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How much does the injury risk between average female and average male anthropometry differ? – A simulation study with open source tools for virtual crash safety assessments

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ABSTRACT

Differences in injury risk between females and males are often reported in field data analysis. The aim of this study was to investigate the differences in kinematics and injury risks between average female and male anthropometry in two exemplary use cases. A simulation study comprising the newly introduced VIVA+ human body models (HBM) was performed for two use cases. The first use case relates to whiplash associated disorders sustained in rear impacts and the second to femur fractures in pedestrians impacted by passenger cars as field data indicates that females have higher injury risk compared to males in these scenarios.

Detailed seat models and a generic vehicle exterior were used to simulate crash scenarios close to those currently tested in consumer information tests. In the evaluations with one of the vehicle seats and one car shape the injury risks were equal for both models. However, the risk of the average female HBM for whiplash associated disorders was 1.5 times higher compared to the average male HBM for the rear impacts in the other seat and 10 times higher for proximal femur fractures in the pedestrian impacts for one of the two evaluated vehicle shapes..

Further work is needed to fully understand trends observed in the field and to derive appropriate countermeasures, which can be performed with the open source tools introduced in the current study.

1. Introduction

While vehicle safety systems have improved over the past few decades, several studies have shown that females and males are not equitably protected (Abrams and Bass, 2020; Forman et al., 2019; Kullgren et al., 2020; Noh et al., 2022; Nutbeam et al., 2022; Parenteau et al., 2013). Specifically, it has been shown that females have higher risk of injury to the lower extremities (Brumbelow and Jermakian, 2022), torso, and cervical spine (Forman et al., 2019) compared to males, while males show higher risks of skull fractures and severe brain injuries (Forman et al., 2019) in comparable frontal crashes.

Some of this difference could be attributed to vehicle design, as shown in a recent study from NHTSA (Noh et al., 2022). The authors showed that the fatality risk for females is greater than that of males in the newest generation of vehicles (equipped with pretensioners and load limited seatbelts and dual airbags) in comparison to earlier generations. However, differences in trends between different age groups could be seen. While the fatality risk for young (<45 years old) females is 18% higher compared to that of males for the newest generation of cars in frontal crashes, this trend changes for elderly drivers (>65 years) where the risk is 12% higher for males, resulting in an overall 7.2 ± 5.5 % higher fatality risk for females (Noh et al., 2022).

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Swedish data Kullgren et al. (2020) shows similar patterns also for injuries leading to long-term consequences. Here too, significant improvements in terms of occupant injury risks in modern cars (years of introduction after 2010) can be seen. However, the overall risk of permanent medical impairment (PMI) is still 1.5 times higher for females (15%) compared to males (10%). The risk for PMI is thereby highest for injuries in the body region "neck" for both genders and age groups, where the risk is nearly twice as high for females (7%) compared to males (4%) for modern cars (Kullgren et al., 2020).

Kullgren and co-authors also showed that different countermeasures addressing whiplash associated disorders (WAD) leading to PMI were not equally effective for females and males, where some even showed an increased risk compared to the standard seat without countermeasures (6.8 ± 1 % risk of PMI for males and 8.9 ± 1% for females in standard seats compared to 1.9 ± 1% for males and 10.1 ± 3.5% for seats with reactive head restraints) (Kullgren et al., 2013).

Gender- and age-specific differences in injury patterns have also been observed in Vulnerable Road User (VRU) crashes (Leo et al., 2021). Female pedestrians showed a significantly higher risk of femur and pelvic injuries in at least two of the three analysed datasets, and this was consistent over age (<60 years and >60 years) and injury severity (AIS 2+ and AIS 3+). However, it was also noted that some crash types (especially on rural roads) are more likely to involve males than females, which complicates comparisons (Leo et al., 2021).

Anthropometric test devices (ATDs), more commonly known as crash test dummies, have been used to evaluate injury risk in crash applications. These crash test dummies are available in three sizes, representing the 5th percentile female (05F), the 50th percentile male (50M), and the 95th percentile male (95M). Of these three, the average male (50M) that is predominantly utilised in vehicle safety assessments in regulatory tests (Linder and Svedberg, 2019). In the study by Schneider et al. (1983), defining the target anthropometry of current crash test dummies, in addition to the three previously mentioned dummy statures, designing a 50th percentile female (50F) ATD was also recommended. However, due to funding constraints, the 50F anthropometry was dropped with the statement *"The resulting three-member dummy family would still bracket the range of important variables, provide for interpolation capability and contain a dummy representing the segment of the population at highest risk, the mid-sized male."* (Schneider et al., 1983).

So, in the early days of crash testing the choice to start making crash safety assessments using the 50M size was justified by the fact that male occupants were, and still today are, a larger percentage of injured and killed road users than females. However, as described in the previous section, several studies have shown that there are several injury and crash types where females are at a higher risk.

Some ATD prototypes representing the 50F to be used for low severity rear impact testing have been developed, the BioRID P50F (Carlsson et al., 2021), and the SET-50F (Karemyr et al., 2022). However, these have so far only been used in research. In standardised rear impact testing only the BioRID 50M crash test dummy is used.

Turning to the safety assessments of VRUs, isolated impactor tests are used instead of dummies for evaluations of vehicle fronts. For headform impactor tests, a wide impact location range is considered within the bonnet and windscreen area, addressing a population from children up to tall adults and cyclists resulting in impact points on the bonnet and windscreen. For the assessment of leg and hip injuries, impactors have been mainly designed and evaluated based on simulations with Human Body Models (HBMs) corresponding to the stature of the average male, which is reflected by the geometry of the leg form impactor as well as the Wrap Around Distance used as impact location (775 mm) as well as the applied thresholds (Euro NCAP, 2022b; Lubbe et al., 2011; Park et al., 2020).

