Comparison of Thorax Responses between WorldSID-5th and SID-IIs in Lateral and Oblique Impacts

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ABSTRACT

Recently, enhancing the biofidelity of the WorldSID-5th percentile adult female dummy (WorldSID-5th), which is an acceptable worldwide fifth percentile adult female side impact dummy, has been investigated and incorporating WorldSID-5th in the GTR no.14 pole side impact as a substitute for SID-IIs is considered. Since the torso design and instrumentation for measuring thorax deflection are different between these two dummies, it is expected that WorldSID-5th can indicate the improved performance of evaluating thorax injuries.

The aim of this study was to clarify a difference of performance in evaluating severity of thorax injuries between WorldSID-5th and SID-IIs by comparing thorax responses in lateral and oblique impacts. In order to understand deformations of ribs, thorax impact simulations were conducted by using WorldSID-5th small female dummy FE model v2.0.3 and SID-IIs dummy FE model SBLD v3.3.2, which are developed by Humanetics Innovation Solutions Inc. A 13.97-kilogram pendulum with 120.7 mm face was impacted into two dummies at the speed of 4.3 and 2.0 m/s, similar to the biofidelity test for thorax without arm shown in 49 CFR Part 572, Subpart V. The centerline of the pendulum was aligned at the level of the centerline of the middle thorax rib in the most lateral side of each dummy. The directions of impacts were set to 0° (pure lateral), ±5°, ±10° and ±15°.

Results from SID-IIs simulations in both high and low speed impacts showed that a thorax deflection measured by potentiometers in pure lateral loading is larger than that in oblique loadings. In contrast, thorax deflections measured by 2D IR-Tracc from WorldSID-5th simulations in high speed impacts were generally constant with loading directions, those in low speed impacts in pure lateral loading are smaller than that in oblique loadings.

According to published papers, it is known that human thorax response shows larger deflections in the antero-lateral oblique loadings than that in the pure lateral loadings. Therefore, WorldSID-5th is supposed to be able to represent characteristics of human thorax more adequately compared to SID-IIs. Since human thorax response in postero-lateral oblique impacts has not been thoroughly investigated, further validation of WorldSID-5th will be needed.

It was clarified that WorldSID-5th can represent human characteristics of thorax response more appropriately than SID-IIs. Furthermore, it was shown that SID-IIs has a possibility of underestimating thorax deflection in oblique impacts. Therefore, it can be expected that the vehicle performance of occupant protection will be enhanced by introducing WorldSID-5th into side impact test protocols sometime in future.

INTRODUCTION

In the United States, according to Fatality Analysis Reporting System (FARS) provided by National Highway Traffic Safety Administration (NHTSA), the number of passenger vehicle occupant fatalities in 2015 was decreased by 26.9% compared with that in 2006. Although the number of passenger fatalities was dropped by 31.2%, that of driver fatalities was only reduced by 23.8% in these ten years [1].

The analysis of fatality and serious injury rate of driver by using National Automotive Sampling System – General Estimates System (NASS-GES) provided by NHTSA [2] shows that a decrease of the fatal or serious injured driver rate in side crash accidents seems to be small compared to that in frontal crash accidents (Figure 1). In addition, the number of fatal or serious injured drivers in Vehicle-to-Pole/Tree type side crash accidents is only 2,479, while that in Vehicle-to-Vehicle type side crash accidents is 17,414 in 2015. However, the fatal or serious injured driver rate in Vehicle-to-Pole/Tree accidents is 6.9% while that of Vehicle-to-Vehicle accidents is 1.0%. This suggests that mitigating the number of fatal or serious injured drivers in Vehicle-to-Pole/Tree accidents must be focused on, as well as that in Vehicle-to-Vehicle accidents.

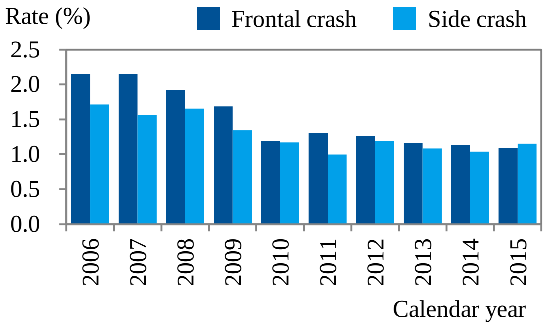

Figure 1. Fatal or serious injured driver rate in U.S.

It is known that the distribution of direction of force in Vehicle-to-Pole/Tree accidents in which occupants sustaining AIS3+ injuries shows that the pure lateral accounts for 50.8% and the antero-lateral oblique accounts for 40.0%, respectively [3]. Additionally, thorax is the most frequent severe injured body region in Vehicle-to-Pole/Tree accidents [4, 5]. For this reason, not only human thorax responses against pure lateral impacts but also those against antero-lateral oblique impacts have been investigated.

Shaw et al. [6] conducted thorax impact tests by using seven Post Mortem Human Subjects (PMHSs) in which a 23.97-kilogram pendulum impacted to the level of the forth interspace of the sternum at the speed of 2.5 m/s. Based on results from seven pure lateral impact tests and seven antero-lateral oblique impact tests, corridors of thorax force-deflection responses for each two impact configurations were developed. The comparison of the averaged maximum forces and the averaged maximum deflections between those two corridors shows that the averaged maximum force in the pure lateral impact is larger than that in the antero-lateral oblique impact; in contrast, the averaged maximum deflection in antero-lateral oblique impact is larger than that in pure lateral impact.

Baudrit et al. [7] conducted twelve thorax impact tests in which a 23.4-kilogram pendulum impacted to the middle of the sixth rib of PMHSs at the speed of 4.2 to 4.4 m/s in pure lateral directions and antero-lateral oblique directions. Based on these results, four thorax force-deflection corridors by combination of two physical sizes and two impact directions were developed; the 50 percentile adult male and the 5 percentile adult female; pure lateral and antero-lateral oblique. Similar to results from Shaw et al., it was shown that the averaged maximum force in a pure lateral impact is larger than that in antero-lateral oblique impacts, and the averaged maximum deflection is larger than that in pure lateral impacts.

In the aim of mitigating occupant injuries in real world side crash accidents, side impact test protocols have been introduced. There are two principally different test configurations for side impact tests. One is called the Moving Deformable Barrier test (MDB test) simulating a crash accident where the vehicle is collided by the other vehicle in its side. The other is called Pole test simulating a crash accident where a vehicle collides into a utility pole or tree. In United States, those tests are introduced by legal requirements FMVSS214 and the consumer information tests U.S. new car assessment program (U.S. NCAP) and Insurance Institute for Highway Safety.

In order to assess severities of occupant injuries, Anthropometric Test Devices (ATDs) have been developed. ES2-re and SID-IIs, which were introduced by FMVSS214 NPRM released on May 2004, are used in side crash tests introduced presently in United States. As for the replacement of those ATDs, WorldSID-50th adult male dummy (WorldSID-50th), developed by ISO task group in

1997, is planned to be introduced in the future U.S. NCAP protocol [8]. Moreover, introducing of WorldSID-5th adult female dummy (WorldSID-5th) which has been developed by WorldSID 5th TEG in the GTR pole test is considered [9].

