# ABDOMINAL RESPONSES TO DYNAMICALLY LAP BELT LOADING

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## ABSTRACT

Seat belts have been shown to be effective in reducing the number of serious injuries in car crashes. However, some injuries have been reported in accident data due to improperly fitted seat belts. This occurs, for example, when the belt rides above the anterior superior iliac spines (ASIS) of the pelvis before impact and loads the abdomen. This loading scenario is often referred to as "submarining".

The objective of this study was to identify the abdominal injury response when a lap belt is initially placed above the ASIS and dynamically cinched, and to determine injury thresholds. For this purpose, 14 post mortem human subjects (PMHS) were tested.

The set-up consisted of a rigid seat with an adjustable seat back and a dynamic cinching device linked to the webbing of a lap belt. The load applied on the lap belt peaked between 2.9 and 7.1 kN while it stabilized from 2 to 4.4 kN at a cinching speed of 6 m/s. Injuries were found in 3 of the 14 tests, at peak loads varying between 6.0 to 6.8 kN with a stable load of 3.6 to 4.1 kN. In these tests, the amount of lap belt web pull in was between 190 to 194 mm.

Data revealed that abdominal responses seem to vary not only with belt pull-in distance and force but also with anthropometric data. Though the results are not significant, the ratio between subject weight and size seem to affect the results.

The findings of this study were used to aid for the design of seat belt tensioning systems. An optimization of the restraint performance needs to be evaluated.

## KEYWORDS

Abdomen, Force, Safety Belts, Seats, Rollover Accidents

SEAT BELTS SERVE AS ONE OF THE PRIMARY OCCUPANT-PROTECTION DEVICES IN VEHICLE CRASHES. In the US, NHTSA (1998) has reported a 40% reduction in the number of fatalities with seat belt usage. Throughout the years, seat belt designs have been improved with respect to crash safety performance and comfort. For example, seat belt configuration has been changed throughout the years to enhance their effectiveness. In the 1970's, seat belt configuration was redesigned from a two-point to a three-point belt system. Later, pre-tensioners were developed. The purpose of pre-tensioners is to remove slack and cinch the occupants to their seat early in the crash event. Pre-tensioners were initially developed for frontal crashes but were shown to be beneficial in various crash modes since they reduce occupant excursion (Moffat *et al,* 1997: Meyer *et al*., 2000), and thus help minimize the potential for occupant to interior contact. Though seat belts provide an overall benefit for the occupants involved in a crash, they have also been reported as a source for injury.

Ryan (1973) reported some minor and some severe injuries associated with seatbelt usage. Often, these injuries are associated with an improper belt routing as for example injuries caused by submarining. Submarining corresponds to the situation where the belt crosses the iliac spine and penetrates into the abdomen (Green *et al.,* 1986). A lap belt which is found above the anterior superior iliac spines (ASIS) of the pelvis before impact is suggested to be factor of many abdomen-belt injuries. (Wells *et. al.*)

Most seatbelt tests are carried out with anthropometric test devices (ATD's). However, tests with ATD's show that increasing belt tension in a crash scenario often result in better occupant performance. However, ATD responses and human tolerance levels related to tensioning are not yet well correlated. To improve seat belt restraint development, identifying injury potentials and defining injury criteria are essential. The objective of this study was to identify the abdominal injury response when a lap belt initially placed above the ASIS and is dynamically cinched, and to determine potential injury thresholds.

# METHOD

## TEST SUBJECTS

Post mortem human subjects (PMHS): Fourteen unembalmed PMHS were obtained from the department of legal medicine at Graz University. The anthropometric data of each subject is given in Table 1. The age varied from about 40 to 87 years old. The preparation of each subject followed the Graz University Protocol.

