**Analysis of Abdominal Injuries Caused by the Submarining Phenomenon in the Rear Seat Occupants**

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## ABSTRACT

Improvements to vehicle safety have targeted mainly the front seating positions, where the rate of seat belt usage was high and there were many casualties. Recently, rear seat occupant protection become an important challenge, with an increase in usage of seat belts by rear occupants due to new regulations and new performance criteria defined by Japanese and European vehicle assessment programs for rear seating occupants. Some prior analyses of accident data indicate that rear seat belted occupants tend to be injured in abdominal regions in comparison with front seat occupants. Due to this, the need to study the cause of abdominal injuries and how to countermeasure it is becoming indispensable for improving the protection performance of the rear seat occupants. The following two phenomenons are considered as factors which great impacts on abdominal injuries: the submarining phenomenon, lap belt intruding into abdominal region, and the incorrect routing of the belt, lap belt existing initially on abdominal region. However, the relationship between these probable causes and the abdominal injuries in the real world accident is not expressly described in prior studies. Therefore, first, the frequency of the abdominal injuries caused by the submarining phenomenon was estimated by micro analysis of the accident data. Second, the influence on abdominal internal organs, to which the lap belt load was applied, was analyzed using human body FE model THUMS. The results of this analysis indicated that the effect might be applied to abdominal internal organs. As the routing of the lap belt on the pelvis was shown as being very important in this study, a parametric study using Madymo was conducted to determine additional factors that might influence the proper routing of the belt on pelvis. This study narrowed down the factors with big contribution and explains how they were determined.

## INTRODUCTION

Crash data analysis clearly shows that seat belt use has an unquestionable advantage in occupant protection. A 2003 NHTSA research [1] estimated that 147,246 occupant lives were saved by seat belt use through 1975 to 2001 in US. The improvements of restraint systems such as seat belt and airbag has been pushed forward by changes in regulation and assessment programs mainly for the front seating positions, where the rate of seat belt usage was high and there were many casualties. In addition, requirements for improving the protection of rear seat occupants are increasing recently. In Japan New Car Assessment Program (JNCAP), off-set deformable barrier (ODB) test with Hybrid III 5%ile female dummy in rear seat started in 2009, while seat belt wearing for rear seat occupants was made mandatory by regulation in 2008 and usage rate is rising. [2][3] In addition, European New Car Assessment

Programme (ENCAP) is conducting frontal full width rigid barrier (FWRB) test with Hybrid III 5%ile female dummy in rear seat starting with January 2015. Due to the above, rear seat occupant protection is being regarded as more and more important.

R.Frampton et al. [4] reported that the abdominal injury risk for the rear seat occupants was higher than for front seat occupants based on UK accident data analysis. Additionally, the report on injuries to older passengers by the Institute for Traffic Accident Research and Data Analysis (ITARDA) [5] indicated that the rate of fatal and serious injuries for rear occupants involving elderly is higher due to abdominal injuries. The following two phenomenons are considered as factors which 1) submarining phenomenon, lap belt intruding into abdominal region, 2) belt malpositioning, lap belt existing initially on abdominal region. In particular, JNCAP and ENCAP put focus on the submarining phenomenon; the score is reduced when submarining occurs in the above-mentioned ODB (JNCAP) or FWRB (ENCAP) evaluations.[6][7]

However the above-mentioned accident data analysis [4][5] does not clearly refer to the relation between abdominal injuries and submarining phenomenon by lap belt. An in-depth analysis about the abdominal organs injuries of belted / non-belted front occupants by K. Ono et al.[8] also did not report any relationship. Due to this, the first objective of this study is to estimate the occurrence frequency of the submarining phenomenon based on accident data analysis and to simulate the severity to the abdominal organs when the submarining phenomenon occurs using the human finite element model. Second objective is to examine the effective control scenario to reduce the submarining phenomenon.

## METHODS

### Crash Data Analysis

The National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) database was used to estimate the frequency of the submarining phenomenon occurrence. In the analysis, 555 injury cases of belted rear seat occupants were extracted from 2007 to 2011 (PDOF 11-1 o'clock).

