Pretensioner Loading to Rear-Seat Occupants During Static and Dynamic Testing

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Received 18 March 2014, Accepted 17 June 2014

Objective: Pretensioners reduce the seat belt slack and couple the occupant early to the restraint system. There is a growing prevalence of rear seat pretensioners and it is essential to determine whether the load from the pretensioner itself can cause injuries to rear-seated children. The aim of the study was to investigate the loading to the neck, chest, and abdomen of various sizes of anthropometric test devices (ATDs) during the pretensioner deployment phase and the crash phase in low-severity frontal sled tests and during static deployment.

Methods: Low-severity frontal sled tests were conducted with the Hybrid III (HIII) 3-year-old, HIII 6-year-old, HIII 5th percentile, and HIII 50th percentile ATDs. Two different retractor pretensioners with varying pretensioner force were used. The child ATDs were restrained on a booster cushion (BC), with and without a back. The loading to the neck and chest was compared to injury assessment reference values (IARVs) reported by Mertz et al. (2003). The chest loading to the HIII 5th percentile and HIII 50th percentile ATDs was also analyzed using age-related injury risk curves. Static pretensioner tests with the Q-series 10-year-old ATD, equipped with an advanced abdominal loading device, were conducted in standard ATD position and out-of-position with the lap belt positioned high on the abdomen.

Results: During the crash phase, head excursion and neck loading were reduced for both pretensioners for all ATDs compared to testing without a pretensioner. The pretensioner reduced chest deflection to the adult ATDs but not to child ATDs when seated on a BC with a back during the crash phase. When the back was removed, chest deflection was reduced below IARV. The head excursion was reduced for all ATDs with both pretensioners.

During the pretensioner deployment phase, the chest deflection exceeded the IARV for the HIII 3-year-old with the stronger pretensioner when seated on booster with a back and it was reduced below the IARV with the lower force pretensioner. For all ATDs, neck and chest loading during the pretensioner deployment phase were reduced when a pretensioner with lower force was used.

Abdominal loading to the Q10 in the static pretensioner deployments indicated a low risk of abdominal injury in all tested positions.

Conclusion: This study indicates the need to balance the pretensioner force and seat belt geometry to gain good pretensioner performance in both the pretensioner deployment phase and the crash phase.

Keywords: pretensioner, rear seat, child, chest injury, abdominal injury

Introduction

Pretensioners were introduced in the front seat during the 1980s and have been shown to be beneficial in terms of reducing the seat belt slack and coupling the occupant early to the restraint system, resulting in reduced forward excursion, improved kinematics, as well as reduced loading to the occupant (Forman et al. 2008, 2009). Furthermore, pretensioners have been shown to reduce the risk of submarining (Håland and Nilson, 1991).

Pretensioners are beneficial for child occupant safety just as they are for adult safety (Lopez-Valdez, Forman, Ash, et al. 2009; Lopez-Valdez, Forman, Kent, et al. 2009). The head is the most frequently injured body region when it comes to severe acute injuries in children, regardless of restraint system and crash direction (Arbogast et al. 2004; Durbin et al. 2003; Howard et al. 2004). Pretensioners can improve the protection to children by reducing head excursion and maintaining a well-restrained torso, thus reducing head impacts with the interior of the vehicle.

It is important to design the restraint system to reduce injury during the crash loading phase, but it is also as important to ensure that the system itself does not cause any harm either. Several studies have investigated the risk of abdominal injury due to seat belt loading as a result of a crash or pretensioning. Rouhana et al. (2010) found that the lowest abdominal belt load that resulted in injury to adults was 6.1 kN, which is well above pretensioner forces used in vehicles today.
There is a growing prevalence of pretensioners in the rear seat where the predominant occupants are children and adolescents. These occupants have different anthropometry, skeletal structure, and therefore injury potential, and it is essential to determine whether the load from the pretensioner itself can cause injuries to children. The aim of the study was to investigate loading to the neck, chest, and abdomen of various sizes of anthropometric test devices (ATDs) during the pretensioner deployment phase and the crash phase in low-severity frontal sled tests and during static deployment.

Methods

The study consisted of 2 parts, one series of 16 sled tests and one series of 5 static deployment tests. Both test setups used the same car body, a large family vehicle. The retractor was mounted on the package shelf with a direct belt outlet. No slack was added to the belt system in terms of winter jacket or padding.

