ASSESSMENT OF A PRE-CRASH SEATBELT TECHNOLOGY IN FRONTAL IMPACTS BY USING A NEW CRASH TEST SLED SYSTEM WITH CONTROLLABLE PRE-IMPACT BRAKING

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ABSTRACT

The objective of this study is to develop a new method and tools required for the evaluation of the potential benefits of pre-impact safety restraint systems.

A pre-crash sled system that can reproduce controlled pre-impact braking in combination with a variety of crash pulses was built. The sled can be customized from existing vehicles to examine a variety of restraint systems. In addition, a previously validated 50th percentile male Hybrid III dummy with a modified lumbar was employed to reconstruct realistic driver's posture changes at the pre-impact braking phase.

In order to evaluate the potential benefits of a pre-crash seatbelt (PSB), the modified dummy was placed on the sled with a standard seating posture and restrained by either a conventional seatbelt (SB) or a PSB controlled by a motor in the retractor. The sled system was then programmed to reach a steady speed of 64 km/h, followed by a 0.8 g deceleration and 0.8 seconds of duration, just before colliding against the barrier at the speed of 48 km/h.

Increased forward travelling of the upper body at the pre-impact braking phase with the SB was measured in comparison to the PSB case.

In the PSB case, full airbag deployment occurred before body-to-airbag contact, allowing the airbag in coordination with the belt to mitigate the neck loading optimally and to reduce a 15% of chest acceleration. In the SB case, body-to-airbag contact occurred before its complete deployment, causing increased neck forces and moments as well as chest acceleration. In contrast, equivalent chest deflections for both types of seatbelts were measured.

In this research, a new pre-crash sled system with the potential to evaluate pre-crash safety restraint systems was developed. Crash tests with dummies were conducted in order to examine the effectiveness of a PSB. By controlling the posture change during an emergency braking, the reduction of neck and chest injury risk in front impacts was achieved. This confirms the potential of a PSB to enhance occupant protection.

INTRODUCTION

Occupant safety in crashes has commonly been discussed by means of experiments or simulations with 50th percentile male crash test dummies and human computer models in normal sitting posture. However, posture changes occur just before the collisions due to occupant evasive maneuvers and occupant inertia, which makes it difficult to keep a normal posture just before the collision.

Changes in driver's posture and velocity during emergency maneuvers exert influence on the injury risks in front impact collisions [1]. In order to mitigate the potentially negative effects of these changes, current vehicles are equipped with pre-impact safety restraint systems. In parallel to the employment of these systems, new protocols and methods to test their performance are needed.

In order to mitigate the potentially negative effects of these posture changes, current vehicles are equipped with pre-impact safety restraint systems, such as a pre-crash seat belt (PSB) system [2][3][4][5].

With regard to the change of posture, Ejima et al. [6], based on multi-body simulations, showed that body size and initial posture affect injury outcome in frontal collision with pre-impact braking. Antona et al. [7], based on calculations with a human Finite Element (FE) model, showed differences in chest and neck interaction with restraint systems in the impact situations with/without pre-impact braking.

The performance of the pre-impact safety restraint systems can be evaluated with different methodologies. Tobata et al. [2], in their numerical and experimental study, indicated that a motor retractor which retracts belt webbing in emergency braking improves initial restraint and thereby reduces the chest acceleration of occupants in crashes. Schoeneburg et al. [5] reported that a pre-crash safety device that includes a reversible (motorized) seatbelt tensioner can reduce neck extension moment in full vehicle crash tests with pre-impact braking.

In the employment of new restraint systems, new reliable protocols and methods to test their performance are also needed. In addition, it is necessary to achieve a good balance between the evaluation of the equipment and the costs associated with the tests.

This study attempts to propose a new experimental method to assess the potential benefits of a pre-impact safety restraint system in front impact collisions. For this purpose, crash tests employing the dummies constrained on a pre-crash sled were conducted to evaluate a pre-impact safety restraint system. In addition, in order to reveal effects of PSB compared with a conventional seat belt (SB), the responses of neck and chest of a crash test dummy between the two tests were discussed.

