Evaluation of THOR Prototype Lower Abdomen in Sled Tests
- Capability of the Prototype Lower Abdomen to Discriminate Loading Conditions -

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Received on November 14, 2016

ABSTRACT: THOR-NT prototype lower abdomen including Abdominal Pressure Twin Sensors was evaluated in 40 kph sled tests. In baseline tests, the dummy was seated according to UMTRI procedure in the front passenger seat of a mass production car. Three other derived test conditions used either a slouched seat back angle or two different knee bolster thicknesses. A pressure peak of 1 bar was recorded when the lap belt was correctly positioned on the pelvis bones whereas up to 3.7 bars were recorded in slouched seat back for the lap belt on the abdomen. Overall, the prototype could discriminate restraint conditions.

KEY WORDS: Safety, Antropomorphic dummy/ crash test dummy, Injury prediction, THOR-NT, Abdomen [C1]

1. Introduction

Accident studies (1, 2, 3, 4) emphasized the need to assess abdominal injuries of car occupants involved in a frontal collision, especially for the oldest ones or occupants sitting in the rear seats. In Japan, Yaguchi et al. (2) highlighted the steady fatality number due to abdominal injuries whereas head and thoracic injuries, by large the most important causes of belted car occupant fatalities in frontal impact, decreased. The severity of the abdominal injuries made the abdomen the first body region regarding serious to fatal casualty rate, 1.9 to 3.5 higher than thoracic and head rates respectively. In Europe, Martin et al. (1) and Frampton et al. (3) showed that rear seat occupants had a higher proportion of abdominal injuries compared to front occupants and that rear occupant injury rates to the hollow organs (colon, jejunum ileum, mesentery) out weighted the rates of drivers and front seat passengers. Elhagediab and Rouhana (5) identified the seatbelt as being the first injury source for digestive/hollow organs. However, Frampton et al. (3) showed that abdominal injury rate was lowered from 14% for a standard belt to 4% for a pretensioned belt. It becomes then important to have an evaluation tool able to assess restraint system performances against abdominal injury risk. In vehicle crashes, possibly injurious loading of the abdomen attributed to the seatbelt could either result from an initial poor positioning of the lap belt lying directly on the abdomen instead of the pelvis antero-superior iliac spine (ASIS) (6), or from the kinematic of the occupant pelvis during the crash (combination of pelvis forward, downward displacement and rotation) which creates a sliding of the lap belt over the ASIS and a loading of the abdomen (7).

In the current study, evaluation of THOR-NT prototype lower abdomen, described in Compigne et al. (2015) (8), was performed in sled tests for the first time. Different configurations of the restraint systems were used to evaluate the sensitivity of the prototype lower abdomen to the initial positioning of the lap belt and to variations of the lap belt force. The submaring phenomenon was not studied.

2. Materials and Methods

2.1. Test set-up

A sedan car body in white was mounted on a reverse acceleration sled. THOR-NT was seated in the front passenger seat and restrained by a 3-point belt with 3 kN load limiter and pretensioner in the shoulder retractor. The passenger airbag was deactivated to follow the dummy kinematics and the lap belt interaction with the prototype abdomen. Delta-V of 40 kph (11.1 m/s) was applied to the body-in-white using the pulse shown in Fig. 1. This pulse simulated the deceleration of a median passenger car crashed into a full-width rigid barrier at 40 kph as requested by the US Federal Motor Vehicle Safety Standard 208 (FMVSS 208).

![Sled acceleration and velocity](image)

Fig. 1  40 kph sled acceleration.
Lap belt position and knee bolster thickness were varied depending on the test configuration as shown in Table 1. The “Standard” configuration (baseline tests) corresponded to a lap belt properly adjusted on the pelvis and the “Out Of Position (OOP)” configuration to a lap belt on the lower abdomen. Additionally, knee bolster thickness was varied to modify the lap belt load and simulate a deployed knee airbag (“Knee bolster” configuration).