Sled Tests

In the sled tests, 4 ATDs were used to cover the range of sizes of rear seat occupants, including a Hybrid III 3-year-old (HIII3y), a Hybrid III 6-year-old (HIII6y), a Hybrid III 5th percentile female (HIII5th), and Hybrid III 50th percentile male (HIII50th) positioned outboard in the rear seat. The child ATDs were restrained on a booster cushion (BC; Britax Kid Plus, Britax Limited Childcare, United Kingdom), tested with and without a back. The complete test matrix is presented in Table 1. Two retractor pretensioners with different pretensioner forces, referred to as pretensioner I (PI) and pretensioner II (PII), were tested and compared to one reference test without pretensioner. Pretensioner I was repeated for the child ATDs. The pretensioners represent different levels of pretension forces (Figure 1). The PI pretensioner has a high pretension force and is typical of a front seat installation. However, in the front seat it is mounted at the lower end of the B-pillar and the seat belt is routed through a D-ring, resulting in reduced pretensioner forces on the occupant than in the shelf-mounted case study herein. The pretensioner II has lower pretensioner force and can be found in the rear seat in vehicles today. The initial pretensioning phase is marked as the “pretensioner deployment phase” in Figure 1. Pretensioner I reached about 3 kN during the pretensioner deployment phase and pretensioner II reached approximately 1.5 kN. Both pretensioners were paired with a load limiter of 6 kN, but it was never activated in this low-severity crash pulse. A new retractor was used for every test. The BC was used 3 times before being replaced.

The recorded data included chest linear acceleration, upper neck forces and moments, chest displacement, chest displacement rate, and lap and shoulder belt forces. For detailed hardware information, see Table A1 (see online supplement). The data acquisition system (Kistler) has a built-in anti-aliasing filter (2,900 Hz 6pole Bessel). The sampling rate was 20,000 Hz. All data was filtered according to FMVSS 208 (NHTSA 2013). Each test was captured by digital high-speed cameras (Roper Scientific HG 2000, 1,000 frames/s) including a front, a side, and a top view. The loading to the neck and chest was compared to injury assessment reference values (IARVs) reported by Mertz et al. (2003). The chest loading to the HIII5th and the HIII50th were also analyzed using age-related injury risk curves, corresponding to a 65-year-old female and male respectively (Laituri et al. 2005).

The low-severity sled tests (Mannesmann Rexroth GmbH, Germany) were conducted at 40 km/h and had an initial deceleration plateau of 6 g, followed by a second plateau with a maximum deceleration of 12 g (Figure A1, see online supplement). The pulse was estimated as severe enough to trigger the pretensioner but still a low-severity pulse, because the goal was to study whether the pretensioner loading by itself could be higher than the loads from a crash where the system was activated. The deployment of the pretensioner occurs early in the crash, at 11 ms, before the ATD has started to move. Therefore, the sled tests could be analyzed as partly static during the pretensioner deployment phase but also dynamic to evaluate the load to the ATD during the crash phase.

Static Tests

A prototype version of the 10-year-old child ATD Q10 was positioned on the left side of the rear seat. These tests focused on the abdominal loading during the pretensioner deployment phase.
deployment phase, because this ATD had an abdominal insert, referred to as abdominal pressure twin sensors (APTS; Beillas et al. 2012b). The APTS consist of 2 cylindrical liquid-filled bladders and the pressure was registered by a sensor in each bladder. There are no injury thresholds available for the Q10, but the Q6 instrumented with the same APTS has a 50% risk of Abbreviated Injury Scale (AIS) 3+ abdominal injury at an APTS level of 1.09 bars (Beillas et al. 2012a).

The Q10 has 2 chest deflection sensors (IR-TRACCS) and they are located along the sternum, on the upper and the lower rib.