Each rib of ES2-re and SID-IIs which are adopted in current side crash test protocols is designed to represent a pair of human's left and right rib by using one rib. Thorax deflection selected as an index for evaluating thorax injuries is measured as a unidirectional deflection between the left and right sides of rib for ES2-re, and a unidirectional deflection between the most lateral side of rib and the spine for SID-IIs. By contrast, WorldSID-50th and WorldSID-5th have been designed as a more human-like thoracic structure, ribs are separately into left and right ribs whose anterior end is connected to the sternum and posterior end is connected to the spine, respectively. Thorax injury measure of WorldSID-50th which is specified in Euro NCAP's protocol is a lateral deflection calculated by using outputs measured by 2D Infra-Red Telescoping Rod for the Assessment of Chest Compression (IR-Tracc). 2D IR-Tracc is capable of measuring a change of a distance between the most lateral point of the rib and the spine, and a change of an angle at the most lateral point of the rib relative to the spine. Then, the lateral deflection is defined as a pure lateral compression of the rib calculated in terms of these two measurements. Hence, it can be said that a performance of evaluating severities of thorax injuries is different between current ATDs and modern ATDs; ES2-re and SID-IIs; WorldSID-50th and WorldSID-5th.

Yoganandan et al. [10] compared thorax responses of ES2-re and WorldSID-50th in pure lateral and oblique side impact loadings by conducting full-scale sled tests. The result shows that WorldSID-50th better sensed the oblique loading than ES2-re. However, thorax responses from 5 percentile female dummies; WorldSID-5th and SID-IIs have not been compared.

The objective of this study was to clarify a difference of performances of thorax injury evaluation between WorldSID-5th and SID-IIs by comparing patterns of rib deformation and thorax injury values.

THORAX RESPONSES IN DIFFERENT ANGLE IMPACTS

Thorax Impact Simulation

Since rib components of full-scale physical dummies are covered with jackets, it is physically impossible to obtain patterns of whole rib's deformation. Therefore, LS-Dyna R6.1.2 finite element (FE) simulations by using WorldSID5th Small Female Dummy v2.0.3 [11] and SID-IIs dummy SBL D v3.2.2 [12] developed by Humanetics Innovative Solutions, Inc. were conducted in order to capture patterns of rib deformation located inside ATDs. Because it is known that a difference of arm positions affects values of thorax deflection [13], thorax without arm impact test's configuration similar to that shown in 49 CFR Part 572 Subpart V [14] was selected in this study.

The seatback of a certification bench was cut off at the height of 300 mm in order not to interfere with a pendulum's movement and modeled as a rigid surface. A WorldSID-5th, while raising the arm to a vertical orientation, was seated on the bench in order that the top of the lower neck bracket was horizontal, and its pelvic tilt sensor showed 19.5 degrees. SID-IIs removed its arm was seated on the bench in order that the thoracic fore/aft plane measured 24.6 degrees and the back of the thorax touched the seatback. It was estimated that no friction force is generated in physical tests because the seat back and base is covered with PolyTetraFlourEthylene sheets. Therefore, a coefficient of friction force of contact characteristic between the bench and the dummy was set to zero in order that the dummy model can glide over the bench model smoothly.

A circular cylindrical pendulum was modeled as a rigid surface with a 120.7 mm face diameter and a 12.7 mm edge. A 13.97-kilogram mass was applied at the center of the shape. The pendulum was made to collide with the dummy at 4.3 m/s similar to the speed specified in 49 CFR Part 572 Subpart V, or 2.0 m/s which is an estimated impact speed that induces negligible thorax deflection.

As for the relative location between the dummy and the pendulum, the height of the center of the pendulum's face was aligned to the height of the centerline of the middle thoracic rib at the most lateral side of the dummy. In the pure lateral impact simulation, the pendulum was positioned so that its centerline was centered vertically on the centerline of the middle thoracic rib. Setups of thorax impact simulation for WorldSID-5th and SID-IIs in pure lateral impact are shown in Figure 2. As shown in Figure 3, the probe was rotated by ±5°, ±10° and ±15° relative to the center of the spine box in each dummy in an antero-lateral or a postero-lateral oblique impact.

Thorax impact simulations were carried out by impacting WorldSID-5th or SID-IIs FE model with a pendulum model. Seven impact directions, two impact speeds and two dummy models were combined to create twenty eight impact simulations.

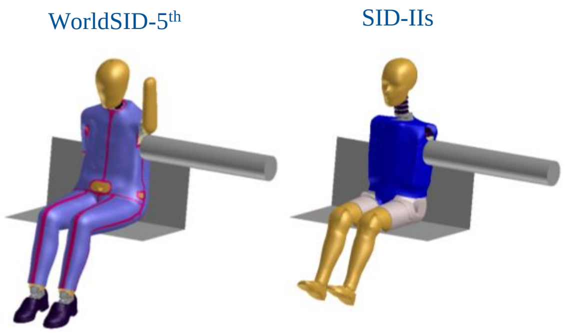

Figure 2. Setups of thorax impact simulation for WorldSID-5t^{h} and SID-IIs.

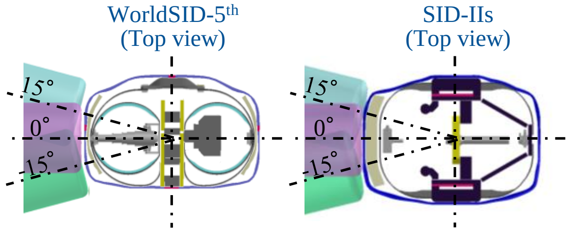

Figure 3. Impact directions for pure lateral and oblique impacts.

Comparison between Physical Dummies and FE Dummy Models in Lateral Impacts

In order to confirm accuracies of thorax responses from the results of FE simulations, thorax impact tests using physical dummies were conducted and results from FE simulations were compared to those from physical tests. Thorax without arm impact test in pure lateral direction at the speed of 4.3 m/s was selected as an impact configuration for this comparison because this is the configuration specified in 49 CFR Part 572 Subpart V [14]. Two physical tests for each dummy were conducted.

An Impact force, lateral accelerations at T4 and T12, and lateral deflections of thorax were compared for WorldSID-5th. An Impact force was calculated by multiplying a longitudinal acceleration of the pendulum filtered at CFC180 by its weight. Time histories of lateral accelerations at T4 and T12 were filtered at CFC180. As for the lateral deflection of thorax, time histories of compression and rotation from each 2D IR-Tracc's output were filtered at CFC600, then lateral deflection was calculated in accordance with WorldSID-5th physical dummy manual [15] by using equations 1 to 3. Symbols used in above equations are shown in Figure 4 and Table 1, in the way of Y direction representing ATD's lateral direction and X direction representing ATD's fore/after direction. Figure 5 show comparisons of outputs between results from simulation and physical tests of WorldSID-5th.

