

INVESTIGATION ON RESTRAINT APPROACH: REDUCE THORACIC INJURY BY DISTRIBUTING HIGH RESTRAINT FORCES IN OBLIQUE CRASHES

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ABSTRACT

The number of traffic fatalities is decreasing due to improvements of vehicle crash safety performance, which is promoted by crash safety regulations and consumer information assessments such as the New Car Assessment Program (NCAP). On the other hand, according to Japanese accident statistics, the reduction of fatality rates of those involved in oblique impact crashes is less than those in frontal and side impact crashes. This is considered because the risk of secondary impacts with interior structures increases as the seat belt slips, or occupants do not properly interact with the airbag due to lateral occupant motion induced by oblique vehicle movement. If restraint force is increased, thereby reducing the amount of occupant movement, it is possible to increase the injury risk of vulnerable people, such as the elderly. Therefore, applying high restraint force while distributing such loading to mitigate occupant injury should be the focus. The objective of this study is to develop restraint approaches that achieve effective occupant restraint and a reduction of injury risks by restraining body regions that have relatively high stiffness.

The stiffness sensitivity of a rib cage was investigated by using the thoracic impactor simulation with the Human Body Model (HBM) and it was found that the stiffness of the shoulder region, which includes upper rib cage and clavicle, has relatively higher stiffness than other thoracic regions. Therefore, it was determined to restrain around the shoulders.

Subsequently, the influences of restraint around the shoulders with respect to occupant kinematics and injury reduction were compared with those of conventional restraint systems under oblique impact simulation with the Test device for Human Occupant Restraint Anthropometric Test Dummy (THOR ATD). In addition, the influences of each restraint system on the number of fractured ribs caused by thoracic loading were investigated with the HBM under the same loading conditions as the THOR ATD simulation.

When the shoulder region was restrained, THOR ATD movement and chest deflection were reduced compared to the conventional restraint systems. The HBM results indicated that shoulder restraint reduces the chest deflection, similar to the THOR ATD, and the number of fractured ribs also reduced.

It was found that the load generated by the shoulder restraints was broadly distributed on the whole thorax, compared to loads of the conventional restraint systems. The restraint force was higher than that of conventional restraint systems and it reduced amount of occupant movement however the concentrated force on the thorax decreased. Based on these findings, an investigation of the mechanisms of load distribution is necessary considering the structural differences between the THOR ATD and the HBM.

This study described an approach to reduce thoracic injury while distributing loads over the whole thorax and keeping high restraint forces by restraining the shoulders, which have a relatively higher stiffness than other thoracic regions. In order to reduce the number of traffic fatalities, it is desirable to develop restraint systems based on the approach in this study.

INTRODUCTION

Bean et al. studied the influence of seatbelts and airbags on fatality reduction in traffic accidents and described that they reduced by 61% [1]. In other words, despite an increased in number of seat belt and airbag usage, a zero fatality rate was still not accomplished. The factor that fatality rate was not reduced by 100% was affected by Corner and/or Oblique crash, according to statistical analysis using the National Automotive Sampling System- Crashworthiness

Data System (NASS-CDS) and Bean et al. indicated that severity of Corner and/or Oblique crash was the second highest risk following high velocity collisions. Oblique crash was defined as “Oblique crashes engaged one of the main longitudinal members and caused the occupant to move in an oblique manner” according to National Highway Traffic Safety Administration (NHTSA) [2]. The occupants in oblique movement do not interact properly with the deploying airbag and that results in reduction in energy absorption, which causes injury rate increase. Iraeus et al. described that a small overlap crash was also a sort of oblique crash, because the small overlap crash causes oblique occupant movement, and studied a mechanism of thoracic injury caused by occupant oblique movement. Asymmetrical seatbelt loading induces outward deformation on the thorax and then door structure impact on the thoracic side might cause rib fractures. In addition, it was shown that the 1st rib to the 3rd rib was fractured by the seat belt loading itself [3]. Rudd et al. showed that oblique occupant movement causes door interaction and it increases the Abbreviate Injury Risk (AIS) 3+ compared to Co-linear crash [4]. Furthermore, Lindquist [5] and Brumbelow [6] showed an increase of fractures on the thoracic side and bilateral contusion under crash mode which causes the occupant to move in oblique manner.

As such, the function of the restraint system does not work properly and reduces energy absorption under an oblique crash, which causes thoracic injury by interior structures. Therefore, it is required to restrain occupant movement in an oblique manner with high restraint forces. However, since loading on the thorax is directly associated with thoracic injury, an increase in input loading on the thorax is a concern. Vulnerable occupants, such as elderly people, have a high possibility of the thoracic injury due to the loading from restraint systems.