METHODS

The methodology of this study consists of the evaluation of the potential benefits of a PSB in comparison with a SB in terms of optimized dummy interaction with the restraint systems and improvement of dummy injury indicators. This was done by conducting one crash test with a PSB and the other with a SB. The tests were conducted with the newly developed customizable pre-crash sled with a programmed pre-impact braking and a controllable crash pulse.

Pre-crash Sled System

A new sled for the crash test that can reproduce pre-impact braking and crash pulse was developed. Crash tests with the pre-crash sled were conducted on the rail of the crash test facility. The sled is accelerated on the rail by a pulling unit until it reaches the prescribed running speed. Then the sled is released from the pulling unit, and the programmed braking pulse is applied before the sled collides against the shock absorbers at the front of the fixed barrier. Figure 1 shows the scheme of the pre-crash sled system.

By replacing the shock absorbers, the sled can be used repeatedly. Hence, the performance of restraint system in crash pulse involving pre-impact braking can be evaluated at a lower cost than full-scale vehicle crash tests. In addition, less visual obstruction of the sled allows capturing the test imagery with both on-board and off-board cameras.

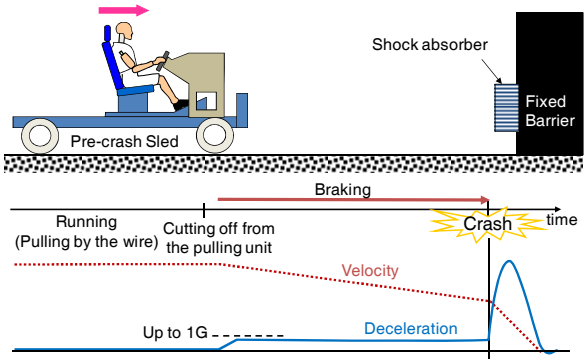


Figure 1. Scheme of the pre-crash sled system.

The sled was designed to minimize pitching mode, providing peak pitching angles at collision with around 1 degree, which allows obtaining reproducible results according to standard specifications for HYGE sleds.

For this study, the pre-crash sled was equipped with a driver's airbag, a rigid seat, a knee bolster, and foot plates. In order to reconstruct realistic driver's posture changes at the pre-impact braking phase, a 50th percentile male Hybrid III dummy with a modified lumbar [8] was employed. The upper body flexion characteristics were improved by modifying the shape of the lumbar section and were validated against low speed impact tests with volunteers [6]. In addition, it was confirmed that trajectory of head and chest after collision and chest sensor readings in the case of the dummy with the modified lumbar were similar to those in the case of normal Hybrid III dummy [9].

The dummy was placed on the rigid seat with a standard seating posture and restrained by a driver's three-point seatbelt in a right hand drive car configuration. Figure 2 shows a picture of the pre-crash sled system and the dummy in testing place.

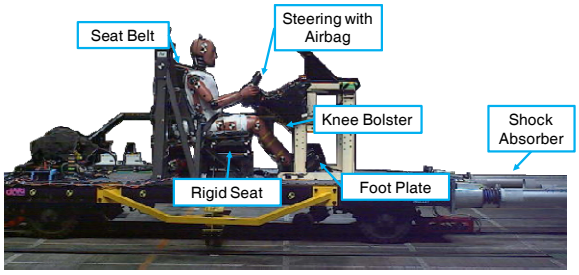


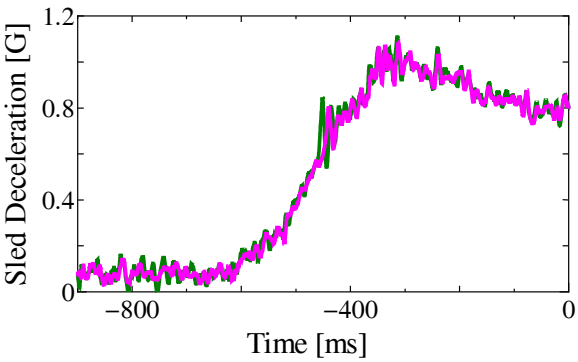
Figure 2. Picture of the pre-crash sled system.