In accordance with SID-IIs physical dummy manual [16], an impact force calculated as in the case with WorldSID-5th, lateral accelerations at T1 and T12 filtered at CFC180, output of potentiometer for each rib filtered at CFC600, were compared. Figure 6 shows the comparison of outputs between results from simulation and physical tests of SID-IIs.

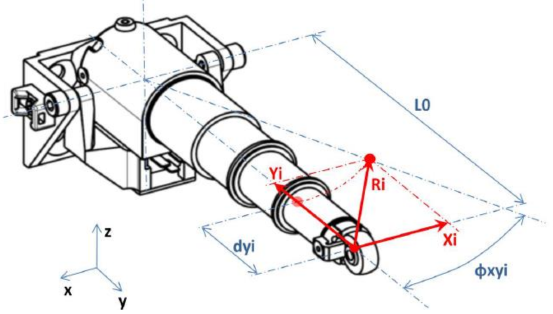

Figure 4. Symbols used in equations for calculating lateral deflection [15].

Table 1.
Calculation- parameters, symbols, and description [15]

Parameter	Description
t_0 [s]	Time zero
L_0 [mm]	Reference length at t_0
Dyi [mm]	IR-Tracc compression at ti
ϕxyi [degrees]	IR-Tracc angle at time i (positive angle indicated)
X [mm]	Calculated x displacement w.r.t x_0 (time zero x)
Y [mm]	Calculated y displacement w.r.t y_0 (time zero y)
R [mm]	Calculated resultant displacement w.r.t R_0 (time zero R)

$$x_i = \left(L_0 - d_{yi}\right) \times \sin\left(\varphi_{xyi}\right) \qquad \textbf{(Equation 1)}$$

$$y_i = L_0 - \left(L_0 - d_{yi}\right) \times \cos\left(\varphi_{xyi}\right) \qquad \textbf{(Equation 2)}$$

$$R_i = \sqrt{\left(x_i^2 + y_i^2\right)} \qquad \textbf{(Equation 3)}$$

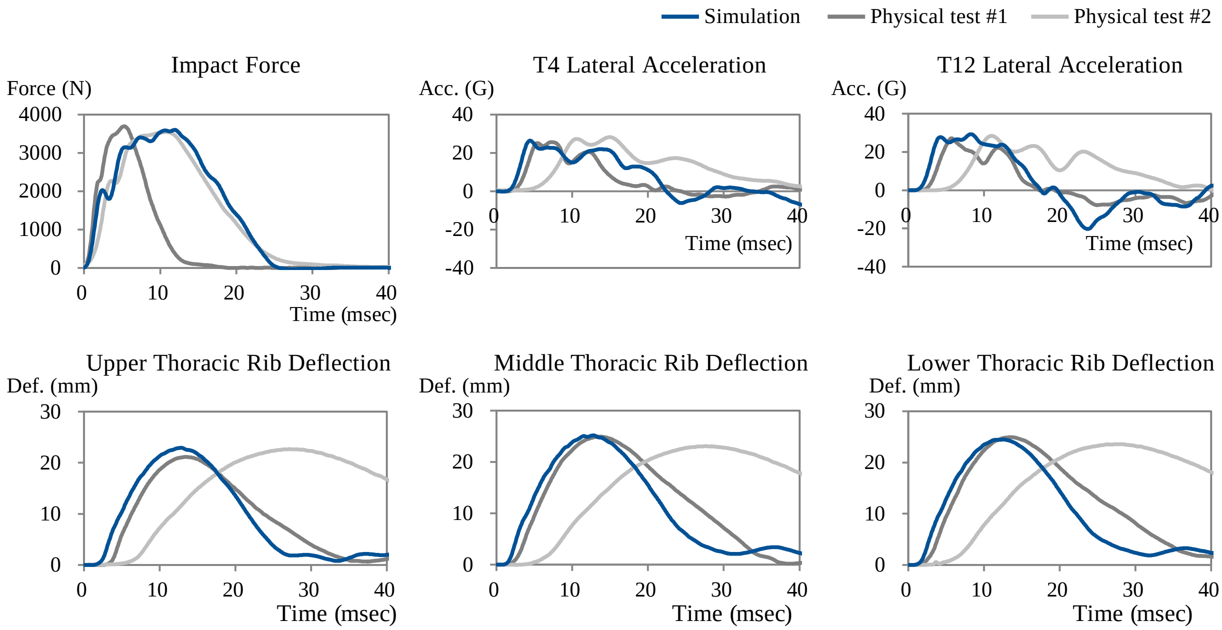

Figure 5. Comparison of results between simulation and physical tests of WorldSID-5th.

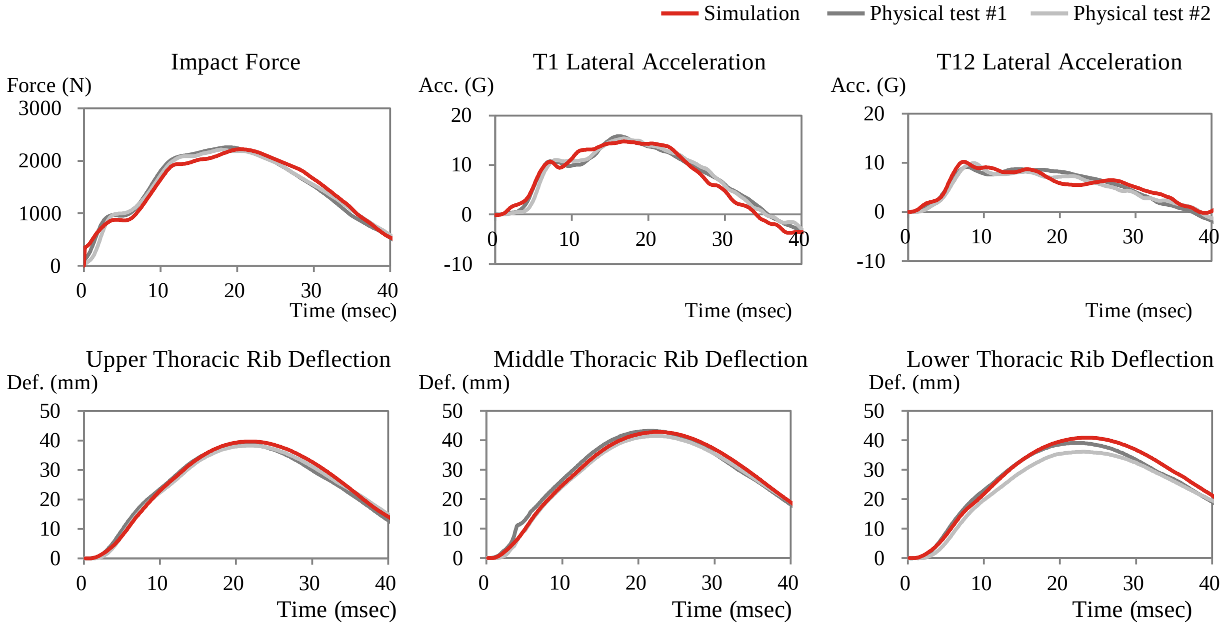

Figure 6. Comparison of results between simulation and physical tests of SID-IIs.

