# Virthuman Application: Is an Autonomous Vehicle with Non-standard Seating Safe in a Side Crash?

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## Abstract

Highly Automated Vehicles (HAVs) will be more comfortable for their occupants than common cars from different aspects. For instance, their occupants can access extra spaces to adjust their seats as there will be no steering wheel and gearbox transmission handle in the interior. Among a wide range of seating configuration possibilities, the majority of passengers prefer to be in the Face-to-Face or the Living room configurations that are known as non-standard seating configurations. The present survey investigated how safe are these non-standard seating configurations in a side crash in comparison with the standard one in which all seats are facing the front windshield. Four identical 50th percentile Virthuman models were integrated into a schematic of automated vehicle's interior. Standard three-point seatbelts fastened bodies to up-right seats made from Polyurethane foam. A 30 km/h crash acceleration pulse was applied to the model for simulating side crash with a virtual sledge test in the Virtual Performance Solution (VPS) environment, PAMCRASH module. Results revealed that the Living room configuration was safer for the Rear Left occupant in comparison with the Standard one. Also, the Front Left occupant did not experience safer occasions in non-standard configurations from a Head & Neck injury point of view.

## Keywords

Virthuman model, autonomous vehicle, seating configurations, sledge test

## 1 Introduction

Wide use of fully automated safety features in vehicle industry for saving the occupants' lives as well as pedestrians in a crash is expected from 2025 (NHTSA, 2020). Common human mistakes are the main cause of serious car crashes all around the world. In the US almost 37,000 people lost their lives because of motor vehicle-related accidents in 2018 (NHTSA, 2020). The influence of such a high amount of casualties and its side effects on economics cannot be ignored easily. In 2010 the National Highway Traffic Safety Administration (NHTSA, 2020) announced: "car accidents cost nearly quarter-billion U.S. dollars and losing workplace productivity cost almost sixty billion U.S. dollars". An automated driving system (ADS), can improve a vehicle's operation by helping to either minimize or remove human error. Hopefully, the ADS will reduce the number of vehicle accidents. In consequence, risk of serious injuries for the passengers/pedestrians will be reduced. Another advantage of using a network of automated cars which are driven at the optimum speed due to traffic conditions is a massive reduction in transportation

prices as a result of decreasing fuel consumption and the cost of maintenances. Such a network of automated vehicles can also help to free up passengers' time up to 50 minutes per day (Bertoncello and Wee, 2015).

Almost all of the current passenger vehicles have seats facing forwards, towards the cars' windshield and this is called standard seating configuration. Occupants who are in the front-row have just two options for their seating position. They can move seats forward or backward as an adjustment which gives extra legroom to them. The other option may help to have slightly comfortable seating positions by reclining seats' back.

The future mobility will not need a driver to take full control of driving for highly automated vehicles (HAV). In fact, the ADS will be in charge for driving cars in inner-city streets and suburban roads. Therefore, vehicle interior designers will not face seating limitations e.g. limited space for legroom. Occupant(s) will also have more options for changing their seats' direction, postures as well as their location. A car's passenger can rotate his/her seat

to sit face-to-face with the other passengers (Jorlöv et al., 2017; Nie et al., 2020). Furthermore, changing occupants' seats orientation can help to reduce the chance of bodily injuries in a crash (Wu et al., 2020).

The present study aims to compare the safety of occupants of a highly autonomous vehicle in non-standard and standard seating configurations in the event of a side crash.

Injury investigations were firstly done on post-mortem human subjects (PMHS) (Kang et al., 2018; Ridella et al., 2009; Yoganandan et al., 2011a; Yoganandan et al., 2011b; Viano et al., 1989). However, it is difficult to keep PMHS for a long time or use them in several tests.

Later on, dummies as full-scale anthropomorphic test instruments were introduced for doing tests and measurements (Yoganandan et al., 2012). They can simulate dimensions, weight proportions and articulation of a body. On consumers' demand, automotive industries do tests and regulations by using dummies as well. However, dummies are capable to be used for several tests in comparison with PMHS. But their disadvantage is the cost of an experiment. In addition, dummies are mono-purpose and are made from engineering materials. Hence, their biofidelity might be problematic in various loading scenarios.

Therefore, Finite Element models of a human body were introduced for simulating crash scenarios to overcome reviewed obstacles, (Cai et al., 2016; García Nieto et al., 2009; Motozawa et al., 2016; Teng and Wu, 2011).