The implementation of virtual testing using HBMs as a complement to crash test dummies can facilitate a more detailed consideration of anthropometric differences, including sex differences. The first HBM of an average female was the VIVA model (Östh et al., 2017), which has been further enhanced and complemented with an average male model using the same modelling approaches (John et al., 2022a). These HBMs are now available open source as the VIVA+ model line-up (John et al., 2022a) on the OpenVT platform (OVTO, 2023). The height and weight of the 50F and 50M VIVA+ models (based on Schneider et al. (1983)) is compared to 50th percentile values provided in ISO 7250-2:2023 (ISO 7250-2) in Fig. 1. The figure shows the large regional differences in average anthropometries around the globe and the body height and weight of the 50F and 50M VIVA+ models based on Schneider et al. (1983).

The VIVA+ models are within the range of body height and weight found in the population globally with countries reporting both lower and higher values.

It is often debated whether the differences in anthropometry between 50F and 50M are large enough to account for differences in the injury risk, or whether the 50M can capture the relevant difference in injury protection of various designs and structures for both anthropometries sufficiently well. In this study, we aimed to quantify the differences in injury risks between 50F and 50M in two exemplary use cases. The first use case relates to whiplash associated disorders (WAD) sustained in rear impacts and the second to femur fractures in pedestrians impacted by passenger cars as field data indicates that females have higher injury risk compared to males in these scenarios.

2. Methods

For both use cases (rear impacts and pedestrian impacts), crash scenarios close to current consumer information testing were considered in order to analyse the differences in injury risks between the average female (50F) and average male (50M) models.

The open-source VIVA+ 50F and 50M HBMs (version 0.3.2) were used in this study, available as occupant models and standing VRU models. They were previously validated on component and full-scale levels (John et al., 2022b; John et al., 2022a; Schubert et al., 2021). The 50M and the standing VRU models, hereafter called the derivative models, differ from the baseline, the seated 50th percentile female model only in terms of geometry and mass distribution. The geometries, also referred to as template meshes, of the outer skin and surfaces of all skeletal parts, for the base line and the three derivative models, were obtained from statistical shape models (John et al., 2022a). All derivative models were generated via a custom morphing code to match the landmarks of the template meshes on the bones and outer shape (John et al., 2022a). This procedure led to sex-specific differences in body and bone shapes and bone thicknesses (where data was available). All contacts, material models and element formulations are the same among all four models, enabling a novel way of comparing the response of the average female and male focusing on geometric differences between average female and male body and bone shapes without any side-effects from differences in the modelling. Throughout the method, result and discussion section of this study, the wording "50F" and "50M" is used to refer specifically to the two versions of the VIVA+ models which have been used and differ in terms of stature, body weight, mass distribution, bone shape and cortical bone thicknesses. Details on the anthropometry of the two models and references to material models and validation are provided in Appendix A-1.

Simulations were performed in LS-Dyna, version R12.1 (rear impacts with the Open Source seat developed within the VIRTUAL project), R12.0 (pedestrian impacts with generic vehicle exterior), or R9.3.1 (rear impact simulations with the seat model from the ADSEAT project) due to different solver versions in which the vehicle environments have been developed. The kinematics and injury risk of the 50F and 50M VIVA+ models have been compared within the simulation load cases specified in Table 1.

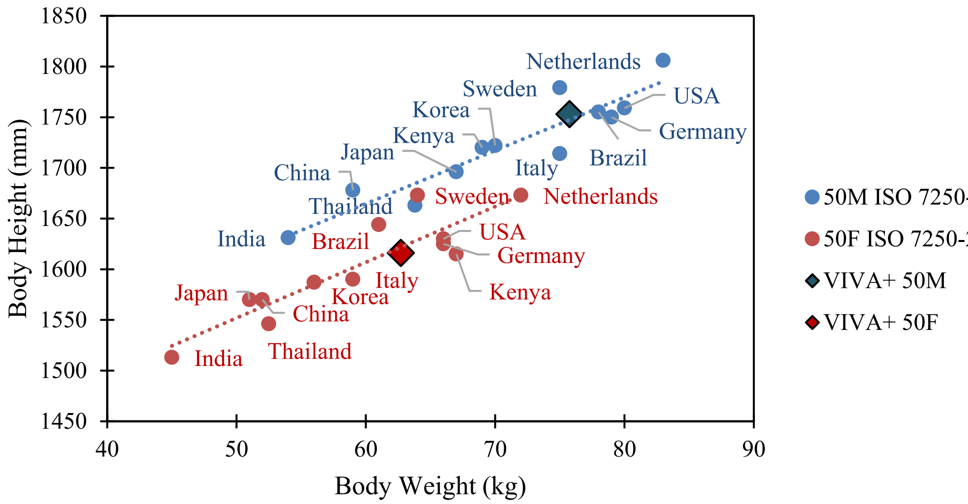

Fig. 1. Global regional differences in the definition of the 50th percentile female (red) and male (blue) anthropometry from ISO 7250-2 compared to the anthropometries of the VIVA+ 50 M and 50F models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Simulation load cases analysed in the current study for the two different use cases.

	Vehicle Environment	Crash Scenarios	Injury Criteria
1. Rear Impact	a) VIRTUAL Seat b) ADSEAT Seat D	Euro NCAP Mid- and High Severity Pulse (MSP, HSP)	WAD risk based on Neck Injury Criterion (NIC)
2. Car-Pedestrian Crash	a) Generic vehicle exterior (GVE) representing Sedan shape b) GVE representing SUV shape	40 km/h centreline collision in two initial perpendicular orientations (rotated around vertical axis of pedestrian)	Proximal femur fracture risk based on 99th Principal Strain (PS) & Femur shaft fracture based on 99th PS

2.1. Simulation set-ups

2.1.1. Rear impacts

As the simulation of rear impacts requires detailed seat models, two models representing seats from production cars were used. The open source VIRTUAL seat model is based on 3D scans of a Toyota Auris passenger seat (model year 2010–2012) and has been validated with impactor tests. The head restraint position was adjusted in accordance to the European New Car Assessment Program (Euro NCAP) Protocol for dynamic testing (Euro NCAP, 2022a).