The aim of this paper was focused on the approach to reduce both the amount of occupant movement and thoracic injury by distributing restraint forces considering the stiffness in the body regions using simulation.

METHOD

Restraint approach on occupant upper body

Three types of restraint surfaces were constructed to reduce the amount of lateral movement of the occupant. The restraint surfaces are shown in Figure 1. Each surface restricts the upper body movement in longitudinal-only direction (Front Plate), in lateral-only direction (Side Plate), and in both directions (Front + Side Plate), respectively. Each plate model was connected to the seat back frame by a beam element with rigid constraint. The Front Plate had a degree of freedom on perpendicular rotation around the connection point between the beam element and seat frame. The Side Plate had no degree of freedom on rotation. The effects of the three types of surfaces were evaluated by the change on the amount of occupant movement and injury criteria. The surfaces were restrained around the clavicle or shoulders, which have relatively high stiffness among the thoracic region according to Maehara [7].

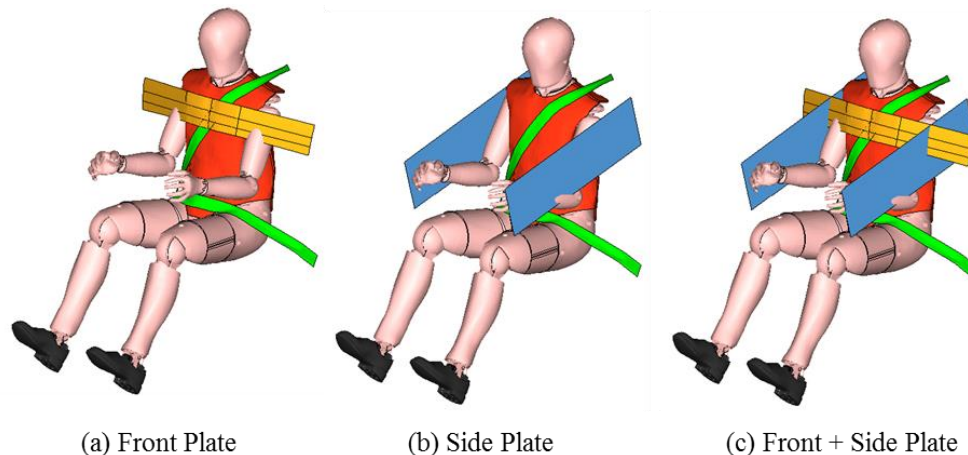


Figure 1. Three types of restraint surfaces

Simulation Model Construction

The evaluations of restraint surfaces were conducted by the Test device for Human Occupant Restraint 50th percentile model (THOR-50th) Metric Version 1.4.1 [8] with LS-DYNA (ver.971 R6.1.2. LSTC, Livermore, CA, USA). THOR model set on the driver seat at mid track in a small sized sedan. The vehicle model was equipped with a seatbelt with a pretensioner and 2 kN load limiter, driver air bag, and collapsible steering column. These conventional restraint systems were defined as baseline restraint systems. The interior structures in the model included a door structure and a center console.

As a secondary evaluation of restraint surfaces, simulations using a Human Body Model (HBM) were conducted and assessed reduction in the injury severity by restraint on the upper region of the thorax. HBM was developed by Dokko et al. [9] and Ito et al. [10] based on the characteristics of a 35 years old and adapted with finite element capable software, LS-DYNA (ver. R7.1 LSTC, Livermore, CA, USA). Thoracic geometry was constructed based on CT scan data from the database of medical CT scan imagery at the University of Michigan Program for Injury Research and Education. The thorax model was validated against thoracic impact tests conducted by Lessley et al. [11] and Shaw et al. [12]. Rib fractures were predicted by element deletion, which occurs when strain on the cortical bone shell exceeds the threshold.

Boundary conditions of collision simulation

Car-to-Car collision simulation was conducted; given the same vehicle class. Delta Velocity was determined as 55 km/h, which covers 90% of traffic accidents according to NASS-CDS. The inclusion criteria were following: case years 2000 to 2013, model year 2000 or later, front right- and left-side seat position, frontal crash condition, belted occupants, and AIS 3+ injury. The collision vehicle interacted with the main frame structure of its counterpart in order to increase the amount of occupant movement since the aim of this research was focusing on the influence of occupant movement on the thoracic injury. The collision angle was determined as 30 degrees, which occupant head did not properly interact with the airbag and the thorax hit the door trim.

