Numerical investigations on the factors affecting thorax injuries in vehicle vs pedestrian accidents

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ABSTRACT – Recent studies have discussed the relevance of injuries to the thorax in vehicle vs pedestrian accidents. The present study reports preliminary investigations on effect of vehicle type, impact location, pedestrian orientation, pedestrian leg position for the walking posture and effect of upper extremity interaction with the vehicle, on the injury to the thorax and specifically the rib fracture. Detailed finite element models of the production vehicles and Human Body Model (HBM) representing 50th percentile American Male were used in the study. The results indicate that injury to the thorax is influenced from several factors both related to the vehicle and pedestrian. Further investigations are needed to comprehensively understand the parameters influencing the injuries and develop strategies for injury prevention.

INTRODUCTION

The prevention of pedestrian injuries has been an integral part of vehicle development. Efforts from vehicle manufacturers, and guidelines and regulations from various bodies (e.g. New Car Assessment Programs, Working Group of the European Enhanced Vehicle-safety Committee, International Standards Organization Working Group on Pedestrian Impact Test Procedures) have been contributing to reduce the risk of injuries and injury severities to the head and lower extremities. Recent studies postulated the need to assess the risk of thoracic injuries to a pedestrian (Zander et al. 2019, Pal et al. 2023). Referring to German In-Depth Accident Study (GIDAS), Staack and Labenski (2022) reported that the thorax is the fourth most frequently injured body region sustaining moderate to fatal injuries.

To derive a meaningful assessment, it is essential to understand the parameters affecting the injury mechanism. Previous studies have reported effects of parameters such as geometric parameters of the vehicle front, vehicle speed, pedestrian anthropometry, impact location (Watanabe et al. 2012, Pal et al. 2023), and pedestrian posture and orientation (Chen et al. 2015) on the pedestrian kinematics and resulting injuries.

The present study intends to report results of the preliminary investigations conducted to understand the effect of vehicle type, impact location, pedestrian orientation, pedestrian leg positions, and effect of upper extremity interaction with the vehicle, on the fracture of pedestrian ribs.

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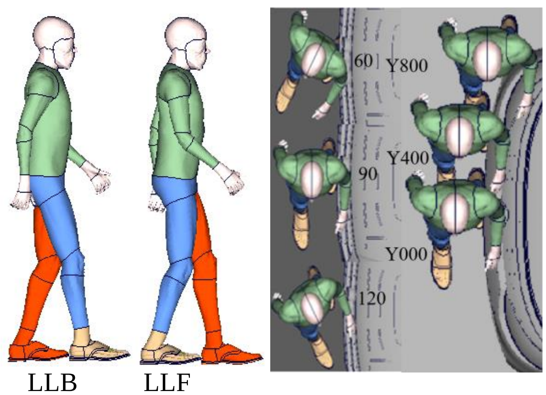
METHODS

The HBM used in the present study was derived from the 50th percentile male THUMS 4.1 (Visual Performance Solution (VPS), ESI group) occupant model. Further enhancements were incorporated in the model to improve its response. The updated model was validated against full body vehicle – pedestrian impact experiments (Forman et al. 2015, Song et al. 2017). The Injury Risk Function for the individual ribs, and the cumulative risk function for the entire ribcage of the model were developed based on various experimental data using a method similar to Forman et al. (2022). The predictability of risk functions was evaluated by simulating a total of 23 real accidents (road users as well as car occupants), under an AUDI AG internal accident research program. The predictions of injury / no injury with a 50% probability threshold were found to be correct in 22 cases. Detailed finite element models of three different vehicles (Sedan, SUV and Van) with passive bonnet were used for the study even if equipped with active pedestrian countermeasures. All the vehicle models were validated internally. Two different leg postures were used during the simulations. For the first posture, the HBM represented the posture, described in EuroNCAP Technical Bulletin 24 v3.0.1. This posture is referred to as LLF (Left Leg Forward). The second posture is mirrored position of the LLF referred to as LLB (Left Leg Backward), where hand and leg positions were interchanged for left and right sides. With each leg posture, the HBM was positioned in front of the vehicle at three different Y locations: at the center of the bumper width (Y000), 400 mm away from the center along the Y direction (Y400) and 800 mm away from the center from the center (Y800). For the measurement of the Y distances, the center of gravity of the HBM head was used as the reference. For each of the positions along the bumper, three different impact angles were investigated: Lateral position (90 deg), clockwise rotation of 30 deg from lateral position (120 deg), and counterclockwise rotation of 30 deg from the lateral position (60 deg). Fig 1(a) shows the two different leg postures whereas Fig 1(b) shows the three different orientations of the HBM. Fig. 1(c) shows the three different Y locations. To investigate the effect of the interaction of the upper extremity and the vehicle, all the simulations were run with the contact between the vehicle and the HBM upper extremity active (CT) and inactive (WoCT) states. Contact between vehicle and shoulder was always active. Hence, the total number of simulations run were 108 i.e., 36 simulations per vehicle were performed using the VPS version 2020. In all simulations, the left side of the HBM was struck by the vehicle at 40 km/h. The friction coefficient between the vehicle and HBM was chosen 0.3.



(a) (b) (c)

Figure 1 Simulation Variations: (a) HBM Postures (b) HBM Orientations and (c) HBM Locations

For each simulation, injury probability to each rib was computed using the approach described above. For any case, if the estimated injury probability of any rib was found to be equal to or more than 50%, it was considered that the rib has sustained a fracture. Identification of exact location of the fracture or to detect the possibility of multiple fractures of a single rib were beyond the scope of the present study.

