INVESTIGATION OF RESTRAINT CHARACTERISTICS FOR ELDERLY OCCUPANT CHEST INJURY REDUCTION

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ABSTRACT

Objective

In recent years, the increase in the number of traffic accident fatalities of elderly in Japan is one of the urgent tasks for future traffic accident countermeasures.
Moreover, from the trend of a global aging society, in the future it is expected that the number of traffic fatalities involving the elderly and the importance of correspondence will also increase. In this research, in order to cope with the reduction of elderly traffic accident fatalities, chest injuries are focused on as one of the factors of elderly occupant fatalities, measures to reduce chest impact of elderly occupants at the time of a frontal collision are examined and then, the direction of the corresponding technology required for realization was considered.

Methods

In this study, using a human body FE model with different physiques to reproduce the bone characteristics and skeletal shape of both adults and elderly people, frontal collision simulations within different collision speed ranges were performed. Comparison of chest injuries was undertaken of elderly occupants, which can occur in the middle and low speed range, to adults. Examination of optimum occupant restraint characteristics by seat belts enabled chest injuries of elderly occupants to be reduced to the same level of adults. Then, the effect of reducing elderly occupant's chest injuries in each physique was confirmed.

Results

The occupant restraint characteristic by the seat belt calculated was able to confirm the chest injury reduction effect of an elderly occupant in each physique in the front collision in the medium to low speed range. In addition, this restraint characteristic combines the restraint characteristics for reduction of chest injuries of elderly occupants with different physiques, and secondary collision damage reduction.

Discussion and Limitations

In this research, focus was on medium and low speed and frontal collision. In order to realize this occupant restraint characteristic, it was necessary to be compatible with occupant protection performance in the collision mode of each regulation. For this purpose, achieving sensing technology to determine the severity of car body deformation at the time of a collision, occupant protection system technology that can change occupant restraint characteristics according to the situation is essential. In order to further reduce the number of deaths, it is necessary to investigate occupant restraint characteristics that can reduce injuries, and look at other measures for reducing chest injuries in the high speed region for each type of collision.

Conclusion

In this study, we used a human body FE model with different physiques to calculate the occupant restraint characteristics necessary for a reduction of chest injuries of elderly occupants and reduction of secondary collision damage in frontal collisions in the medium and low speed range, and confirm the effect. In order to further reduce elderly occupant injuries, as a type of integrated safety technology with more damage mitigation effects, collision prediction technology by evolution of ADAS's external detection technology uses identification of an occupant's physique, posture, and age judgment technology It is necessary to evolve protection device technology, which can vary occupant restraining force and time according to situation and occupant.

INTRODUCTION

According to Japanese traffic accident statistics [1], the percentage of elderly people 65YO and over traffic accident fatalities (within 24hours) has recently been increasing. Measures to address traffic accidents involving the elderly is one of the urgent issues faced as part of Japan's efforts to reduce traffic accident fatalities. Statistical data from the Institute for Traffic Accident Research and Data Analysis (ITARDA) [2] on fatalities and injuries in automobile accidents that occur while riding in passenger cars, limited to drivers wearing seatbelts, was aggregated by age group and most severe injury. According to the results, a comparison between those 64YO and under and those 65YO and over by most severe injury body region shows that the percentage of fatalities due to chest injuries among adults 64YO and under was 27%, while the percentage among the elderly 65YO and over was 51%, and same trend in severe injury of AIS3+ (Figure 1). The percentage of fatalities due to chest injuries was conspicuously high compared to other injury body regions.

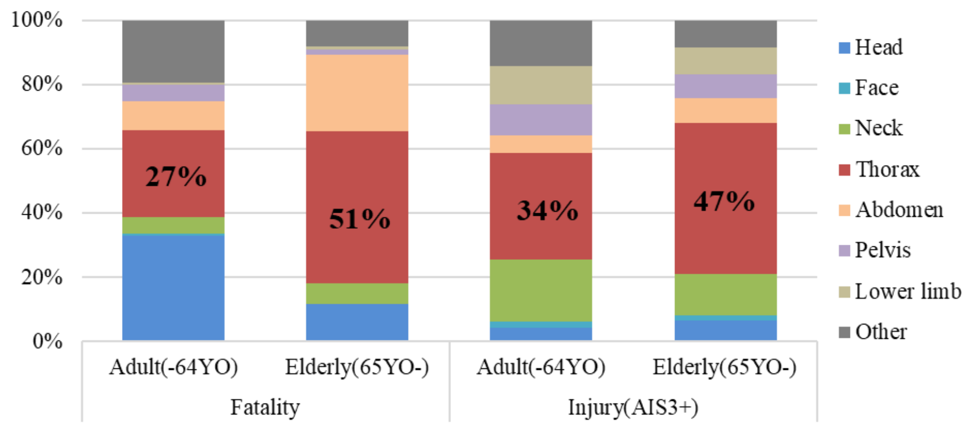


Figure 1. Injured body region on passenger car occupant by age groups (Driver)

Research by Kent et al. [3] suggests the significant differences between adults and the elderly in their skeletal structures, bone strengths, skeletal shapes, and bone structures, which are already known to medical science. Therefore, elderly seem to have a higher possibility of injury at medium and low speed. World population statistics [4] also point to a global trend toward the aging of societies so that the number of traffic accident fatalities among the elderly is projected to increase, and measures to counter that increase are considered a matter of growing importance. The present research seeks to support the reduction of traffic accident fatalities among the elderly by concentrating on the reduction of chest injuries, which are one of the causal factors in the death of elderly occupants in motor vehicles. Measures to reduce the thoracic load on elderly occupants during frontal collisions were investigated and approaches for the technology needed in order to realize such measures were considered.