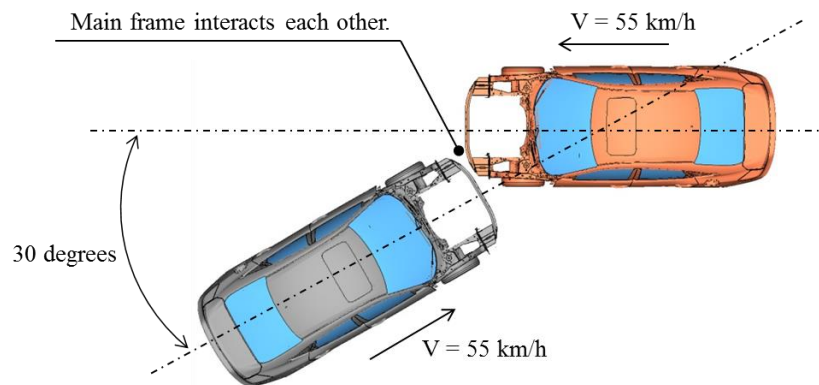


Figure 2. Boundary condition of Car-to-Car collision simulation

Evaluation items

The performance of restraint surfaces on the injury were evaluated by the amount of occupant movement, generated restraint force, and injury criteria. The THOR dummy movements against the vehicle were measured at Head, T1, T4, T12, and Pelvis, which were the locations of the accelerometers. The restraint forces on the dummy were measured seat belt tensile force, contact force of airbag, and the restraint surfaces. Seatbelt tensile forces were measured at two locations, on the upper location of the shoulder (Seatbelt Upper) and directly over the seat belt tongue (Seatbelt Lower). Thoracic injury was evaluated by the chest deflections measured by four 3D IR-TRACCs (Infra-Red Telescoping Rod for the Assessment of Chest Compression) in four quadrants, which was indicated as upper left and upper right, lower left and lower right. Measurement deflection data in the x, y, and z directions in the local spine coordinate were processed in resultant deflection. Input loading around the clavicle and shoulder was measured by a medial clavicle load cell.

HBM evaluated restraint surface by similar method as the THOR dummy. The amount of occupant movement was measured at the Head, T1, T9, L2, and Pelvis, which were close to the THOR dummy sensor locations as shown in Figure 3. Loading forces were measured at the same locations as THOR; seat belt force, airbag contact force, and restraint surfaces. Thoracic deflection was measured at the 4th and the 8th ribs as injury criteria, which were geometrically close in location to THOR IR-TRACCs. Rib deflection was measured between the tip of rib and costovertebral joint of the 4th and the 8th ribs. The resultant of x, y, and z directional deflections were calculated. As a specific injury criterion of HBM, rib fracture was defined as injury criteria. Rib fracture was expressed by rib element deletion. Loading around the clavicle and shoulder was measured at the medial clavicle section.

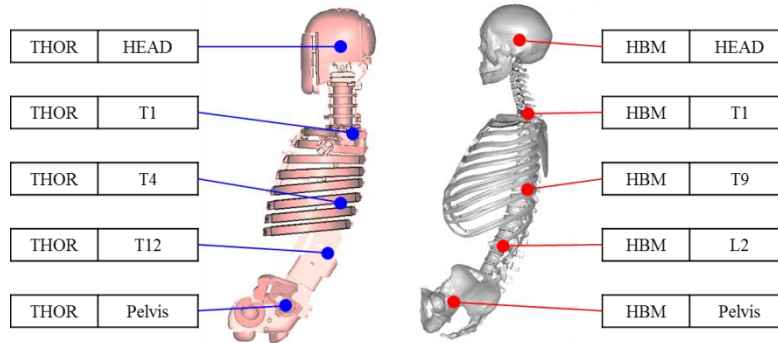


Figure 3. Measurement location of THOR and HBM

RESULTS

Simulation results by THOR

Seatbelt tensile force and contact forces on THOR were shown in Table 1 and 2, respectively. Seatbelt Upper force was not different among each restraint system by the function of load limiter. On the other hand, Seatbelt Lower forces under restraint surface decreased against baseline restraint systems. Total contact force increased by the effects of restraint surfaces, although airbag contact force was reduced.

Clavicle forces were shown in Table 3. Front Plate and Front + Side Plate increased clavicle force, however Side Plate did not increase loading on the clavicle. As mentioned in the methodology, the purpose of the restraint surface was restraint around the shoulders, thus Front Plate and Front + Side Plate could increase the load on the region.

Longitudinal and lateral direction movement of each measurement point from overhead view was shown in Figure 4. Longitudinal and lateral direction were defined as X and Y direction, respectively. Restraint force increased by surfaces reduced occupant upper body movement. Occupant movement reduction was considered to result in the decrease in Seatbelt Lower tensile force against baseline restraint as shown in Table 1. Figure 5 shows that the THOR dummy interacted with the door structure under the baseline restraint system, which was a similar incident as indicated in the previous paper [3]. Interaction with the door structure did not occur with every restraint surface.