Test Conditions

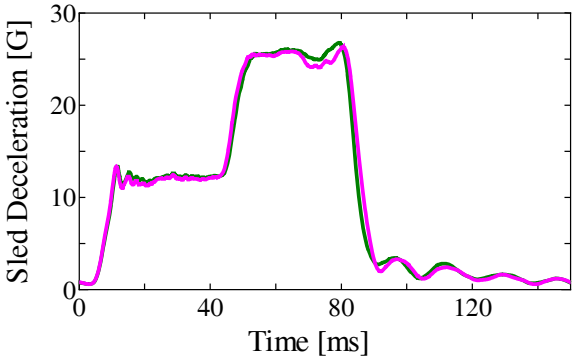
Two crash tests preceded by pre-impact braking were conducted with a SB and a PSB, respectively. Both belt systems are furnished with an emergency lock retractor, a pretensioner, and a force limiter. In addition, the PSB had a motorized retractor, which automatically tightens the belts when the vehicle's pre-collision sensing system determines an imminent collision.

Both tests were conducted under the same braking and crash conditions. The sled system was programmed to reach a steady speed of 64 km/h, followed by a 8 m/s^2 deceleration and 0.8 seconds of duration (Figure 3 (a)), just before colliding against the barrier at a speed of 48 km/h. The crash pulse (Figure 3 (b)) was based on the longitudinal component of a deceleration pulse of Offset Deformable Barrier (ODB) crash tests typically employed for passenger vehicles.

The forces exerted on the dummy were measured by load cells attached to the foot plates, the seat, the shoulder belt, and the lap belt. Kinematics of the dummy was evaluated by using dummy built-in sensors and high speed video analysis of target markers on the dummy surface.



(a) Braking Pulse



(b) Crash Pulse

Figure 3. Comparison of braking and crash pulses recorded from the tests.

RESULTS

In order to examine the differences between SB and PSB, comparisons of dummy responses in terms of sensors readings, dummy interactions with belts and airbag, and overall body kinematics are presented.

Dummy kinematics

Figure 4 indicates the comparison by means of sequential images of the tests with SB and with PSB at 0, 50, and 100 ms from the beginning of the crash

Figure 5 shows the comparison of the dummy's posture changes in two cases with respect to the seat as processed from the on-board high speed camera. Larger forward travelling distances of the upper body at the pre-impact braking phase in the SB case was measured in comparison with the PSB case. Shown in Figure 5, head displacement after the collision in the SB case was smaller than that in the PSB case because of the forward travelling distances of the upper body during the pre-impact braking. This was especially apparent in the head motion from 50 ms to 90 ms: the head in the SB case stopped rapidly after 70 ms, while the head in the PSB case decelerated gradually over crash event. In other words, the head of the dummy in the SB case stopped in a shorter distance than that in the PSB case. These results indicate that much more load was applied to head and neck of the dummy in the SB case.

