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Short communication

Average female and male dummy responses in rear impact tests with car seats compared to real-world injury outcomes

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Globally, 1.19 million people lose their lives annually in the road transport system, and around 10 million people are severely injured. Motor vehicle crashes resulting in soft tissue neck injuries, referred to as whiplash injuries, are the most common and costly disabling injuries for vehicle occupants. Injury statistics show that seat design plays an important role in the protection from these injuries in low severity rear impact crashes. In addition, the injury protection varies based on occupant sex. Relatively, most car models provide better protection for males, although that is not always the case. In the assessment of occupant safety, both in regulation and consumer tests, the average male model represents the average adult occupant. The hypothesis of this study was that vehicle seats that have shown different real-world performance regarding whiplash protection between female and male car occupants, could show differences in dynamic responses for crash test dummies representing both sexes in crash tests. In this study an average female and male crash test dummy were used in tests at 16 km/h in two different seats (Saab 9-3 and Audi A4), which had shown significant differences in neck injury protection performance for females and males in real-world injury crashes. The results showed noticeable differences in the dynamic responses, highlighting that evaluation results for one dummy sex, exclusively, are inadequate for providing insights into the dynamic response of the other. This study is pioneering assessing crash injury protection for the two main types of the adult population, female and male, using average size, mass, geometry and dynamic properties models, that also shows the link between real-life injury outcome and assessment of safety performances pointing to the future of how a more robust assessment of occupant safety can be achieved to further reduced the loss of life and health in the road transport system.

1. Introduction

Globally, 1.19 million people lose their lives annually in the road transport system, and for children and young adults up to the age of 29, it is the leading cause of death (WHO, 2023). Furthermore, around 10 million people are severely injured of which some of the injuries are causing permanent medical impairment (PMI). This is an epidemic, which can be substantially reduced by applying the knowledge of injury biomechanics, engineering and technologies preventing crashes from occurring. The Safe System and Vision Zero (among others Tingvall & Haworth, 1999; Corben et al., 2022; WHO,

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2022; Edvardsson Björnberg et al., 2023 aim to ensure safe transport for all road users by safeguarding that human tolerance levels in a crash shall not be exceeded. Many studies have shown higher risk or odds for females than males in the event of a crash (among others Evans, 2000; Bedard et al., 2002; Bose et al., 2011; Parenteau et al., 2013 and Forman et al. (2019). Kullgren et al. (2020) showed that the injury risk for females and males remains in the order of 50% higher for females than males, despite improvements in vehicle safety since the 1980s. Craig et al. (2026) combined 22 years of data of severe and fatal injuries from the National Automotive Sampling System–Crashworthiness Data System (NASS-CDS) and the Crash Investigation Sampling System (CISS) in the US to document the odds of various injury outcomes for females versus males in 150 different models. The study showed that females had significantly higher odds of injury than males in 39 (OR > 1.0, p-value .05) out of 150 models. For the remaining 111 models, females had non-significantly (p > .05) higher injury odds in 81, compared to 30 for males. Males did not have significantly higher injury odds in any models. The largest difference in injury risk is found for soft tissue neck injuries, so called whiplash injuries. Injury statistics from the late 1960s until today show that females have a higher risk of sustaining whiplash injuries than males, ranging from 1.5 to 3 times higher (among others Kihlberg, 1969; O'Neill et al., 1972; Otremski et al., 1989; Morris & Thomas, 1996; Dolinis, 1997; Temming & Zobel, 1998; Richter et al., 2000; Chapline et al., 2000; Kullgren et al., 2003; Krafft et al., 2003; Jakobsson et al., 2004; Storvik et al., 2009 and Kullgren et al., 2020). Furthermore, some concepts for whiplash protection seats have proved to be more effective for males than females (Kullgren & Krafft, 2010; Kullgren et al., 2013).

Motor vehicle crashes resulting in soft tissue neck injuries, referred to as whiplash injuries, are still the most common and costly of vehicle occupant injuries leading to PMI (Kullgren et al., 2020). Kullgren et al. (2020) shows that the difference between protection performance between females and male has remained constant during the four decades that the study covers. Based on insurance data from one of Sweden's largest insurance companies, Folksam, Kullgren et al. (2020) shows that the injury risk for females and males remains in the order of 50% higher for females than males, despite improvements in vehicle safety since the 1980s. Two-car crashes reported by the police were used to calculate relative risk of any injury, fatal and serious, respectively (n=117,234). Occupant injuries reported by Swedish hospitals were used to assess risk of PMI (144,521 diagnoses for 55,597 occupants). The cars were categorised in 10-year periods according to year of introduction. Injuries leading to PMI for different body regions, in both females and males, were also compiled. The study shows that although vehicle safety has improved since, the difference in protection of females and males, the risk for females is still in the order of 50% higher. For the latest model year of introduction interval (2010-2019) in Kullgren et al. (2020), soft tissue neck injuries accounted for 43% of all injuries resulting in long-term consequences. These injuries most often occur at low changes of velocity, between 10 and 25 km/h (Eischberger et al., 1996; Hell et al., 1998; Krafft et al., 2005), and the majority occur in rear impacts (among others Lundell et al., 1998; Watanabe et al., 2000). Crash test dummies are used to evaluate human responses in different crash configurations. Current occupant safety testing standards utilise dummies of the average male size as the norm (Linder & Svedberg, 2019; Linder & Svensson, 2019). In the evaluation of occupant safety, crash tests are focusing on the 50th percentile (average) male dummy (height: 177 cm; mass: 78 kg). The vehicle regulations in the United Nations Economic Commission for Europe (UNECE) requires that an average male model is used as the driver in all tests with an occupant model. The same applies for the Federal Motor Vehicle Safety Standards (FMVSS) with one exception. In the high-speed frontal test, FMVSS No. 208 (FMVSS, 2026), a small occupant model, the Hybrid III 5F (5th percentile female) is placed in the driver seat.

