

THE GEOMETRICAL RELATIONSHIP BETWEEN THE LAP BELT AND OCCUPANTS' ANTERIOR SUPERIOR ILIAC SPINE

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ABSTRACT

The restraint of the pelvis by the lap belt is a prerequisite for occupant protection in a 3-point seatbelt system. If the lap belt slips over the anterior superior iliac spine (ASIS), the lap belt can penetrate the abdominal area during impact, leading to abdominal injuries. Many studies of this phenomenon (known as submarining) have focused on cases in which the lap belt is initially positioned correctly, but slips off due to the dynamics of impact. However, lap belt riding over the iliac bone can also occur when the lap belt is placed on the abdomen from the beginning, without overlapping the iliac crest. In this research, the relationship of the lap belt to the ASIS of seated occupants was investigated, first by statically measuring the initial lap belt-ASIS overlap in a group of volunteers and then by using FE analysis to assess the dynamic interaction of the lap belt with ASIS during test-sled crash simulations.

The lap belt-ASIS overlap of ten volunteers was measured as they sat in a small car's rear seat (where the lap belt anchor is further back). The lap belt did not overlap with the ASIS for four volunteers: of these, three had a body mass index (BMI) of less than average (that is, $<24.1 \text{ kg/m}^2$). Further measurements of 20 male volunteers sitting in a rigid seat were conducted to examine the factors which affect the lap belt-ASIS overlap. When volunteers sat in an upright posture, the overlap increased as the height of the ASIS relative to the thigh increased. When they sat in a slouching posture, for low-BMI volunteers the lap belt was located higher on the (flat) abdomen and the overlap of the lap belt with the ASIS tended to decrease.

FE analysis was carried out for rear seat occupants whose ASIS was located at the torso-thigh junction. For the occupant with a protruding abdomen, even though the lap belt did not initially overlap the ASIS, during impact the lap belt was pulled rearward and down; there was sufficient time for the lap belt to interact with the ASIS. However, for the occupant with a flat abdomen, since the abdomen fore-aft diameter and the flesh thickness on the ASIS was small, there was not enough time for the lap belt to interact with the ASIS even though the lap belt was pulled downward, and the lap belt penetrated into the abdomen. Thus, for low-BMI occupants in the rear seat both the initial lap belt-ASIS overlap and the dynamic interaction of the lap belt with the ASIS during vehicle deceleration tend to be insufficient for effective restraint of the pelvis.

INTRODUCTION

The lap belt's ability to restrain the pelvis is a key factor in protecting car occupants during a head-on impact. The lap belt should remain on the forward edge of the iliac wing, and the anterior superior iliac spine (ASIS) works as a hook. When the lap belt slips off the ASIS, the lap belt can translate to the abdomen (a phenomenon known as

submarining) and cause serious injuries. Many studies have investigated the mechanics and parameters which cause submarining [1-5]. During impact, the pelvis rotates rearward because of the inertial force of the lower extremities; if the tangential force of the lap belt along the forward edge of the iliac wing is larger than the maximum friction force, the lap belt slips off the ASIS [1,2]. Thus the angle of the lap belt relative to the pelvis is a criterion for predicting submarining [2]. The submarining occurrence factors and countermeasures for preventing submarining are listed by Östling et al. [5] as: 1. the initial position of the occupant (e.g., slouched or reclined); 2. the relative position of the lap belt and the occupant (e.g., fore/aft position of the lap belt anchorages); 3. restraint system conditions (levels of initial slack in belt and pre-tensioning); 4. seat pan design, geometry and stiffness; and 5. leg/knee support.

Many studies focused on the submarining that occurs when the lap belt initially interacts with the iliac bone, but slips off the ASIS and rides over the iliac crest during impact. However, the lap belt riding over the iliac crest can also occur if the lap belt is poorly positioned initially. The placing of the lap belt on the pelvis depends on lap belt geometry, occupant posture and seatbelt slack [3]. In addition, it has been pointed out that occupants should be careful to wear the lap belt correctly on the pelvis [3].