To capture the interaction between the HBM and seat correctly, initial equilibrium was simulated. Thus, the HBM positioning was part of the simulation sequence to ensure realistic contact forces when initiating the simulation, in order to ensure quasi-equilibrium at the start of the crash pulse. The HBM was positioned on the seat according to the regression model presented by Park et al. (2016). This was done within the first 300 ms of the simulation (before the crash pulse was applied), by pulling the HBM into the desired position using constant force beams. More details of the positioning method are described in Appendix A-3.

The second seat model represents a serial seat with an integrated head restraint (specifically Seat D in the ADSEAT study (Lemmen et al., 2013)). The HBM was positioned relative to the seat in a similar procedure as for the first seat, again using the regression model from Park et al. (2016) as the target, however, allowing the body to adjust to the seat during the initial positioning phase as the resulting position did not seem plausible for the specific seat without this step. The final HBM positions are documented in Fig. A2 for both seats.

Simulations with pulses according to the Euro NCAP medium severity pulse (MSP) with delta v = 16 km/h and high severity pulse (HSP) with delta v = 24.5 km/h were performed for both seats.

No seatbelt was used in the rear end simulations as previous studies (Lawrence and Siegmund, 2000; Viano, 2023) have shown that this has negligible effect during the early phase, which was of most interest for the current study.

2.1.2. Pedestrian crash simulations

For the analysis of pedestrian crashes, two generic vehicle exteriors (GVE) representing generic sedan and SUV shapes were used as boundary conditions. The collision speed was set to 40 km/h. The GVE were based on Revision 3 of the CoHerent (TB 024, 2021; Klug et al., 2019) generic vehicle models. However, as part of this study, the stiffness of the different parts of the GVE were re-evaluated, comparing them with data available from literature regarding different stiffness levels of the current European fleet (Feist et al., 2019). The results of the impactor tests can be found in Figs. A8 and A9. The standing VIVA+ models were positioned in a pedestrian stance in accordance with the specifications of the Euro NCAP TB024 (TB 024, 2021) using the PIPER software (Jolivet et al., 2014) with pre-simulations. The positioned models are available on the openVT platform. The pedestrian model was positioned perpendicular to the vehicle in two different initial orientations: once with the struck side leg (SSL) facing backwards (impact angle of 90°) and once facing forwards (impact angle of 270°). An overlay of the two anthropometries in the initial position at 90° is shown in Fig. A9.

2.2. Simulation outputs

The LS-Dyna output (binout) files were postprocessed using the Python library Dynasaur (Klug et al., 2018; Schachner et al., 2018). For the rear impact simulations, the rotation of each vertebrae Centre of Gravity (CoG) around the global y axis, the head and T1 accelerations and the Neck Injury Criterion (NIC), were analysed. The NIC values were converted into injury risks applying a risk function based on reconstructed real-world cases (involving 11 females and 9 males) (Ono et al., 2009). Strain-based lower extremity fracture assessment (risk of proximal and femur shaft fracture) was calculated for the pedestrian simulations, using model-based risk functions based on 99th percentile principal strains (Schubert et al., 2021). More detailed documentation of the applied injury risk functions is available in Appendix A-2.

3. Results

3.1. Rear impacts

An overview of the simulation results with both pulses and seats is shown in Table 2.

The NIC was more or less independent of the pulse and the sex of the occupant for the simulations with the VIRTUAL seat.

In the simulations with the ADSEAT seat, however, the NIC observed in the simulations with the 50F model was more than 30% higher than for the 50M model. The detailed analysis of kinematics (Fig. 2) shows the motion pattern of the 50F is affected by the height of the horizontal bar within the head restraint, ultimately compressing the 50F spine, while the head of the 50M is properly supported. The graphs of the other rear impact simulations are shown in Appendix B-1.

3.2. Pedestrian impacts

The results of the pedestrian simulations are summarised Table 3. The proximal femur fracture (fx.) risk of the struck side leg (SSL) was very high for the 50F in all load cases (89–100%), while it was only 6–13% for the 50M for the Sedan load cases, but 100% for the SUV load cases. At the same time, the risk for femur shaft fractures (fx.) was similar for both anthropometries (but on average slightly higher for the 50M), being higher in the sedan load cases than the SUV cases and up to 13 times higher for the 50M compared to the 50F in the SUV load cases (1% for the 50F vs. 13% for the 50M for the 270° cases).

4. Discussion

The current study showed that the injury risks for the analysed load case between the 50F and 50M can differ greatly depending on the system (seat or vehicle shape) and body region considered. The use of the open-source tools developed within the VIRTUAL project was demonstrated within the current study. The tools can be used for equitable safety assessments to objectively compare the injury risks of female and male anthropometries.

While in field data gender-specific differences are caused by a combination of differences in exposure, differences in anthropometries and biological differences between females and males, the aim of the current study was to investigate geometric differences in an isolated way. Therefore, only differences in height, weight, body shape, bone shape, cortical bone thickness and soft tissue distributed have been considered. These differences showed effects on the injury risk in some of the load cases within the analysed body regions.

Table 2
Results of rear impact simulations with the medium severity (MSP) and high severity pulse (HSP). Where two NIC values are presented, two different definitions were applied for calculation, which are further discussed in the discussion section whereby the first value was used for injury risk calculation.

	VIRTUAL Seat		ADSEAT Seat	
	50F	50M	50F	50M
MSP				
NIC [m^2/s^2]	15.7	15.5	23.1 (67 ms) 34.6 (137 ms)	17.3
Injury Risk	49%	48%	82%	57%
HSP				
NIC [m^2/s^2]	15.6	15.6	21.1 (68.4 ms) 35.9 (151.6 ms)	15 (74 ms) 15.9 (157 ms)
Injury Risk	48%	48%	21%	15%

4.1. Rear impacts

While the NIC values of the 50M (NIC ranging from 15 to 17.3) were very similar across the two seats and the two pulses, more sensitivity was observed for the 50F (NIC ranging from 15.6 to 23.1) where higher values were observed for the ADSEAT seat together with overall unfavourable kinematics (compression of the neck when the head went below the head restraint structure). Thus, following current test procedures, considering only the 50M, the issue with the ADSEAT seat for the 50F would not have been identified. The VIRTUAL seat, although from a car with model year 2010–2012, shows a good performance for both HBMs. The seat was chosen since there are several real-word cases which can be used in future studies.