| | Subject | | | | | |
|---|---|---|---|---|---|---|
| Test N° | sex | Height [m] | weight [kg] | age [years] | circumf. pelvis [cm] | circumf. abdomen [cm] |
| 1 | Dummy H3 50% with styrofoam abdomen | | | | | |
| 2 | Dummy H3 50% with standard abdomen | | | | | |
| 3 | Dummy H3 50% with standard abdomen | | | | | |
| 4 | Dummy H3 50% with standard abdomen | | | | | |
| 5 | male | 1.9 | 75 | 47 | 84 | 79.5 |
| 6 | male | 1.82 | 85 | 49 | 99.5 | 93.5 |
| 7 | female | 1.62 | 71 | 73 | 99 | 96.7 |
| 8 | female | 1.66 | 60 | 40 - 45 | 95 | 88 |
| 9 | male | 1.74 | 100 | 58 | 108 | 121 |
| 10 | female | 1.76 | 97.1 | 64 | 106 | 108 |
| 11 | male | 1.8 | 95.5 | 59 | 100 | 102 |
| 12 | male | 1.75 | 75 | 50 | 87 | 99 |
| 13 | female | 1.71 | 70.1 | 87 | 99 | 98 |
| 14 | male | 1.69 | 52 | 66 | 79.5 | 78 |
| 15 | male | 1.72 | 79.3 | 54 | 98.5 | 96 |
| 16 | female | 1.51 | 43.5 | 95 | 82 | 69 |
| 17 | male | 1.83 | 72.2 | 69 | 93.5 | 96.5 |
| 18 | female | 1.48 | 52.2 | 84 | 930 | 77.5 |

Table 1. Human Test Subject Anthropometric Data

Anthropometric Test Device: A 50$^{th}$ percentile male dummy was used in various seat configurations (Table 1). Note that in test 2, 3 and 4, the abdomen insert was used in each test.

## TEST SET-UP

The set-up consists of a rigid seat with an adjustable seat back and a dynamic cinching device linked to the webbing of a lap belt.

Seat: The seat consists of the seat bottom and the seat back based on the ECE R16 seat requirements. The seat bottom was fixed with a 10 degrees longitudinal rotation, while the seatback could either be rotated to 25 or 45 degrees depending on the test matrix. The seat back was made of 2 parts: 1) the seat back on which the subject rested, and 2) the back support which was longer and wider than the seatback for head and belt anchor support. A 19-mm thick plywood was attached to a metal seat . Figure 1 shows the dimensions of the seat.

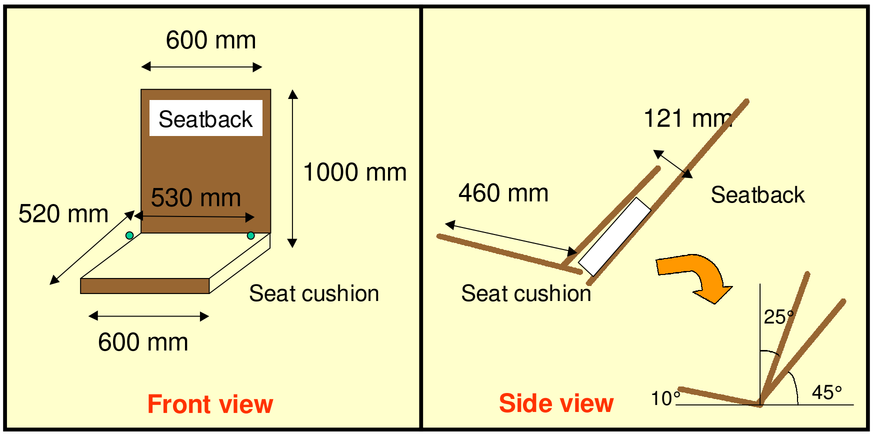


Figure 1. Seat Dimensions

Belt System: The lap belt system consists of lap belt webbing, a fixed outboard anchor attached to the seat, a free rotation D-ring guide and a loop to adjust the length of the webbing. The D-ring guided the inboard portion on the lap belt to the loop. The D-ring guide could rotate freely and was used to reduce friction between the seat and the belt webbing. The lateral distance between the D-ring guide and the outboard anchor was 0.53 m (Figure1), while the vertical distance was similar. The loop was linked to the arm of the cinching device (Figure 2).

Cinching device: The device (Figure 2) consists on a spring system linked to a pivoting arm that was attached to the belt webbing. Depending on the test, the spring was initially compressed using compressed air. During testing, the air was released, decompressing the spring that resulted in a webbing pull.