Although time histories of results from SID-IIs simulation matched well with those from physical tests, only maximum levels of each output from WorldSID-5th simulation matched to those from physical tests. In addition, comparing time histories from physical tests between WorldSID-5th and SID-IIs (Figures 5 and 6), it seems that WorldSID-5th has a possibility to have a poor repeatability. For this reason, parametric study by conducting simulation was selected in this study.

It is known that the thoracic component of SID-IIs FE model is validated in terms of oblique impacts [17]. However, those validations for WorldSID-5th FE model have not been reported yet. Therefore, results from WorldSID-5th simulation were compared to those of physical tests from the published study in which thorax impact tests similar to the simulation in this study were shown. Been et al. [18] conducted thorax impact tests with WorldSID-5th revision 1 dummy where the head, arm and jacket were removed. The dummy was seated on the platform, and impacted by a 14.0-kilogram pendulum at the speed of 2.5 m/s in the antero-lateral oblique impact (+15 degree) and the postero-lateral oblique impact (-15 degree). The wooden block was fitted to the front of the pendulum so that the first contact point was the most lateral aspect of the upper thoracic rib. Since the heights of impact level were different between the tests and this study, lateral deflections of the upper thoracic rib in Been et al. and the middle thoracic rib in this study were selected as outputs used in a comparison for thorax deflection. Table 2 shows the comparison of the maximum impact forces, and Table 3 shows the comparison of the maximum thoracic lateral deflections.

Table 2.
Comparison of impact force between results from physical tests (Been et al. [18]) and CAE simulations (this study)

Impact Direction	Been et al.	This study
Antero-lateral (15 degree)	909 N	1599 N
Pure lateral (0 degree)	904 N	2125 N
Postero-lateral (-15 degree)	835 N	1511 N

Table 3.
Comparison of lateral deflections between results from physical tests (Been et al. [18]) and simulations (this study)

Impact Direction	Been et al.	This study
Antero-lateral (15 degree)	27.8 mm	8.5 mm
Pure lateral (0 degree)	29.5 mm	9.8 mm
Postero-lateral (-15 degree)	18.1 mm	7.2 mm

The weights of pendulums in both studies were similar. However, the impact speeds were faster in the simulations than in the physical tests, and the impact forces applied to the dummy were more concentrated in the physical tests than in the simulations. For this reason, the levels of impact forces were thought to be higher in the simulation, and the levels of deflections were thought to be higher in the physical tests. Nevertheless, both results of physical tests and simulations show higher impact forces in oblique impacts and higher deflections in pure lateral impacts. Therefore, it is qualitatively confirmed that WorldSID-5th FE model used in this study can estimate a response of physical WorldSID-5th ATD.

Thorax Responses from WorldSID-5th Simulation

Trajectories of the most lateral points of each inner rib relative to the spine box for 4.3 m/s impact simulations were shown in Figure 7, in which red lines show trajectories at upper thoracic ribs, yellow lines show those at mid thoracic ribs and green lines show those at lower thoracic ribs, respectively. Figure 8 shows the deformations of the middle rib in 15° antero-lateral impact, pure lateral impact and -15° postero-lateral oblique impact at 4.3 m/s impact simulations of WorldSID-5th.

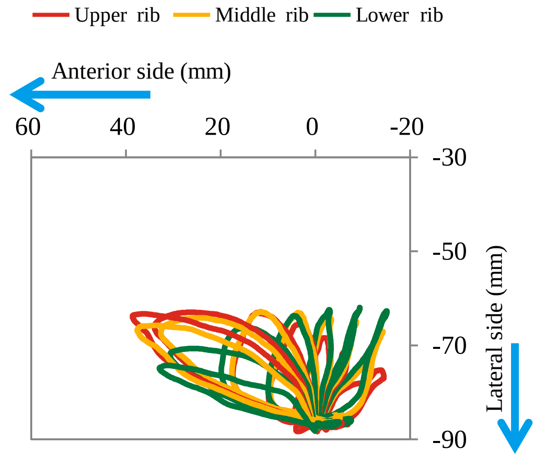

Figure 7. Trajectories of most lateral points of thoracic ribs of WorldSID-5th in 4.3m/s impacts.

Additionally, Figures 9 to 11 show time histories of compressions and rotations from 2D IR-Tracc, and Figures 12 to 14 show time histories of lateral deflections and impact forces, in the cases of 4.3 m/s impacts in 15° antero-lateral impact, pure lateral impact and -15° postero-lateral oblique impact, respectively.

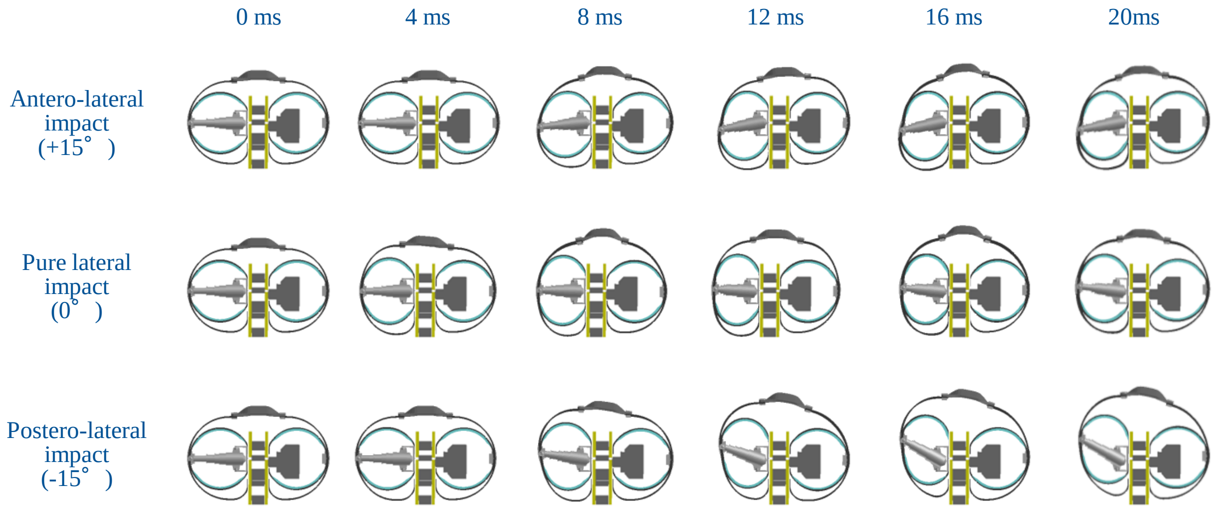

Figure 8. ***Middle thoracic rib deformations of WorldSID-5th in 4.3m/s impact (top view).***

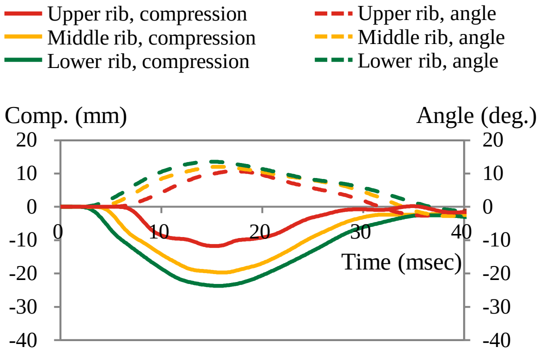

Figure 9. Time histories of IR-Tracc outputs in 4.3m/s, antero-lateral oblique impacts (**15°**).