METHODS

Human Body Model and Vehicle Model

In the present research, simulation used the FE models of adult and elderly vehicle occupants [5] [6] [7] that employs the explicit dynamics code of PAM-CRASH^{TM} to reproduce the bone characteristics and skeletal shape of adults and elderly people. These human body FE models were used for three different physique types in the United States, namely the AF05, corresponding to a small female physique, the AM50, corresponding to a standard male physique, and the AM95, corresponding to a large male physique. As in the research by Sugaya et al. [8], these types were prepared through simple geometry scaling by body height and mass ratios. Figure 2 shows the front view of the models scaled to three physiques and Table 1 shows the scale factors for each physique.

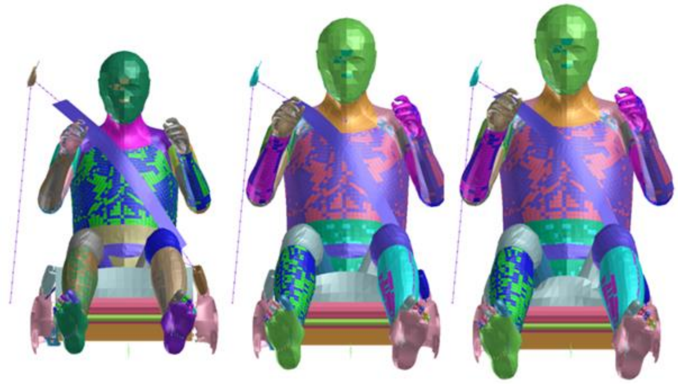


Figure 2. Human FE Models of Three Physiques (Left Side AF05, Center AM50, Right Side AM95)

Table 1. Scaling factors for each physique

Physique	Height	Mass
AF05	0.862	0.612
AM50	1.0	1.0
AM95	1.066	1.323

In the present research, a vehicle body FE model of a typical mid-sized sedan was used to reproduce the steering wheel and steering column, and the driver's seat, driver airbag, and seatbelt with three-point seatbelt with pretension (equivalent to mass produced products). Each collision simulations were performed with human body FE models for each physique in place.

Figure 3 shows the vehicle body model with a settled occupant model. The AF05 was seated at front-most, the AM50 at neutral, and the AF95 at rear-most positions in the seat slide range.

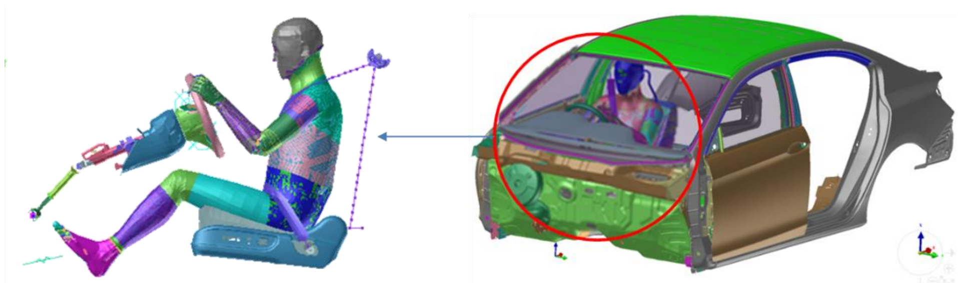
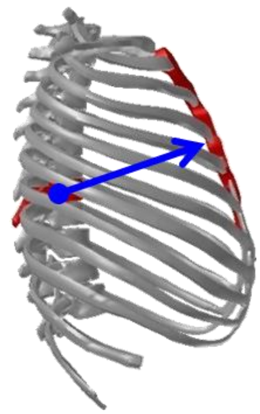


Figure 3. Vehicle FE model and occupant seating condition (AM50)

Parametric Studies for Rib Fracture (Rib Fx) Mitigation

Sled simulation of full-overlap frontal collisions was performed using the vehicle body decelerations that corresponded to 26 km/h and every 4 km/h increments up to 50 km/h. The airbag deployment timing and seatbelt pretensioner onset timing were varied according to the vehicle deceleration at the time of collision. The chest injuries that can occur to adult and elderly occupants under those conditions were evaluated by the thoracic deflections expressed by the relative deflection between the middle of the sternum and the T8 interbody as shown in Figure 4, and by the number of rib fractures expressed by the 'element elimination' when the strain of an element of rib cortical bone exceed a specified critical value as shown in Figure 5.

Next an examination was made of the optimal occupant restraint characteristics of seatbelts. The seatbelt load limiter characteristic was taken as a parameter and the load was varied by 0.25 kN increments between 2.25 kN and 3.0 kN as shown in Figure 6. The state of the chest injuries that occurred were confirmed for each of the elderly occupant's physiques. A comparison was made of the results obtained at that time for occurrence of thoracic deflections and rib fractures by physique and by seatbelt load limiter characteristics, and the seatbelt lower limit load characteristics for rib fractures that occurred with each physique were derived. The results obtained by the above parametric study were used to determine the optimal occupant restraint characteristics for seatbelts that could reduce elderly occupant chest injuries to the same level as adult chest injuries. The chest injury reduction effects for the elderly occupants of each physique were confirmed.