### Analysis of the influence on abdominal organs

A series of simulations using 50%ile male human finite element model, THUMS Version3, was conducted to examine the influence to abdominal organs when the submarining phenomenon occurs. The severity of pressure to the abdominal organs due to the position of the lap belt, which assumed submarining phenomenon and belt malpositioning, was simulated and compared with the output of the lap belt worn appropriately. In this study, the geometry, seat belt parameters and deceleration of 56km/h full width rigid barrier test of actual vehicle were used. Abdominal organs deflection and deflection velocity were considered as characteristic indexes indicating the severity. However, the deflection mode and the injury mechanism of the abdominal organs were different because variation in structure (such as the solid and hollow). The characteristic value suitable for each internal organ was not expressly shown as various studies on those injury mechanism might be ongoing. Therefore, this study adopted both the deflection and the deflection velocity as the characteristic index.

### Parametric Study for Submarining Performance

A parametric study using Madymo was conducted to narrow down the parameters with large impact to anti-submarining performance and to clarify their proper design values. The angle between the belt-to-pelvis (abbreviated BTP from now on) from the submarining phenomenon index used in the study of J. Horsch and W. Hering [9] was used in this analysis. (Figure 1)

The mechanism of the submarining phenomenon was based on the following hypothesis:

"The pelvis receives the torso internal force $F_{Chest}$, the femur internal force $F_{Femur}$, the resistance force from the seat cushion $F_{Seat}$ as well as the lap belt force $F_{Belt}$ and moves forward with rotation. Due to this displacement of the pelvis, the lap belt direction for the iliac spine changes. As this displacement increases, the BTP increases counterclockwise and the force of the upper direction along the iliac spine increases. Due to the change in this load distribution, it becomes very likely that the submarining phenomenon will occur."

According to this hypothesis, "continuously maintaining a small BTP" is important to control the submarining phenomenon. Therefore, the extraction of the factors that influence the change of lap belt angle $\theta_B$ and iliac perpendicular angle $\theta_P$, and the contribution degree of each factor were derived.

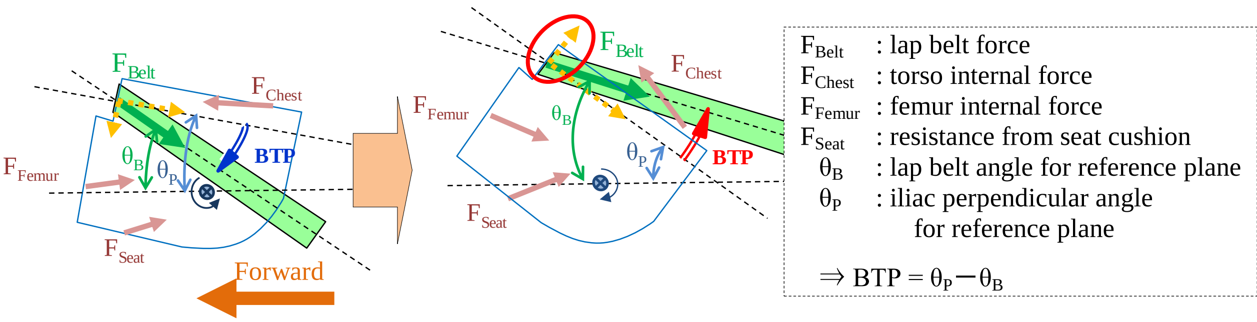



***Figure1. Force acting on pelvis and BTP***

**RESULTS**

**Crash Data Analysis**

According to the distribution ratio of the Abbreviated Injury Scale (AIS) from the extracted cases, 89% of the injuries in the rear seat were minor injuries with an AIS 1; the reduced severity of the injuries was attributed to the use of restraint system such as seat belt. This study researched the remaining 11% of AIS 2 and greater(AIS2+).

Injury source for the AIS2+ injuries in the rear seat (Figure 2a), injury description of the injuries by belt restraint system (Figure 2b), the rate of the injured abdominal organs (Figure 2c) are illustrated in below Figure 2. Results indicate that 28% of the injuries in the rear seat were caused by the belt restraint system, of which 34% were injuries to the abdominal region. In addition, 65% of the injured abdominal organs were distributed in the lower abdomen such as the intestine or the mesentery.