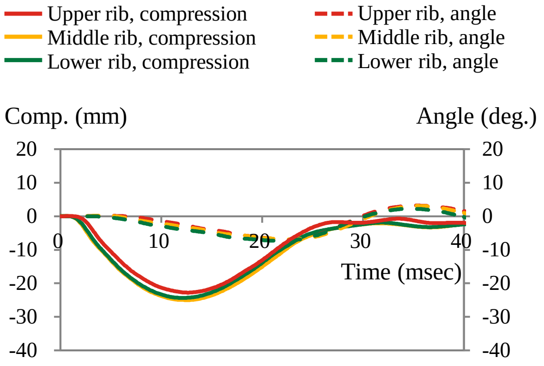

Figure 10. Time histories of IR-Tracc outputs in 4.3m/s, pure lateral impacts (**0°**)

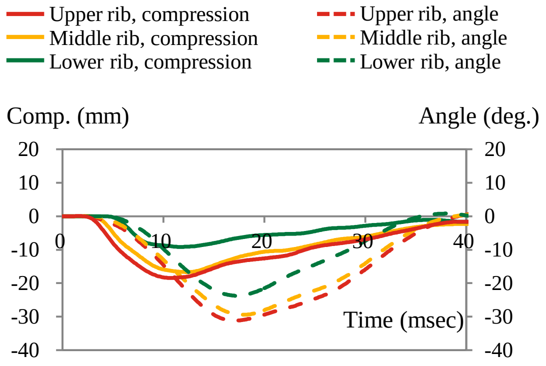

Figure 11. Time histories of IR-Tracc outputs in 4.3m/s, postero-lateral oblique impacts (**-15°**)

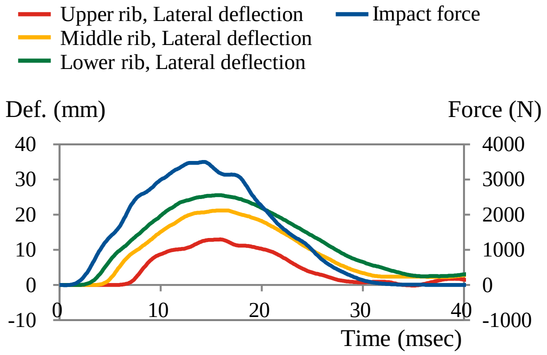

Figure 12. Time histories of lateral deflections and force in 4.3m/s, antero-lateral oblique impacts (**15°**).

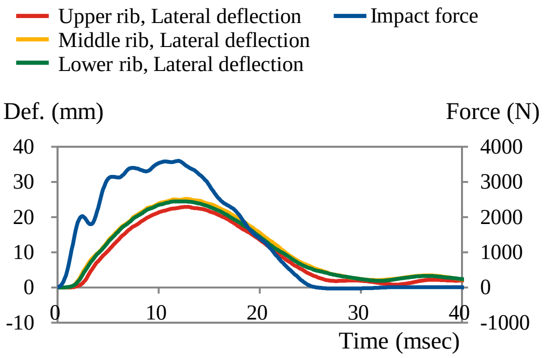

Figure 13. Time histories of lateral deflections and force in 4.3m/s, pure lateral impacts (0°)

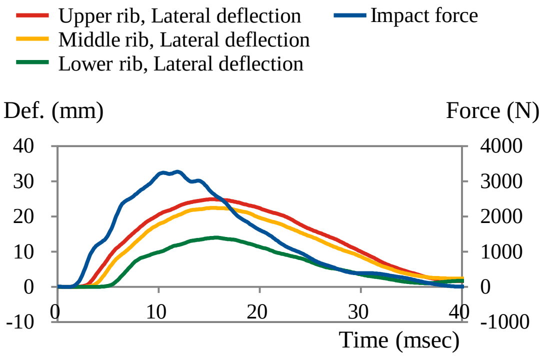

Figure 14. Time histories of lateral deflections and force in 4.3m/s, postero-lateral oblique impacts (-15°)

In the antero-lateral oblique impact, compression and angle output of each 2D IR-Tracc reach its maximum values almost simultaneously (Figure 9). For this reason, the most lateral points of ribs draw sharp edges when those outputs reach to their maximum values (Figure 8). Because the ATD's sternum displaces on the anterior side after the rib was compressed in the postero-lateral oblique impact (Figure 7), the time when the angle output reaches its maximum value occurs later than the time when the compression output reaches its maximum value (Figure 11). Therefore, the most lateral points of ribs move in the large range (Figure 7). In addition, trajectories of the upper, middle, lower ribs in same loading condition are quite different. This suggests that each rib moves individually.

Thorax Responses from SID-IIs Simulation

Trajectories of the end points of each potentiometer relative to the spine for 4.3 m/s impact simulations were shown in Figure 15, in which red lines show trajectories at upper thoracic ribs, yellow lines show those at mid thoracic ribs and green lines show those at lower thoracic ribs, respectively.

Figure 16 shows the deformations of the middle rib in 15° antero-lateral impact, pure lateral impact and -15° postero-lateral oblique impact at 4.3 m/s impact simulations for SID-IIs.

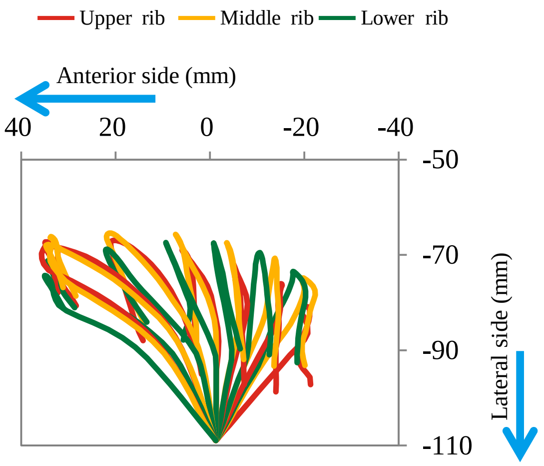

Figure 15. Trajectories of most lateral points of thoracic ribs of SID-IIs in 4.3m/s impacts.

Figures 17 to 19 show time histories of thoracic deflections which are resultant deflections measured by potentiometers and are specified as a thorax injury measure for SID-IIs, and calculated impact forces, in cases of 4.3 m/s impacts in 15° antero-lateral impact, pure lateral impact and -15° postero-lateral oblique impact, respectively.

Trajectories of the end points of each potentiometer in same load direction show similar shape (Figure 16). In addition, time histories of thoracic deflections in the upper, middle and lower ribs change their values uniformly (Figure 17 to 19). For this reason, it seems that three thoracic ribs deform with conjunction with each other.