The major challenge in the analysis of the rear impact cases was the question of a significant injury predictor of whiplash injuries to the neck. NIC was designed to predict potential nerve injury causing pressure transients in the vertebral canal, presented by (Svensson et al., 2000), here denoted Aldman pressure. Analysing the NIC only, other mechanisms have been neglected in our current analysis. An observed compression of the cervical spine for the 50F in the ADSEAT seat simulations (shown in Fig. 2) is expected to be related to the injury mechanism focusing on the strains in the facet joints, which have not been considered in the current study. In a previous study by Kitagawa et al. (2015), higher first peaks of strains in the joint capsule were observed for simulations with a 50F HBM compared to a 50M HBM. In the field, a combination of injury mechanisms might be present, which is currently not reflected by any injury predictor and should be considered in future research.

Furthermore, NIC was originally designed for the initial retraction phase of the neck kinematics, up until the first negative pressure peak is reached at maximum neck retraction (in smooth laboratory tests) (Svensson et al., 2000). In the current study, multiple peaks were observed in most of the load cases whereby the maximum values often occurred rather late. Such an example is given in Fig. 3, showing the MSP load case with the 50F and the ADSEAT seat. Two peak values of the NIC are present in two different phases (with negative NIC values in between), whereby the NIC value of 21.1 (Peak 1) would be in accordance with the original idea (Svensson et al., 2000), although the second peak (NIC value of 35.9) would reflect the definition in the current Euro NCAP Whiplash protocol. In the current study, the maximum value in the first phase (before the NIC curve drops to negative values) was used for the subsequent risk calculation.

More sophisticated injury criteria, such as fluid dynamic models of the Aldman pressure (Yao et al., 2016) could accommodate the problem with the different phases and seat-dependent interactions between the head and head restraint. However, no injury risk function based on Aldman pressure is currently available and the current implementation of the tool developed by Yao et al. (2016) does not enable comparison between male and female subjects directly, as sex-differences in spinal canal properties are currently not implemented.

These sex-differences are also not considered in the NIC where previous studies therefore have suggested a reduced NIC threshold for risk of injury of 12 for the average female, compared to 15 for the male (Schmitt et al., 2012). However, the injury risk curve from Ono et al. (Ono et al., 2009) applied in the current study included both, males and females.

Another limitation in the occupant simulations is the definition of comparable seating positions and resulting postures between the 50F and 50M. We have endeavoured to find a compromise in this study between defining comparable positions between the 50F and 50M, and positions that are realistic for both, as they are based on regression models from volunteer studies. This, however, could also be a contributory factors in different injury risks. Differences in WAD risks between females and males observed in the field could also result in differences in head restraint adjustments, which was not considered in the current study in which the head restraint position was kept constant. Integrated

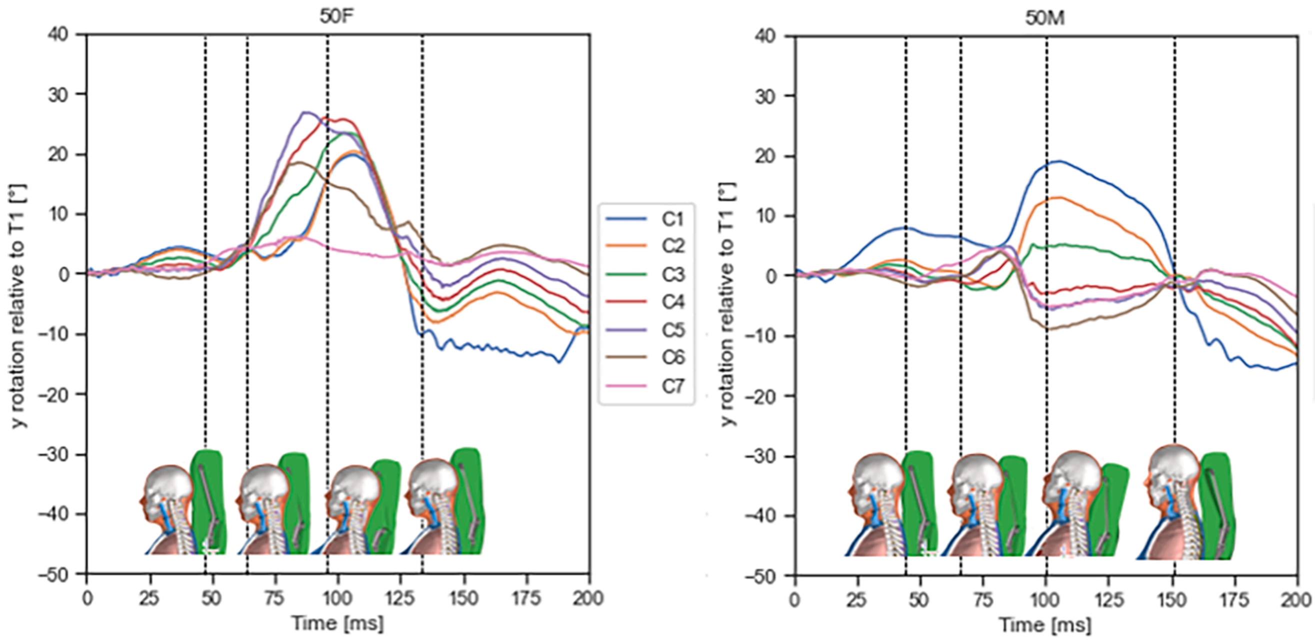

Fig. 2. Neck kinematics for VIVA+ 50F (left) and 50F (right) simulations in the ADSEAT seat with integrated head restraint in the MSP load case. The vertical lines indicate the times at which the animations are sown (time of head-head restraint contact, time of maximum NIC value, time of maximum rearwards movement and end of contact time) loaded with the "Medium Severity Sled Pulse".