It is believed that, in general, the lap belt overlaps with the ASIS of occupants when they fasten their seatbelt carefully and correctly. In crash tests with the commonly used Hybrid III dummy, the ASIS is higher than the torso-thigh junction in the initial sitting posture, and the lap belt usually overlaps the ASIS [7]. With the standard restraint systems, the lap belt usually interacts with the Hybrid III's ASIS during impact and submarining does not occur. In offset frontal impact tests conducted by JNCAP (Japan New Car Assessment Program), the scores of the Hybrid III AF05th in the rear seat are reduced if submarining occurs, which is decided based on the drop of the ASIS load cell force. In JNCAP tests from 2010 to 2016, submarining occurred on both sides of the ASIS in one car, and on the inboard side of the ASIS in three of 99 cars.

Some studies investigated the lap belt path with respect to the human ASIS. Wells et al. [8] surveyed volunteers, reporting that lap belt-ASIS overlap was frequently insufficient. 42% of the lap belt centerline was above the ASIS, and 89% partly overlap the ASIS. Reed et al. [9] measured the lap belt position with respect to the ASIS of volunteers. In obese occupants, the lap belt was further away (in the anterosuperior directions) from the ASIS. Another study reported that the lap belt was positioned lower relative to the ASIS in the Hybrid III AM50th and AF05th dummies than in volunteers [10]. Hence, crash tests using the Hybrid III dummies are likely to overestimate the effectiveness of the lap belt at preventing submarining in humans; the lap belt layout may not be adequately assessed in these tests.

The lap belt's interaction with the ASIS has been investigated for obese occupants. In accident analysis, no clear tendency was observed for the frequency of abdominal injuries caused by the lap belt to increase with BMI [11]. Using cadavers to test for comparisons between obese and non-obese occupants, Kent et al. [12] showed that the forward displacement of the pelvis of the obese occupant was greater before the lap belt interacted with the ASIS. Using accident data, Hartka et al. [13] surveyed the location of subcutaneous injuries caused by the lap belt to front-seat occupants in vehicle frontal collisions. They examined computed tomography scans of the abdomen for evidence of the radiographic seatbelt sign. As BMI increased, the anterior displacement of the radiographic seatbelt sign relative to the ASIS increased, whereas the superior displacement decreased. They postulated that the lap belt applied rearward and downward force to the obese occupant (toward the anchor), and that the lap belt interacted with the ASIS during impact, even though the lap belt did not initially overlap the ASIS. Although many research studies focused on occupants of standard-size and obese, there is a little research which examined the pelvis restraint by a lap belt for thin occupants. Izumiya et al. [6] investigated pelvis locations using X-ray image for 85 volunteers in standing and seated postures, and found that low-BMI occupants tend to have kyphosis of the lumbar spine along with the rear-inclined pelvis. They also conducted an FE analysis of a low-BMI occupant model with the pelvis in an initially reclined posture in a rear seat. The pelvis rotated rearward during impact and the lap belt slipped off the ASIS, although they initially interacted.

In this research, the interaction between the lap belt and the ASIS was investigated based on volunteers' measurements (statically) and finite element (FE) simulations (dynamically). We focused on rear seat occupants for two reasons. One is that once the lap belt has slipped off the ASIS, severe submarining can occur because the knees

are not stopped by the instrument panel, as they would be in the front seat. The second reason is that the lap belt-ASIS overlap may be inadequate since the lap belt anchors in the rear seat tend to be very far back, creating a shallow lap belt angle. In this research, the actual situation was first investigated by measuring the lap belt-ASIS overlap of ten male volunteers seated in the rear seat of a small car. Next, to understand the factors which affect the overlap, 20 volunteers sat in a simple rigid seat, and the relationship between anthropometry and lap belt-ASIS overlap was examined. Finally, a human FE model was used to examine the dynamic interaction of the lap belt with the ASIS. The research and the procedure for obtaining the anthropometric measurements of volunteers were both approved by the ethics committee of the School of Engineering, Nagoya University (Document Number 18-1).