Table 1 Test configurations.

| Test Id. | Lap belt position | Knee bolster (thickness) |
|----------|-------------------|-------------------------|
| A / B / C | Standard          | No                      |
| E / F    | OOP               | No                      |
| G        | Standard          | Yes (d= 80 mm)           |
| H / I    | Standard          | Yes (d= 100 mm)          |

2.2. THOR dummy

The Test Device for Human Occupant Restraint (THOR) NT version (9) equipped with the prototype lower abdomen and the THOR-Lx legs was used in this sled test series performed in 2012. Therefore it has to be acknowledged that dummy response might not be fully representative of the response of the latest version of the dummy (THOR-Metric). However, it is believed that this test series is still of interest as it is the first time ever published prototype lower abdomen dynamic evaluation.

2.2.1. Prototype lower abdomen

The THOR lower abdomen prototype was made from THOR-NT abdomen components (Fig. 2). Virgin front and rear blocks of foam were ordered and two vertical holes of 51 mm diameter were made in the front foam block to receive the Abdominal Pressure Twin Sensors (APTSs). The APTSs version 2 were inserted with their caps downwards. The APTSs version 2 consist of a 50 mm diameter soft polyurethane bladder filled with paraffin oil. Pressure measures were made by XPR30 subminiature pressure sensors (Measurement Specialties, Les Clayes, France) placed in the balled cap at the interface with the oil (Beillas et al., 2012) (10). The APTSs had the advantage over the DGSPs and the IR-TRACCs instrumentation used in THOR-NT and THOR-Metric respectively to be easier to use, more robust and equally sensitive to different loading directions. Additionally, the mounting brackets to the spine and the abdomen internal plate geometries were simplified to allow a simpler mounting and dismounting of the entire abdomen assembly. Fifteen steel cylinders of 30 mm diameter and 10 mm thickness were attached to the front of the abdomen bag to better mimic Post Mortem Human Subject’s response under seatbelt loading. These cylinders represented an additional mass of 825 g. The prototype assembly was slightly heavier than the NT assembly (3.12 kg versus 2.68 kg for the NT).

The prototype lower abdomen was evaluated by Compigne et al. (2015) (8) under component tests. Generally, its force-penetration response was closer to Post Mortem Human Subject (PMHS) corridors and the APTS pressures accounted well for impact severity.
2.3. Instrumentation

Seatbelt forces were measured at upper shoulder, lower shoulder and outer lapbelt points using seatbelt load cells. Standard THOR-NT and Lx leg channels were recorded. Additionally, APTS pressures of the prototype abdomen were measured.

2.4. Data processing

Data were acquired and filtered according to SAE J211 practices. Accelerations, pressures and displacement measurements were filtered with a low pass band Butterworth filter CFC180. Forces and moments were filtered with a low pass band Butterworth filter CFC600. Two high speed cameras recorded test scene from the right and right-front side of the dummy at a rate of 1000 frames/s. Two other high speed cameras were mounted on the sled and recorded two close views of the abdomen from the left side and top of the dummy at a rate of 1000 frames/s.

Chest and pelvis excursions were calculated from the double integration of the longitudinal acceleration of the thorax (at T6 level) and pelvis tri-pack assemblies subtracted by the sled longitudinal displacement. Result analysis focused on lower torso measurements, APTS pressures and belt forces to evaluate the prototype abdomen sensitivity to restraint conditions.

3. Results

3.1. Standard and OOP tests

Outer and inner shoulder belt force as well as outer lap belt force are shown in Fig. 6 to Fig. 8 for standard position tests and OOP tests. Almost a two times higher lap belt force peak was recorded in the OOP tests compared to the standard tests due to a much larger dummy pelvis excursion (Fig. 8). This higher forward motion of the dummy resulted in higher lap belt force. The peak also came later in time at around 100 ms compared to 70 ms in the standard tests. In standard tests, outer lap belt force peak timing corresponded with right ASIS force peak (Fig. 10 - Top) and the inner shoulder belt force with the left ASIS force peak timing (at 80 ms, Fig. 11 - Top). APTS pressures showed a plateau close to 1 bar (100 kPa) between 70 and 100 ms in standard tests, whilst in OOP tests, up to 3.7 bars were recorded at around 80 ms, earlier than inner shoulder and lap belt force peaks (Fig. 9). ASIS forces are in the range of 50 N due to the fact that the seat belt is positioned above ASIS location (Fig. 10-Bottom and Fig. 11-Bottom).
In OOP tests, equivalent and much lower resultant accelerations (around 200 m/s²) than in the standard tests were recorded at chest, T12 and pelvis levels (Fig. 12 to Fig. 14). In the standard tests, the lower torso was well restrained as shown by T12 and pelvis resultant accelerations reaching on average 350 and 450 m/s² respectively whereas in OOP tests, dummy restraint was made later and mainly applied to the upper torso.
Fig. 12 Chest resultant acceleration (Top: Standard, Bottom: OOP).

