the full variety of real-world occupants.

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