The restraint recommendations, legal requirements, and common practice of how 10-year-old children are restrained vary by country. In Europe, some countries have legal requirements compelling children of up to 150 cm in height to be restrained on BCs, whereas other European countries have an upper limit of 135 cm. In the United States, the American Academy of Pediatrics recommends children to keep using the BC until 144 cm (Durbin 2011). Based on British data, a 50th percentile 10-year-old has a height of 139 cm (Pheasant 2006). However, real-life observation studies have shown that the majority of 10-year-old children are seated directly on the car seat (Osvalder and Bohman 2008). Therefore, in order to cover recommendations, legal requirements, and real-life situations, 4 different seating positions were chosen for testing. First, a standard ATD position on a BC was used (Britax Kid Plus, with back removed; Figure 2a). The second position was out-of-position, with the ATD on a BC and the lap belt positioned high on the abdomen (Figure 2b). In the third position, the ATD was seated directly on the car seat with good sitting posture (Figure 2c). The fourth position was out-of-position with the ATD in a poor slouching position on the car seat (Figure 2d). The position with the lap belt above the guiding loops of the BC (Figure 2b), represents common misuse in real life (Osvalder and Bohman 2008). The Q10 positioned directly on the car seat (Figure 2c) represents a common real-life scenario. The retractor pretensioner evaluated in the static tests was the same pretensioner as pretensioner I used in the sled tests.

All sensors were recorded at 20 kHz and filtered according to the Society of Automotive Engineers J211 recommendations. The recorded data included linear chest acceleration (Channel Frequency Class [CFC] 180), chest displacement with upper and lower IR-TRACCS (IR-TRACC IF-372, CFC600), abdominal pressure on the left and right sides (APTS, CFC 180), and shoulder belt and lap belt forces (Messring DK11-36-23, CFC600). The data acquisition system used in the static tests was the same as the data acquisition system used in the sled tests. Each test was captured by digital high-speed cameras (Roper Scientific HG 2000, 1000 frames/s) including a front view.

Results

Sled Tests With HIII ATDs

A total of 16 sled tests were conducted. The loading to the ATDs is presented in Table 2. The loading to the neck and chest did not exceed the IARV for any of the tested configurations, except for the chest deflection to the HIII3y and HIII6y when seated on booster with a back.

Three different scenarios were evaluated with the HIII ATD family. The first scenario, (Figure 3a) evaluated pretensioner I compared to a standard retractor. Neck tension and neck flexion were reduced in all ATDs, compared to tests without pretensioner I used in the sled tests.

Fig. 2. Figures show whether head excursion and loading to the neck and chest increased (arrow up) or decreased (arrow down) with a pretensioner, compared to tests without a pretensioner for child and adult ATDs. (a) Includes pretensioner I and child ATDs positioned on booster with back, (b) includes tests with pretensioner II and child ATDs positioned on booster with back, and (c) includes tests with pretensioner I and child ATDs positioned on booster without back. The circle indicates loading exceeding IARV.
a pretensioner. Chest deflection was reduced for both adult ATDs compared to tests without a pretensioner. Neck tension and chest deflection were higher during the crash phase compared to the pretensioner phase. Chest deflection to the HIII5th and the HIII50th during deployment with pretensioner I corresponded to a 4% and 2% risk, respectively, of an AIS 3+ thoracic injury to a person aged 65 years. The corresponding chest injury risk during the crash phase was 12% and 13%, respectively. Head excursion was reduced for all ATDs for the PII tests compared to the standard retractor. The difference between maximum head excursion in the reference test and test with pretensioner II ranged from 65 to 80 mm.

In the third scenario, the child ATDs were tested on the booster with the back removed and with pretensioner I (Figure 3c). Neck loading was reduced compared to tests without pretensioner. For the HIII3y, the chest deflection reached the same levels as the test without pretensioner on a booster with a back in the crash phase. Maximum chest deflection was reached in the crash phase. In this scenario, chest deflection at the pretensioner peak was 39%-58% of the loading during the crash for the 2 ATDs. The difference in head excursion could not be calculated because the test without a pretensioner was tested with a seat back.

During the pretensioner phase, loading to neck and chest was reduced in all 3 scenarios during tests with the lower power pretensioner (pretensioner II) compared to the tests with the higher power pretensioner (pretensioner I) for all ATDs. In addition, all neck and chest measurements values were below IARVs during the pretensioner phase for tests with the lower power pretensioner.

It is important to note that the initial shoulder belt load path of the HIII3y and HIII6y was on top of the chest deflection transducer when seated on a booster with a back. When the pretensioner was deployed, the shoulder belt had some limited movement toward the neck of the dummies, meaning that the main loading of the shoulder belt would still be on the upper neck. The difference between maximum head excursion in the reference test and test with pretensioner II ranged from 65 to 80 mm.