Table 3
Pedestrian simulation results for VIVA+ 50F and 50F in the analysed scenarios.

Car v [km/h]	Coll. Angle [°]	Vehicle Shape	VIVA+	SSL prox. femur fx. risk	SSL femur shaft fx. risk
40	270	Sedan	50F	99%	69%
40	270	Sedan	50M	6%	65%
40	90	Sedan	50F	89%	44%
40	90	Sedan	50M	13%	60%
40	270	SUV	50F	100%	1%
40	270	SUV	50M	100%	13%
40	90	SUV	50F	97%	1%
40	90	SUV	50M	100%	11%
	Average	Sedan	50F	94%	57%
	Average	Sedan	50M	9%	62%
	Average	SUV	50F	98%	1%
	Average	SUV	50M	100%	8%

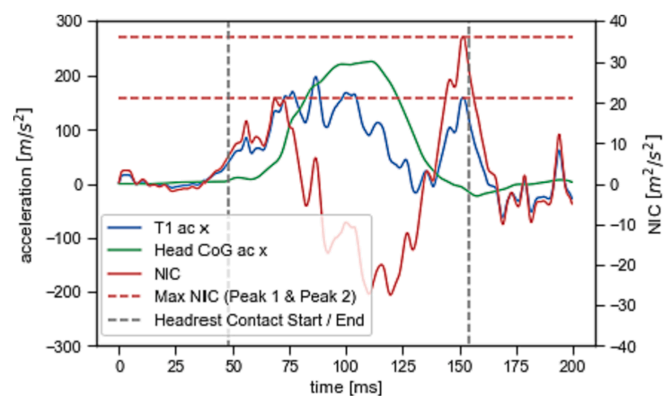

Fig. 3. Head, T1 accelerations and resulting NIC for VIVA+ 50F simulation with the ADSEAT seat in the MSP load case. The vertical grey lines show the start and end time of the contact between head and head restraint based on the measured contact force. The red horizontal lines show the two identified NIC peaks within the time of head contact. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

head restraints could potentially solve issues with wrong adjustments of the head restraint, however, as shown in the simulations with the ADSEAT seat, consideration of different statures is required when developing the inner structure of such head restraints to avoid unfavourable loading for smaller or taller occupants than the 50M.

The difference in vertebral kinematics and NIC values between 50F and 50M under identical accident conditions, indicates that simulations using only the 50M cannot predict the response and potential injury risk in a 50F.

4.2. Pedestrian impacts

Two generic vehicle exteriors (generic Sedan and SUV) were used in the simulated pedestrian crashes. Although the GVE have been tuned to simulate a representative stiffness, the models are still more simplified and homogeneous than a real car.

Furthermore, only one initial posture was simulated and analysed in the current study and only two different orientations (perpendicular to the vehicle with either left or right leg as struck-side).

The current analysis indicated that the higher femur fracture risk observed in females in field data (Leo et al., 2021) is predominantly caused by the proximal femur. The higher proximal femur fracture risk compared to the femur shaft is consistent with real-world crashes (Schubert et al., 2021).

The higher proximal femur fracture risk observed in the simulations with the 50F can be related to the different impact locations and angle of the femur due to the different stature, which is shown in Fig. 4 and Fig. 5.

The lower impact point of the 50M compared to the 50F femur results in lower fracture risks for the proximal femur of the 50M, but does not increase the fracture risk for the femur shaft compared to the 50F. This indicates that the injury risk is not simply moved to another region. In Table B2 also further injury risks are provided for the risk of 3+ rib fractures, AIS4+ brain injuries and skull fractures. For the rib fracture risk, no clear trend was observed. To a great extent the fracture risk depends on the interaction between the chest and the vehicle While in

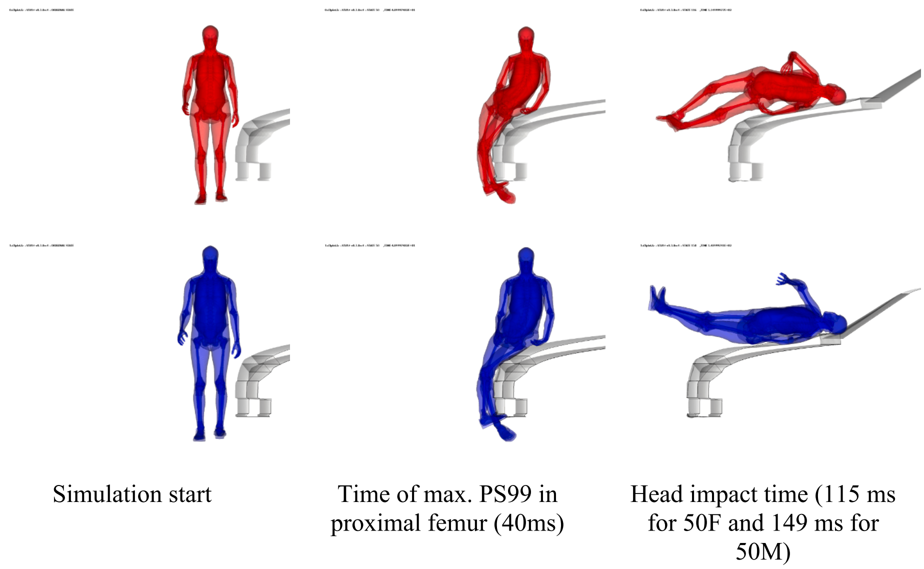

Fig. 4. Pedestrian simulations with the VIVA+ 50F (red) and 50 M (blue) model, impacted by the Sedan GVE at 90° impact angle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