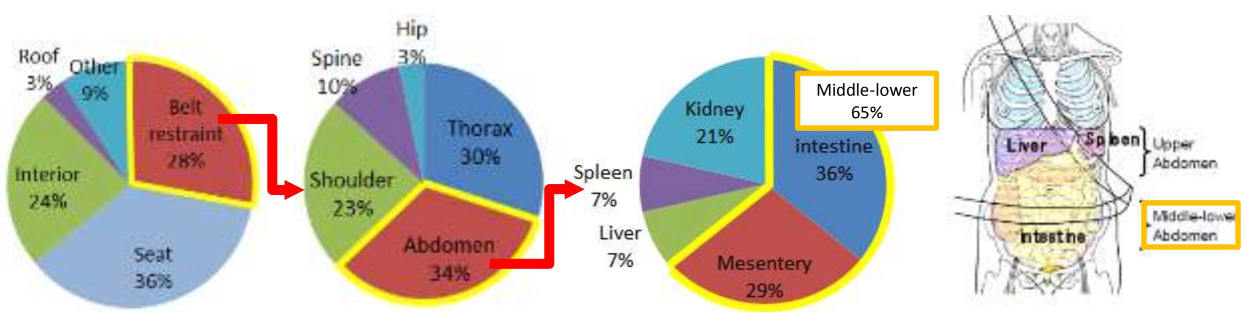



**Figure 2a** **Figure 2b** **Figure 2c** **Figure 2d [10]**

***Figure 2. Injury source for the AIS2+ injuries in the rear seat (Figure 2a), Injury description of the injuries by belt restraint system (Figure 2b), Rate of the injured abdominal organs (Figure 2c)***

Here, the micro-analysis of abdominal organs injury cases was researched to determine the relation between abdominal injuries and the submarining phenomenon. Results indicate that 30% of the abdominal organs injury cases were recieved abrasion and contusion to the hips by the belt restraint system. It was confirmed that the lap belt was fitted on the iliac spine at the start of the crash event and it became very likely for the submarining phenomenon to occur during the collision.

In four cases, rear seating occupants sustained the pelvic fractures with an AIS2 caused by the belt restraint system. After further analyzing these four cases, three were specified the fracture point and one of them was fracture of the anterior superior iliac spine on which the lap belt was fitted on; however, for this case, the cause of the fracture is believed to not be due to high load from the lap belt due to a low barrier equivalent speed of 45km/h. Two of the fractures were pelvic breaking away from iliac spine. From the collision velocity and involved region, it was assumed that the fractures were partly due to a contact with the buckle, the seat, another interior part or an unbalanced load by the vehicle behavior.

**Analysis of the influence on abdominal organs**

Vertical section views (in the initial stage of the restraint, in the maximum movement of the pelvis, and in the rebound of the pelvis) of the lap belt fitting on the iliac spine properly or the abdomen, maximum amount of abdomen deflection, and deflection velocity changes by time are illustrated in Figure 3. Here, the amount of abdomen deflection and deflection velocity were calculated using two places, top and bottom, that assume a division between spine and organs shown in vertical section views. This THUMS model used the abdominal organs model which is united; the upper part is equivalent to the upper abdomen including the liver and the spleen, and the lower part is equivalent to the lower abdomen including the intestine and the mesentery. Results indicate that the amount of abdomen deflection and deflection velocity in fitting of the lap belt on the abdomen were higher in the lower measurement part, equivalent to the lower abdomen, which has seen increased injury in the accident analysis compared to the upper part. This result matched the actual accident situation in the real-world. The maximum amount of abdomen deflection in fitting of the lap belt on the abdomen at the lower measurement part was increased by approximately 3.4 times compared with fitting of the lap belt on the iliac spine properly. Additionally, abdomen deflection velocity was increased by approximately 2.3 times. The above results showed that, when the lap belt was fitted on the abdomen, the characteristic value of abdominal injuries increased. This confirms the uttermost importance of properly routing the lap belt on the iliac spine in order to restrain the occupants properly.