For low severity rear impacts, the average male size BioRID (Davidsson et al., 1999), is still the only available dummy, despite several inherent differences between females and males known to influence both human body dynamic response and its interaction with the seat. Apart from the obvious difference in body stature, seated height and mass, the differences also include the shape of the torso (shoulder width, breasts and waist), centre of gravity of the torso, hip and pelvis dimensions, and the joint stiffness of the spine corresponding to muscle strength. The data of an average female was compiled in the virtual dummy model EvaRID (Linder et al., 2013). Later, building on the concept of BioRID, the world first crash test dummy of an average female, the Seat Evaluation Tool (SET) 50F, together with its male counterpart, the SET 50M, for low severity rear impact crash testing, were developed (Karemyr et al., 2022). The SET 50F and 50M are the first pair of crash test dummies representing both an average female and an average male, based on the same design and the same set of anthropometric data. Using average size, mass, geometry and dynamic properties models of the two main types of the adult population, females and male, a more robust assessment of occupant safety can be achieved.

The hypothesis of this study was that vehicle seats, that have shown different real-world performance regarding whiplash protection between female and male car occupants, can be identified in crash tests with crash test dummies representing both sexes of the population. Thus, the objective of this study was to identify potential differences in dynamic response of the SET v0.2 50F and 50M in rear impact tests, according to the protocol of the European New Car Assessment Programme (Euro NCAP), in two different seat types chosen based on their significant differences in real-world crash protection outcomes for females and males.

2. Materials and methods

Two different seats showing significant differences in protection of female and male occupants in real-world injury statistics were exposed to the Euro NCAP Medium severity whiplash testing pulse at 16 km/h (Euro NCAP, 2023). The tests were conducted with two different dummies representing an average female and male adult occupant, the SET v0.2 50F and 50M.

2.1 Two seats with different real-world injury protection performances for females and males

The seats were chosen based on their protection performance of females and males based on real-world injury data from Folksam Insurance (as per data used in Kullgren et al., 2013). Two seats were selected. One seat that has been shown to provide better protection against injuries leading to PMI for males compared to females, the Saab 9-3 (year model 1998-2002 with a reactive head restraint, RHR), and one seat that, conversely, has been shown to provide better protection for females compared to males, the Audi A4 (year model 1995-2000). Table 1 shows number of persons with initial symptoms, risks of PMI and confidence intervals (CI). Due to changes in the classification of long-term consequences used by Swedish medical experts for the duration of the data collection, weight factors for calculating the number (n) of PMIs in Table 1 were used (described in detail in Kullgren et al., 2013). This resulted in n PMI becoming a decimal number.

The Audi seat is a standard seat without specific features addressing the protection of whiplash injuries. The Saab seat has a particular design, the SAHR system, aimed at protecting the occupant. The mechanical principle of the SAHR system is that a mechanism inside the seat is activated by the torso when it sinks into the seat, and thereby the head restraint is moved forward to provide earlier head-to-head restraint connection, and thereby improved injury protection.

Table 1. The number of injured persons (N), number of PMIs (n), risks of PMI and 95% confidence intervals (CI) for females and males in the two selected seats, the Saab 9-3 and the Audi A4 (based on the data in Kullgren et al., 2013)

	Females				Males			
Car, year model / seat	Number initial symptoms (N)	Number PMI (n)	Risk of PMI (%)	Risk of PMI, 95% CI	Number initial symptoms (N)	Number PMI (n)	Risk of PMI (%)	Risk of PMI, 95% CI
Saab 9-3, 98-02 /RHR	163	7.8	4.8	3.3	80	0.0	0.0	0.0
Audi A4, 95-00 / -	486	7.3	1.5	1.1	413	10.4	2.5	1.5

2.2 The SET 50F and 50M in brief and the SET v0.2 compared to the SET v0.1

The geometries of the two SETs correspond to those of a 50-year-old average female and male, respectively, generated from the database HumanShape (https://humanshape.org/). These are the same geometries as those used for the virtual human body models (HBMs) VIVA+ 50F and 50M (John et al., 2022). Experience from the development of the BioRID, BioRID II (Davidsson et al., 1999; Linder, 2002) and BioRID P50F (Carlsson et al., 2021) served as input for the development of the SETs. The first version of the SETs, the SET v0.1 is described in Karemyr et al. (2022) with the drawings available at OpenVT.eu. Two changes were implemented in SET v0.2 compared to SET v0.1. Firstly, the mass was increased to better match the equivalent sections of the VIVA+ 50F and 50M. Secondly, rubber blocks were placed between the vertebrae of the neck to provide improved stability of the neck in its initial position.