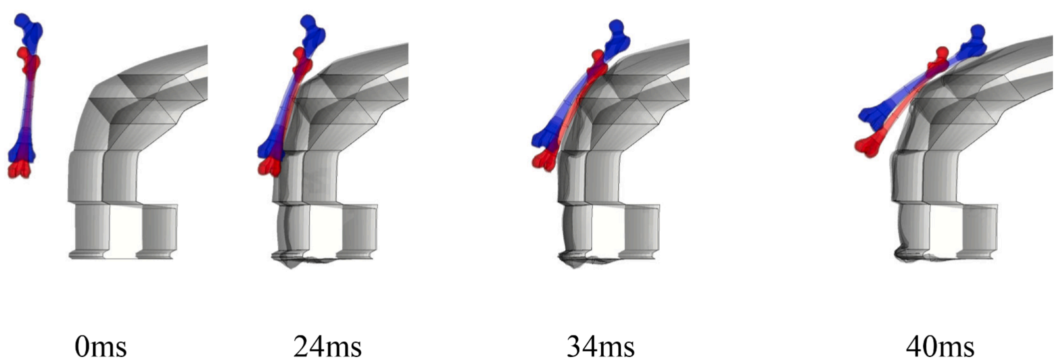

Fig. 5. Femur kinematics from the simulations with the VIVA+ 50F (red) and 50 M (blue) model, impacted by the GVE Sedan at 90° impact angle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

some scenarios there is no contact between chest and vehicle due to the arm support (see Fig. B5 as one example), in other cases, direct impact and therefore higher injury risks are observed. The head injury risk is greatly dependent on the impact location (Fig. B6) and was higher for the 50M compared to the 50F in our evaluations. As current cars are tested over a wide range of impact locations with head form impactors, the differences in statures are addressed by the assessment method. This is not the case for the assessment with the upper leg form impactor, where tests are performed only at one Wrap Around Distance, which corresponds to the femur geometry of an average male. While the centre of the hip joint (measured as the centre of acetabuli) is at 939 mm for the 50M, it is at 844 mm for the 50F relative to the ground. This results in different impact locations on the vehicle and different impact angles, as shown in Fig. 5 for the Sedan, which has a bonnet leading edge height of 740 mm.

4.3. Limitations

The geometries of the 50F and 50M VIVA+ models are based on regression models representing average fifty-year-old females and males, selected to represent the average age of the injured adult population involved in car crashes. However, in the field we can see peaks for the younger and the older population. The population most at risk is generally affected by different factors (vehicle type, crash type, body region and injury severities considered, etc.). Variability within the anthropometry of females and males has not been taken into account in this study but should be further investigated in future.

Sex-related differences in material properties were not considered on the tissue level in the VIVA+ models. However, the literature suggests that there are no statistical sex related differences in bone tissue (Katzenberger et al., 2020).

Material properties represent average values reported in the literature, which does not necessarily correspond to the target age of 50 years due to the bias towards elderly donors.

The VIVA+ models were validated for a wide range of load cases. However, considerable scatter is frequently observed in the validations for the experiments. Furthermore, the validation level of the applied injury risk curves is another limitation, especially for rear impacts, as discussed in the previous section. Furthermore, sex-specific injury risk curves might be required for kinematic injury metrics such as NIC (Schmitt et al., 2012), which requires sufficient data for calibration.

As the current study focused on the simulation of load cases similar to standardised tests without variations of extrinsic and intrinsic factors present in real-world crashes, no direct comparison with field data is possible.

4.4. Future Work

Additional load cases in a variety of initial positions and postures should be investigated in the future. By this, the open source tools introduced in the current study could be used in larger simulation campaigns, thus allowing comparison with field data. Also, simulations with scaled versions of the 50F and 50M model scaled to each other's size could be performed as a next step. This would enable further insights into the main contributing factors for the differences in injury risks between females and males, and ultimately help in deriving appropriate countermeasures.

The current study has highlighted the limitations of considering only one anthropometry for safety evaluations. With the implementation of virtual testing a wider range of anthropometries could be considered in the future to address the current limitations of available hardware and consider the diversity of vehicle occupants and VRUs.

However, before virtual testing can be applied in regulatory testing, further work is needed to ensure comparable and trustworthy results.

4.5. Conclusions

Based on the current study, it cannot be confirmed that the 50M and 50F show similar injury risks, or that by simulations with the 50M, the level of protection for the 50F can be adequately predicted for the analysed impact scenarios. However, the importance of including different anthropometries in safety evaluations was demonstrated. It is recommended to include the 50F anthropometry in future studies as a first step to account for a broader injury risk assessment. In the longer run, virtual testing provides the opportunity to consider even more anthropometries (i.e., models representing obese or elderly individuals) and also to make sure that vehicle safety systems provide equitable protection.

CRediT authorship contribution statement

Corina Klug: Conceptualization, Methodology, Validation, Formal analysis, Visualization, Writing – original draft. **David Bützer:** Investigation, Writing – review & editing. **Johan Iraeus:** Conceptualization, Methodology, Writing – review & editing. **Jobin John:** Methodology, Writing – review & editing. **Arne Keller:** Methodology, Writing – review & editing. **Michal Kowalik:** Methodology, Investigation, Visualization, Writing – review & editing. **Christoph Leo:** Methodology, Investigation, Visualization, Writing – review & editing. **Ines Levallois:** Conceptualization, Resources, Writing – review & editing. **I. Putu A. Putra:** Writing – review & editing. **Felix Ressi:** Methodology, Visualization, Writing – review & editing. **Kai-Uwe Schmitt:** Writing – review & editing. **Mats Svensson:** Conceptualization, Supervision, Writing – review & editing. **Linus Trummler:** Methodology, Investigation, Visualization, Writing – review & editing. **Wim Wijnen:** Methodology, Writing – review & editing. **Astrid Linder:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The tools and results of this study are openly available on the OpenVT platform https://openvt.eu/. The only exceptions are the used ADSEAT seat model, which cannot be shared due to IP restrictions.