No.8 Thoracic Vertebra(T8)-Sternum Relative deflection

Figure 4. Measurement location of thoracic deflection

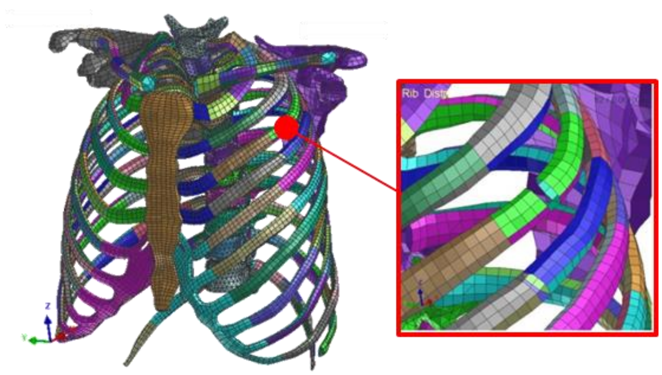


Figure 5. Rib fracture condition using element elimination option

Table 2. Parametric study for comparison of rib fracture condition

Vehicle Type	Mid-Size Sedan
Floor G Condition	26kph～50kph Full lap
Restraint Devices	Load limiter (3kN Constant) with Pretensioner, Airbag
Human FE Model of Occupant	Adult / Elderly
Physique	AM50

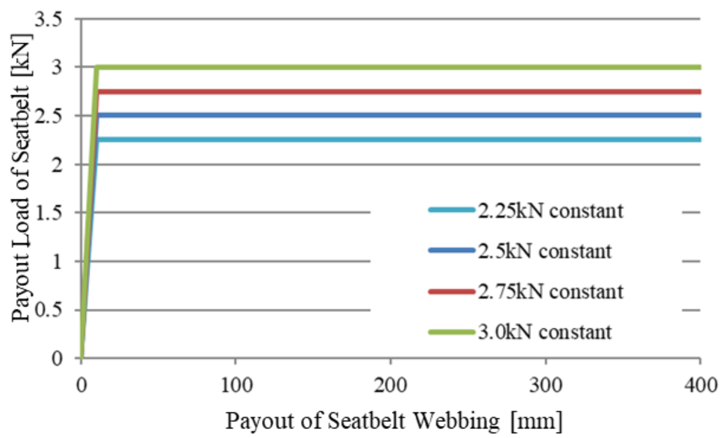


Figure 6. Seatbelt payload characteristic for parametric study

RESULT

Comparison of Rib Fracture between Adult and Elderly and Setting of Target Collision Speed

As a baseline examination, a comparison was made of differences in occurrence of chest injuries in adult/elderly occupants in frontal collision simulations at different collision speed ranges using the AM50 model. The number of rib fractures in the elderly model were compared with the number of rib fractures and resulting thoracic deflections in the adult model. The comparison results showed that one rib fracture occurred in the adult in a collision with speed equivalent to 40 kph, and as defined in AIS2005, this was AIS1, while at the same collision speed, it was found that four rib fractures occurred in the elderly, for a code of AIS3 as shown in Figure 7. However, the AIS code for rib cage injuries varies according to whether or not hemo/pneumothorax occurs. This cannot be evaluated with the present model, so the AIS was evaluated solely by the number of rib fractures. Based on these results, the target was defined as achieving the same or lower level of injury from chest injuries in elderly occupants in a medium-speed collision at a speed of about 40 kph as occur in adults as maked in Figure 7.

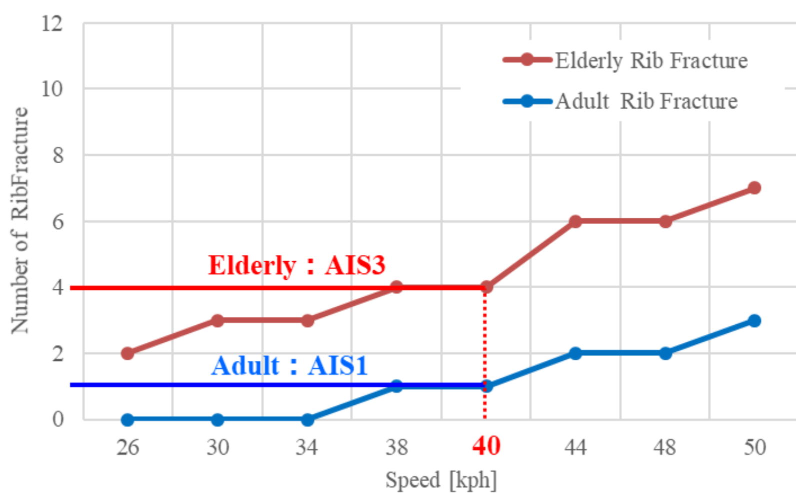


Figure 7. Rib fracture comparison between adult and elderly and target collision speed

Examination of Seatbelt Payout Load Characteristic for Each Physique for Elderly Rib Fracture Reduction

The optimal occupant restraint characteristics for seatbelts were examined. This involved taking the seatbelt load limiter characteristic as a parameter and confirming the circumstances of chest injury occurrence among elderly occupants with AF05, AM50, and AM95 physiques. The results for the circumstances of thoracic deflection and rib fracture occurrence in collisions at 40 kph by physique and by seatbelt load limiter characteristics were compared in terms of the circumstances of thoracic deflection and rib fracture in each physique model as shown in Table 3. The seatbelt lower limit load characteristics were derived for those rib fractures coded as AIS1 or above that occurred in each physique. The results were 2.5 kN for AF05, 3.0 kN for AM50, and 2.5 kN for AM95 as shown in Figure 8. However, even though the thoracic deflections in AM95 were smaller than in the other physiques, fractures did occur with a seatbelt payout load of 2.5 kN.