Table 2. Loading to the neck and chest at pretensioner peak and at crash peak for all sled tests, difference in max head excursion relative the test without pretensioner, as a function of different ATDs and different pretensioners

| Dummy     | Pret. | Booster | Upper Neck Tension N | Upper Neck Ext. Nm | Chest defl. mm | Shoulder belt force kN | Upper Neck Tension N | Upper Neck Flexion Nm | Chest defl. mm | Diff. in max head excursion relative test without pretensioner mm | Shoulder belt force kN |
|-----------|-------|---------|----------------------|--------------------|-----------------|-------------------------|----------------------|----------------------|-----------------|---------------------------------------------------------------|------------------------|
| IARV HIII5y |       |         | 1380                 | 17                 | 28              | 587                     | 1380                 | 42                   | 28              |                                                                               |                        |
| HIII3y    | -     | BCwB    | 296                  | 8                  | 34              | 512                     | 15                   | 34                   | 67              |                                                                               | 2.4                    |
| HIII3y    | PI    | BCwB    | 359                  | 7                  | 34              | 521                     | 8                    | 30                   | 82              |                                                                               | 2.2                    |
| HIII3y    | PI    | BCwB    | 150                  | 5                  | 20              | 519                     | 7                    | 30                   | 79              |                                                                               | 2.4                    |
| HIII3y    | PI    | BC     | 121                 | -1                 | 11              | 526                     | 7                    | 28                   | -               |                                                                               | 2.3                    |
| IARV HII16y |      |         | 1820                | 24                 | 31              | 696                     | 1820                | 60                   | 31              |                                                                               |                        |
| HIII6y    | -     | BCwB    | 403                  | 9                  | 26              | 579                     | 15                   | 34                   | 67              |                                                                               | 2.5                    |
| HIII6y    | PI    | BCwB    | 363                  | 13                 | 26              | 592                     | 15                   | 35                   | 69              |                                                                               | 3.0                    |
| HIII6y    | PI    | BCwB    | 200                  | 5                  | 17              | 553                     | 16                   | 34                   | 60              |                                                                               | 2.9                    |
| HIII6y    | PI    | BC     | 239                 | 4                  | 18              | 626                     | 18                   | 31                   | -               |                                                                               | 2.3                    |
| IARV HIII5th |     |         | 2070                | 39                 | 41              | 870                     | 2070                | 95                   | 41              |                                                                               |                        |
| HIII5th   | -     | -       | -                    | -                  | -               | 870                     | 34                   | 26                   | -               |                                                                               | 3.5                    |
| HIII5th   | PI    | -       | 365                  | 13                 | 12              | 526                     | 25                   | 20                   | 82              |                                                                               | 3.0                    |
| HIII5th   | PI    | -       | 197                  | 8                  | 8               | 495                     | 23                   | 20                   | 85              |                                                                               | 3.1                    |
| IARV HIII50th |   |         | 3290                | 78                 | 50              | 793                     | 3290                | 190                  | 50              |                                                                               |                        |
| HIII50th  | -     | -       | -                    | -                  | -               | 793                     | 46                   | 30                   | -               |                                                                               | 3.8                    |
| HIII50th  | PI    | -       | 454                  | 12                 | 12              | 511                     | 29                   | 28                   | 88              |                                                                               | 3.2                    |
| HIII50th  | PI    | BCwB    | 350                  | 9                  | 11              | 416                     | 23                   | 25                   | 57              |                                                                               | 3.1                    |

BCwB = Booster Cushion with Back.
a booster without a back, the initial shoulder belt path was below the chest deflection transducer, but as the pretensioner was deployed, the shoulder belt moved up the chest in the direction of the chest deflection transducer.

The initial shoulder belt load path to the HIII5th and the HIII50th was directly on top of the chest deflection transducer (Figures A4 and A5, see online supplement). When the pretensioner was deployed there was some lateral movement of the belt at the shoulder level for the HIII5th and HIII50th, but the position at the mid sternum was similar to that before the deployment (Figure A4 and A5).

### Static Tests With Q10 ATD

The results of the static tests with the Q10 are shown in Table 3. The abdominal pressure on the left side (lower anchorage side) varied between 0.07 and 0.15 bar depending on test configuration and varied between 0.1 and 0.3 bar on the right side (buckle side). Abdominal loading increased when the ATD was positioned directly on the vehicle seat or with the lap belt in an out-of-position compared to the correct position on a booster cushion.