For the current study Virthuman body model was chosen (Mecas, sro., 2016b). This human body model was introduced to the virtual performance solution (VPS) environment. This model does not have the limitations that has been already mentioned for PMHS and dummies. The model can be setup easily and be used for number of tests. An embedded injury assessment algorithm (Mecas, sro., 2016a) is available for this model in VPS that helps to measure injury index for different body parts.

## 2 Methods

### 2.1 Virthuman

Virthuman Fig. 1, was built based on a multi-body-system (MBS) concept and has deformable segments (hybrid model). Rigid body parts i.e. upper leg, lower leg, foot, etc. are interconnected via joints. Additional breakable joints are considered into account with particular body parts for accounting fractures (Hyncik et al., 2013; Mecas, sro., 2016b; Vychytil et al., 2014). Extensive database of anthropometric data of more than 10,000 individuals was used to prepare the scaling algorithm that is embedded within the model. Therefore, this model is capable to be used for simulating
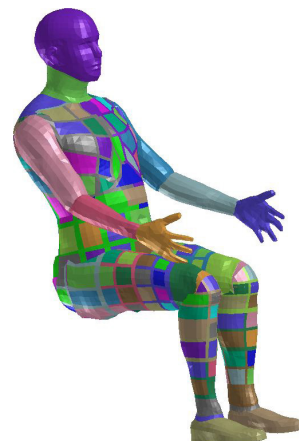


**Fig. 1** Virthuman model (50th percentile male, 30-year-old, height: 176 cm, weight: 78 kg)

different genders, ages, heights and weight categories of the population. To ensure its biofidelity, the model was validated both on the base of component and full-scale tests and can be used for a wide range of tests (Mecas, sro., 2016b). For details on validation tests, see (Vychytil et al., 2014).

The body's surfaces are based on the geometry of the reference 50th percentile male and are created according to the civilian American and European surface anthropometry resource database (CAESAR). The body's external surfaces as individual parts are connected to the relevant basic MBS structure by transnational joints which have nonlinear stiffness and damping characteristics for representing a tissue's deformation.

Since the model is based on an MBS structure with 263 rigid bodies and 262 joints, it is easy to position and requires low computational time. It also includes automatic algorithm for evaluation of injury risk during a collision scenario, as it is detailed in Section 4.

### 2.2 Vehicle interior

A schematic of a highly automated vehicle is shown in Fig. 2. The interior represented a simplified model on the basis of Chrysler Neon car. The interior's length, width and height are 2,646 mm, 2,070.704 mm and 1,422.604 mm, respectively.

For modeling passengers' seats the geometry of the Volvo XC70 Station Wagon driver's seat (Ozmumcu, 2012) was used. Seats were positioned in up-right posture that their back was reclined at an angle of 20 deg.

Seats and lower part of vehicle interior (the walls, see. Fig. 2) are supposed to be deformable and made from Polyurethane foam (PUR) (Špirk et al., 2018). The interior's lower parts were also covered by 50 mm Polyurethane foam. Common glass material was opted for the interior's upper parts.
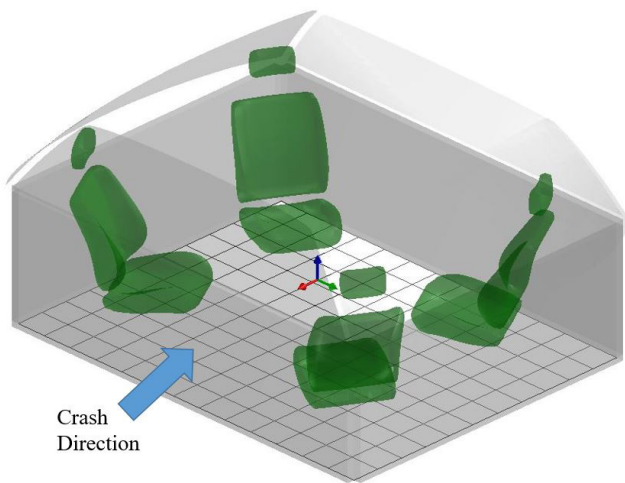
**Fig. 2** Polyurethane foam seats in the schematic interior

The three most desired seating configurations (Jorlöv et al., 2017) which were chosen for this study are illustrated in Fig. 3.

In the Standard seating configuration, all passengers sit facing toward the vehicle's front windshield. For Face-to-Face configuration front row seats are rotated 180 degrees meanwhile there is no relocation for rear seats. So, occupants can sit in front of each other in this configuration. In a Face-to-Face configuration, where the seats are rotated 30 degrees inward one has a Living room seating configuration.