Table 3. Result of elderly rib fracture and chest deflection at each seatbelt payout load at 40kph (AM50)

Payout Load [kN]	2.5	2.75	3.0
Max Def. [mm]	46.3	49.0	51.1
Max Def. Time [ms]	67.8	66.8	64.8
Number of Rib Fractures	0	0	2
Part of Rib Fractures			
Rib Fracture Location			R3, L10

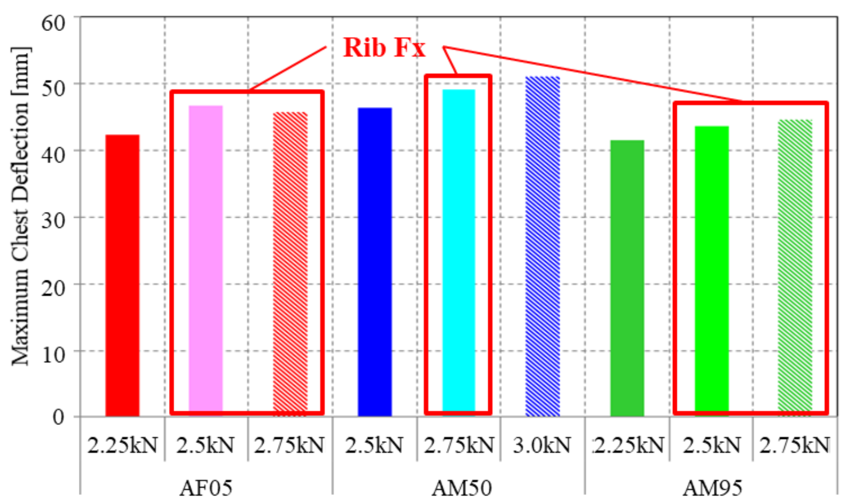


Figure 8. Result of rib fracture and chest deflection of each physique and seatbelt payout load

Target Setting for Secondary Collision Avoidance

The results, including occupant movement, were examined in detail for AM95. It was found that due to the low restraint load, contact with the steering wheel (STRG) occurred at every seatbelt payout load as shown in Figure 9 and Figure 10.

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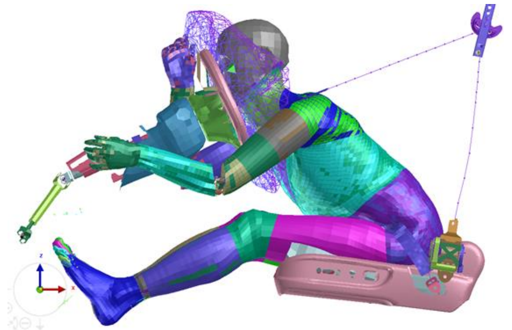


Figure 9. Secondary Collision of AM95 with STRG at 40kph

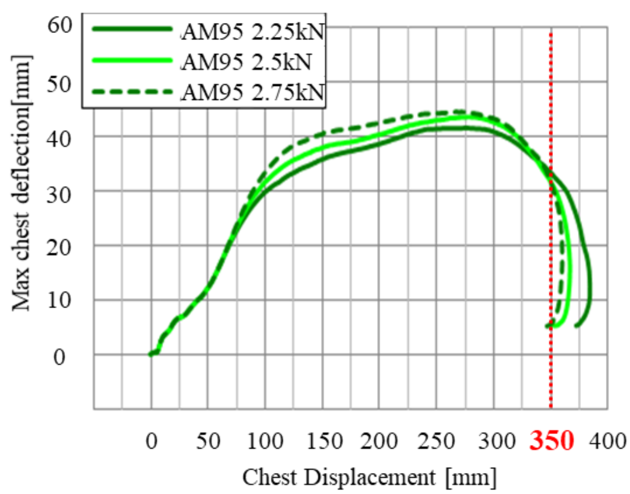


Figure 10. Chest displacement of AM95 for each payout load at 40kph

Consequently, the absence of contact with STRG was added to the target performance for the purpose of avoiding secondary collision in AF05 and AM95. An examination was made of the combination of seatbelt load limiter characteristics and collision speed that would enable avoidance of rib fractures and of contact with STRG in AF05 and AM95.

The seatbelt limit load and limit speed that could achieve the status of non-rib fracture and non-contact with STRG was calculated while lowering the collision speed to 34 kph that reduced the occupant's initial energy. The result was that the limit load for non-rib fractures in AF05 was 2.25 kN or lower, and the limit speed for non-contact with STRG and none rib fracture in AM95 was 36 kph.

Based on the above results, the relationship between the upper limit seatbelt payout load of seatbelt for none rib fractures and the maximum seatbelt payout needed to restrain the occupant at that point was put into an organized form. As shown in Table 4 and Table 5, the result was that the speed range enabling reduction of chest injuries and avoidance of secondary collision injuries, and the seatbelt payout load needed to restrain the occupant, differed for each of the AF05, AM50, and AM95 physiques.

Table 4. Result of elderly rib fracture for each seatbelt payout load at 34/36/40kph (AF05)