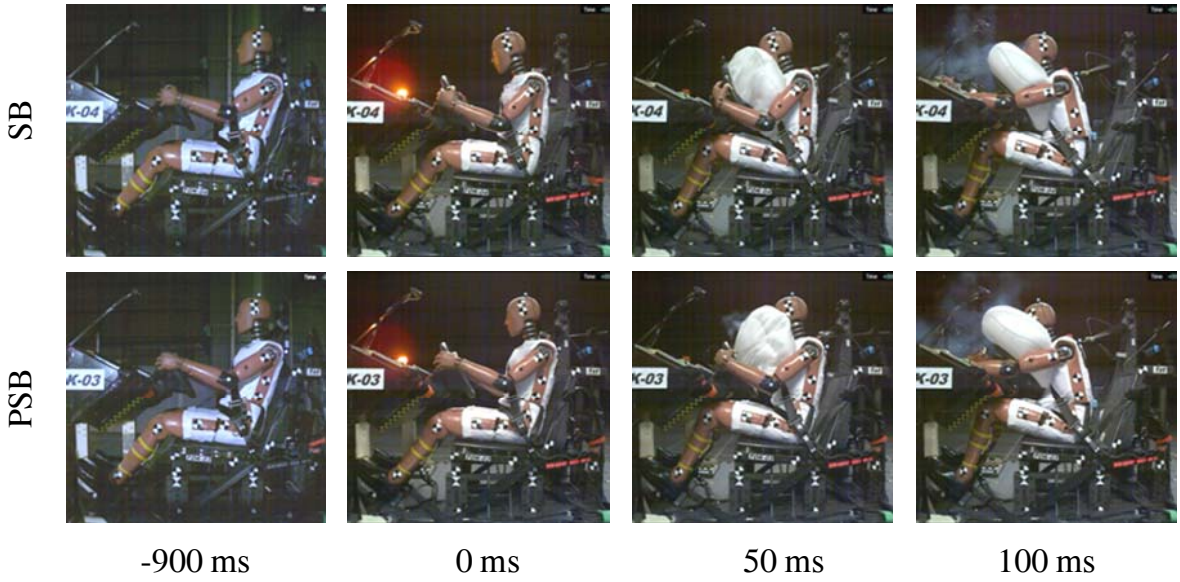
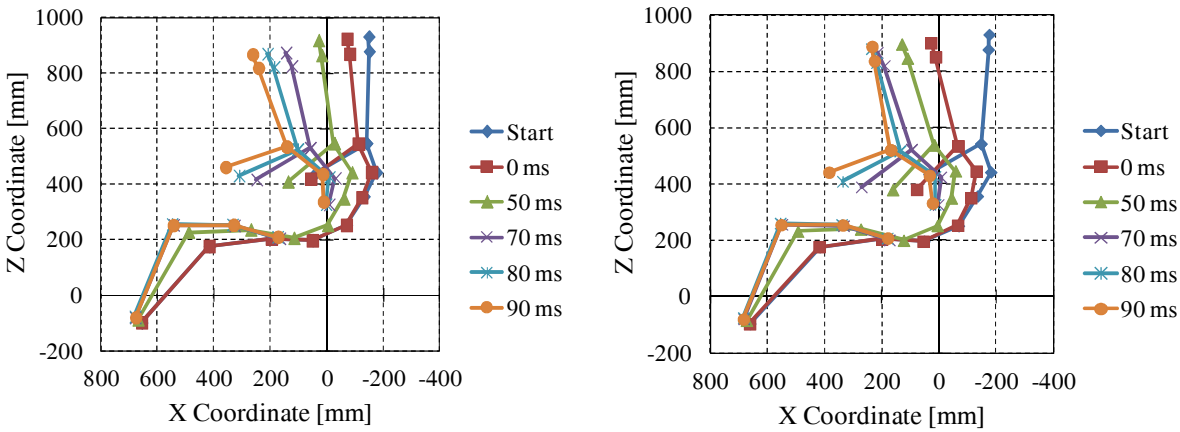
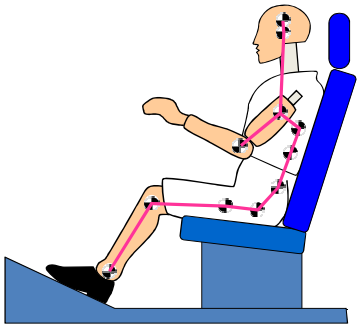


Figure 4. Sequence of pictures at -900, 0, 50 and 100 ms from the initiation of the crash for the SB test (above) and the PSB (below).



(a) PSB case

(b) SB case



(c) Marker location on the dummy

Figure 5. Trajectory of target markers attached on the head and chest with respect to seat.

Dummy sensors readings

Figure 6 to 10 show comparisons of the dummy readings of head acceleration, neck force, neck moment, chest acceleration, and chest deflection.

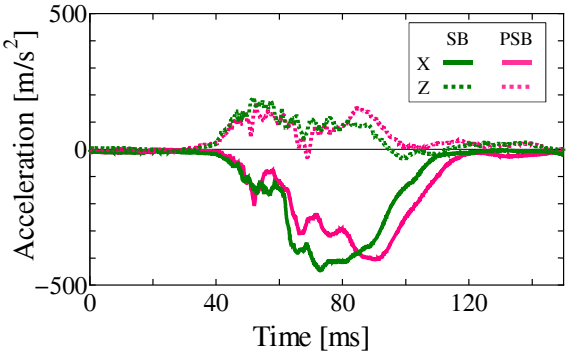


Figure 6. Head acceleration.