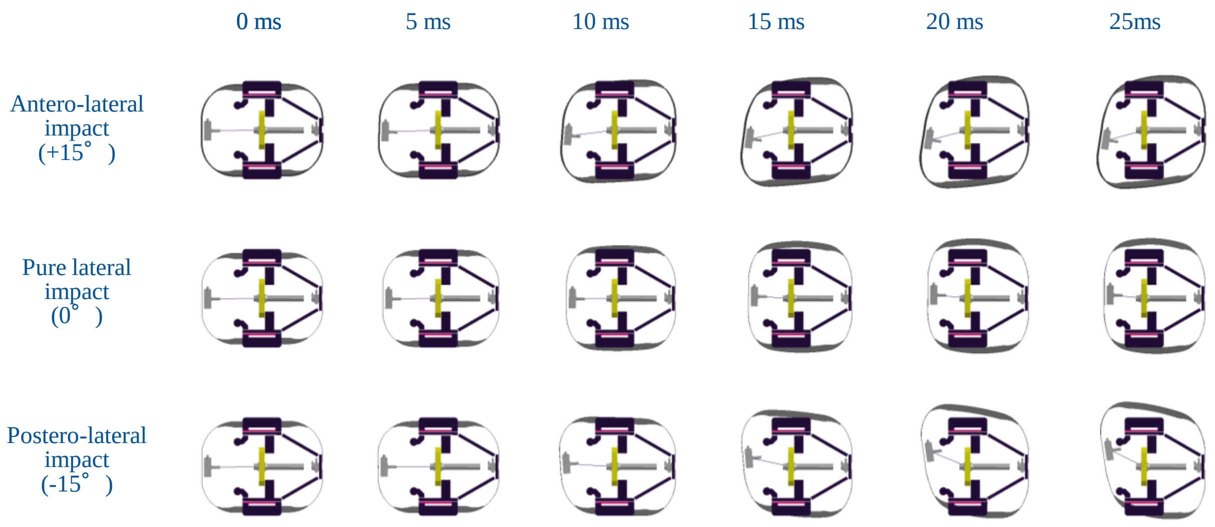

Figure 16. Middle Thoracic rib deformation of SID-IIs in 4.3m/s impact (top view).

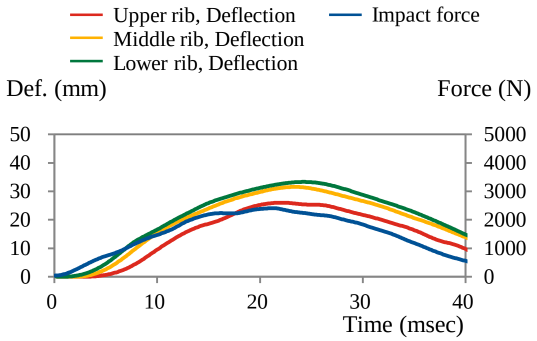

*Figure 17. Time histories of SID-IIs outputs in 4.3m/s, antero-lateral impacts (*15°*)*

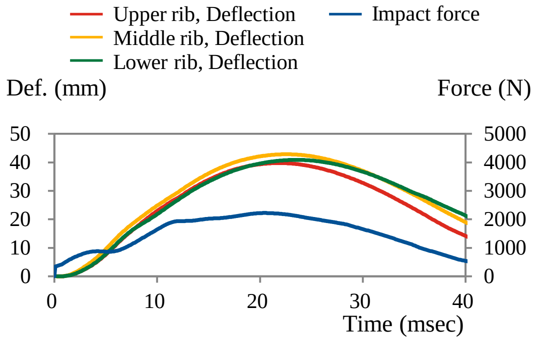

*Figure 18. Time histories of SID-IIs outputs in 4.3m/s, pure lateral impacts (*0°*)*

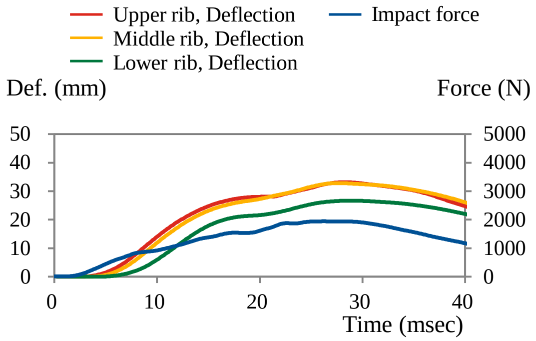

Figure 19. Time histories of SID-IIs outputs in 4.3m/s, postero-lateral impacts (-15°*)*

DISCUSSION

Comparison of Normalized Deflections between WorldSID-5th and SID-IIs

Since levels of thoracic deflections are different between WorldSID-5th and SID-IIs, even under same impact speed and same impact direction, all of the output values are normalized by using its values at pure lateral impact in each combination of impact speed and dummy. Figures 20 to 25 show comparisons of normalized values for thoracic deflections of the upper, middle and lower thoracic ribs, the averaged thoracic deflections between three ribs, the maximum thoracic deflections between three ribs and the maximum impact forces.

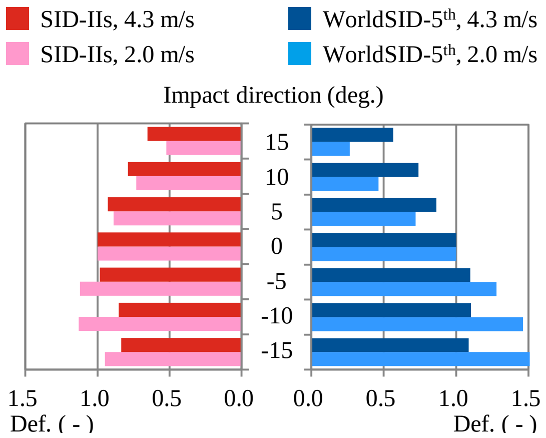

Figure 20. Comparison of normalized deflection of upper thoracic rib.

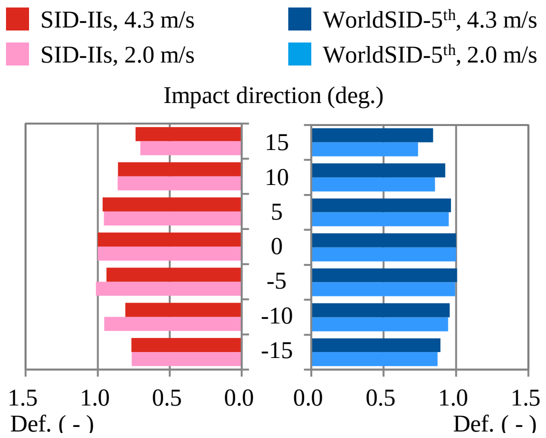

Figure 21. Comparison of normalized deflection of middle thoracic rib.