The SETs' thoracic and lumbar spine segments can bend in the frontal and sagittal planes and allow axial rotation. The number of vertebrae has been reduced compared to the BioRID II, with the springs and the rotational damper placed inside the head of the SETs (as opposed to along the thoracic spine in the BioRID II). Two different stiffness properties of PLIXXOPOL FI 4710W033 were used for the chest and stomach. The chest consists of two left/right halves, and the lower part of the torso was cast in one piece. Metal pins extending laterally from the spine guide the chest and stomach in place. The shoulder is movable forwards and rearwards relative to the torso.

In the construction of the SETs, some parts were sourced from other crash test dummies. For the SET 50F, the head and arms of the Hybrid III 5F were used. The Hybrid III 5F head was used unchanged. The mass and size of the arms and legs were adjusted to that of the 50th percentile average female from HumanShape and the upper arms modified to make it attachable on the shoulder of the SET 50F. The BioRID pelvis was used with modifications, i.e., increased width and decreased depth (described in more detail in Karemyr et al., 2022). For the SET 50M, the Hybrid III 50M head, arms and legs were used unchanged, except for the upper arms that were adjusted to attach to the shoulder of the SET 50M. The pelvis from the BioRID was used for the SET 50M. The mass of the SETs v0.2 was increased, compared to the SETs v0.1 (Karemyr et al., 2022), to match the total mass and the distribution of the mass, of the head, arms, torso, pelvis and legs of the VIVA+ models, Table 2.

2.3 Rear impact sled tests

The sled tests were run on the Inverse Crash System by Mannesmann-Rexroth, at Autoliv, Sweden. Seats within the year range of the car models (Table 1) were acquired from car dismantling facilities in Sweden and were in good condition without any visible damage. A new seat was used for each test. The seats were positioned in accordance with the Euro NCAP protocol for dynamic testing version 4.2 (Euro NCAP, 2023). The head restraint position, seat back and height adjustment were positioned in accordance with this protocol. To position the SET v0.2 50M and 50F on the seat, they were lowered onto the seat from above and guided

Table 2. The mass of the SET v0.2 50F and 50M and the VIVA+ 50F and 50M

	SET v0.2 50F mass (kg)	VIVA+ 50F mass (kg)	SET v0.2 50M mass (kg)	VIVA+ 50M mass (kg)
Head	3.9	3.8	4.4	4.4
Arms	5.2	6.0	9.5	7.7
Torso and Pelvis	37.6	32.5	39.9	40.6
Legs	16.0	19.9	23.5	23.5
Total	62.7	62.2	77.3	76.2

backwards into the seat back. The head was adjusted when needed to mimic a forward-viewing position. The SETs were restrained with a conventional 3-point seat belt, the same generic 3-point retractor seat belt was used for both seats. On-board high-speed video cameras recorded the tests at 1,000 fps. The SETs had video targets placed on the head, the first thoracic vertebra (T1) and pelvis. Gyros with 3-axis accelerometers were placed inside the head and at T1, T8 and pelvis (described in more detail in Linder et al., 2023). The signals were sampled at 10 kHz and filtered according to the SAE J211 recommendations, which for the head linear acceleration is Channel Frequency Class (CFC) 1000. The Neck Injury Criterion (NIC) was calculated and NICmax identified in accordance with Boström et al. (1996) and Boström et al. (2000). NIC is calculated as:

$$\text{NIC} = 0.2 * a_{\text{rel}} + v_{\text{rel}}^2$$

where a_{rel} and v_{rel} are the relative T1-to-head centre of gravity, x-acceleration and velocity, respectively.

3. Results

The results of the sled tests, when applying the mid severity Euro NCAP whiplash tests pulse with the SET v0.2 50F and 50M in the seats, showed both similarities and differences in the dynamic response of the two different seats. The head and T1 x-acceleration of the SETs v0.2 from tests with the Saab 9-3 and Audi A4 seats, are shown in Figure 1 and 2. The calculated NIC as a function of time is shown in Figure 3.

The NICmax of the calculated NIC (Figure 3) is listed in Table 3 together with the risk of PMI for females and males from Table 1.

The difference in both initial position and the dynamic response of the SET 50F and 50M in the Saab and Audi seat is shown in the images of the initial position and the position of the dummies at NICmax (Figure 4 and 5).

4. Discussion

The Safe System and Vision Zero aim to ensure safe transport for all road users meaning that human injury tolerance levels shall not be exceeded in a crash. The results of the present study are a clear example of the potential for improvement by making sure that countermeasures are tested for protection also of the female part of the population.

When comparing the response of the crash test dummies SET v0.2 50F and 50M in the Saab 9-3 and Audi A4 seats in the mid severity Euro NCAP whiplash test, noticeable differences in dynamic head-neck response were observed. The two seats were selected from the dataset of Kullgren et al. (2013). In Kullgren et al. (2013) the Saab 9-3 (Model Year (MY) 1998-2002) seat showed better protection for males compared to females, while the Audi A4 (MY 1995-2000) seat showed better protection for females. The risk of PMI for males in the Saab 9-3 seat was 0.0 % and 4.8 % for females. In the Audi A4 seat, the risk of PMI was 2.5 % for the males and 1.5 % for females. Table 3 shows NICmax for the SET 50F and SET 50M together with the risk of PMI, for females and males. Regarding whiplash protection, the two seats are of different generations. The Saab 9-3 has a reactive head restraint (Wiklund & Larsson, 1998) that pushes forwards and upwards when the body presses against the seat back, while the Audi A4 (95-00) was launched before whiplash protection systems were introduced and does not have a specific protection system.