Fig. 13 T12 resultant acceleration (Top: Standard, Bottom: OOP).

Fig. 14 Pelvis resultant acceleration (Top: Standard, Bottom: OOP).

In Fig. 15 and Fig. 17, the correlation between the APTS pressures and the lap belt forces are demonstrated. In standard tests (Fig. 15), where the lap belt was at the ASIS level, the APTS pressure increased first linearly with the lap belt force and then remained stable until the maximum lap belt force was reached. The period during which the APTS pressures increased corresponded to the lower abdomen being compressed by the lap belt up to the ASIS level in the antero-posterior direction. Afterwards, the lap belt relied on the ASIS and did not compress further the lower abdomen.

ASIS forces versus lap belt force are shown in Fig. 16 for the standard tests. The ASIS forces increased first slowly with the lap belt force and then more rapidly once all pelvis flesh in front of the ASIS was compressed (from around 2500 N lap belt force). After this phase, the left and right ASIS curves had a different shape. It can be observed that whereas the right ASIS force peaks corresponded to lap belt force peaks, the left ASIS force still increased while the lap belt force slightly decreased. The left ASIS force peak was in fact reached at a time that corresponded to the inner shoulder belt force peak (Fig. 7 and Fig. 11 – Top) and remained relatively high until the lap belt load decreased below 600 N. This revealed the influence of the shoulder portion of the belt on the left ASIS measurement.
In OOP tests (Fig. 17), the APTS pressures increased with the lap belt force. At 79 ms (4700 N lap belt force), the APTS pressures decreased as the lap belt went over the lower abdomen and seemed to be trapped between the lower abdomen and the upper abdomen. This entrapment phenomenon would need to be prevented as it may damage the chest instrumentation (Fig. 18).

Shoulder and lap belt forces are presented in Fig. 19 and Fig. 20. Due to the knee bolster, low lap forces were recorded (almost 2000 N for the smallest knee bolster thickness and around 1000 N for the largest knee bolster thickness) and up to 1800 N resultant force were recorded at the acetabulum (Fig. 21). This resulted in very low ASIS forces (Fig. 22) and APTS pressures close to 1 bar as in the standard tests (Fig. 23).
Fig. 19 Outer (Top) and inner (Bottom) shoulder belt forces.

Fig. 20 Lap belt force.

Fig. 21 Left and right acetabulum resultant forces.

Fig. 22 Left and right ASIS forces.

Fig. 23 Left and right APTS pressures.

Fig. 24 shows APTS pressures versus lap belt force. It can be seen that especially for the larger knee bolster thickness (tests H and I), the APTS pressures continued to increase whereas the lap belt force decreased. Table 2 shows APTS pressures at lap belt force peak and APTS pressure peaks. The pressure increase observed after the lap belt force peak was between 0.28 and 0.92 bar (Table 2). The increase was higher in tests H and I with larger knee bolster thicknesses. The pressure maximum value was correlated with the maximum chest excursion (Fig. 25) and not with the maximum pelvis excursion (Fig. 26).
Table 2  Lap belt force and APTS pressure peaks
(1 bar=100 kPa).

| Test | Lap belt force peak (N) | (1) L&R APTS pressures at lap belt peak (bar) | (2) L&R APTS pressure peaks (bar) | Pressure increase (bar): (2)-(1) |
|------|------------------------|---------------------------------------------|---------------------------------|-------------------------------|
| G    | 1901                   | 0.55 / 0.75                                 | 0.93 / 1.03                    | 0.38 / 0.28                   |
| H    | 892                    | 0.195 / 0.48                                | 1.11 / 1.12                    | 0.92 / 0.64                   |
| I    | 1254                   | 0.355 / 0.53                                | 0.97 / 1.08                    | 0.62 / 0.55                   |

4. Discussion

4.1. APTS repeatability and sensitivity

In identical test conditions, APTS measures showed a very good repeatability with a coefficient of variation (CV) less than 5% (on average 5.2% and 2.1% CV for right and left APTS respectively in standard, OOP and knee bolster repeated conditions).