## 2.3 Seat belts

Three-point integrated seat belts with standard materials are used to fasten models to seats during the test. There is no penetration or intersection between models and seat belts. Seat belts include a Buckle which is located near the cushion on right side that connects shoulder and lap belt together. An Anchor that is close to the cushion on left side is placed where the lap belt ends. There is a D-ring for shoulder belt which is located on the top left of the seat's back. In the present study, Retractors with 35 N pre-loading pulled back belts at the beginning of the simulation. The seat belt includes two components with different materials. Membrane elements are used for shoulder and lap segments. On the other hand nonlinear bar elements are used for connecting shoulder and lap belt together. In addition these bar elements are considered for modeling the connection of membrane belts to the Retractor as well as the Anchor.

## 3 Simulation

Simulation was run in two phases. Since deformable seats were considered here it was needed to release body models from rest slightly above seats at first for 50 ms (see in
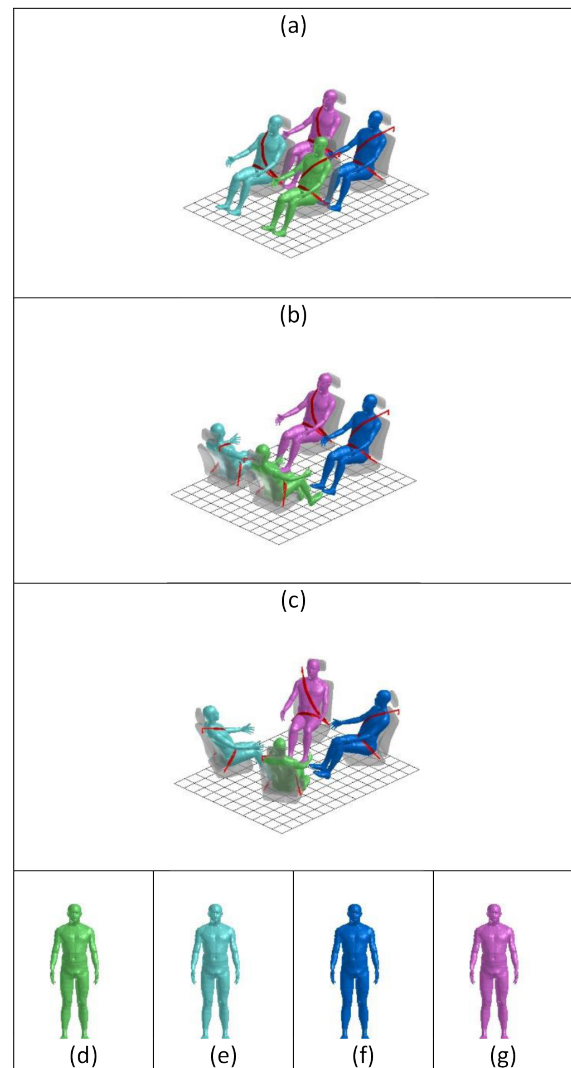


**Fig. 3** Seating positions; (a) Seating positions; (a) Standard;
(b) Face-to-Face; (c) Living room, passengers; (d) Front Left;
(e) Front Right; (f) Rear Left; (g) Rear Right

Fig. 4). This time was enough for bodies to accommodate to the seats' foam. The bodies and seats were just subjected to gravity acceleration in this period and seat belts' retractors were activated to pull back seat belts with the force of 35 N. After that, the seat belts were locked and bodies were affixed to their seats. The crash test was simulated for a low-speed (30 km/h) crash's acceleration pulse (Vezin et al., 2002), Fig. 4. The pulse was applied to a node which was located in the center of geometry included all seats as well as the schematic interior.

## 4 Part injury assessment

An algorithm is available for post-processing results and evaluating injury indexes of the Virthuman's parts. Evaluation is done according to a part's degree of injury in
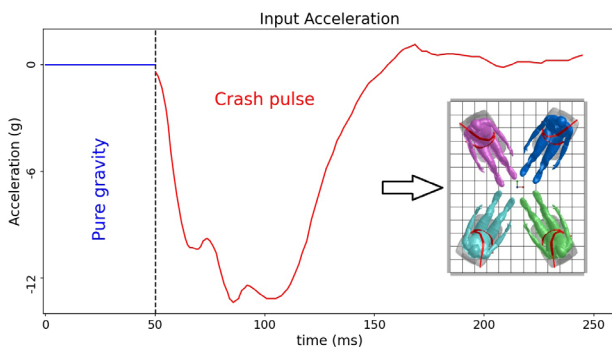
**Fig. 4** Acceleration pulse



**Fig. 5** Injury indexes for bodies

the current time interval (Mecas, sro., 2016a). A particular segment's degree of injury is the worst injury's degree in the time interval from the beginning to the current time step. In this regard, the last animation's step returns an injury's value for a part.