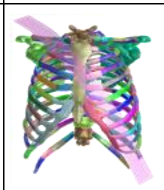
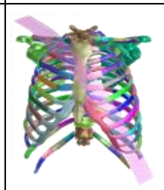
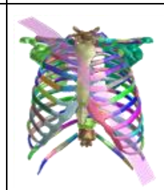
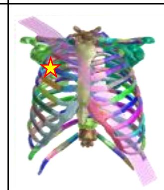
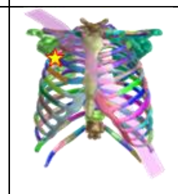
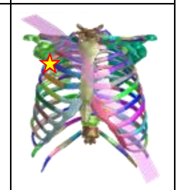
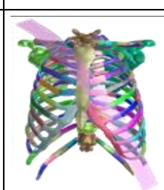
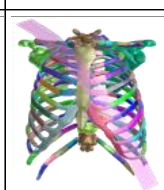
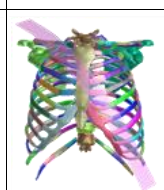
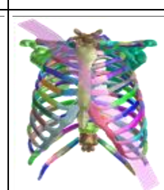
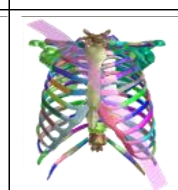
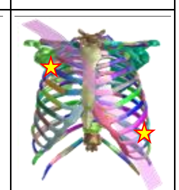
Physique	AF05					
Payout Load [kN]	2.25			2.5		
Speed [kph]	34	36	40	34	36	40
Max Def. [mm]	37.5	37.0	42.2	38.7	40.1	46.7
Max Def. Time [ms]	65.0	65.3	61.8	68.3	68.5	61.5
Number of Rib Fractures	0	0	0	1	1	1
Part of Rib Fractures						
Rib Fracture Location				R3	R3	R3
Chest Def. [mm]	105.5	112.9	114.2	99.7	109.8	93.4

Table 5. Result of elderly rib fracture for each seatbelt payout load at 34/36/40kph (AM95)

Physique	AM95					
Payout Load [kN]	2.25			2.5		
Speed [kph]	34	36	40	34	36	40
Max Def. [mm]	38.0	40.2	41.6	39.4	40.2	43.6
Max Def. Time [ms]	83.5	82.5	83.3	85.8	85.3	84.5
Number of Rib Fractures	0	0	0	0	0	2
Part of Rib Fractures						
Rib Fracture Location						R3,L8
Chest Def. [mm]	336.6	353.0	384.2	318.4	336.0	366.6

Comparison of Adult and Elderly Rib Fracture

The next step was to ascertain the seatbelt restraint characteristics that could maximize the injury reduction effect for elderly occupants of AF05, AM50, and AM95 physiques regardless of physique differences. This was done by fixing the collision speed at 35 kph, with reference to the limit speed for STRG contact by AM95, and setting the lower limit seatbelt payout load at 2 kN. Then a parametric study was carried out with the seatbelt load limiter characteristic set to increase gradually and consistently in conjunction with the seatbelt webbing payout, keeping it inclusive of the fracture limit load for each of the AF05, AM50, and AM95 physiques as shown in Figure 11.

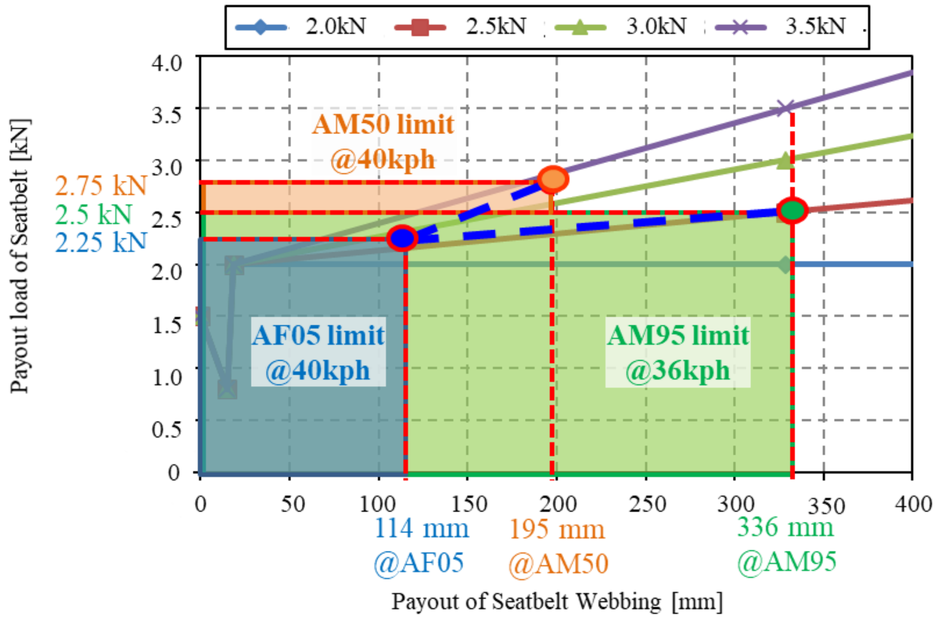


Figure 11. Relation of rib fracture and seatbelt payout load characteristic

Simulation using three physiques and four seatbelt restraint loads obtained the results for locations and numbers of rib fracture, for the fracture timing, and for the seatbelt webbing payout at the point where the upper body of the occupant moved farthest forward as shown in Table 6. These results were put in order and the seatbelt force limiter characteristic capable of realizing zero rib fractures while avoiding bottoming out against the STRG even for AM95 was successfully verified within the parametric study.

Table 6. Result of elderly rib fracture each seatbelt payout load at 35kph (AF05/ AM50/ AM95)

Physique	Payout Load @330mm	Max.Chest Def. [mm]	Chest Def.@Fx [mm]	Fx or No Fx	Time [ms]	Rib Fx location
AF05	2.0	72	-	No Fx	-	-
	2.5	66	65	Fx	87	R1
	3.0	66	37	Fx	66	R2
	3.5	66	35	Fx	63	R2
AM50	2.0	189	-	No Fx	-	-
	2.5	176	-	No Fx	-	-
	3.0	169	111	Fx	74	R3
	3.5	158	98	Fx	72	R3,4
AM95	2.0	338	-	No Fx	-	-
	2.5	314	-	No Fx	-	-
	3.0	291	-	No Fx	-	-
	3.5	289	255	Fx	97	R3

With seatbelt payout load on the vertical axis and seatbelt webbing payout on the horizontal axis, the above results for seatbelt payout and occurrence or non-occurrence of fractures were put in order and plotted by physique and seatbelt payout load in Figure 12. When the seatbelt load limiter characteristic was traced against the boundary for occurrence or non-occurrence of fractures with each physique, the result was a payout load characteristic that trended steadily upward. The restraint load characteristic obtained through this parametric study that enables mitigation of chest injuries and damage from secondary collision regardless of physique, and that has an energy absorption (EA) load that also increases together with the increase in payout of seatbelt webbing, will hereafter be referred to as Progressive EA.