Table 1.
Maximum seatbelt force on THOR

	Shoulder Upper [N]	Ratio to baseline	Shoulder Lower [N]	Ratio to baseline
Baseline	4,058	-	4,260	-
Front Plate	4,038	1.00	3,507	0.82
Side Plate	4,148	1.02	3,826	0.90
Front + Side Plate	4,025	0.99	3,459	0.81

Table 2.
Maximum contact force on THOR

	Air Bag [N]	Front Plate [N]	Side Plate [N]	Total Contact Force [N]	Ratio to baseline
Baseline	5,098	-	-	5,098	-
Front Plate	2,303	7,696	-	9,999	1.96
Side Plate	3,040	-	10,290	13,330	2.61
Front + Side Plate	2,351	5,586	2,898	10,835	2.13

Table 3.
Maximum force on the clavicles of THOR

	Clavicle R [N]	Ratio to baseline	Clavicle L [N]	Ratio to baseline
Baseline	550	-	773	-
Front Plate	782	1.42	3,068	3.97
Side Plate	332	0.60	663	0.86
Front + Side Plate	828	1.51	1,536	1.99

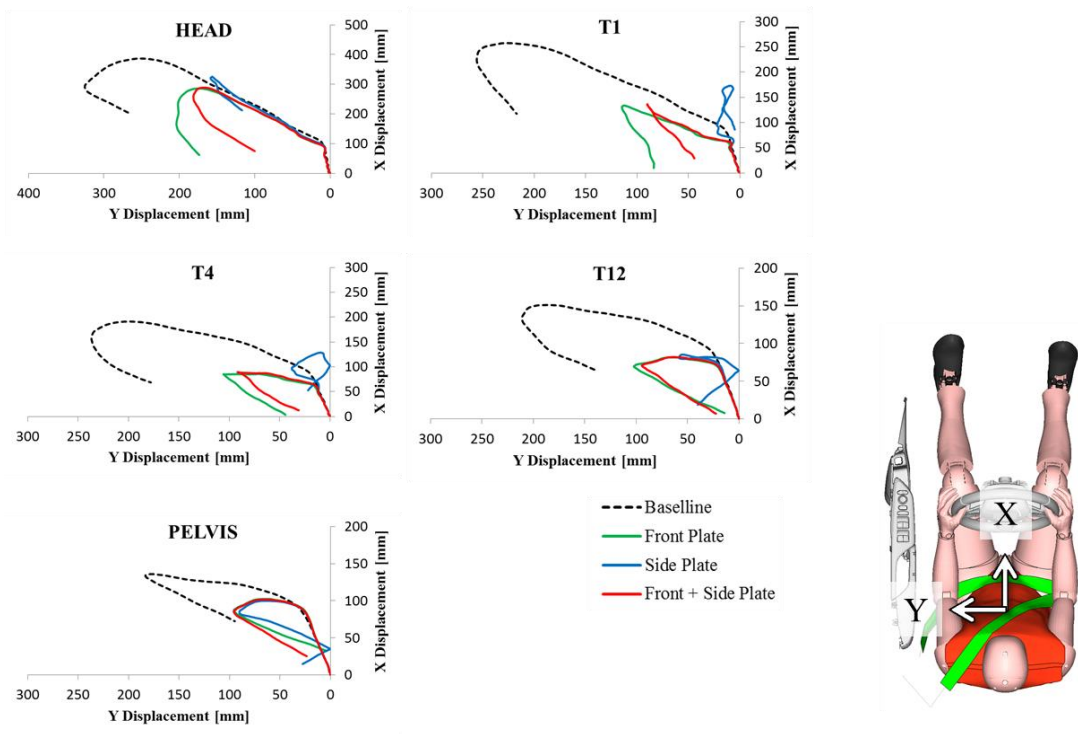


Figure 4. THOR Trajectory on XY plane

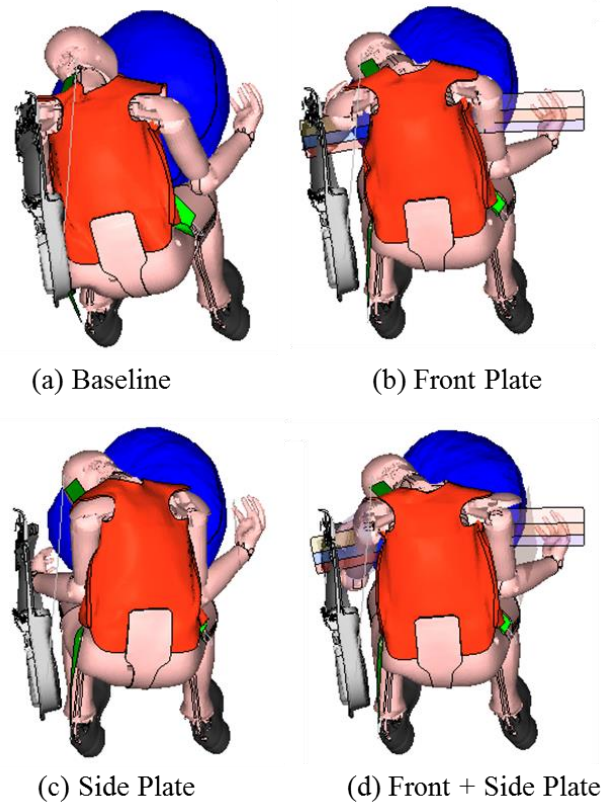


Figure 5. Comparison of the back view of THOR at maximum displacement

Thoracic maximum deflections measured by IR-TRACCs were shown in Figure 6. Front Plate and Front + Side Plate reduced thoracic deflection, although restraint loading on the thorax increased roughly twice as much as the baseline restraint system. Side Plate increased thoracic deflection on lower right side and showed different trends from other restraint surfaces.

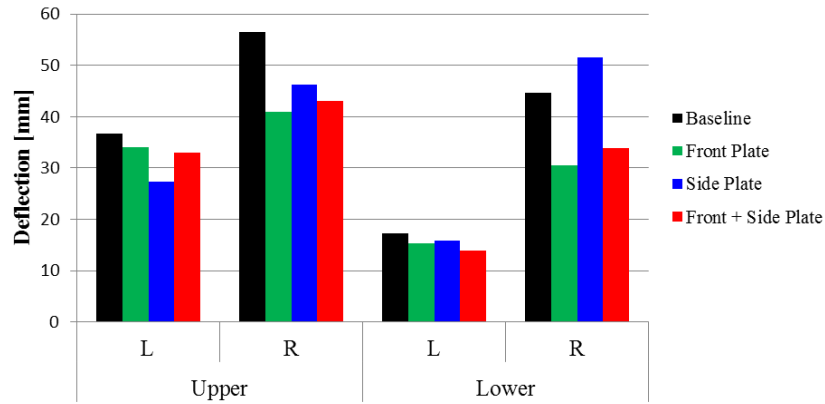


Figure 6. Comparison of IR-TRACCs between each restraint