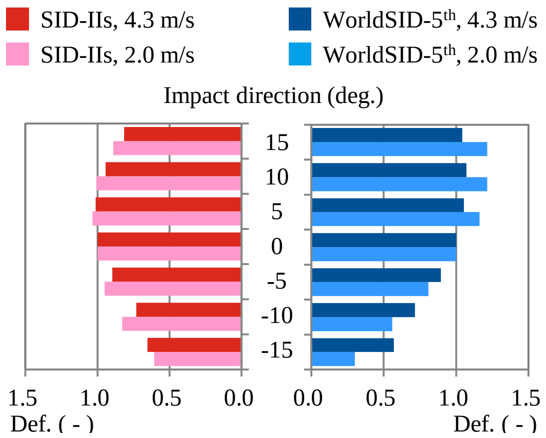

Figure 22. Comparison of normalized deflection of lower thoracic rib.

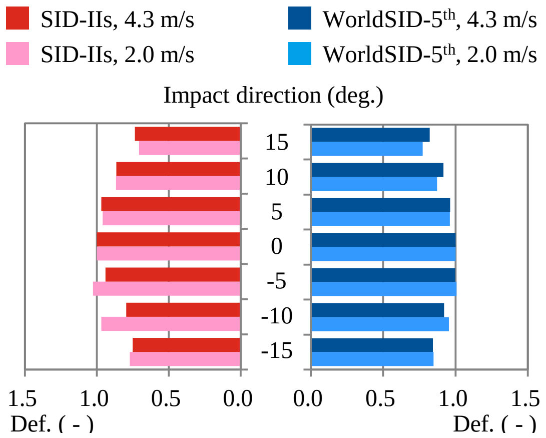

Figure 23. Comparison of normalized average deflection between three thoracic ribs.

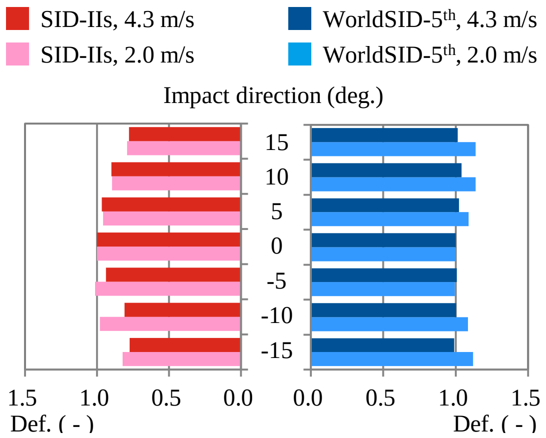

Figure 24. Comparison of normalized maximum deflection between three thoracic ribs.

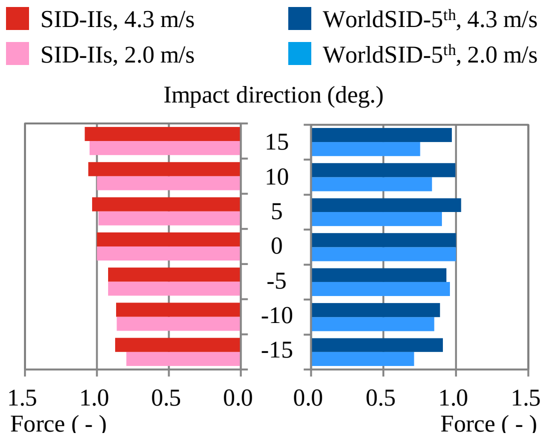

Figure 25. Comparison of normalized impact force.

The upper, middle and lower thoracic ribs of SID-IIs are connected to the same part called the upper bib-ribs, and the thorax pad covers the upper bib-ribs with cable tie wraps (Figure 26). For this reason, all three thoracic ribs deform in conjunction with each other, and this results in that comparison of three ribs shows same tendency like that thoracic deflections in pure lateral loadings show generally larger than that in oblique impacts (Figures 20 to 22).

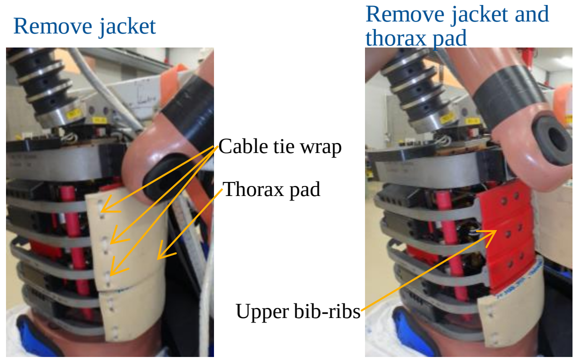

Figure 26. SID-IIs Thorax Component.

Although, a comparison of the middle thoracic rib deflection for WorldSID-5th (Figure 21) shows same tendency as that for SID-IIs, deflection of the upper thoracic rib decreases as the dummy is impacted in more anterior direction (Figure 22). In addition, that of the lower thoracic rib decreases as the dummy is impacted in more posterior direction (Figure 23). As for the design of assembling thorax component of WorldSID-5th, lateral sides of three thoracic ribs and two abdominal ribs are only connected to the thorax pad by using Velcro® (Figure 27). Since, lateral sides of ribs are not connected firmly, thoracic ribs of WorldSID-5th seem to be able to deform independently. Although the anterior and the posterior ends of inner ribs and the posterior ends of outer ribs are rigidly connected to the same spine box, the anterior ends of outer ribs for left and right thorax are only linked to the sternum, which is divided by each rib location. For this reason, the anterior part of the outer rib of the right thorax moves forward along with the anterior part of the outer rib of left thorax, especially in the case that left thorax is applied in the postero-lateral oblique loading. The pendulum initially engaged with the upper thoracic rib in postero-lateral oblique impacts (Figure 11). By contrast, it is initially engaged with the lower thoracic rib in antero-lateral oblique impacts (Figure 9). The deflection of the lower thoracic rib in the antero-lateral oblique impact is 1.2 times larger than that in the pure lateral loading (Figure 22), on the other hand, the deflection of the upper thoracic rib in the postero-lateral oblique impact is 1.5 times larger than that in the pure lateral loading (Figure 20). This suggests that a rib component of WorldSID-5th is easy to deform in postero-lateral impacts.

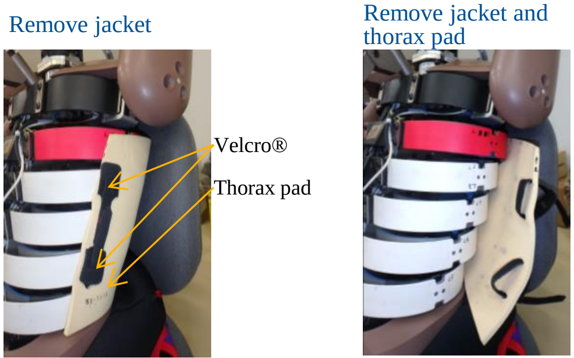

Figure 27. WorldSID-5th Thorax Component.