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Appendix A. Supplementary data

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References

Abrams, M.Z., Bass, C.R., 2020. Female vs. male relative fatality risk in fatal crashes. In: 2020 IRCOBI Conference Proceedings. IRCOBI Conference, postponed (online). IRCOBI, pp. 47–85.

Brumbelow, M.L., Jermakian, J.S., 2022. Injury risks and crashworthiness benefits for females and males: Which differences are physiological? Traffic Inj. Prev. 23, 11–16. https://doi.org/10.1080/15389588.2021.2004312.

Carlsson, A., Davidsson, J., Linder, A., Svensson, M.Y., 2021. Design and evaluation of the initial 50th percentile female prototype rear impact dummy, BioRID P50F - Indications for the need of an additional dummy size. Frontiers in Bioengineering and Biotechnology 9, 687058. https://doi.org/10.3389/fbioe.2021.687058.

Euro NCAP, 2021. Pedestrian Human Model Certification, 3rd ed. https://cdn.euroncap.com/media/66108/tb-024-pedestrian-human-model-certification-v301.pdf.

Euro NCAP, 2022a. The Dynamic Assessment of Car Seats for Neck Injury Protection Testing Protocol. Version 4.1.2, 57 pp. https://cdn.euroncap.com/media/70322/euro-ncap-whiplash-test-protocol-v412.pdf.

Euro NCAP, 2022b. Euro NCAP Pedestrian Testing Protocol 9.0.2. Euro NCAP. https://cdn.euroncap.com/media/75475/euro-ncap-vru-testing-protocol-v902.pdf (accessed 19 February 2023).

Feist, F., Sharma, N., Klug, C., Roth, F., Schinke, S., Besch, A., Dornbusch, F., 2019. GVTR: A Generic Vehicle Test Rig Representative of the Contemporary European Vehicle Fleet. In: The 26th ESV Conference Proceedings. International Technical Conference on the Enhanced Safety of Vehicles, Eindhoven, Netherlands. 10-13 June.

Forman, J., Poplin, G.S., Shaw, C.G., McMurry, T.L., Schmidt, K., Ash, J., Sunnevang, C., 2019. Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions. Traffic Inj. Prev. 20, 607–612. https://doi.org/10.1080/15389588.2019.1630825.

ISO 7250-2. Basic Human Body Measurements for Technological Design - Part 2: Statistical Summaries of Body Measurements from National Populations, 2023.

John, J., Putra, I.P.A., Iraeus, J., 2022b. Finite Element Human Body Models to study Sex-differences in Whiplash Injury: Validation of VIVA+ passive response in rear-impact, in: 2022 IRCOBI Conference Proceedings. IRCOBI Conference, Porto, Portugal. 14.-16.9. IRCOBI, pp. 215–227.

John, J., Klug, C., Kranjec, M., Svenning, E., Iraeus, J., 2022a. Hello, world! VIVA+: A human body model lineup to evaluate sex-differences in crash protection. Front. Bioeng. Biotechnol. 10 https://doi.org/10.3389/fbioe.2022.918904.

Jolivet, E., Petit, P., Janak, T., Lemaire, T., Peres, J., Chhabra, A., Paruchuri, S., Singh, S., Faure, F., Chawla, A., Beillas, P., 2014. PIPER: Open source software to position and personalize Human Body models for crash applications. In: 5th International Symposium: Human Modeling and Simulation in Automotive Engineering. Munich, Germany. 16.-17.10.2014. carhs.

Karemyr, M., Pettersson, T., Svensson, M., Linder, A., 2022. Seat Evaluation Tools (SETs): Development of Prototype Concepts of the SETs of an Average Female and Male for Low Severity Rear Impact Crash Testing. VTI Rapport 1147A, 82 pp. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1709745.

Katzenberger, M.J., Albert, D.L., Agnew, A.M., Kemper, A.R., 2020. Effects of sex, age, and two loading rates on the tensile material properties of human rib cortical bone. J. Mech. Behav. Biomed. Mater. 102, 103410 https://doi.org/10.1016/j.jmbbm.2019.103410.

Kitagawa, Y., Yamada, K., Motojima, H., Yasuki, T., 2015. Consideration on gender difference of whiplash associated disorder in low speed rear impact. In: 2015 IRCOBI Conference Proceedings. IRCOBI Conference, Lyon, France. 9.-11.9.2015. IRCOBI, pp. 233–245.

Klug, C., Luttenberger, P., Schachner, M., Micorek, J., Greimel, R., Sinz, W., 2018. Postprocessing of human body model results – Introduction of the open source tool DYNASAUR. In: 7th International Symposium: Human Modeling and Simulation in Automotive Engineering. Berlin, Germany. 18.-19.10.2018.

Klug, C., Feist, F., Schneider, B., Sinz, W., Ellway, J., van Ratingen, M., 2019. Development of a certification procedure for numerical pedestrian models. In: The 26th ESV Conference Proceedings. International Technical Conference on the Enhanced Safety of Vehicles, Eindhoven, Netherlands. 10-13 June, 1-24.

Kullgren, A., Stigson, H., Krafft, M., 2013. Development of Whiplash Associated Disorders for Male and Female Car Occupants in Cars Launched Since the 80s in Different Impact Directions, in: 2013 IRCOBI Conference Proceedings. IRCOBI Conference, Gothenburg, Sweden. 11.-13.9.2013. IRCOBI, pp. 51–62.

Kullgren, A., Stigson, H., Axelsson, A., 2020. Developments in car crash safety since the 1980s. In: 2020 IRCOBI Conference Proceedings. IRCOBI Conference, postponed (online). IRCOBI, pp. 86–99.

Lawrence, J.M., Siegmund, G.P., 2000. Seat back and head restraint response during low-speed rear-end automobile collisions. Accid. Anal. Prev. 32, 219–232. https://doi.org/10.1016/s0001-4575(99)00108-6.