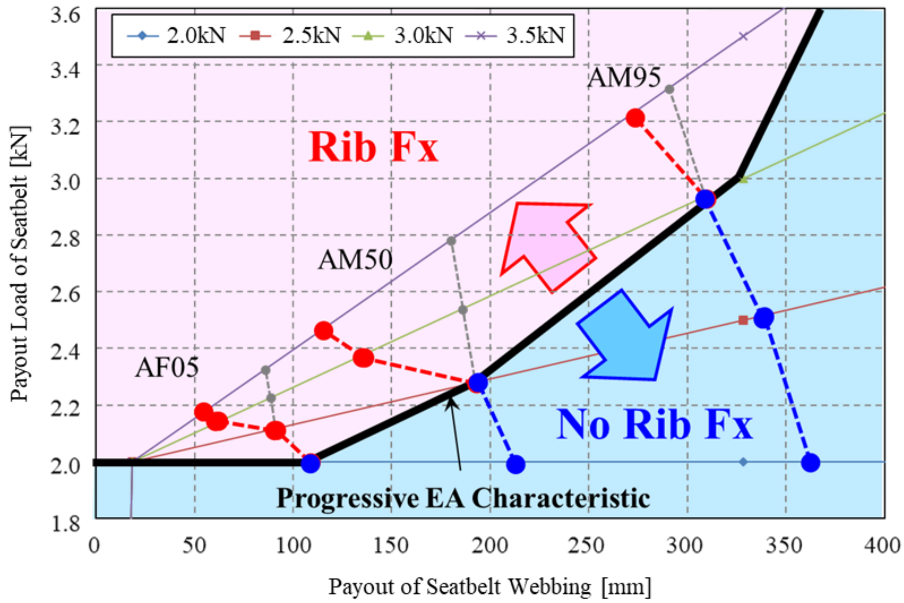


Figure 12. Relation of rib fracture and seatbelt characteristic (Progressive EA) at 35kph

DISCUSSION

The characteristics obtained through the present research are the simulation results for frontal collisions at low to medium speed. In order to confirm the collision angle and speed range covered by the characteristics obtained, a model that reproduces the interior and door trim of a mid-size sedan was used. For comparison of confirmed effectiveness, simulations were carried out with the seatbelt payout load fixed at 3 kN and with the Progressive EA seatbelt payout load varied from 2 kN to 3 kN, with the angle of collision with the barrier varied by 15° increments from 15° to 45°, and with the collision speed varied by 4 kph increments from 28 kph to 60 kph.

The changes in the number of rib fractures under the respective seatbelt payout loads were scrutinized. As shown in Figure 13, even with the seatbelt payout load fixed at 3 kN, which served as the base for comparison, the number of rib fractures was one or fewer under every collision angle as long as the collision speed was 28 kph. By contrast, although simulation with the Progressive EA characteristic successfully held down rib fractures under every collision angle up to a collision speed of around 36 kph, it was found that the number of fractures gradually increased as the collision speed. In some cases, this is because fracture occurs from collision with the center console or the door trim due to the collision angle and the rising speed. In the case of rib fractures occurred close to 40 kph, however, fracturing of the lower ribs was observed due to compression of the lower rib cage by the webbing on the shoulder belt side close to the seatbelt buckle as shown in Figure 14.