Upper chest deflection varied between 6 and 13 mm and lower chest deflection varied between 3 and 9 mm. Chest deflection was lower when the Q10 was positioned directly on the vehicle seat compared with on the booster cushion.

### Discussion

Pretensioners are important to reduce forward excursion, thus reducing the risk of impacting the head against the vehicle's interior, a primary cause of severe injuries to children. However, it is important that the load from the pretensioner itself cannot harm rear-seated children. Therefore, this study evaluated the risk of pretensioner loading-induced injury to the chest and abdomen across a range of ATDs.

### Sled Tests

A wide range of occupants may be present in the rear seat, where it is recommended to seat children. According to ECE R44, children weighing 15 kg or more are allowed to be restrained on booster seats. A child of 15 kg corresponds to an average 3-year-old (Pheasant 2006). In the United States, the NHTSA recommends children to stay in their child restraint seats with internal harness until they outgrow it, which is about at 18 kg (NHTSA 2005). However, in reality, 31% of U.S. children weighing between 9 and 18 kg were restrained on boosters or directly on the vehicle seat (NHTSA 2010). Therefore, it is relevant to include tests with a HIII3y, because children of this size can be exposed to 3-point belt loading (either with or without a booster) when restrained in the rear seat.

In this low-severity crash scenario, the pretensioner reduced neck and chest loading during the crash phase compared to the standard retractor for the adult ATDs. For the child ATDs, neck loading was reduced during the crash phase when a pretensioner was deployed compared to a standard retractor, but chest deflection increased. However, more important, for the child ATDs there was a reduction in head excursion. In real life, children would be less likely to have such snug belt fit as the ATDs in this study, because the belt is not usually tighten after bucking up in typical real-world usage, and children are likely to have additional clothing, such as winter jackets, which introduces additional slack in the belt (Osvalder and Bohman 2008). In a real-life scenario with a similar crash severity, the pretensioner benefit in terms of reduced excursion may be even greater than in this study as it would have reduced this slack as well.

Chest deflection was equal to or exceeded the IARV for both HIII3y and HIII6y at the time of the crash. Pretensioner II showed lower loading to the chest during the pretensioner deployment phase compared to pretensioner I where the IARV was exceeded for the HIII3y. The chest deflection injury criterion has been linked to risk of rib fractures in the adult population. However, children have a different chest injury pattern compared to adults in frontal impacts. Rib fractures are rare in children and they sustain predominantly lung contusions and pneumothoraces (Arbogast et al. 2012). Furthermore, children normally heal very well from lung contusions (Haxhiha et al. 2004). Consequently, the IARVs for the chest for children are tied to injuries that do not necessarily have equivalent clinical consequences as the same injuries in adults. The relationship between the IARV and other AIS 4+ injuries in children such as severe injuries to the heart is not well defined. However, until a pediatric-specific IARV for the chest is defined, the current values utilized in this study are the industry standard.

Both child ATDs sustained higher chest loading when restrained on booster with a back compared to the tests without a back. When the back was removed, the initial vertical position of the shoulder belt was lower over the chest for both the HIII3y and the HIII6y, as when seated in booster with a back (Figures A2 and A3). In another vehicle with different seat belt

### Table 3. Loading to abdomen and chest in static pretensioner test with Q10, varying booster cushion (BC) or car seat and ATD position (normal or out-of-position)