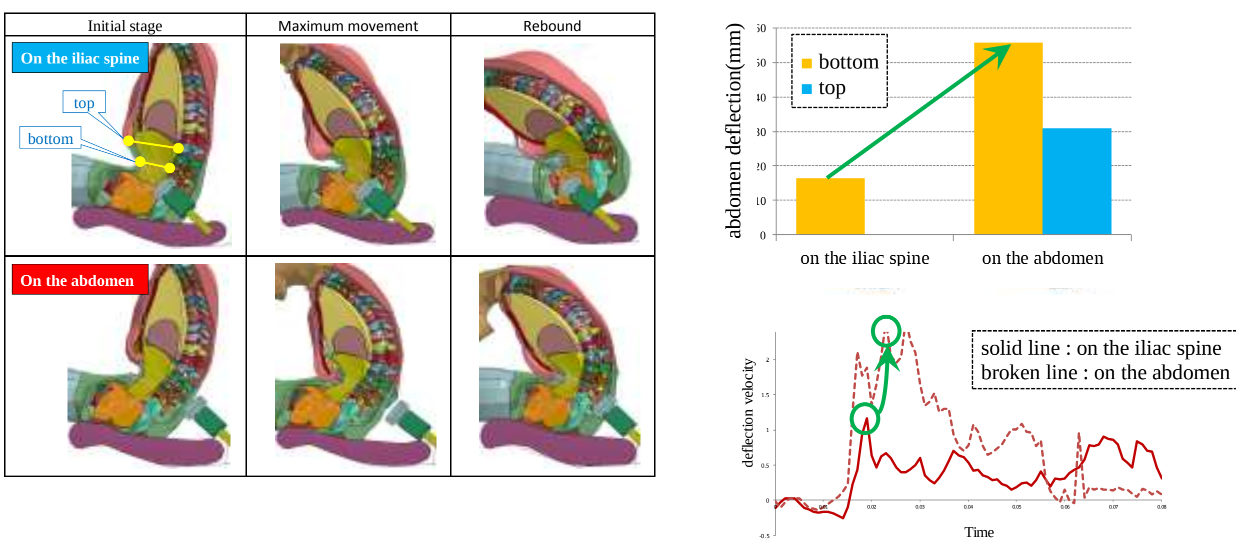



***Figure3. Vertical section views of fitting the lap belt on the iliac spine properly or the abdomen (Figure 3a), maximum amount of abdomen deflection (Figure 3b), time change of deflection velocity (Figure 3c).***

**Parameter Study of the Anti-Submarining phenomenon**

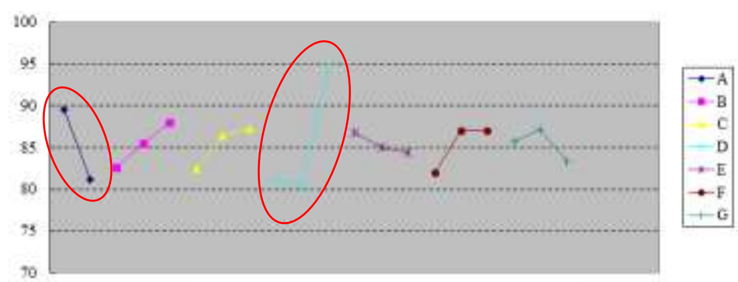
The above analysis of abdominal injuries showed that the submarining phenomenon may cause a significant load to the abdomen and it was also confirmed, by simulation, the importance of fitting the lap belt on the iliac spine. Therefore, it is essential to improve the anti-submarining performance as much as possible.

At the beginning of the study, the factors impacting the lap belt angle $\theta_B$ and the iliac perpendicular angle $\theta_P$ were selected as shown in Table 1 - seat belt specification, inner anchor point, seat cushion characteristic and front seat position. In addition, the levels were set in realistic range applied to actual vehicle and provided in regulation. Hybrid III 5%ile female dummy model was used as this was considered to be worst case for the submarining phenomenon because of its small pelvis. The initial sitting position and posture were neutral and the lap belt was fitted on the iliac spine.