Injury indexes are returned in four levels (see in Fig. 5). If there is a small degree of injury or none the algorithm evaluates the part's index as Good. With increasing effective parameters on the computation of part's injury index, either Acceptable or Marginal injury level can be assigned to a part. Last but not least injury index due to serious injuries is presented by Poor level Injuries. Criteria for injury indexes are evaluated for Virthuman in (Vychytil and Špirk, 2020). Metrics for injury indexes are described in the Virthuman Post processing Manual (Mecas, sro., 2016a). Injury criteria for the Virthuman are based on injury of both hard and soft tissues. However it is not so easy to express what exactly happens to these tissues. So the injury indexes are presented with some simplifications. For instance head injury criterion (HIC) is considered for evaluating the head's injury index. Bending moment, as well as shear and tension forces of upper neck's joints, are used for computing the injury index of a model's neck. Injury of the model's thorax is determined based on ribs' deflection and parts' viscous criterion (VC). Compression and pubic forces are important parameters to investigate the index of injury for the abdomen and pelvis, respectively. Femurs, knees and tibiae' injury indexes are related to compression force and moments in these parts.

Virthuman's body parts in the current study were divided into three dominant sections:

1. Head & Neck,
2. Trunk (thorax, abdomen and pelvis),
3. Legs (femurs, knees and tibiae).

The worst injury's degree of a part in a section determines the overall injury index of that section. The injury index in non-standard 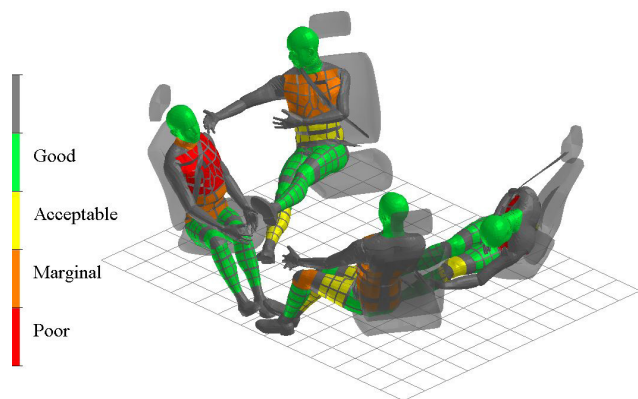seating configurations for each bodies' section of models was compared with the relevant section in standard seating configuration, as seen in Table 1. For occasions where the injury index of a section was decreased (red in Table 1) it meant the safety of the body's section in a seating configuration was worse than in another one. On the other hand, the safety of a body section was improved when the injury index was increased (green in Table 1). When no changes were seen between two seating configurations from the section's injury index point of view no colors were assigned to the section in Table 1.

## 5 Discussion

Occupants' kinematics in a side crash and different seating configurations are illustrated in Table A1 in the Appendix. Additionally, injury indexes for bodies in different seating configurations are shown in Fig. 6.

According to the data collected from comparing simulation outcomes in Table 1, it is elaborated that non-standard seating configurations cannot improve the safety of the Front Left occupant's Head & Neck. This happens because of the orientation of the shoulder belt which does not restrict the body's motion effectively in Face-to-Face configuration. The model's head hits the interior's side.

In Living room configuration, because seats are rotated inward, Front Left model's head does not hit the interior but its neck rotation is more significant compared to the Standard configuration.