| Booster  | Seating position | Abdominal pressure | Chest deflection | Belt force |
|----------|------------------|--------------------|------------------|-----------|
|          |                  | Left (bar) | Right (bar) | Lower (mm) | Upper (mm) | Shoulder (kN) | Lap (kN) |
| BC       | Normal           | 0.07      | 0.10      | 8          | 12         | 3.3          | 0.2 |
| BC       | Normal           | 0.08      | 0.13      | 9          | 13         | 2.9          | 0.1 |
| BC       | Out-of-position  | 0.10      | 0.18      | 6          | 12         | 2.2          | 0.3 |
| Car seat | Normal           | 0.11      | 0.25      | 5          | 7          | 2.8          | 0.7 |
| Car seat | Out-of-position  | 0.15      | 0.30      | 3          | 6          | 2.3          | 0.4 |
deflection measurement locations and instrumented abdomen
crushed measurement capability in terms of multiple thoracic
to evaluate this risk, due to its improved biofidelity and in-
population using Hybrid III 50th percentile male and 5th per-
restraint systems. For the update of the ECE frontal regulations
advantages as well as the disadvantages of new advanced re-
important that the ATDs are sensitive enough to evaluate the
pretensioners have caused any harm to the front seat passen-
was very low during the pretensioner phase. To the authors'
pretensioner phase as well as during the crash phase. The cor-
the head into the interior.
the back, resulting in the head getting closer to the vehicle interior
such as the back of the front seat and B-pillar (Andersson et al.
but it also has benefits in keeping a sleeping child in position
the head is the most frequently
injured body region among children in car crashes (Arbogast
and re-
loading, which indicates that the shoulder belt has limited
the configuration with the smallest difference in left and right
loading on the shoulder belt force component acting on the chest, due to the angle of the shoulder belt between the shoulder and vehicle D-ring (Figure A6, see online sup-
The particular child seat in this test is representative in design for this category of child seats. However, there are booster seats with slimmer backrests, reducing the forward position of the child. There are also integrated booster seats that do not add any forward position to the child at all. Studies have also shown that the side wings make children choose a more forward posture with no shoulder contact with the seat back, resulting in the head getting closer to the vehicle interior such as the back of the front seat and B-pillar (Andersson et al. 2010), but it also has benefits in keeping a sleeping child in position (Forman et al. 2011). The head is the most frequently injured body region among children in car crashes (Arbogast et al. 2004; Durbin et al. 2003; Howard et al. 2004) and re-
straints that position the child closer to the vehicle interior should be avoided because they increase the risk of impacting the head into the interior.

Chest loading to the adult ATDs was moderate during the pretensioner phase as well as during the crash phase. The corresponding injury risk from chest deflection for a 65-year-old was very low during the pretensioner phase. To the authors’ knowledge, there are no studies of real-life data indicating that pretensioners have caused any harm to the front seat passen-
g, where the pretensioner has been present for decades. As restraint systems become increasingly sophisticated, it is im-
important that the ATDs are sensitive enough to evaluate the
advantages as well as the disadvantages of new advanced re-
strain systems. For the update of the ECE frontal regulations (R94), the risk of thoracic injury is proposed to be based on
injury risk curves for 65-year-olds to account for the elderly population using Hybrid III 50th percentile male and 5th per-
centile female ATDs. Although the THOR frontal ATD is still in development, it has been suggested that it is a better tool to evaluate this risk, due to its improved biofidelity and increased measurement capability in terms of multiple thoracic deflection measurement locations and instrumented abdomen (Lemmen et al. 2013; Parent et al. 2013; Sunnevång et al. 2014).

**Static Tests**

There are no official IARVs for the chest deflection of the Q10; however, deflection up to 13 mm could probably be considered as moderate taking into account that the shoulder belt was across the torso (Figure A7, see online supplement). In high-
severity sled tests performed by Croatto and Masuda (2013), the Q10 has shown low chest deflection due to the shoulder belt moving close to the neck and away from the chest deflec-
tion sensors, but that was not the case in this study. The lack of torso pitch in the static tests may explain the difference in shoulder belt movement compared to sled tests. Chest deflec-
tion was decreased when the Q10 was positioned directly on the vehicle seat, compared to when restrained on the BC, due to changes in the belt geometry resulting in the shoulder belt being positioned higher on the torso.

The loading to the abdomen was higher on the buckle side than on the lower anchorage side. The lap belt position was at a similar level on both sides (Figure A7). This study only
measured the lap belt force at the anchorage side, but normally when a retractor pretensioner is used, the belt force is higher on the buckle side than on the lower anchorage side (Eickhoff 2012). This could explain the higher abdominal load on the buckle side. The shoulder belt did not contribute to the ab-
dominal loading on the buckle side in the 2 test configurations with the Q10 on the vehicle seat or in the out-of-position test with the Q10 on BC. In those tests, the shoulder belt had a very high position on the torso (Figure A7). In the position on
BC with correct belt geometry, the shoulder belt might have contributed somewhat to the abdominal load due to its lower position across the torso (Figure A7). However, this was also the
configuration with the smallest difference in left and right
loading, which indicates that the shoulder belt has limited influence on the abdominal loading.