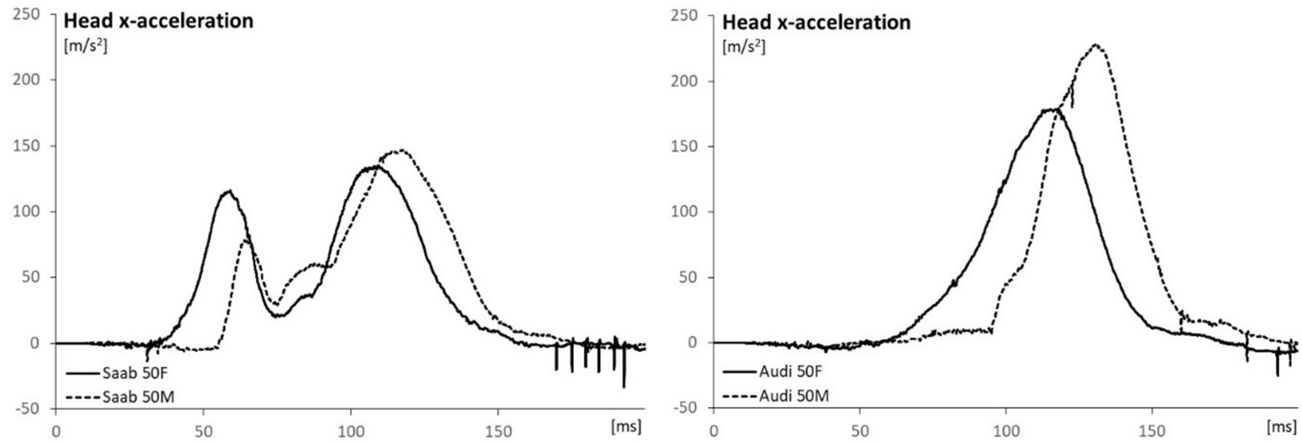

Figure 1. The head x-acceleration of the SET 50F and SET 50M in the Saab 9-3 and Audi A4 seats in the mid severity Euro NCAP whiplash tests pulse.

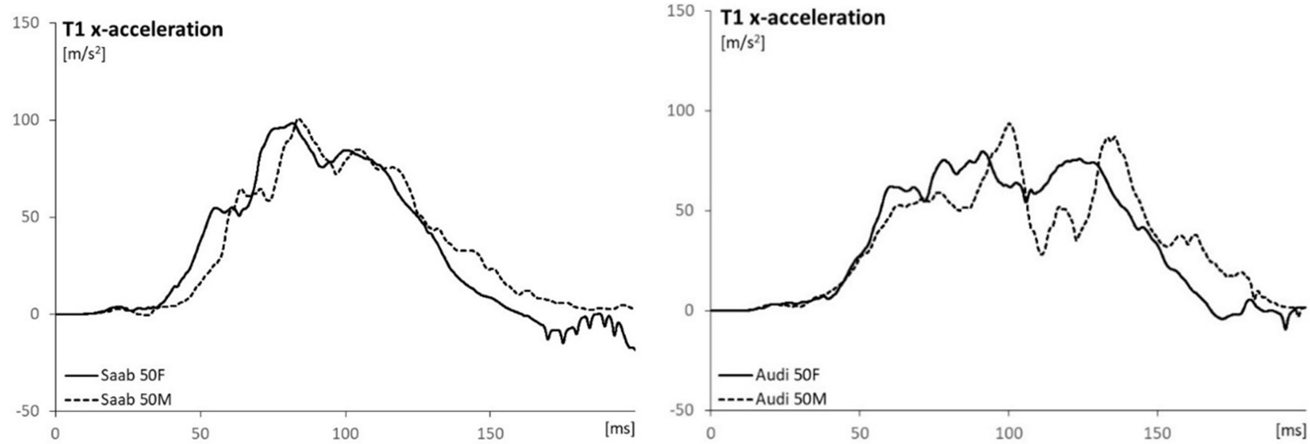

Figure 2. The T1 x-acceleration of the SET 50F and SET 50M in the Saab 9-3 and Audi A4 seats in the mid severity Euro NCAP whiplash tests pulse