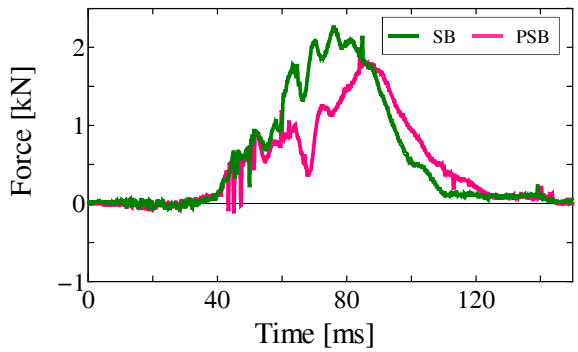


Figure 7. Neck tension-compression force.

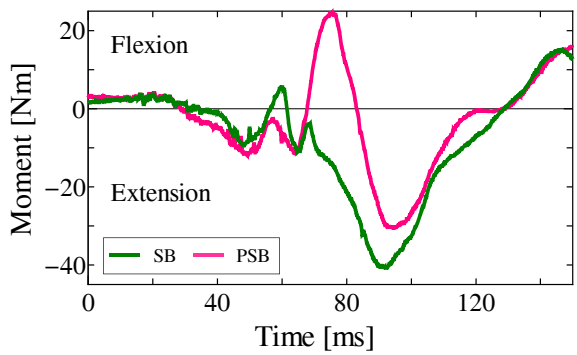


Figure 8. Neck flexion-extension moment.

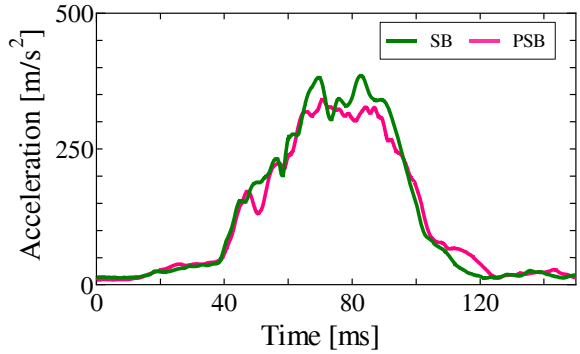


Figure 9. Chest resultant acceleration.

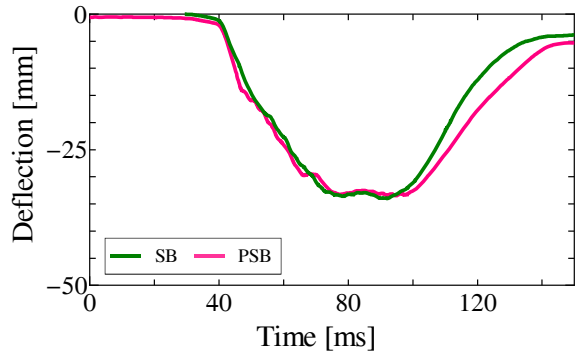


Figure 10. Chest deflection.

Comparatively higher values were obtained in the SB case regarding neck tension, neck extension, and chest resultant acceleration. As for the neck loading mechanism, while the PSB case showed both flexion and extension, only extension occurred in the SB case, with higher peak than in the PSB case.

Interaction with the belts: Measured forces

Figures 11 to 13 show the comparison of the shoulder belt forces measured at the upper right and the lower left hand side of the dummy, and the the lap belt forces measured at the dummy's right hand side. At the crash timing, the shoulder belt forces in the PSB case were slightly higher than those in the SB case. These difference are associated with the belt retraction by the PSB during the pre-impact braking. However, at crash initiation, all readings were identical in both cases, which indicates that only dummy posture differed.

During the impact, the upper shoulder belt force in the PSB test was slightly higher than that in the SB case, this effect being associated with a slight reduction of chest acceleration (Figure 9) without affecting maximum chest deflection (Figure 10).