THE LAP BELT-ASIS OVERLAP FOR OCCUPANTS OF A SMALL CAR

The geometrical relationships between the lap belt and the ASIS were measured for ten volunteers (Table 1) and two human surrogates, Hybrid III and THOR. The volunteers wore a thin, full bodysuit and sat on the rear seat of a small car. They were directed to sit and place the shoulder belt and lap belt by themselves as usual. The volunteers' ASIS coordinates were measured with a FaroArm coordinate measuring machine. The lap belt's upper and lower edges were also measured along its path. The ASIS location was identified by a medical doctor. The ASIS position was expressed by its projection onto the lap belt: the ASIS point was extended in the vehicle-forward direction until it intersected with the lap belt.

Figure 1 shows the sitting posture of Volunteers 1, 4, and 10, THOR, and Hybrid III. Note that the volunteers were arranged in ascending order of body mass index (BMI). The bottom edge of the lap belt is fitted around the torso-thigh junction at the ASIS for Volunteers 1 and 4 (Figure 1(a) & (b)). The ASIS is above the top edge of the lap belt for Volunteer 1 and Hybrid III. However, for Volunteer 10, who has a high BMI (30.6 kg/m²), the top edge of the lap belt is fitted around the torso-thigh junction at the ASIS, and the lap belt was fitted in front of the ASIS, as shown in Figure 1(c). This lap belt path is similar to THOR's (Figure 1(d)).

Figure 2 shows the distance of the right and the left ASIS from the bottom edge of the lap belt of inboard (buckle) and outboard side in the rear seat. The ASISs of four volunteers (Nos. 3, 4, 5, and 8) were below the lap belt's bottom edge (poor lap belt fit, which would lead to submarining in the event of a crash); three of them, Volunteers 3–5, had BMIs of less than 23.6 kg/m². In the sitting posture in the rear seat, the ASISs of Volunteers No. 3, 4, 5, 8, and 9 and the dummy THOR were positioned on the torso-thigh junction. However, for THOR half of the lap belt overlapped with the ASIS because the lap belt was placed forward, due to the protruding abdomen. In contrast, the pelvic height was high enough that the ASIS was above the torso-thigh junction for the other volunteers (Nos. 1, 6, and 7) and Hybrid III; as a result, more than two-thirds of the lap belt overlapped with the ASIS. The height of the ASIS relative to the torso-thigh junction is probably an important parameter to determine the lap belt-ASIS overlap.

Table 1. Volunteer height and weight sat in the rear seat of small car

No.	Height (cm)	Weight (kg)	BMI (kg/m ²)	Age
1	172	60	20.3	23
2	174	64	21.1	28
3	176	72	23.2	25
4	171	68	23.3	24
5	177	74	23.6	65
6	163	63	23.7	35
7	174	73	24.1	27
8	177	79	25.2	33
9	173	80	26.7	36
10	179	98	30.6	42
Ave.	173.6	73.1	24.1	33.8