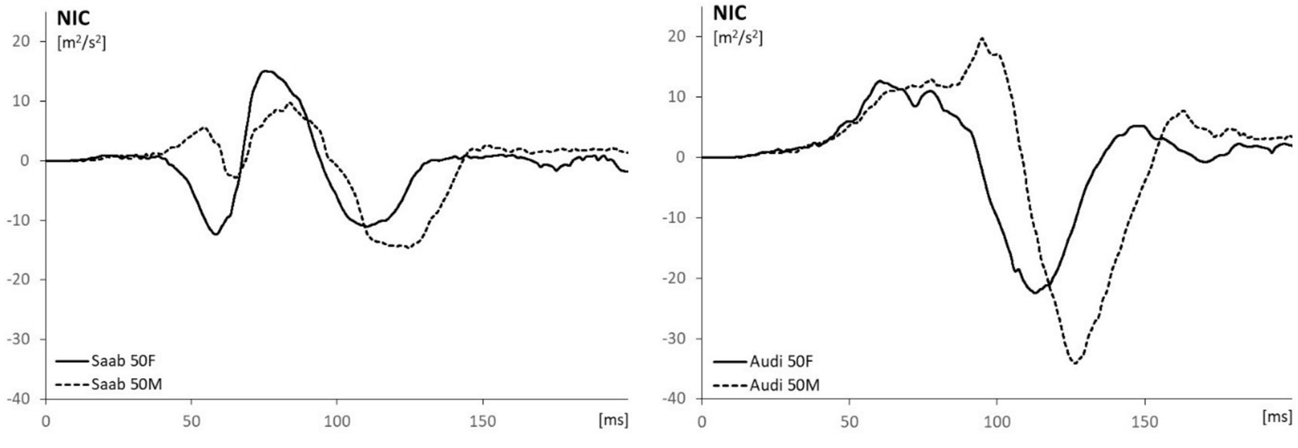

Figure 3. The calculated NIC values based on the measurements of the SET v0.2 50F and 50M in the Saab 9-3 and Audi A4 seats in the mid severity Euro NCAP whiplash tests pulse

Table 3. The NICmax for the SET 50F and SET 50M (Table 3) in the Saab 9-3 and Audi A4 seats in Euro NCAP mid severity whiplash test and the risk of PMI for females and males from Table 1

Car model	Femalerisk of PMI (%)	SET 50FNICmax (m^2/s^2)	Malerisk of PMI (%)	SET 50MNICmax (m^2/s^2)
Saab 9-3	4.8	14.5	0.0	9.7
Audi A4	1.5	12.3	2.5	19.0

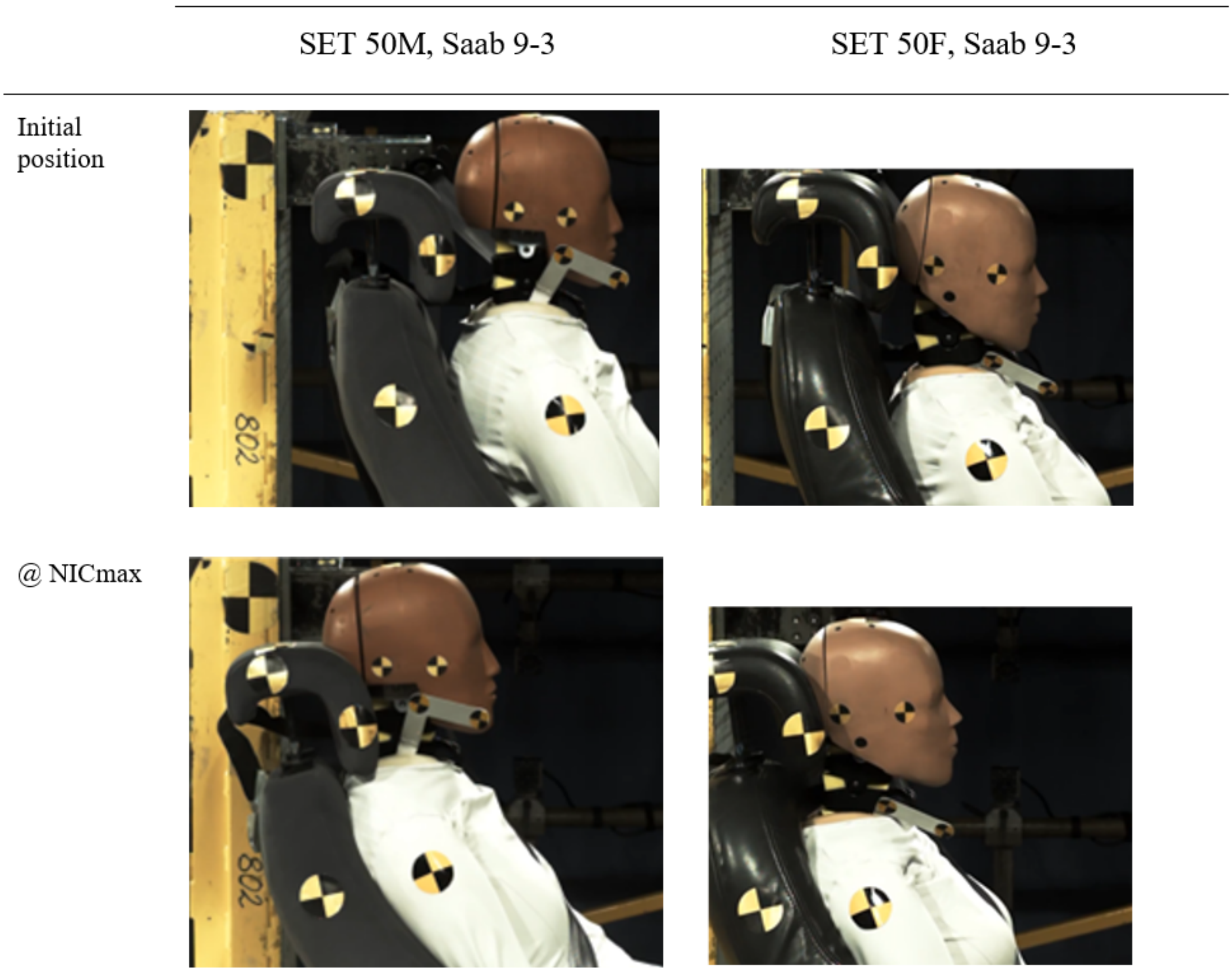

Figure 4. SET 50M (left) (top) and SET 50F (right) in the Saab 9-3 seats, initial position (top) and at the occurrence of NICmax (bottom) from the high-speed video of the impacts. Picture credits: Autoliv

The NIC was chosen for the comparison of the risk of injury based on the conclusions of Ono et al. (2009), that NIC is an appropriate neck injury evaluation parameter. Further research is required to establish thresholds of injury criteria for the average female model, such as has been done for the average male model. In addition, regarding NIC, the influence of negative values before the maximum value is recorded should be thoroughly researched. Potentially, NICmax could be complemented to capture the protraction motion prior to retraction and its influence on risk of injury.