Simulation results by HBM

Seatbelt tensile force and contact forces on HBM were shown in Table 4 and 5, respectively. HBM also showed Seatbelt Lower force reduction under restraint surfaces. Seatbelt Upper force was not different among each restraint system due to the function of load limiter. Total restraint force increased from the baseline. This result showed similar trend as THOR.

The clavicle section force was shown in Table 6. Front Plate and Front + Side Plate increased loading on the clavicle against baseline.

The amount of HBM movement was reduced by restraint surfaces, as shown in Figure 7, and the door structure interaction did not occur, as shown in Figure 8.

Table 4.
Maximum seatbelt force on HBM

	Shoulder Upper [N]	Ratio to baseline	Shoulder Lower [N]	Ratio to baseline
Baseline	3,706	-	4,488	-
Front Plate	3,782	1.02	3,679	0.82
Side Plate	3,770	1.02	3,709	0.83
Front + Side Plate	3,792	1.02	3,554	0.79

Table 5.
Maximum contact force on HBM

	Air Bag [N]	Front Plate [N]	Side Plate [N]	Total Contact Force [N]	Ratio to baseline
Baseline	2,011	-	-	2,011	-
Front Plate	1,216	8,686	-	9,902	4.92
Side Plate	1,838	-	9,702	11,540	5.74
Front + Side Plate	1,266	5,519	3,173	9,958	4.95

Table 6.
Maximum force on the clavicles of HBM

	Clavicle R [N]	Ratio to baseline	Clavicle L [N]	Ratio to baseline
Baseline	377	-	376	-
Front Plate	673	1.78	343	0.91
Side Plate	143	0.38	583	1.55
Front + Side Plate	593	1.57	377	1.00