Figure 2. Test Set-Up for Dynamic Cinching

INSTRUMENTATION

Belt loads: 2 belt load cells were used to measure the load applied by the cinching mechanism. One load cell was placed on the outboard side and the other on the inboard side. The load cells were placed closed to the test subject but without contact.

Accelerometer: An accelerometer was attached to the moving arm of the dynamic cinching device to measure the acceleration, speed and distance of belt-webbing pull-in.

Switch: A switch was used to provide time 0 to synchronize the initiation of the cinching device with the acquisition system.

FILM ANALYSIS

Targets: Targets were used for film analysis of the subject and belt kinematics. Targets were placed on the front forehead and chin of the subjects, on their arms, and abdomen (Figure 3). Two targets were also placed on the seatback, (215 mm apart), on the seat cushion (250 mm apart), and on the front corners of the seat cushion (460 mm apart).

Reference boards: a checkered reference board was attached to the seat back support in the front view and another on the outboard side in the lateral view. A stripped fixed reference board was placed behind the inboard distal portion of the belt webbing.

Belt marks: Belt marks were drawn on the inboard distal portion of the lap belt.

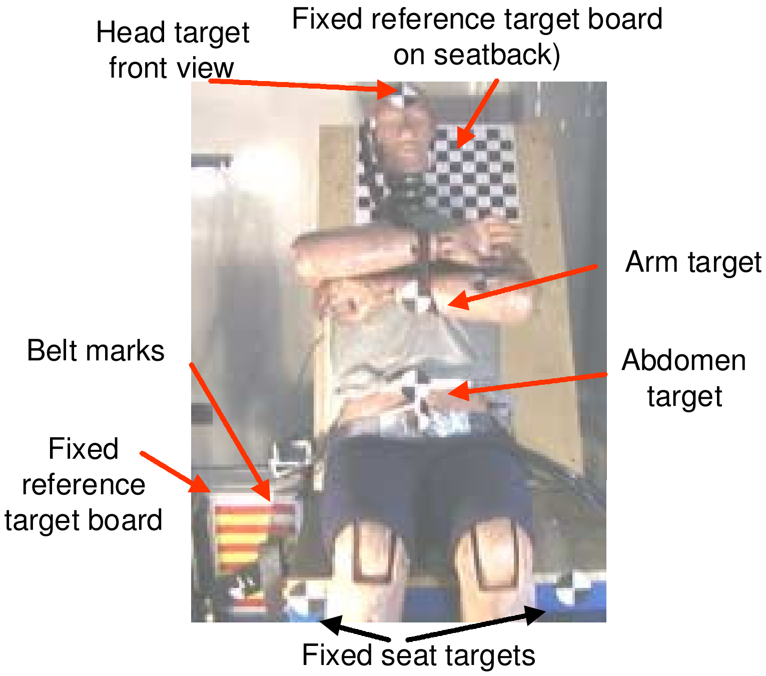

Figure 3: Test Set-Up for Film Analysis

Cameras: Three high speed cameras were used:
- Camera 1 is a high speed color camera focussing on inboard side view of the subject.
- Camera 2 is a high speed black and white camera focussing on the overall front view of the subject.
- Camera 3 is a high speed color camera focussing on the front view of the inboard belt webbing and cinching device.

MEASUREMENTS

Belt pull-in distance: This measurement was obtained in 3 ways:
1) dynamically via film analysis,
2) by double integration of the acceleration, and
3) statically by measuring the relative distance between a marker placed on the back of the webbing and the D-ring after each test.

INJURY ASSESSMENT

Injuries were assessed after each test during a post mortem medical examination.

NORMALIZING

To normalize the test results by the proportions of the subject, a body mass index (BMI) was calculated. BMI is determined by dividing the subject weight by height squared. The peak and stable forces and maximum belt pull-in distance were divided by BMI.

## RESULTS

### HYBRID III

Prior to the PMHS test series, tests were carried out with the Hybrid III. Table 2 shows the peak forces measured at the inboard and outboard belt sensors and the peak web pull-in distance for various sitting configurations. Test results are not available for test 1 due to problems with the data acquisition system. When the seatback was reclined 45° and the belt was positioned on the abdominal area (test 2), the maximum pull-in distance was 48 mm. This resulted in an initial peak in the inboard load cell of 4 kN which quickly stabilized at 2.2 kN (Fig. 4). The initial peak is likely due to friction.