The characteristics of the T1 x-acceleration were similar for both the SET v0.2 50F and 50M in each of the seat models. However, the head x-acceleration differed distinctly between the seats. For the SET v0.2 50F in the Saab 9-3 seat, the head never rotated rearwards, instead the head underwent a forward motion

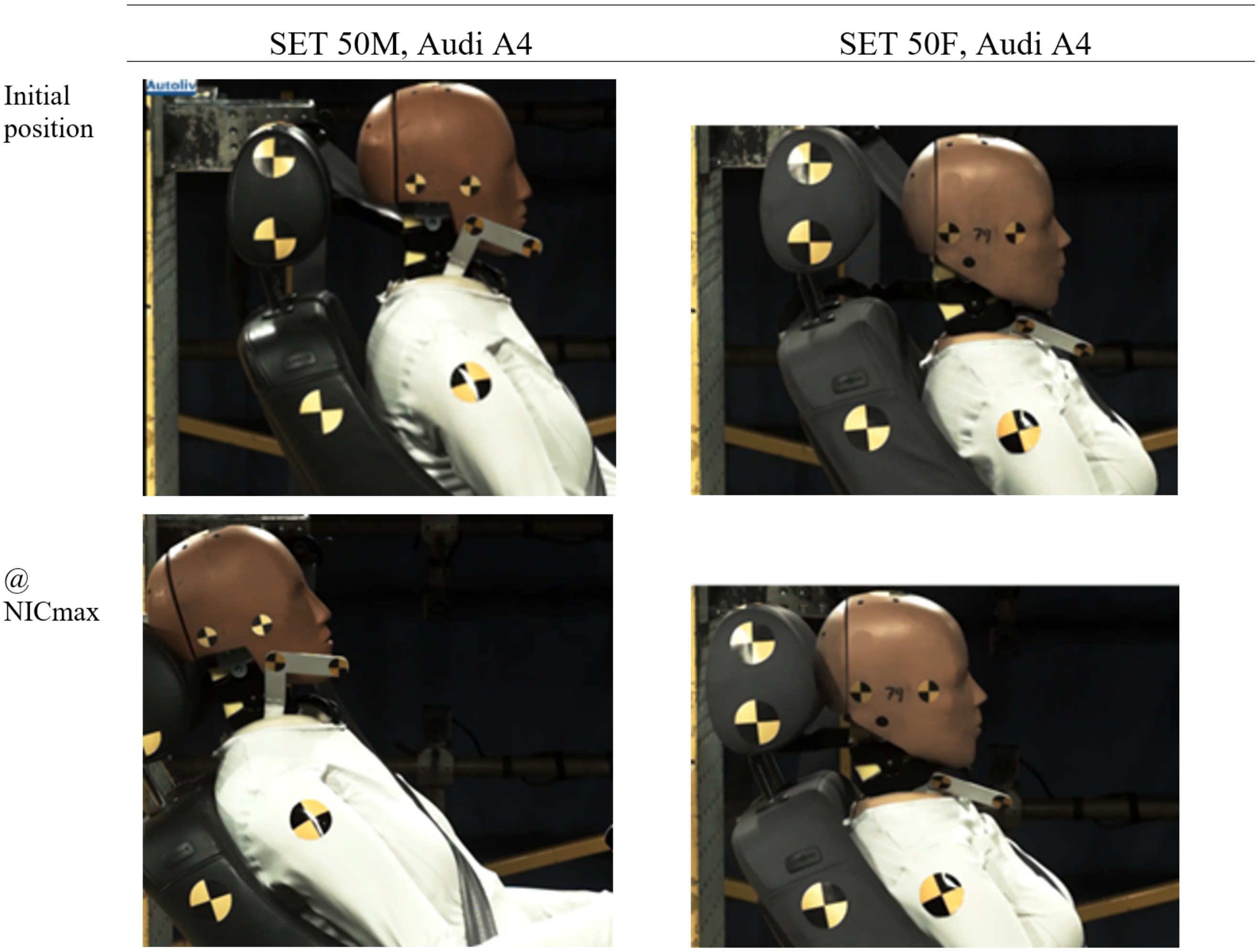

Figure 5. SET 50M (left) (top) and SET 50F (right) in the Audi A4 seats, initial position (top) and at the occurrence of NICmax (bottom) from the high-speed video of the impacts. Picture credits: Autoliv.

creating flexion of the neck, showing an early double peak in the head x-acceleration. In fact, in contrast to the three other tests, the head x-acceleration was initiated before the T1-acceleration. In the Audi A4 seat the head of the SET 50F was supported earlier in the event than the SET 50M, and the SET 50F showed an earlier peak head x-acceleration.