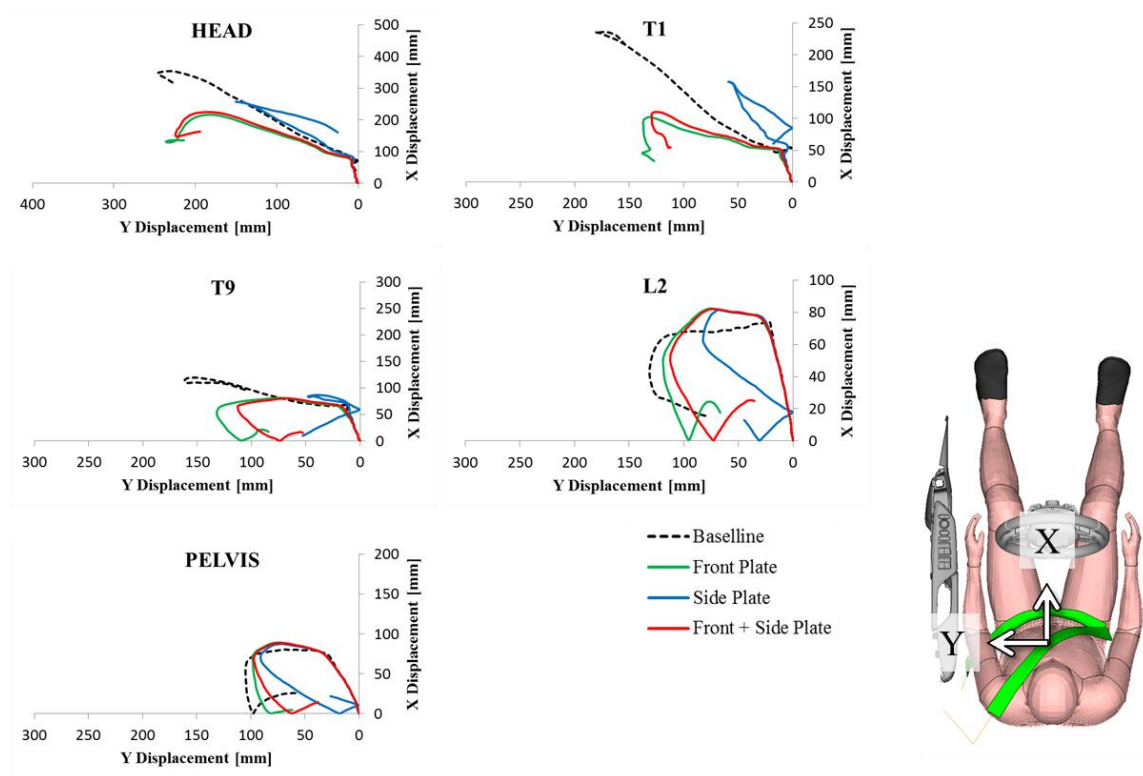


Figure 7. HBM Trajectory on XY plane

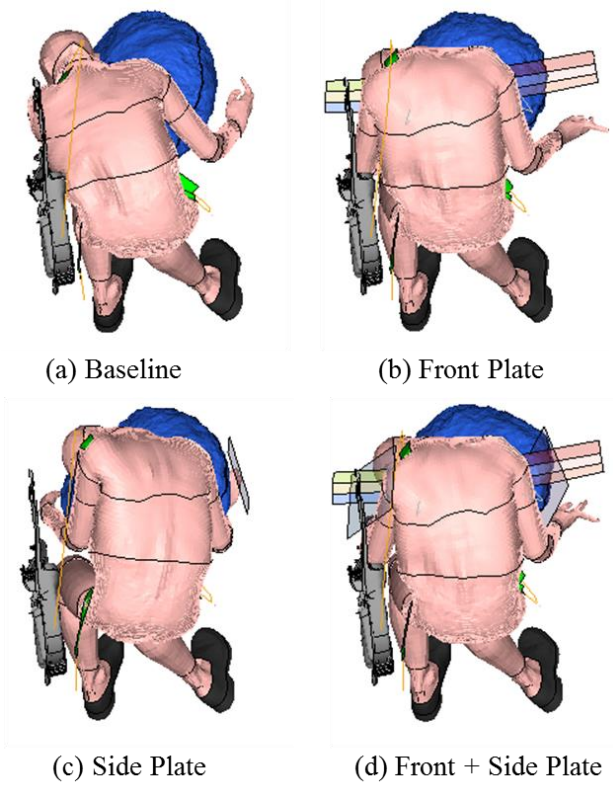


Figure 8. Comparison of the back view of HBM at maximum displacement

Maximum rib deflections at the 4th and the 8th ribs were shown in Figure 9. The amount of reduction in rib deflection was not as much as those of THOR. Front + Side Plate reduced rib deflections more than Front Plate. Side Plate did not reduce rib deflections; on the contrary, deflection on the lower part increased.