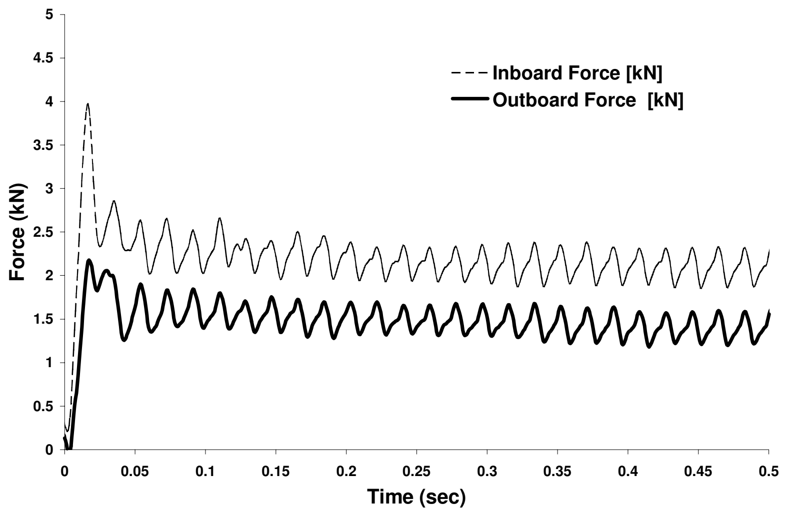


Figure 4: Seat Belt Force-Time Characteristics

Table 2: Peak Seatbelt Forces and Pull-in Distance using a Hybrid III and Post Mortem Human Subjects

| | Subject | | | | | |
|---|---|---|---|---|---|---|
| | Inboard Force (kN) | | Outboard Force (kN) | | Pull-in Dist (mm) | |
| **Test N°** | **Peak** | **Sustained** | **Peak** | **Sustained** | **Max** | **Injuries** |
| | ***Hybrid III*** | | | | | |
| 1 | - | - | - | - | - | |
| 2 | 4 | 2.2 | 2 | 1.5 | 65 | |
| 3 | 3.2 | 1.9 | 2.2 | 1.6 | 101 | |
| 4 | 3.8 | 2.1 | 2 | 1.4 | 99 | |
| | ***PMHS*** | | | | | |
| 5 | 4.1 | 2.5 | - | - | 118 | - |
| 6 | 3.4 | 2.3 | 2.6 | 2.3 | 125 | - |
| 7 | 2.9 | 1.0 | 2.0 | 1.0 | 138 | - |
| 8 | 4.4 | 3.0 | 3.0 | 2.0 | 104 | - |
| 9 | 3.4 | 1.6 | 2.1 | 1.5 | 167 | - |
| 10 | 4.0 | 1.6 | 2.5 | 1.6 | 180 | ? |
| 11 | 5.5 | 4.0 | 5.1 | 4.0 | 124 | - |
| 12 | 6.3 | 4.0 | 5.0 | 3.4 | 140 | - |
| 13 | - | - | 3.4 | 3.0 | 187 | - |
| 14 | 6.8 | 4.4 | 5.8 | 3.7 | 192 | small intestine rupture (15mm) |
| 15 | 6.2 | 3.3 | 4.7 | 3.0 | 200 | - |
| 16 | - | - | - | - | 190 | small intestine rupture |
| 17 | 6.0 | 3.6 | 3.2 | 2.5 | 194 | rupture of mesentery |
| 18 | 7.1 | 3.9 | 5.3 | 3.6 | 200 | - |

PMHS

Tests were carried out with 14 PHMS. The seat belt peak forces and pull-in distance are summarized in Table 2. The results varied from one subject to another. For example, for a pull-in distance of about 125 mm, the force peaked at 2.6 kN and stabilized at 2.3 kN in test 6, while it peaked at 5.5 kN and stabilized at 4.0 kN in test 11. Both subjects were males with an average height of 180 cm. However, there was a difference of 10 kg in weight between the 2 subjects.