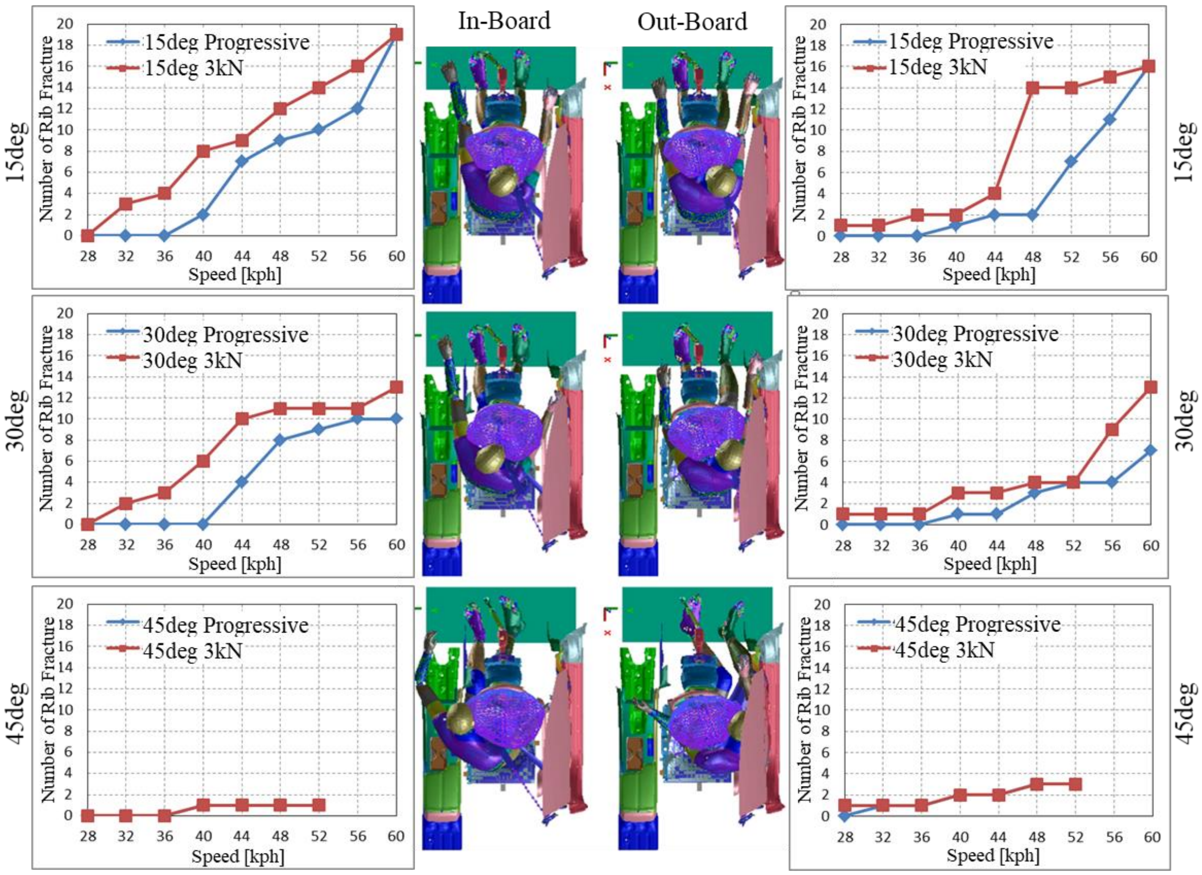


Fig. 13. Comparison of amount of rib fracture by collision direction / velocity (75YO)

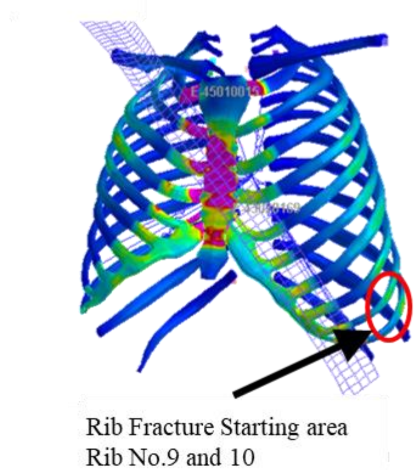


Fig. 14. Occurring rib fracture in oblique collision (75YO)

As to methods used in the present investigation for directly confirming rib fractures, evaluation of the fractures themselves is possible. However, evaluation of fractures in the lower ribs is not possible using another indicator, which is the measurement of chest deflection at representative points. In order to further reduce chest injuries in elderly occupants, the issues to be addressed include achieving a balance of necessary occupant protection performance in the collision modes specified in regulations and statutes for the purpose of realizing these occupant restraint characteristics. At the same time, they also include expanding the range of collision speed and collision angle supported by the device while formulating indicators allowing for appropriate evaluation of the effectiveness of injury reduction in the lower ribs. The chest deflections and chest deflection reduction amounts achieved by the present simulation under the various seatbelt payout loads in the vicinity of 40 kph were compared in terms of the relative displacement between the sternum and T8, which were adopted as representative points for the present investigation, and the relative deflection between ribs 9 and 10 and T8 as shown in Figure 15, which are starting points for fractures of the ribs. Table 7 shows comparison of chest deflection reduction rate difference of measurement point.

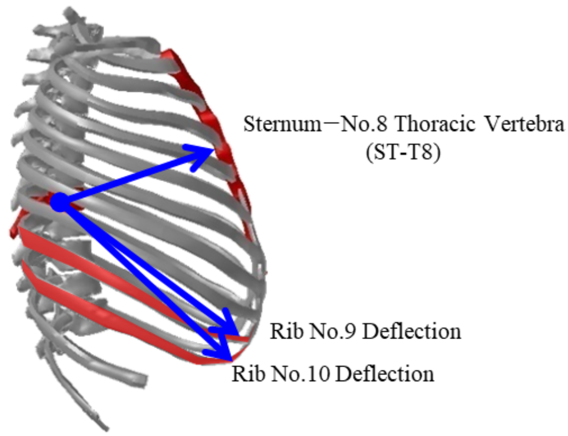


Figure 15. Comparison of chest deflection reduction effective measurement by collision direction

Table 7. Comparison of chest deflection reduction rate difference of measurement point

Payout Load	ST-T8 [mm]	Def. Reduction [mm]	Reduction Rate [%]	Rib Def. [mm]	Def. Reduction [mm]	Reduction Rate [%]
3kN	50.9	–	–	L9:23.4	–	–
				L10:15.0	–	–
2kN-3kN	44.0	6.9	**13.6**	L9:12.9	10.5	**45.0**
				L10:6.7	8.4	**55.7**

Where there was relative deflection between the sternum and T8, the reduction in chest deflection amounted to 6.9 mm, which was a reduction rate of 13.6%. By contrast, the reduction in displacement of ribs 9 and 10 was from 8 mm to 10 mm. Although very small, this reduction achieved the significant reduction effect of around 45-55.7%, and it will be necessary to devise an index that enables appropriate evaluation of this reduction effect for use in future investigation of devices supporting the protection of elderly occupants.

In Figure 16, one example can be seen when these simulation results are plotted by the number of fractures on the vertical axis and by the consequent chest deflection at representative points on the horizontal axis. Inspection of the correlation between rib cage displacement and the number of fractures shows large variations. No distinct correlation can be seen. This suggests that the evaluation of rib fracture injuries by representative points on the rib cage is inadequate as an indicator. For future investigation of chest injury reduction taking the real world accidents into consideration, it will no doubt be necessary to create an appropriate injury evaluation method that can be used to evaluate the rib fracture reduction effect in the ribs as a whole, such as suggested in the research of Kawabuchi et al. [9]. This needs to be in addition to injury evaluation by measurement of rib cage displacement at four points using a recent THOR dummy equipped with IR-TRACC.