Lemmen, P., Gupta, A., Carlsson, A., Svensson, M., Schmitt, K.-U., Levallois, I., Linder, A., Tomasch, E., 2013. Seat optimization considering reduction of neck injuries for female and male occupants – Applications of the EvaRID model and a scaled down BioRID. In: The 23rd ESV Conference Proceedings. International Technical Conference on the Enhanced Safety of Vehicles, Seoul, Republic of Korea. 27.-30.5.2013, 1-15.

Leo, C., Rizzi, M.C., Bos, N.M., Davidse, R.J., Linder, A., Tomasch, E., Klug, C., 2021. Are there any significant differences in terms of age and sex in pedestrian and cyclist accidents? Front. Bioeng. Biotechnol. 9, 677952 https://doi.org/10.3389/fbioe.2021.677952.

Linder, A., Svedberg, W., 2019. Review of average sized male and female occupant models in European regulatory safety assessment tests and European laws: Gaps and bridging suggestions. Accid. Anal. Prev. 127, 156–162. https://doi.org/10.1016/j.aap.2019.02.030.

Lubbe, N., Hikichi, H., Takahashi, H., Davidsson, J., 2011. Review of the EURO NCAP Upper Leg Test. In: The 22nd ESV Conference Proceedings. International Technical Conference on the Enhanced Safety of Vehicles, Washington, D.C., USA. 13.-16.6.2011. NHTSA.

Noh, E.Y., Atwood, J.R.E., Lee, E., Craig, M., 2022. Female Crash Fatality Risk Relative to Males for Similar Physical Impacts. NHTSA Technical Report DOT HS 813 358.

Nutbeam, T., Weekes, L., Heidari, S., Fenwick, R., Bouamra, O., Smith, J., Stassen, W., 2022. Sex-disaggregated analysis of the injury patterns, outcome data and trapped status of major trauma patients injured in motor vehicle collisions: a prespecified analysis of the UK trauma registry (TARN). BMJ Open 12 (5), e061076. https://doi.org/10.1136/bmjopen-2022-061076.

Ono, K., Ejima, S., Yamazaki, K., Sato, F., Pramudita, J.A., Kaneoka, K., Ujihashi, S., 2009. Evaluation Criteria for the Reduction of Minor Neck Injuries during Rear-end Impacts Based on Human Volunteer Experiments and Accident Reconstruction Using Human FE Model Simulations. In: 2009 IRCOBI Conference Proceedings. IRCOBI Conference. IRCOBI, York, United Kingdom, pp. 381–398.

Östh, J., Mendoza-Vázquez, M., Linder, A., Svensson, M.Y., Brolin, K., 2017. The VIVA OpenHBM finite element 50th percentile female occupant model: Whole body model development and kinematic validation. In: 2017 IRCOBI Conference Proceedings. IRCOBI, Antwerp, Belgium. 13.-15.9.2017. IRCOBI, pp. 443–466.

OVTO, 2023. The openVT platform - Platform for Open Access Virtual Testing for Enhanced Road Users Safety. https://www.openVT.eu.

Parenteau, C.S., Zuby, D., Brolin, K., Svensson, M.Y., Palmertz, C., Wang, S.C., 2013. Restrained male and female occupants in frontal crashes: are we different? In: 2013 IRCOBI Conference Proceedings. IRCOBI Conference, Gothenburg, Sweden. 11.-13.9.2013. IRCOBI.

Park, J., Ebert, S.M., Reed, M.P., Hallman, J.J., 2016. Statistical models for predicting automobile driving postures for men and women including effects of age. Hum. Factors 58, 261–278. https://doi.org/10.1177/0018720815610249.

Park, S., Park, J., Park, G.-J., 2020. Analysis and evaluation of the Euro-NCAP upper Legform to WAD 775 mm test. Int. J. Automot. Technol. 21, 1507–1518. https://doi.org/10.1007/s12239-020-0142-4.

Schachner, M., Micorek, J., Luttenberger, P., Greimel, R., Klug, C., 2018. Dynasaur. https://gitlab.com/VSI-TUGraz/Dynasaur.

Schmitt, K.-U., Weber, T., Svensson, M., Davidsson, J., Carlsson, A., Björklund, M., Jakobsson, L., Tomasch, E., Linder, A., 2012. Seat testing to investigate the female neck injury risk – preliminary results using a new female dummy prototype. In: 2012 IRCOBI Conference Proceedings. IRCOBI Conference, Dublin, Ireland. 12.-14.09.2012. IRCOBI, p. 263.

Schneider, L.W., Robbins, D.H., Pflüg, M.A., Snyder, R.G., 1983. Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, volume 1.: Final Report. UMTRI-83-53. Technical Report UMTRI-83-53-1. UMTRI. https://deepblue.lib.umich.edu/handle/2027.42/259.

Schubert, A., Erlinger, N., Leo, C., Iraeus, J., John, J., Klug, C., 2021. Development of a 50th percentile female femur model. In: 2021 IRCOBI Conference Proceedings. IRCOBI Conference. IRCOBI, Munich, Germany, pp. 308–332.

Svensson, M.Y., Boström, O., Davidsson, J., Hansson, H.-A., Håland, Y., Lövsund, P., Suneson, A., Säljö, A., 2000. Neck injuries in car collisions — a review covering a possible injury mechanism and the development of a new rear-impact dummy. Accid. Anal. Prev. 32, 167–175. https://doi.org/10.1016/s0001-4575(99)00080-9.

Viano, D.C., 2023. Analysis of the lack of restraint with and without belt pretensioning in 40.2 km/h rear impacts. Traffic Inj. Prev. 24, 196–202. https://doi.org/10.1080/15389588.2022.2121143.

Yao, H.-D., Svensson, M.Y., Nilsson, H., 2016. Transient pressure changes in the vertebral canal during whiplash motion–A hydrodynamic modeling approach. J. Biomech. 49, 416–422. https://doi.org/10.1016/J.JBIOMECH.2016.01.005.