To compare the relationship between force and anthropometric dimensions, the body mass index (BMI) was calculated by dividing the weight of the subject by the square of his/her height. The smallest BMI was 18.21 Kg/m$^2$. The lap belt outboard force results were then normalized with their corresponding BMI. No injury correlation was observed between the BMI and the peak and stable forces. The maximum web pull-in distance was also divided by the BMI. The results were highest in tests 14 and 16, at 624*10$^{-5}$ and 660*10$^{-5}$ m$^3$/Kg respectively. Note that injuries were observed in both of these tests. Thus, there seems to be a correlation between the ratio of maximum web pull-in distance and BMI and injury outcome (Figure 5, Figure 6).

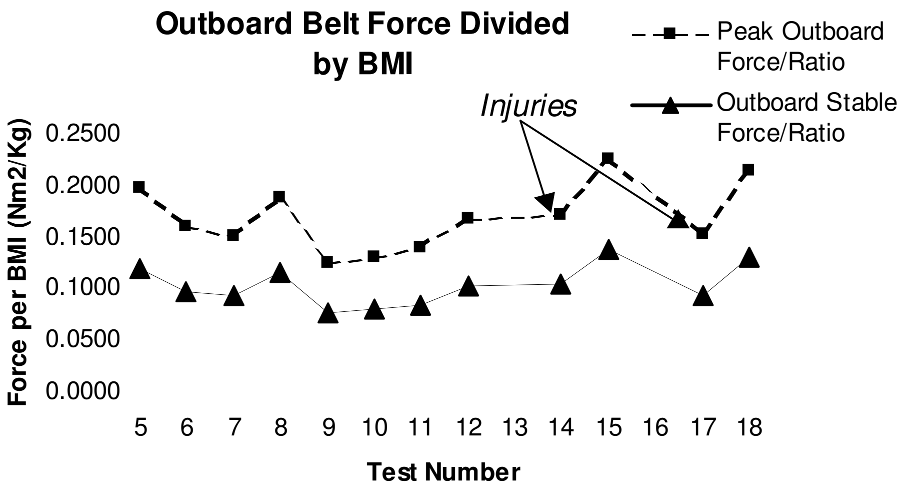


Figure 5: Seatbelt Forces as a Function of BMI

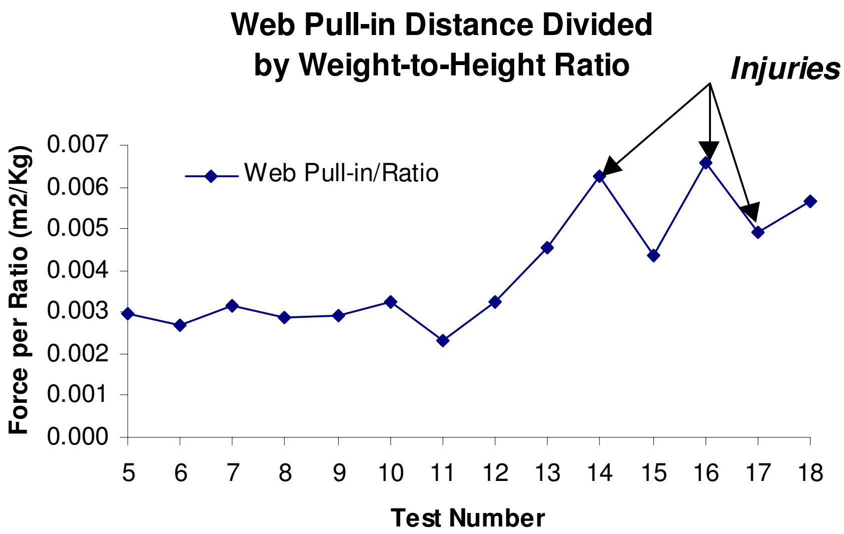


Figure 6: Seatbelt Pull-in Distance a Function of BMI

PMHS VS. HYBRID III RESPONSES

For comparison between the human and dummy response, test 2 and test 6 were chosen due to the same sitting configuration, and also to their height and weight similarity. The peak seat belt force applied to the Hybrid III was 4 kN which dropped to 2.2 kN. Similarly, the peak force in the human was 3.4 kN, dropping to 2.3 kN. The webbing pull-in distance was however twice as high in the human than in the dummy, at 94 mm and 48 mm respectively. This result suggests a higher compliance in the human abdomen.