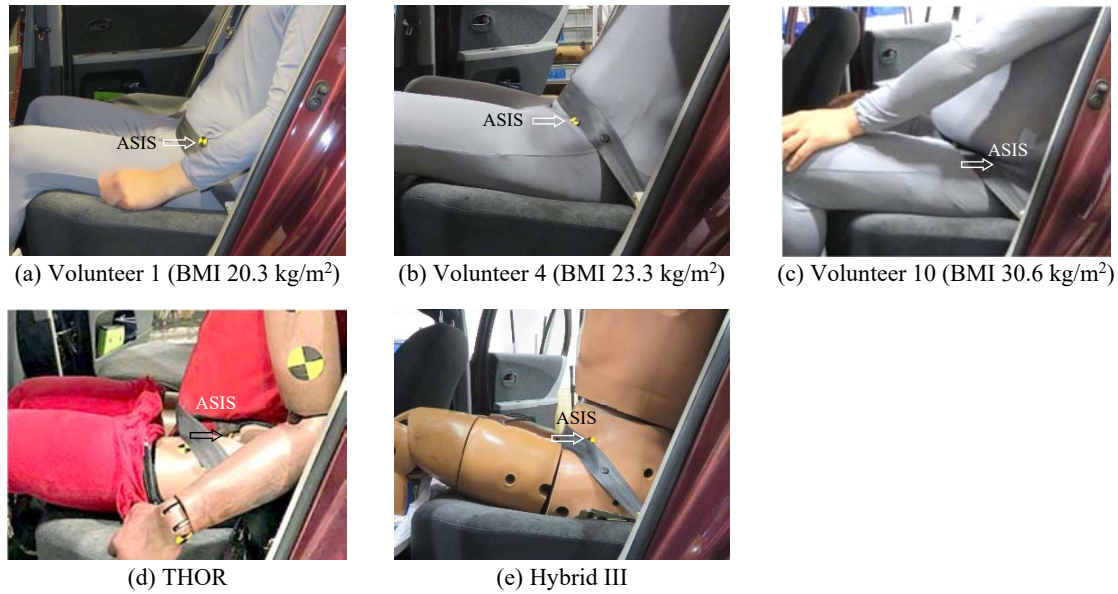


Figure 1. The lap belt and ASIS locations in volunteers, THOR and Hybrid III in the rear seat of a small car.

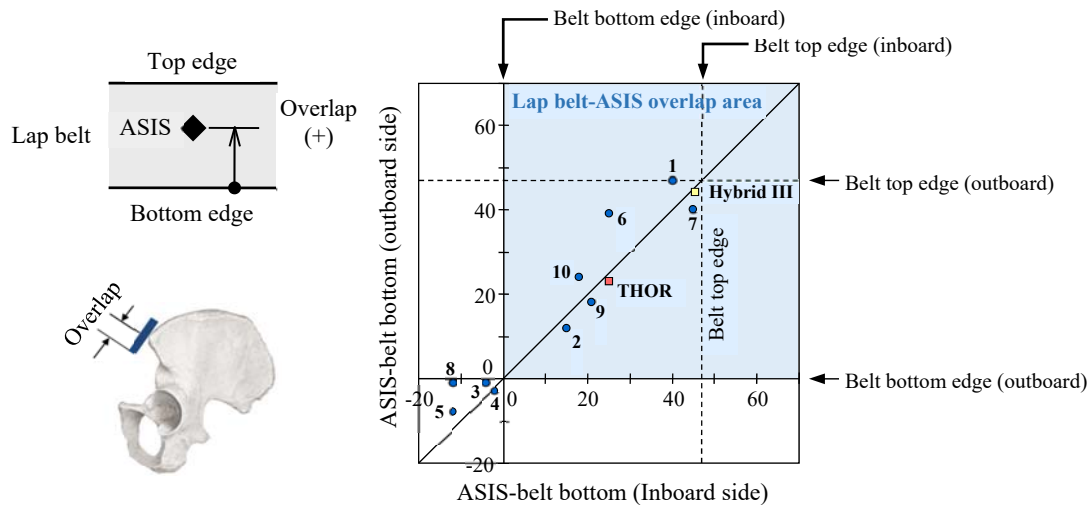


Figure 2. The distance of the ASIS from the bottom edge of the lap belt of inboard (buckle) and outboard side in the rear seat. The blue circles represent the volunteers (numbered w.r.t. BMI) and the squares the test dummies.

FACTORS AFFECTING LAP BELT-ASIS OVERLAP OF OCCUPANTS

A simple rigid seat was used to examine basic factors which affect the lap belt-ASIS overlap. The seat's width, depth, and height was 400 mm, 500 mm, and 550 mm, respectively. Twenty male volunteers sat in an upright posture placing a 3-point seatbelt by themselves (Figure 3). In addition, they also sat in slouching posture so that the pelvis was moved forward by 100 mm. Their BMIs ranged from 17.6 to 32.1 kg/m² (average 24.2). The relative positions of thigh, ASIS, and lap belt were measured by a FaroArm coordinate measuring machine. For three of the volunteers (Volunteer 2, 13 & 20), additional measurements were conducted: body outer shape was measured by a 3D LED scanner (Artec Eva), and all measurements were repeated after both lap belt anchors were moved forward by 100 mm from the standard anchor positions.