This study provides examples of differences in dynamic response between average female and average male crash tests dummies in rear impacts and related differences in loading of the structures of the neck. The results in Figures 1-3 illustrate the differences in occupant responses of the two seats, as well as the female and male models (SET 50F and SET 50M). In the Saab seat, the SET 50F showed an initial forward head motion which was not present in the SET 50M. In the Audi seat, the SET 50F head relative to T1 motion was reduced compared to the SET 50M, where the seat back angulated backwards delaying the head-to-head restraint contact. This study comprises the results of two different seats at one impact severity. Future tests with additional seat types with known real world protection performance with the SET 50F and 50M, as well as additional severities, would be required to establish how well the tests capture differences in known protection levels found in real world data.

The motion data from the tests in this study are found in Hjort et al. (2026). Hjort et al. (2026), presents an open-source software that provides motion data from sensors in a crash test dummy. Sensors needed for such analysis are a combination of gyros and accelerometers. The evaluation was done using signals from the sensors at four locations, one inside the head and at three locations along the spine of the SET v0.2 50F and 50M. The comparison showed differences in the time history of the displacements for SET 50F compared to SET 50M in the Saab and the Audi seats. For the linear displacement, the peak values were higher for the SET 50M than the SET 50F (Hjort et al., 2026), while the opposite was found for the relative angular displacement. In addition, for the Saab seat the peak head relative to T1 angular and horizontal displacement (measured during the first 150 ms after impact) had a positive sign for the SET 50F and negative for the SET 50M. The results illustrate that average female, and male responses are not scalable to each other. The responses depend on several factors, such as the construction and the dynamic properties of the seat in addition to the loading patterns of the dummies, which require representation of both parts of the adult population to assess the safety performances for both sexes.

In this study, seats with known injury protection performance were tested. Could the SET 50F and 50M also reveal differences in the dynamic responses of seats in new cars? Endo et al. (2026) performed rear-impact sled tests using the SET 50M and SET 50F dummies, seated in a regular 2025 model-year vehicle seat. The test conditions were in accordance with the Euro NCAP test protocol (Euro NCAP, 2023), including seat position and acceleration pulses. Two acceleration pulses were applied: the Medium (16 km/h) and High (24 km/h) severity pulses, maximum acceleration 11 g and 7.5 g, respectively. The head and the T1 x-displacement relative to the sled were smaller for the SET 50F than the SET 50M. The tests also show that the SET 50F exhibits a larger relative rotation angle between the head and T1 compared to the SET 50M, which is in line with the results of Hjort et al. (2026).

The interaction between the dummy and the seat in a rear impact is a complex dynamic event. There are several properties of the average female and male that can influence the safety performances in such an event. Not only do the weight and stature of the average female and male bodies differ, the centre of gravity of their torsos also differs, as do the width of the hip and chest area in addition to differing joint stiffness levels (to mention some but not all differences). Also influencing the dynamic response is the initial loading pattern of the seat by the dummies. The static deformation of the vehicle seat cushion was studied using the SET 50F and SET 50M by John et al. (2026). In John et al. (2026), the deformation was measured at nine measurement points across the seat cushion of a Toyota Auris seat. The pins were inserted through the cushion, and vertical displacement was recorded under static load. The results show that the rear part of the cushion was more deformed by SET 50M than SET 50F. The deformation is influenced both by the larger mass of the average male, and the differences in the contour of the hip area.

A limitation of this study is that used seats were used in the testing. However, injury data are not available for new seats. The approach applied in this study is a way to extract as much knowledge from the injury data as possible, whilst well aware that it is impossible to create identical conditions for comparable testing to the real-world cases. The question remains; are the performance of the Saab and Audi seats interchangeable. Such a result seems unlikely based on the images from the high-speed film and supported by the acceleration and motion data, Figure 1- 4. A further limitation is that repeatability of the SET v0.2 response was not included in this study. Hence, further studies are required to establish repeatability. A related limitation is that the sled test set-up uses a generic 3-point retractor belt that is not fully representative of the belt system of the actual car. However, since the seat belt does not take any load until late in the crash test, it has no influence on the critical early phase of the dummy motion, where the most severe neck motion and loading are observed.

A potential limitation of this study is that the weight and stature of the SETs may differ from the average sizes in the accident sample.

However, any differences in anthropometrical data in the Swedish population (Hanson et al., 2008) are expected to be insignificant in comparison to the anthropometrical data of the SETs. The difference in average height and stature is similar for the males and females in the Swedish population and the SETs. Swedish population: Female 66.1 kg, 166.2 cm, male 82 kg/180.0 cm, SET V0.2 50F 62.7 kg, 161.6 cm, SET v0.2 50M 77.3 kg/175.6 cm. The difference in weight between the SET v0.2 50F and 50M is 14.6 kg, and the difference between the average female and male in the Swedish population is 15.9 kg. The difference in stature between the SET v0.2 50F and 50M is 15 cm, and the difference between the average female and male in the Swedish population is 13.8 cm.

Currently, all adult occupants in low severity rear impact tests for the assessment of occupant protection, are represented by the average male model. As shown in this study, the availability of the SET 50F allows running tests with both a model of an average female and average male, either with the SET 50F together with the BioRID or the SET 50F together with the SET 50M, facilitating detection of differences in protection in new cars. Additional studies establishing thresholds for injury criteria and seating procedures for an average female model are required, before assessing safety using the model of the average female together with the average male. However, since injury criteria thresholds have been established for the average male model, the same procedure can be applied for the average female model. Regarding the NIC, Lemmen et al. (2013) suggested a threshold of 12 m^2/s^2 for an average female dummy, compared to 15 m^2/s^2 for the average male BioRID II. In addition, Lemmen et al. (2013) also suggested thresholds for the upper neck load force and moment for the average female. Force and moment are used to calculate the neck injury criterion Nkm (Schmitt et al., 2002). The H-point machine is used to position the pelvis of the average male models in the seat before testing. No such procedure is yet available for an average female model.