## DISCUSSION

In this study, 18 tests were carried out to evaluate the effect of dynamically cinching the lap belt on the abdomen: 4 with the Hybrid III dummy and 14 with post mortem human subjects. Data was however not available for tests 1, 13 and 17 due to failure with the data acquisition system.

The cinching load was originally set-up to apply an estimated peak lap belt force of 3 kN. This load was approximated based on the dimension of the abdomen, its stiffness characteristics and the peak compression for 25% probability of AIS 3+. This information was obtained from a previously published study (Rouhana et al., 1999). However, in this study, injuries were not found at a peak load of 3 kN. The load was then increased to 4, 5 and 6 kN. Injuries were then reported at peak loads of 6-7.1 kN and at stable loads of 3.3-3.9 kN. In this study, it is difficult to assess if the injuries were produced during the peak phase of loading or during the stable phase where the load remained applied for about 400 ms (Fig. 7).

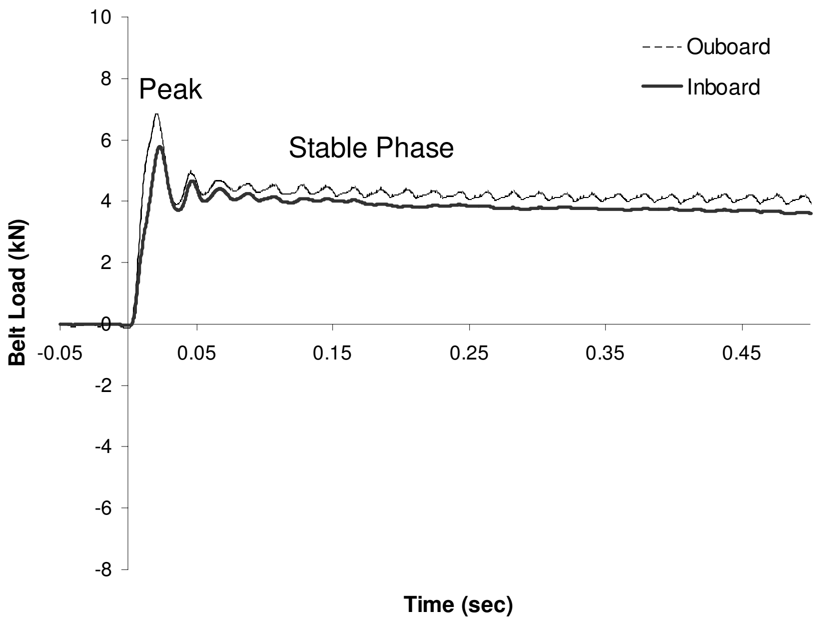


Figure 7: Seatbelt Forces as a Function of Time for Test 14

Miller et al. (1989) reported that, at lower speeds, injuries are best correlated with maximum compression or by the product of maximum compression and force. In this study, the time for maximum compression was assessed by reviewing the kinematics files. In the three injury cases, maximum compression occurred in the stable phase. This suggests that injuries were likely to be produced in the stable load phase rather that at the peak load phase. Furthermore, there seems to be a correlation between injury outcome and the ratio of maximum web pull-in distance and BMI. This supports the suggestion that injuries were likely to be produced in the stable phase where belt pull-in reached its maximum. This observation also suggests that, for the same amount of cinched webbing, slim occupants are more likely to get injured than fat occupants.

In the development of cinching belt devices, controlling the amount of web pull-in thus seems significant. For similar BMI's, a belt pull-in distance of less than 120 mm does not seem to produce injury (tests 5 & 8) while a pull-in distance of 190 mm and above lead to injury (tests 14, 15 & 17).

It should also be noted that the tests were carried out using unembalmed PMHS and that no internal pressurization techniques were used. The lack of pressurization may have an effect on results. To better understand this effect, further studies on cinching a lap belt on pressurized and non-pressurized PMHS need to the carried out.

In this study, the same test set-up was carried out with PMHS and a Hybrid III dummy. The responses were different, in particular in the amount of web pull-in. This suggests that a better correlation between the Hybrid III and the human abdomen needs to be identified so the Hybrid III can be used to evaluate lap belt cinching devices.

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