Face-to-Face configuration is not safe for the Front Right occupant's legs in comparison with the standard one. It is the result of hitting the models right leg to the cushion of the front left seat (see Table A1 (200 ms)). In standard configuration the model's leg goes over the front left seat's cushion and in the Living room configuration the legs go under the front left seat because the models' position is rotated. In Face-to-Face configuration right leg's

**Table 1** Injury index comparison per body sections

| | Body part | Face-to-Face vs. Standard | Living room vs. Standard | |
|---|---|---|---|---|
| Front Left | Head & Neck | | | |
| | Trunk | | | |
| | Legs | | | |
| Front Right | Head & Neck | | | |
| | Trunk | | | |
| | Legs | | | |
| Rear Left | Head & Neck | | | |
| | Trunk | | | |
| | Legs | | | |
| Rear Right | Head & Neck | | | |
| | Trunk | | | |
| | Legs | | | |



(a)



(b)



(c)

**Fig. 6** Injury indexes for bodies in different
seating configurations; (a) Standard;
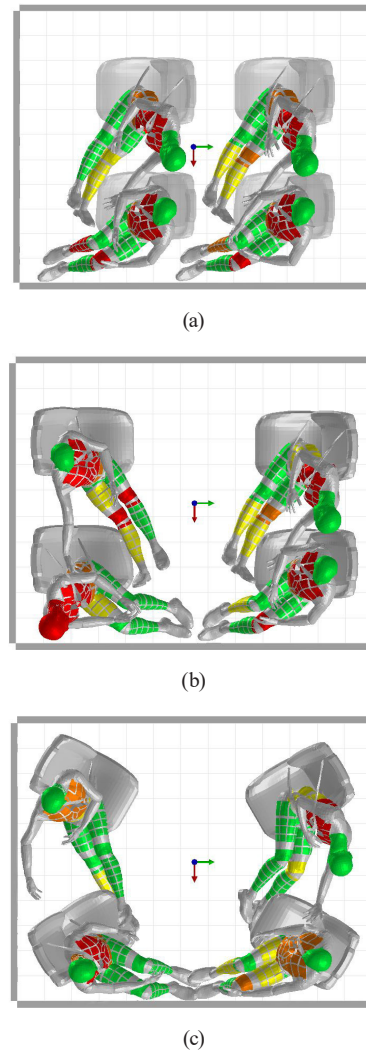(b) Face-to-Face; (c) Living room

tibia hits the cushion and dramatically increases forces and moments in the knee's joint (see Fig. 6).

Because of seats' inward rotations and orientation of shoulder belts for Front Right and Rear Left occupants' trunk injury index is changed from poor to marginal. It is interpreted as a safety improvement for these bodies.

The general rotation of seats in Living room configuration could slightly change the models' kinematic in side crash and improves rear row occupants' leg injury index. The only exception is Front Right occupants' legs. In the Standard configuration, its leg's left femur faintly touches the cushion of the adjacent seat which leads to an acceptable injury level. However, in the Living room configuration, its right femur is in contact with the adjacent seat's cushion. Here, because seats are rotated, the femur goes under the cushion. As far as no rigid elements are considered in this study for connecting seats to the interior bottom no serious injury is detected Fig. 6. Henceforth comparing Living room configuration and standard one does not reveal any changes from the leg's injury index point of view.

**6 Conclusion**

Body injury indexes of a highly automated vehicle's occupants in non-standard and standard seating configuration were compared together in the present study. Four identical 50th percentile Virthuman models were integrated into a schematic of a vehicle in a virtual performance solution (VPS) environment. Body models were located on deformable seats and fastened by three-point integrated seat belts. A side crash was simulated for a 30 km/h acceleration pulse. Three sections on bodies, i.e.: Head & Neck, Trunk and Legs were selected for comparing overall injury indexes between seating configurations.

Based on Numerical simulation results the following points can be highlighted:

- Non-standard seating configuration does not provide safer conditions for an occupant who is in the Front Left position because of head and neck injuries. However, these configurations can improve safety for legs.
- In Face-to-Face seating configuration, the Front Right occupant's leg may face some serious knee injuries. But no obvious changes are seen for the rest of its body concerning Standard configuration.
- Inward rotation of seats in Living room configuration causes that Front Right and Rear Left occupants experience lower injury indexes on their trunk. Also,

this configuration helps to decrease the legs' injury index for rear occupants.

- Considering the latter mentioned points, Living room configuration is safer for Rear Left occupants in comparison with Standard one. On the other hand, non-standard configurations for the Front Left occupant's Head & Neck are not safe at all.
- Comparing injury indexes for body sections in standard and non-standard seating configurations elaborated that Living room is safer than Face-to-Face and standard one if a side crash happens to a highly automated vehicle.

- Validating the present research outcomes against experimental crash tests has to be done, because the injury indexes of Virthuman's parts are evaluated by some simplifications. Meanwhile a simplified schematic of an autonomous car interior was used here.

## Acknowledgement

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## Appendix

**Table A1** Occupants' kinematics in a side crash and different seating configurations.