The location of rib fracture was shown in Figure 10. Rib fracture occurred on upper left side rib under baseline restraint. Front + Side Plate did not exhibit fractures on the region. On the other hand, fractures occurred on the 1st and the 2nd rib on the right side. Front Plate exhibited rib fracture on the same right side region as baseline restraint, and the other fracture occurred on the right side. Side Plate exhibited fractures on the 3rd to the 9th ribs on the left side. This was caused by the left arm which was stacked between the thorax and Side Plate.

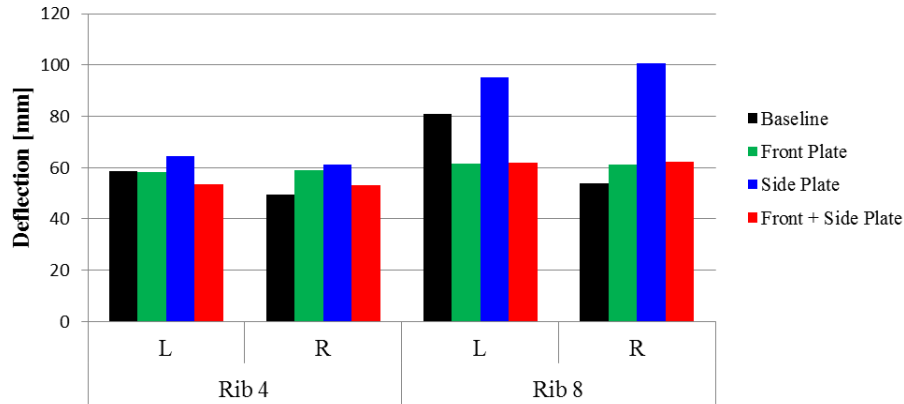


Figure 9. Comparison of rib deflection between each restraint

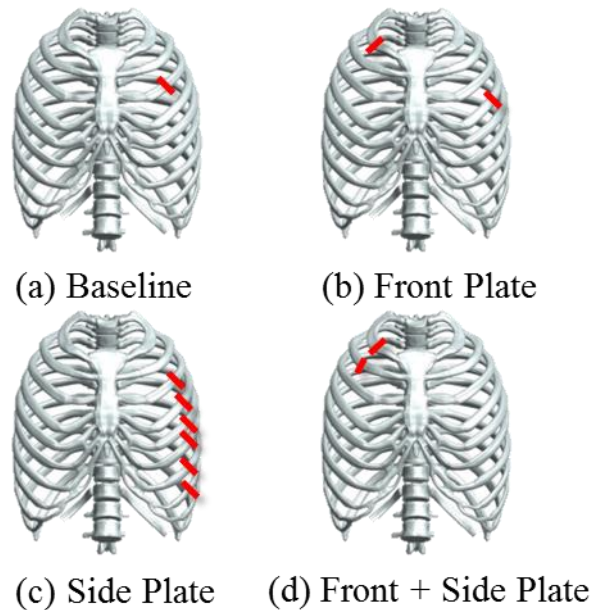


Figure 10. Comparison of rib fractures by each restraint

DISCUSSION

Simulation by THOR and HBM showed that restraint plates increased loading on the upper body. It reduced the amount of movement by half and prevented interaction with the door structure. Moreover, the simulation result indicated that the restraint on the region around clavicles and shoulders by surfaces has the possibility of reduction in thoracic injury, although high restraint force was loaded on the thorax.

This result was considered to have originated from distributing restraint force on the upper region of the thorax by Front Plate without increasing the force on the rib cage. Front Plate increased both the clavicle loads of THOR and HBM as shown in Table 3 and 6, respectively. The clavicle force of HBM showed an increase only on the right side, however, the total force on the right and left clavicle was increased. On the contrary, the clavicle load was not increased by Side Plate, although the largest contact force was generated among each four simulations of THOR and HBM. Small load distribution under Side Plate restraint was considered to result in small reduction in thoracic deflection. This result indicates that it is a highly efficient approach to distribute the restraint load on the upper thoracic region, which has a relatively high stiffness than that of other parts.

Side Plate constraint showed different occupant kinematics from other boundary conditions. Right shoulder of occupants moved forward and upper body counterclockwise rotation occurred under Side Plate, as shown in Figure 11. The rotation occurred by a combination of oblique occupant movement limited by Side Plate and seatbelt. The center of rotation is located at seatbelt interaction point. The seat belt slipped to the center of the body due to oblique occupant movement; on the other hand, Side Plate restricts sideward movement of the upper body, thus the shoulder belt location stayed on the outside of the left clavicle. In addition, left shoulder lateral movement was restricted by Side Plate, nevertheless the occupant still moves forward due to inertia force. In consequence, a counterclockwise rotation around the belt interaction point was more apt to occur and seatbelt contact force concentrates on the thorax, which was supported only by the seatbelt. The effect of belt force concentration was also implied by an increase in the lower right thoracic deflection with Side Plate on both THOR and HBM. Upper body rotation was considered to result in thoracic deflection. The effect of Front Plate was not only load distributing, but also to prevent seatbelt force concentration by upper body rotation.