The SETs were developed to provide physical tools for the validation of virtual seat models in virtual rear impact neck injury risk assessment. The SETs are based on the same female and male body geometries as the average female and male HBMs VIVA+ models (John et al., 2022). Furthermore, the recently developed finite element (FE) SETs (Alvarez et al., 2024), facilitates assessment of the whole virtual test chain of soft tissue neck injury protection in low severity rear impact. By using both the SETs and the FE SETs, virtual seat models can be validated and then used in the assessment of safety performance of seats in rear impacts. Such assessments are expected to be included in virtual testing procedures by Euro NCAP (Euro NCAP, 2024) and the Insurance Institute for Highway Safety (IIHS, 2023), among others, in the near future. In addition, enhanced insights into the safety performance of new cars through HBM simulations are expected, once procedures for such simulations have been fully developed and established.

This is a unique study that makes use of the world first pair of crash test dummies that represent the average sizes of both female and male car occupants. The study compares real-world injury data separate for females and males, and the test results show distinct differences between the sexes in the dynamic dummy response, that reflect the differences in real-world safety performance. The results point to the potential for future safety assessment that takes into account both female and male occupant properties. This will allow car makers to develop countermeasures that address the safety of both sexes and thereby close the current gap in safety performance. This is the essence of both the Safe System and Vision Zero, that the human tolerance levels shall not be exceeded in the event of a crash. In the event of a crash, the safety performance of the vehicle has the potential to reduce the risk of the occupant being injured or killed. The assessment of safety performance is key to identifying and selecting the safest performing vehicles. In a robust safety assessment, a range of occupants with different dimensions and properties is essential for representing variations such as height, mass, sex and age. The latest development in crash tests dummies, which this study is an example of, and the potential of virtual testing as a complement to physical testing, can improve the robustness of the assessment of vehicle safety performance and thus further contribute to reaching the goals of a road transport system without loss of life and health. This study is focused on whiplash injuries, further research focusing on differences in risk of other injury types and body regions would be desirable. Securing the protection of all users in the event of a crash is needed to achieve the aims of the Safe System and Vision Zero approaches, as long as crashes occur. Representation of both the female and the male population in the assessment of safety is a step in that direction.

5. Conclusion

The loss of life and health in the road transport system could be reduced further by implementing the knowledge available related to avoiding exceeding the biomechanical tolerances of humans in the road transport system and identifying the countermeasures that provide the best protection in the event of a crash, as exemplified in this study. The hypothesis of this study was that vehicle seats, that have shown different real-world performance regarding whiplash protection between female and male car occupants, could show differences in dynamic responses for crash test dummies representing both sexes in crash tests. The study identifies differences in dynamic response of the SET v0.2 50F and 50M in rear impact tests in two different seat types. The study shows that differences related to potential injury causing loading to the human body could be identified in crash testing with test dummies representing both sexes of the population. The two tested seat models have shown differences in real-world performance regarding whiplash injury risk for females and males.

This study is pioneering comparing the risk of disabling neck injury outcomes from real-world data, in a potential injury causing impact in the same seat, for females and males in low severity rear impacts. The results highlight the improved resolution of the assessment of the protective performance of the seats, by using representation of both the female and male part of the population.

When comparing the response of the crash test dummies SET v0.2 50F and 50M in the Saab 9-3 and Audi A4 seats, respectively, noticeable differences in dynamic head-neck responses were observed. Also, the NICmax value and its timing differed between the SET 50F and 50M in the two different types of seats. These NICmax differences correspond with the field accident injury outcome in which the Saab seat provided less protection for females compared to males, and the Audi seat less protection for males compared to females. The Audi seat showed higher NICmax for the 50M than the 50F, and vice versa for the Saab seat. The crash tests dummies used in this study, the SET v0.2, have been refined compared to the earlier version, v0.1, with the weight improved to resemble that of the data from HumanShape as well as improved initial stability of the neck.

The SET 50F and 50M are the first pair of crash test dummies representing both an average female and an average male, based on the same design and the same set of anthropometric data. The results of testing both SETs in the seats provide insight into how to expand the robustness in the evaluation of injury protection of adult occupants in the event of a low severity rear crash. It is important to note that without access to the two dummies representing the average of each occupant sex, the difference in responses could not have been identified, emphasising the importance of enhancing the scope of how to assess the prevention of whiplash injuries more effectively.

CRediT contribution

Astrid Linder: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Anders Kullgren:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Validation, Writing – original draft, Writing – review & editing. **Mats Svensson:** Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

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Declaration of competing interests

The authors report no competing interests.

Declaration of generative AI use

The authors declare that no generative AI was used in this work.

Prior dissemination declaration

This manuscript presents original work that has not been previously published or disseminated in any form.

Ethics statement

No ethical approval was required for this study since no living organisms, only mechanical devices, were used as test subjects.

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The data are available on request to the authors.

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Code sharing is not applicable to this article, as no custom code was produced or used.

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