The APTS discriminated well the OOP tests by measuring a pressure 3 to almost 4 times higher than when the lap belt was lying on the ASIS.

4.2. ASIS load cells and APTSs

The ASIS load cells and the APTSs provided complementary information. The tests carried out highlighted three main configurations in terms of restraint conditions that ASIS load cells and APTSs allowed to identify:

Fig. 24 Left and right APTS pressures versus lap belt force.

Fig. 25 Left and right APTS pressure versus chest excursion.

Fig. 26 Left and right APTS versus pelvis excursion.
1) The dummy was in standard configuration restrained by the 3-point belt with the lap belt on the ASISs: the APTS pressure increased up to 1 bar until the lap belt force relied on the ASIS. Then, APTS pressure remained stable as there was no further compression of the abdomen due to the contact of the lap belt with the ASIS and the ASIS forces increased (Fig. 27).

2) The dummy was in OOP configuration with the lap belt on the abdomen. The dummy was mainly restrained at the abdomen and upper torso level: the APTS pressure increased with the lap belt force up to 3 or 4 times the value of the standard configuration and the ASIS recorded almost no load (Fig. 28).

3) The dummy was in standard configuration but with the knees restrained by a knee bolster. The lap belt loads were small resulting in low ASIS forces (on average 74 N on left side). The APTS pressure increased until the lap belt came into contact with the ASIS. In this configuration, APTS pressure continued to increase up to 1 bar due to the torso flexion while ASIS forces decreased (Fig. 29).

4.3. Pressure increase in APTS due to torso flexion

In tests G/H/I, the pressure continued to increase in APTSs while the lap belt already reached its maximum value and started decreasing. The additional pressure represented 0.28 to 0.92 bar depending on the APTS side and the test configuration (Table 2). This suggested that another phenomenon than the compression of the APTS by the lap belt contributed to increase the pressure in the APTSs. The maximum pressure appeared to be correlated with the maximum chest displacement (Fig. 25). In this test configuration, the chest rotation was larger than in the standard configuration (Fig. 30) and the lower abdomen was certainly more compressed between the upper torso (upper abdomen and rib cage, Fig. 31) and the pelvis base. The dummy forward flexion obtained in tests G/H/I could be considered as the worst case scenario for APTS response in torso flexion but similar kinematics might be found in rear seats where torso is not restrained by an airbag. In future, dummy design solutions might be found to limit the pressure increase due to the torso flexion. Such threshold might be set as a percentage of the injury threshold defined for the prototype abdomen. It has to be noted that this influence might also vary depending on dummy spine adjustment (Fig. 32). The current tests were performed in neutral position for T12 joint. Slouched and super slouched adjustments would certainly lead to an earlier and higher pressure increase whereas erect adjustment to fewer or no pressure increase.

Fig. 27 Left APTS pressure versus left ASIS force in standard configuration.

Fig. 28 Left APTS pressure versus left ASIS force in OOP configuration.

Fig. 29 Left APTS pressure versus left ASIS force in knee bolster configuration.

Fig. 30 Dummy maximum chest forward bending (Left: test A – Standard configuration, Right: test I – Largest knee bolster configuration).

Fig. 31 APTS position with respect to the upper abdomen (Left: R&L APTS, Right: Side view).
5. Conclusion

Eight sled tests were performed with THOR-NT equipped with the prototype lower abdomen. The dummy was seated in the passenger seat of a 4-door sedan car and the dummy was restrained by a 3-point seatbelt with pretensioner and 3 kN force limiter. A 40 kph delta-V was applied to the sled.

Pressures measured by the APTS were repeatable with a CV lower than 5%. The prototype lower abdomen gave pressure levels in relation to the loads applied by the lap belt on the lower abdomen.

The combination of the ASIS force measures and of the APTS pressures gave information on interaction between the dummy lower torso and the lap belt.

The tests with knee bolster which resulted in a large chest excursion showed that the APTS pressures could be influenced by the upper torso interaction. OOP tests revealed that lap belt could go over the lower abdomen with a risk to be trapped between the lower abdomen and the upper abdomen. Interaction between the lower abdomen and the upper torso might need further investigations leading potentially to dummy design improvements in this area.

This paper is written based on a proceeding presented at 2016 JSAE Congress (Autumn).

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