There is no accepted injury threshold for the abdominal
sensor for the Q10. However, for the Q6 the IARV is set to 1.09
bar for AIS 3+ abdominal injury. The Q6 threshold is based on tests with the same instrumentation as the Q10 (Beillas et al. 2012b). Furthermore, Beillas et al. (2012a) performed sled tests with the Q10 correctly restrained on a BC, which resulted in abdominal loading of 0.3 bar on the outer anchor-
age side and 0.78 bar on the buckle side, whereas the sled tests including misuse of the belt resulted in abdominal loading of more than 1.5 bar. Real-life data show that BC use elim-
ates abdominal injuries (Durbin et al. 2003), which makes the abdominal loading of 0.3 bar found in the current study a realistic noninjury level. Overall, the loading to the abdomen
and the chest was moderate.

**Limitations**

This study only included one vehicle and therefore one seat belt geometry. The seat belt geometry has great influence on the chest loading to the ATDs. Tests in other vehicles with
different geometries may result in higher or lower loadings re-
goingly to the ATDs for these specific tested pretensioners. Consequent-
ly, this study points out the importance of evalu-
ating the effect of the pretensioner deployment phase in future
vehicles that include pretensioners in the rear seat.

This study was limited to a low-severity sled pulse, and other trends might have been found if a high-severity sled pulse had been used. However, a low-severity crush pulse represents a
scenario where the loading to the occupant due to the preten-
sioner phase might be larger than the crash itself. Therefore,
it is of interest to evaluate whether or not the restraint system itself may cause injury to the occupant.

This study has used chest deflection to evaluate the chest load to the ATDs. Chest displacement rate may also be a relevant injury criterion for evaluating pretensioner loading to the ATDs. The chest displacement rate injury criterion was developed by Mertz et al. (1982) in order to evaluate the effect of out-of-position airbag tests and it is based on testing piglets with inflatable devices. This criterion has been used to evaluate the effect of thoracic side airbags in out-of-position tests with child ATDs (Lund 2003), positioning the IIII3y kneeling and facing the seatback with the chest against the side airbag (peek-a-boo position), evaluating the frontal chest deflection due to side airbag interaction. The pretension loading is not a distributed load like the airbag load; rather, it is a fast-loading condition compared to the crash itself. Injuries to thoracic organs may be rate dependent. However, further investigations are needed to determine whether chest displacement rate is a relevant injury criterion for pretensioner loading. In addition, the viscous criterion, which is a rate-dependent criterion, should be further investigated to determine its relevance for this load case.

Conclusions

In a crash, pretensioners reduce the risk of injuries by coupling the occupant to the vehicle early in the crash event and by reducing forward excursion. This may be an important countermeasure for rear-seated restrained occupants in order to reduce the risk of head impacting the vehicle interior.

Low-severity crash tests, involving restrained ATDs in the rear seat with pretensioner deployment, resulted in loadings below the IARV for all ATDs during deployment of the less powerful pretensioner (PII), whereas IARVs for chest loading to the IIII3-year-old were exceeded for the most powerful pretensioner (PI) during the pretensioner deployment loading phase. Furthermore, the ATD loading during the pretensioner phase was reduced below IARV levels even for the most powerful pretensioner by removing the backrest of the BC. Finally, low risk was indicated for the abdomen loading in all static deployment test conditions.

During the crash phase, the chest deflection to the child ATDs was equal or greater to the IARVs, in both types of BCs. Furthermore, the chest deflections to the child ATDs were greater or equal to the chest deflections observed in the test without pretensioner, in both types of BCs. The chest deflection to the adult ATDs were below IARVs and below the chest deflection observed in the test without pretensioner. The head excursion was reduced for all ATDs with both pretensioners.

This study indicates the need to balance the pretensioner force and seat belt geometry to gain good pretensioner performance in both the pretensioner deployment phase and in the crash phase.

Acknowledgments

The authors thank Christian Verheyen at Autoliv North Germany for supporting the study with pretensioners, Mikael Enänger, Börje Jansson, and Henrik Gillgren at Autoliv Sweden for assistance in data collection and processing.

Supplemental Materials

Supplemental data for this article can be accessed on the publisher’s website.

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