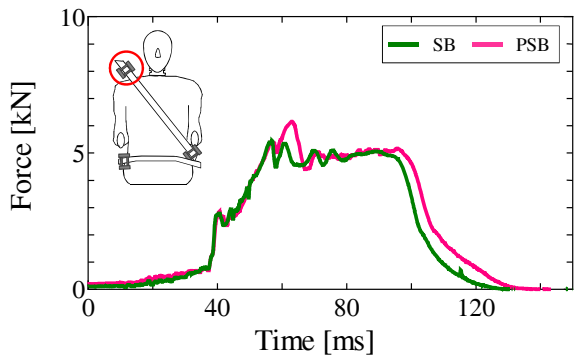


Figure 11. Upper Shoulder belt force.

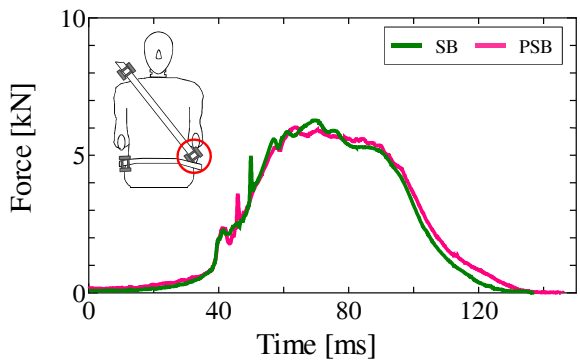


Figure 12. Lower Shoulder belt force.

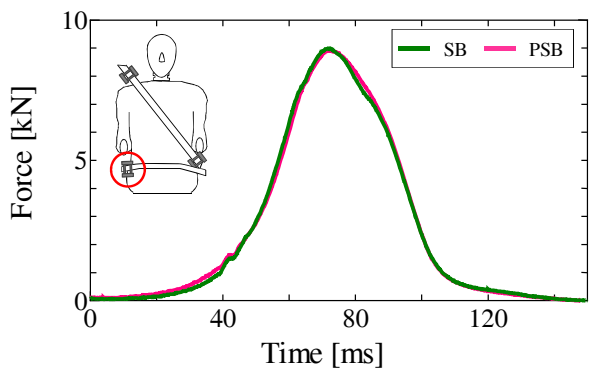


Figure 13. Lap belt force.

Interaction with the airbag: Estimated forces

In both tests, the head of the dummy initiated the contact with the airbag at around 50 ms after the beginning of the impact. From then on, the responses of head and neck showed clear differences, as indicated in the neck readings (Figures 7 and 8). In the SB test, forward bending posture of the body resulted in contact between the dummy face and the airbag before full deployment. This induced higher head and neck loads in terms of acceleration (Figure 6) and tension force (Figure 7), respectively, when compared with those in the PSB test.

In order to examine the body interaction with the airbag in more detail, time histories of the contact force with the airbag were estimated following a free body diagram method [10] sketched in Figure 14. With this method, translational motion of the head was expressed by means of neck forces and airbag contact forces in the following equation of motion:

$$m\boldsymbol{a}_{\text{head}} = \boldsymbol{F}_{\text{neck}} + \boldsymbol{F}_{\text{A/B}} \qquad (1)$$

Where

- m: mass of the dummy head (4.54 kg)
- $\boldsymbol{a}_{\text{head}}$: head acceleration vector
- $\boldsymbol{F}_{\text{neck}}$: neck force vector
- $\boldsymbol{F}_{\text{A/B}}$: contact force vector between the head and the airbag.

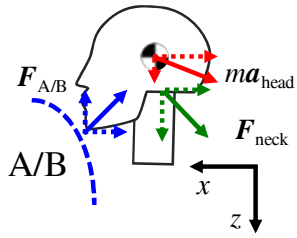


Figure 14. Sketch of free body diagram.

The airbag contact forces estimated according to equation (1) are shown in Figures 15 and 16. The contact force waveform in the longitudinal direction was similar to that of the head acceleration in longitudinal direction. The curve in the vertical direction was similar to neck tension curves, which reinforces the evidence that neck extension of the occupant out of position in the SB case is caused by the upstroke force from the airbag presented above.