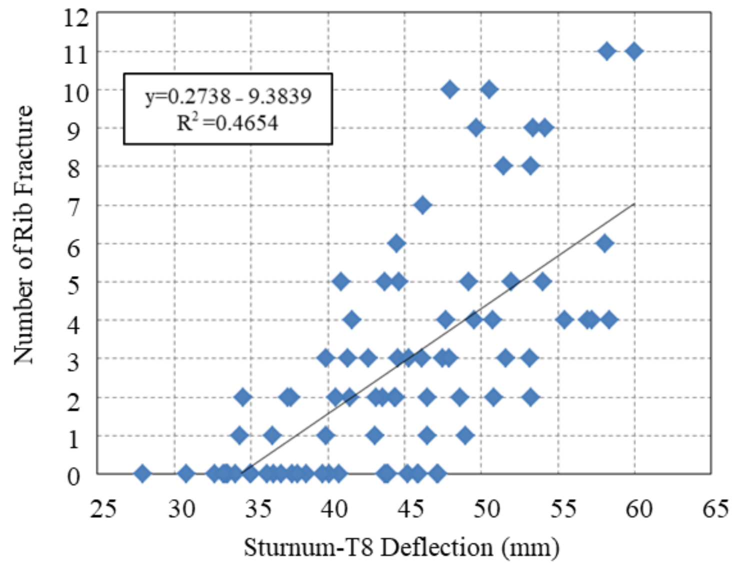


Figure 16. Correlation of human chest deflection and rib fracture

In addition, in order to further reduce fatalities among elderly occupants, it will also be essential to have technology for occupant protection systems capable of varying occupant restraint load and timing continuously, according to collision pattern and occupant variation. And, as an integrated safety technology that has greater damage reduction effectiveness, sensing technology needs to determine the severity of vehicle body deformation during a collision in combination with technology for collision prediction using evolved Advanced Driving Assistance System (ADAS) technology for sensing the external environment, and also for identifying occupant physique and posture and for determining age. It is also considered necessary to investigate occupant restraint characteristics capable of injury reduction, and measures capable of reducing chest injuries at high speeds, for collision patterns other than frontal collision. The results of this study, combined with these integrated safety technologies, will be able to reduce injuries not only elderly people but also various vehicle occupants.

CONCLUSION

In the present research, further reduction of fatalities, we were examined by focusing on chest injuries, which are one of the causal factors in the fatal of elderly people while riding as occupants in automobiles. Measures to reduce the thoracic load on elderly occupants during frontal collisions were investigated and approaches for the technology needed in order to realize such measures were considered. As a result, Progressive EA characteristics that are a seatbelt load limiter characteristic capable of reducing damage from chest injuries and secondary collision regardless of the elderly occupant's physique were obtained through simulation using a human model.

Issues that remain for the future include the creation of appropriate injury evaluation methods capable of evaluating effectiveness in reducing rib fractures in the ribs as a whole in the course of investigating chest injury reduction that takes real world accidents into consideration further chest injury reductions.

In addition to this, it will be necessary to create occupant restraint technology that is capable of covering an expanded range of collision speeds, collision angles, and adjust to each occupant in various situations, by using ADAS sensing information and varying occupant restraint load and timing.

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APPENDIX A

Table A1. Result of elderly rib fracture and chest deflection at each seatbelt payout load at 40kph (AF05)

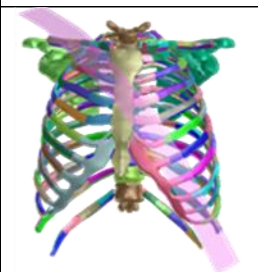
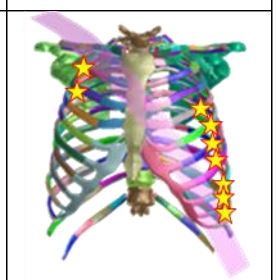
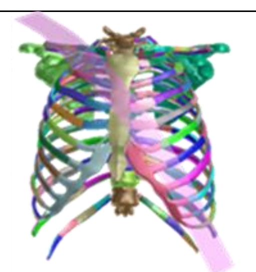
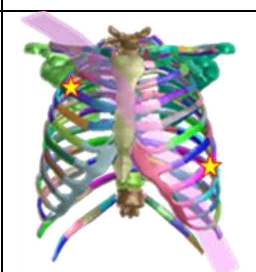
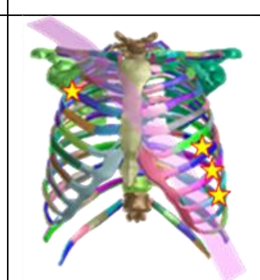
Payout Load [kN]	2.5	2.75	3.0
Max Def. [mm]	42.2	46.7	45.8
Max Def. Time [ms]	61.8	61.5	61.5
Number of Rib Fractures	0	1	9
Part of Rib Fractures			
Rib Fracture Location		R3	R2-3, L4-10

Table A2. Result of elderly rib fracture and chest deflection at each seatbelt payout load at 40kph (AM95)

Payout Load [kN]	2.5	2.75	3.0
Max Def. [mm]	41.6	43.6	44.5
Max Def. Time [ms]	83.3	84.5	84.3
Number of Rib Fractures	0	2	4
Part of Rib Fractures			
Rib Fracture Location		R3, L8	R3, L7-9