Figure 4 shows the contribution degree to BTP of each factor listed in Table 1. All factors had some contribution degree to BTP, and it was confirmed to reduce the submarining phenomenon by proper parameter settings. In particular, it was determined that the contribution degree of the inner anchor point (longitudinal) and the seat cushion characteristic were particularly large.

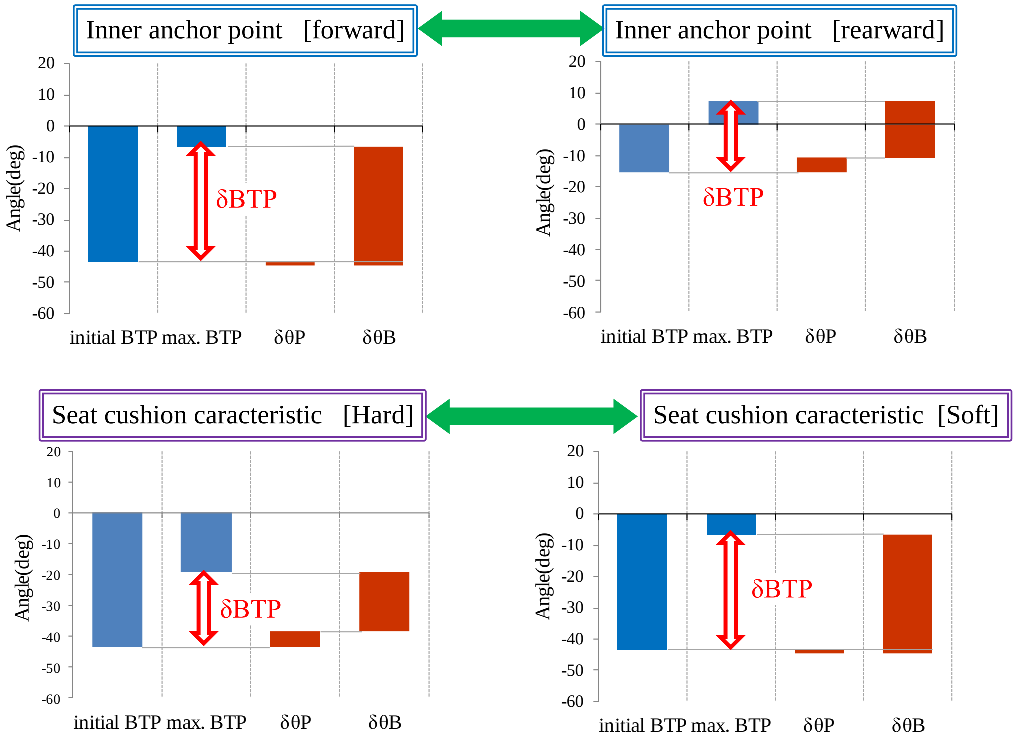
**Table1.**
**Factor and Level**

| | | factor | level 1 | level 2 | level 3 |
|---|---|---|---|---|---|
| Seat Resistance force | A | Seat cushion caracteristic | Soft | Hard | |
| Torso internal force | B | Shoulder Force limiter | low | middle | high |
| Femur Internal force | C | Front seat position | front | middle | rear |
| Lap belt force | D | Inner anchor point (longitudinal) | forward | middle | rearward |
| | E | Inner anchor point (crosswise) | inner | middle | outer |
| | F | Inner length | short | middle | long |
| | G | Lap force limiter | | low | high |



***Figur4. Cause and effect diagram***

Figure 5 shows the amount of BTP change (δBTP) during the crash event by changing the parameters of these two main factors. This shows that higher anti-submarining performance is achieved by following two items: ensure the initial relative angle by the front configuration of the inner anchor point, and reduce the relative angle change by the effect of the seat cushion caracteristic controlling the forward and downward pelvis displacement. In addition, the amount of BTP change (δBTP) was provided as the difference between the iliac perpendicular angle change ($\delta\theta_P$) and the lap belt angle change ($\delta\theta_B$); however, the change of $\delta\theta_P$ was small and the change in $\delta\theta_B$ was big. This confirmed that, in order to prevent the submarining phenomenon, the forward configuration of the inner anchor point, to make the initial BTP smaller, and moreso the pelvis restraint to reduce the forward and downward displacement during crash event were important.