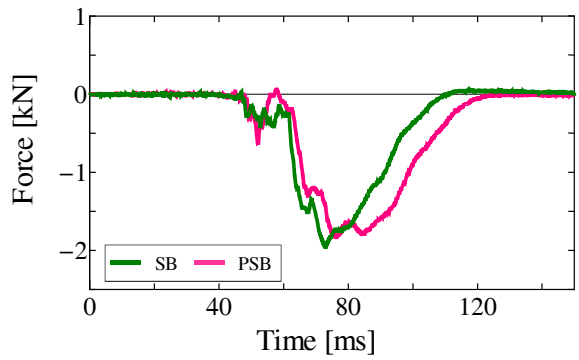


Figure 15. Estimated airbag force in longitudinal direction.

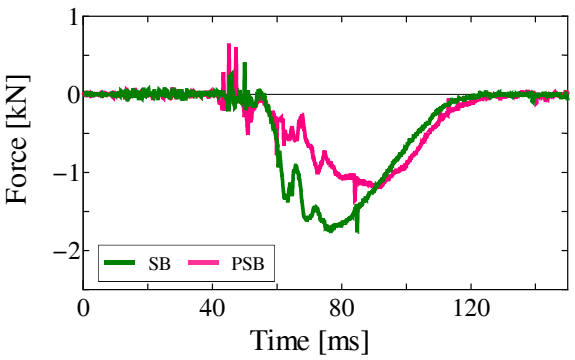


Figure 16. Estimated airbag force in vertical direction.

Figure 17 shows a comparison of acceleration vs. displacement (G-s) curves for chest and pelvis in both tests. The accelerations were taken from the dummy chest sensors in longitudinal direction and the displacements were presented as obtained from video marker tracking analysis. These curves show that the PSB worked effectively in reducing chest acceleration and forward displacement by improving initial restraint. In contrast, the G-s curves for pelvis show no difference between the two tests, observation consistent to the identical lap belt force time history measured (Figure 13), and show the lack of evidences of different contact with the knee bolster in both tests.

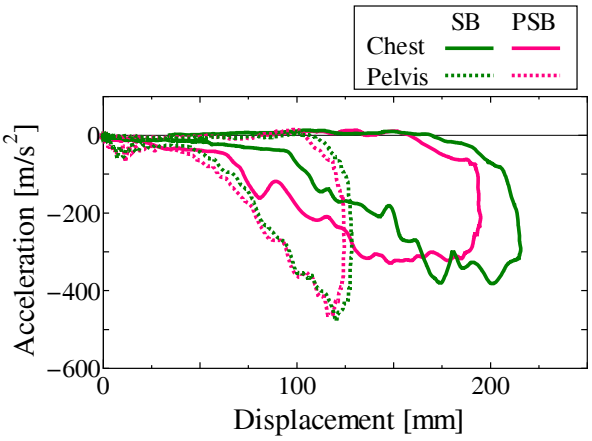


Figure 17. Acceleration-displacement curves for chest and pelvis.

Injury measures

Figure 18 shows the ratios of injury measures of the dummy to the injury criteria for these tests. These injury criteria are adopted in FMVSS 208.

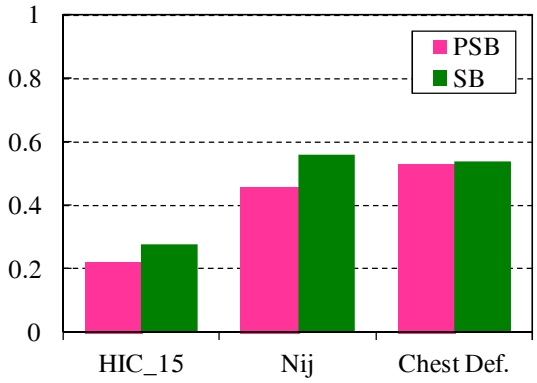


Figure 18. Dummy injury measures to injury criteria ratio.

No injury measure exceeded the corresponding injury criterion in this study. The differences of the results between the two tests were small in terms of the chest injury criteria, whereas the injury measures for head and neck in the SB case were substantially larger than those in the PSB case.

DISCUSSION

In this study, it was confirmed that neck and chest responses were improved by the PSB in crash pulse involving pre-impact braking as reported in the literature.