In comparisons of SID-IIs, deflections in pure lateral loadings show the largest deflection both in the comparison of the averaged and the maximum rib deflection (Figures 24 and 25). In those of WorldSID-5th, deflections in pure lateral impacts show the largest deflection in the comparison of the averaged rib deflections (Figure 24), the deflections in oblique impacts are as large as or equal to that in pure lateral impacts in the comparison of the maximum rib deflection (Figure 25). A thoracic deflection is not included as an injury measure in the current protocol of neither FMVSS214 nor U.S. NCAP, however, the maximum thoracic rib deflection is introduced as an injury measure in the future U.S. NCAP protocol [8]. If WorldSID-5th is introduced as a dummy instead of SID-IIs and the maximum thoracic deflection is selected as an injury measure in the future, thorax injuries seem to be evaluated more severely compared to the present.

Lateral Component of SID-IIs Thoracic Deflection

A thoracic rib deflection of SID-IIs is specified as a unidirectional deflection between the most lateral point of the rib and the spine box. In contrast, that of WorldSID-5th is specified as a lateral component of deflection between them. Since it is possible that the difference of measurements causes the difference of characteristics of thorax responses between SID-IIs and WorldSID-5th, lateral components of thoracic deflection are additionally measured from results of SID-IIs simulations. Those outputs can be measured in physical dummy tests by using an optical system named RibEYE which can measure three dimensional movements of ribs relative to the spine [19].

Figure 28 shows the comparison of normalized averaged deflection between original thoracic deflection and lateral component of thoracic deflection. Deflections used as denominators in normalization were, 16.6 mm for the original deflection and 16.6 mm for the lateral component of thoracic deflection in 2.0 m/s, 42.8 mm for the original deflection and 43.2 mm for the lateral component of thoracic deflection in 4.3 m/s, respectively. All of the deflections used as denominators are output of the middle thoracic ribs.

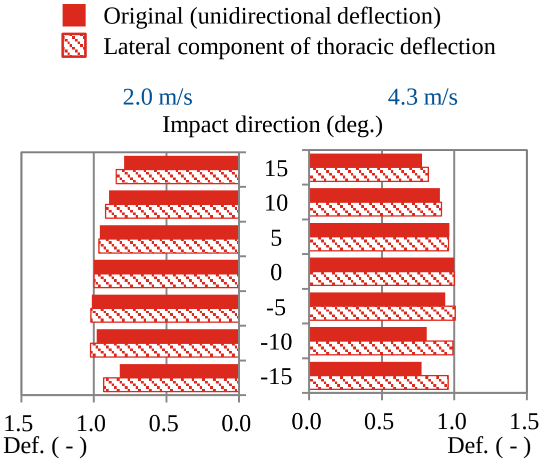

Figure 28. Comparison of Normalized Maximum deflection between three thoracic ribs of SID-IIs.

Although each lateral component of thoracic deflection shows larger deflection compared to the original deflection in each impact configuration, lateral deflections in oblique impacts show smaller than or equal to that in the lateral impact in both impact speeds. This suggests that a difference of thorax responses between SID-IIs and WorldSID-5th is not because of the difference of measured physical quantities but the difference of thoracic design.

Biofidelity Evaluation

In order to clarify whether WorldSID-5th or SID-IIs can represent more human-like thoracic response, results from this study were compared against the published data.

Shaw et al. [6] conducted thorax impact tests in which a 23.8-kilogram pendulum impacted to the level of the forth interspace of the sternum at the speed of 2.5 m/s. Based on the results from seven pure lateral impact tests and seven antero-lateral oblique by 30-degree impact tests, corridors of force-deflection responses for two impact directions were developed. Average values of the maximum thoracic deflection and an impact force scaled into the midsized adult male show that a thoracic deflection in the antero-lateral oblique impact is 1.27 times as large as that in the pure lateral impact, and an impact force in the antero-lateral impact is 0.72 times as large as that in the pure lateral impact.

As for the thorax response in high-speed impacts, Baudrit et al. [7] conducted twelve thorax impact tests in which a 23.4-kilogram pendulum impacted to the level of the middle of sixth rib at the speed of 4.2 to 4.4 m/s. Then, four corridors of thorax responses by combinations of two physical sizes and two impact directions were developed; 50 percentile adult male and 5 percentile adult female; pure lateral loadings and antero-lateral loadings by 30-degree. Based on the averaged responses for 5 percentile adult female, the maximum thoracic deflection in the antero-lateral oblique impact is 1.25 times as large as that in the pure lateral impact, the maximum impact force in the antero-lateral oblique impact is 0.8 times as large as that in the pure lateral impact.

Proportions of the maximum thoracic deflection or impact force in antero-lateral oblique impacts to those in pure lateral impacts shown in Shaw et al., Baudrit et al. and results from simulation in this study are compared in Table 4.

Table 4.

Proportion of maximum thorax deflection or maximum impact force in antero-lateral oblique impacts to that in pure lateral impacts

Source	**Impact velocity**	**Proportion**	
		deflection	**force**
PMHS (Shaw et al.)	2.5 m/s	1.27	0.72
PMHS (Baudrit et al.)	4.3 m/s	1.25	0.80
WorldSID-5th (this study)	2.0 m/s	1.14	0.75
	4.3 m/s	1.01	0.97
SID-IIs (this study)	2.0 m/s	0.79	1.05
	4.3 m/s	0.78	1.09

In both of the impact speeds, simulation results for SID-IIs show a smaller deflection and a larger impact force in antero-lateral oblique impacts than in pure lateral impacts. By contrast, those for WorldSID-5th show a larger deflection and a smaller impact force in antero-lateral oblique impacts than in pure lateral impacts. Since the impact angle used in both of the PMHSs' studies was 30 degrees and it is larger than the impact angle used in the simulation of this study, proportions should be compared qualitatively. However, it can be said that proportions for WorldSID-5th are more similar to those from PMHSs' studies than SID-IIs. Consequently, it can be said that WorldSID-5th can represent more human-like thoracic responses than SID-IIs.

LIMITATION

At present, WorldSID 5th TEG has a plan to enhance the biofidelity of WorldSID-5th female dummy, and the modification of thoracic design has been discussed. However, the basis of its design is not supposed to be a major modification. Therefore, it can be asserted that WorldSID-5th can represent more human-like thoracic response compared to SID-IIs in future.

There is a limitation of published data showing human thoracic responses against various impact directions, the biofidelity evaluation in this study is limited to responses in pure lateral and antero-lateral oblique impacts. Accordingly, a biofidelity of WorldSID-5th in postero-lateral impacts must be evaluated in the future.

CONCLUSIONS

In this study, thorax impact simulations were conducted by varying impact speeds and directions. As a result, the following conclusions were reached;

- Three thoracic ribs in SID-IIs tends to deform in conjunction with eatch other, by contrast, those in WorldSID-5th deform independently.
- SID-IIs shows similar values in the maximum thoracic deflection and the averaged thoracic deflection. However, the maximum thoracic deflection in WorldSID-5th shows larger values compared to the averaged thoracic deflection.
- SID-IIs has a possibility to underestimate the severities of thorax injuries in oblique impacts regardless of a method of mesurement compared to WorldSID-5th.
- Based on a proportion of a thoracic deflection and an impact force in the antero-lateral oblique impact to that in the pure lateral impact, it can be said that WorldSID-5th represent human chraracteristics of thorax reseponse more adequately than SID-IIs.

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