RESULTS

The Figure 2 shows the total number of times ribs at a given rib level fractured during 108 simulations. In general, rib 2 is the most frequently injured rib, followed by rib 1 and rib 7. Rib numbers 11 and 12 were not fractured in any of the cases. For the 36 simulations with Sedan a total of 34 ribs were fractured, and it is the only vehicle type causing fracture of ribs 4 to 6. SUV caused fractures in 14 ribs, while the Van caused fractures in only 5 ribs. The number of fractured ribs was also considerably affected by the contact condition between the HBM upper extremity and the vehicle. For instance, in case of Sedan CT setting, a total of 14 ribs were fractured in 18 simulations, compared to 20 fractured ribs in 18 WoCT simulations.

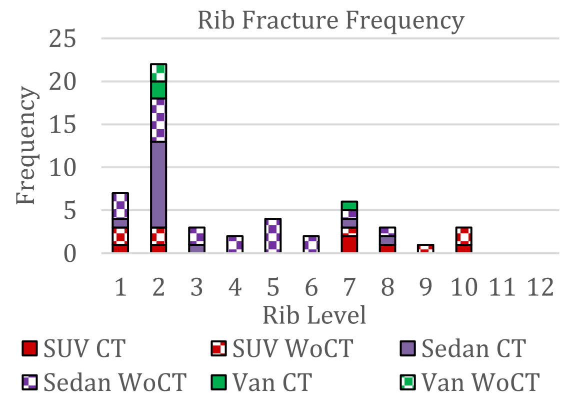


Figure 2 Number of times ribs at given levels fractures for vehicle type (Sedan, SUV, Van) and contact definition between upper extremities and vehicle (CT: Contact active, WoCT: Contact inactive)

DISCUSSION

A total of 108 simulations were performed to investigate the effect of parameters affecting the injury to the thorax of a pedestrian specifically rib fracture. Some of the results of the study are in agreement with previously reported findings. For instance, Pal et al. (2023) observed that the chest impact velocity was highest in case of a Family Car, which has front geometry comparable with the sedan of the present study. In present study also, the HBM chest had higher impact velocities for the impact with sedan, consequently resulted in largest number of fractured ribs. However, this could not be confirmed by field data, as Staack and Labenski (2022) found the Van front causing more number of moderate to severe thorax injuries. Kerrigan et al. (2012) also observed considerable amount of variations in the thorax injuries as well as its occurrence in their evaluation of 41 pedestrian full body PMHS tests. The observed differences in these studies can be attributed to various vehicle and subject parameters.

Chen et al. (2015) and Watanabe et al. (2012) observed a smaller number of fractures in their study compared to the present study. However, most of the reported fractures in Chen et al. (2015) were in the upper thorax region. This observation is also consistent with the finding in the present study, where first two ribs together were the most frequently fractured ribs. Some possible reasons for the differences between rib fracture frequency reported by Chen et al. (2015) and the present study could be the effect of HBM location, types of vehicles and the effect of contact between the HBM upper extremity and the vehicle, as well as the injury prediction method. Chen et al. (2015) used a single value of strain for depicting fracture, whereas present study uses an injury prediction function. The effect of upper extremity contact was considerable for the sedan, but not for the other vehicle types. Watanabe et al. (2012), has reported investigations with different HBM sizes, impact velocity and two different impact locations along the bumper. Results of present study deviates from the observations of Watanabe et al. (2012) for the sedan car. Watanabe et al. (2012) did not observe any rib fractures up to 40 km/h. Whereas in the present study, large number of fractured ribs were observed. Among others, reasons might be the effect of HBM orientation, effect of upper extremity contact condition, methods of fracture prediction and variability between tested PMHS subjects. In present study, 24 of the 34 fractures for the sedan were observed for the orientation other than 90 degrees. The observed variations suggest that considering only one scenario to evaluate potential rib fracture could result in an oversimplification. Though the present study helps to understand the effect of various parameters on the rib fracture in a vehicle – pedestrian accident, there are some limitations of the present study which should be addressed in the future. The most important limitations are the use of only one HBM size (50^{th} percentile male) and no investigations of the secondary impacts. Furthermore, the effect of age on the material property of the bone was not included. In addition, though present study uses two different leg positions, one may reach to different results for different postures. Usage of method to depict the injury may also affect the outcomes significantly.

Despite the limitations, the complexity involved in the investigations of the injuries to the thorax of the pedestrian were brought out. As many previous studies already pointed out, the risk of rib fracture (and other thoracic injuries) in pedestrian collision is affected by many parameters which are difficult to be summarized by simple scenarios before understanding the interrelations completely. Further studies are needed to fully understand the injury mechanisms. In particular, future studies should take full body kinematics into account (e.g. HBM), as simplified tools like Thorax Injury Prediction Tool (TIPT) (Zander et al. (2019), Pal et al. (2023)) cannot provide comprehensive understanding of the complex interrelations of parameters and injury mechanisms.

CONCLUSION

1. Parameters affecting the rib fracture in vehicle – pedestrian impacts have been investigated.
2. The study was performed with detailed finite element models of production vehicles and a detailed HBM.
3. Distribution of the fracture is scattered over almost all rib levels, although the upper ribs are the most frequently injured ribs.
4. Orientation of the HBM, the HBM location and upper extremity contact condition, were found to affect the rib fracture considerably.
5. Findings reported in the manuscript are aligned with previous studies.
6. Further investigations are needed to develop effective strategies for the assessment of injuries to the thorax of pedestrians.

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