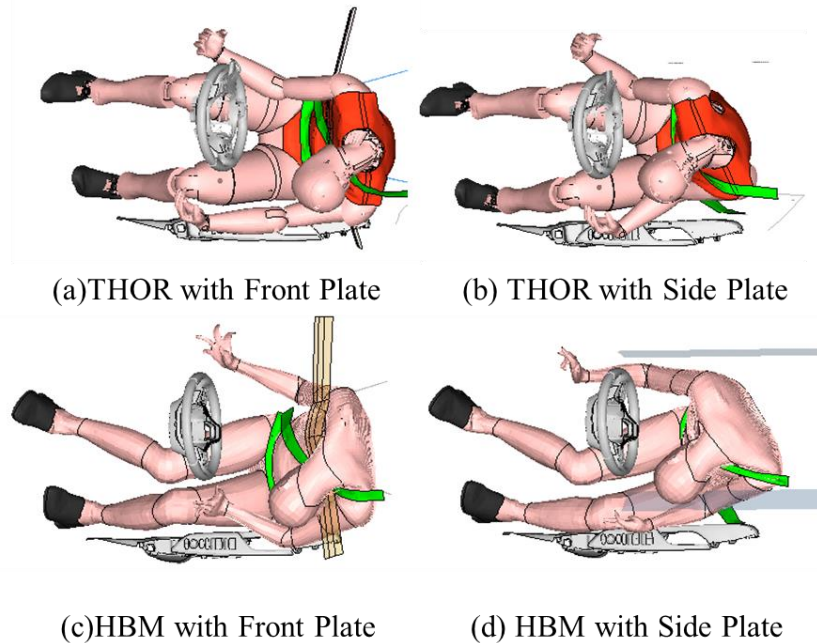


Figure 11. Counterclockwise kinematics caused by Side Plate

Meanwhile, comparing HBM and THOR simulation results, they have differences on the degree of rise in clavicle force and reduction in thoracic deflections.

Firstly, an increase in clavicle force was lower on HBM than THOR. This is considered to be ascribed to the difference of their shoulder structure. The THOR metric mimics human shoulder structure and it can straighten the shoulder, which is defined as shoulder retraction. The limit of the amount of THOR shoulder retraction was determined by the structure interactions. On the other hand, the human shoulder has more a flexible structure than THOR because the shoulder consists of bones and soft tissue such as muscles. Thus, the THOR shoulder generates a larger reaction force than that of the HBM. The small reduction in upper thoracic deflection on HBM was considered to be the result of low force distribution on the clavicles due to the difference of shoulder structure.

Secondly, the effect of Front and Front + Side Plate on HBM thoracic deflection reduction was smaller than that of THOR. This difference between THOR and HBM was considered to be ascribed to the difference of structural stiffness. Rib cage lateral stiffness of the human body is lower than longitudinal stiffness. On the contrary, lateral stiffness of the THOR rib cage is higher than longitudinal stiffness according to Maehara [7]. Since the upper body moves in an oblique direction, Front Plate generates force in both longitudinal and lateral directions. Front + Side Plate restricts directory from the side thus the lateral force on the thorax was obviously smaller than that of Front Plate. The difference in amount of the lateral direction force results in the difference in the amount of lateral thoracic deflection between Front Plate and Front + Side Plate. HBM thorax is more apt to deform by the lateral force than THOR because of the difference of lateral rib cage stiffness. As considering human body structure, this restraint approach would be preferable to combine front and side surface to restrict both upper body rotation and sideward movement. In addition, this result implied the biofidelity concerns on THOR.

Front + Side Plate occurred a rib fracture on the upper right side of the thorax despite the fracture on the upper left side region in baseline. In addition, rib fracture occurred on the side thorax through an arm by Side Plate. Since the restraint surface was connected by rigid constraint, excess load was generated on the body. In order to practically apply this restraint approach to a real vehicle as a restraint device, sort of load limiter is required.

CONCLUSIONS

This study suggested the approach which increases restraint force on the thorax to reduce the amount of upper body movement, with thoracic injury decreasing. It was confirmed that the approach has similar effects not only on the dummy but also on the human body. However, sort of load limiter is required for practical application. It was not enough to restrict only lateral movement under oblique crashes because upper body rotation had a possibility to increase thoracic injury. In addition, lateral movement generated lateral force on the thorax and induced transverse thoracic deformation. Based on these results, this restraint surface was preferable combining front and side surfaces when considering human body structure.

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