Schoeneburg et al. [5] reported that a pre-crash safety device with reversible (motorized) seatbelt pretensioner reduced neck extension moments in real vehicle crash tests with pre-impact braking. This improvement was associated with the improved timing interaction between the dummy and the airbag, which are usually designed for optimal protection of occupants in standard seating posture. Similar effects have been identified in different experimental studies employing out-of-position dummies [11] or Post Mortem Human Subjects (PMHS) [12], and in simulation based studies with human FE models [7].

This study is consistent with the studies mentioned above: In the SB test, the upper body of the dummy moved forward during pre-impact braking as shown in Figure 5. Therefore, the upper body was closer to steering wheel when the airbag was activated in the SB case. It is strongly possible that this difference of the posture led to the contact with the airbag before full deployment. As a result, the upstroke force from the airbag acted on the dummy face, causing neck extension shown in Figure 16. In contrast, in the PSB test, the dummy was restrained against the seat back during the pre-impact braking, which left additional space between the occupant and the steering wheel, allowing full airbag deployment before the contact to

the body or the head. This led to optimized interaction with the airbag, prevention of upstroke effect on the neck, and reduction of neck moment and Nij.

Besides neck, improvements in terms of chest accelerations were observed. Early restraint facilitated higher absorption of occupant energy through the shoulder belt at an early stage of the crash, which led to a reduced transference of residual energy into the chest at the following stage. As a result, the peak value of chest acceleration as well as the chest displacement decreased.

On the other hand, since SB and PSB did not show differences in terms of chest deflection (Figure 10), the potential benefits of the PSB compared in terms of reduction of chest loading were not able to be confirmed in this study. The shoulder belt forces at the upper and lower sides shown in Figure 11 and 12, which directly influence the chest deflection measured at mid-sternum of the crash test dummy, were almost identical in both SB and PSB cases. Therefore, it appears that the identity for chest deflection was reasonable. However, the possibility that the reason for this identity is associated with the lack of biofidelity of the Hybrid III dummy employed in this study still remains. On one hand, the thoracic section of the dummy lacks biofidelity when compared with PMHS based corridors for chest deflection [13]. On the other hand, evaluating chest injury risk through mid-sternum to thoracic spine deflection in dummies may not be representative of the real injury risk for rib fractures. The latter is supported by an FE based study in which Mroz et al. [14] compared mid-sternum and multi-point based deflections of a Hybrid III FE model with a validated human FE model. In that study, it was concluded that multi-point rib deflection exceeded mid-sternum deflection in the human model, while the same effect were not confirmed with the dummy model. This indicates that it may not be possible to capture the potentials of PSB and SB for rib fractures in frontal impacts with pre-impact braking by current dummy testing and that improved dummies and complementary work with human FE models would be needed.

In order to evaluate the effects of different pre-crash restraint systems for occupant safety in vehicle crashes, conditions such as posture changes and inertia forces close to those occurring during real-life pre-impact braking need to be reproduced. Furthermore, the crash configuration involving pre-impact braking may reveal not only a new load transfer process from the restraint system and interior parts but also injury mechanism of the occupants which have not been considered so far. The sled employed in this study allows customizing the configurations of actual restraint systems, controllable combinations of braking and crash pulses, high repeatability at a low cost. This enables manufacturers to evaluate the effects of parameters of each restraint system on the occupant injury outcomes. Therefore, it can be expected that the sled contributes to the reduction of lead time for product development process and improvement of occupant safety system.

CONCLUSIONS

The new sled system developed to evaluate the potential benefits of pre-impact safety restraint systems on dummy responses at collisions has been presented. This sled can reproduce targeted crash pulses with pre-impact braking, would lead to the development of different restraint systems from current vehicles, and enables to conduct repeatable crash tests with pre-impact braking at a reduced cost. Therefore, it can be said that the sled can contribute to curtail the development period of occupant safety systems and optimize the properties of these systems.

Two crash tests were conducted to evaluate the effectiveness of a pre-crash seatbelt (PSB) system in a frontal crash with pre-impact braking. Test results showed that, in comparison with the SB, the PSB reduced forward movement during pre-impact braking. This contributed to an optimized interaction with the restraint systems, which leads to the reduction of neck tension force, neck flexion-extension moment, and chest acceleration during the impact.

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