***Figur5. BTP change (δBTP) by changing the parameters of the inner anchor point (forward / rearward) and the seat cushion characteristic (Hard /Soft)***

## DISCUSSION

The accident analysis indicated that 65% of the injured abdominal organs were distributed in the lower abdomen such as the intestine or the mesentery. According to the simulation used FEM, it was confirmed that the lap belt positioned on the abdomen might be the cause for the large amount of deflection and deflection velocity, particularly in the lower abdomen. The conclusion, based on the above, is that it is important to hold the lap belt on the pelvis in order to reduce the load on the abdomen and prevent abdominal organs injuries. Although the combination of the anterior arrangement of inner anchor point and the measures for reducing the forward and downward movement of the pelvis described above are effective, the anterior arrangement is likely to increase the forward displacement of the pelvis by restraint performance degradation of the lap belt. Due to this, changes to the BTP should be considered but attention should be paid to the contradictory relationship with forward displacement suppression of the pelvis. However, in this analysis conditions, the effect of the initial BTP was larger than the BTP change during crash event and the most anterior arrangement, within the limit of regulation, was the optimum layout. Additionally, the decrease of pelvis restraint performance leads to the increase of the inner belt load and may have an influence to thoracic deflection. Therefore, it is necessary to design the proper location of the inner anchor in accordance with the geometry of vehicles or the crash characteristic.

## LIMITATION

The above study of submarining phenomenon was intended for the occupant sitting in proper position and with proper posture, but there may be various sitting conditions in the real-world. Research of sitting position and posture in the rear seat of sedan and minivan was conducted using 50 subjects (age; 24-51, gender; 76% male / 24% female). The results showed that the hip of 46% subjects were positioned in excess of 20mm forward compared to proper position and 15% were positioned in excess of 60mm. Because it is thought that when the pelvis is positioned forward, the lap belt will usually be fitted on the abdomen, it is important not only to sit down in a posture which easily fits the lap belt on the pelvis as much as possible, but also to promote education for understanding the importance of the correct use of seat belts.

As mentioned during the results of the accident analysis, the pelvic fractures are due to contact with the hard interior or unbalanced load by the vehicle behavior. However, the investigation of McCalden et al. [11] indicate that the breaking strain of the femur cortical bone decreases with age. Since the similar reduction can be considered against the pelvis, it is necessary to control of the seat belt force in consideration of elderly.

## CONCLUSIONS

The investigation into abdominal injuries due to the submarining phenomenon and the mesurements from this study were carried out with the aim to further improve the protection performance of the rear seat occupant. The findings of this study show that:

1. Accident analysis indicated that 65% of the injured abdominal organs were distributed in the lower abdomen such as the intestine or the mesentery.

2. Simulation using human finite element model found that fitting the lap belt on the abdomen might cause the abdominal injuries as the maximum amount of abdomen deflection was increased by approximately 3.4 times, and abdomen deflection velocity was increased approximately by 2.3 times relative to properly fitting the lap belt on the iliac spine. This confirmed that it is very important to route the lap belt on the pelvis in order to reduce the load on the abdomen and prevent abdominal organs injuries.

3. To prevent the submarining phenomenon, the forward configuration of the inner anchor point, to make the initial BTP smaller, and the countermeasure of increasing the restraint force of the pelvis to reduce the BTP change during crash event are valid.

4. The forward configuration of the inner anchor point can cause side-effects which impacts the lap belt angle during crash event or influence other injury values. Therefore, when designing the layout of the inner anchor point, the confirmation and the optimization based on the geometry and the crash characteristic of the target vehicle should be considered. And, in case of applying countermeasures to increase the restraint force of the pelvis, it is necessary to consider the pelvic tolerance of vulnerable population, such as elderly.

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