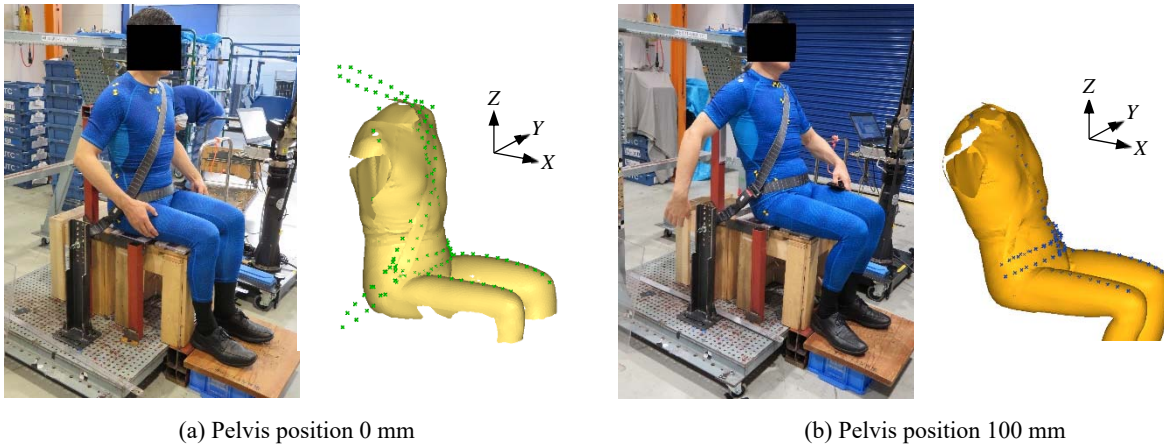


Figure 3. Measurements of volunteer in a rigid seat. From the origin of the seat (center of cross line of seat and seat back), the coordinates of the outer and inner belt anchors were $x=21$ mm, $y=284$ mm, and $z=-50$ mm and $x=-46$ mm, $y=-274$ mm, and $z=-23$ mm, respectively. 3-dimensional shape was made by 3D scanner, and points were measured by coordinate measuring machine.

Anthropometry

The lap belt path depends on the anthropometry of the occupant. The anthropometric parameters abdomen fore-aft diameter, ASIS position, and thigh height were examined based on BMI (see Figure 4). Thigh height was measured at the torso-thigh junction in the sagittal plane of the ASIS. Accordingly, the ASIS height relative to the thigh indicates the protrusion of the ASIS from the torso-thigh junction.

Figure 5 graphs the abdomen fore-aft diameter against the BMI for all volunteers. Each circle in the figure corresponds to a volunteer (as before, numbered in order of ascending BMI). The fore-aft diameter of the abdomen increases as BMI increases. The heights of the left and right thighs also increase with BMI for both pelvis positions (Figure 6). However, the correlation of thigh height with BMI is lower for the 100-mm forward pelvis position than for the original position. Figure 7 shows the ASIS height plotted against the BMI. The ASIS heights do not depend significantly on the BMI. Comparing Figure 7(a) to (c) and Figure 7(b) to (d) makes it clear that the ASIS heights do not change significantly, even though the pelvis posture angle changes when the pelvis moves forward 100 mm. As shown in Figure 8, the ASIS height relative to the thigh decreases with an increase in BMI, because thigh height increases with BMI whereas the ASIS height has little relation to BMI. This correlation exists for both pelvis positions (0 mm and 100 mm).

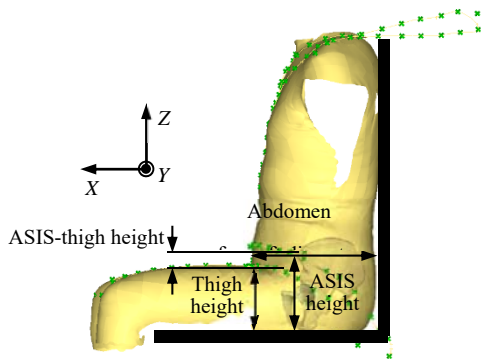


Figure 4. Anthropometric measurements

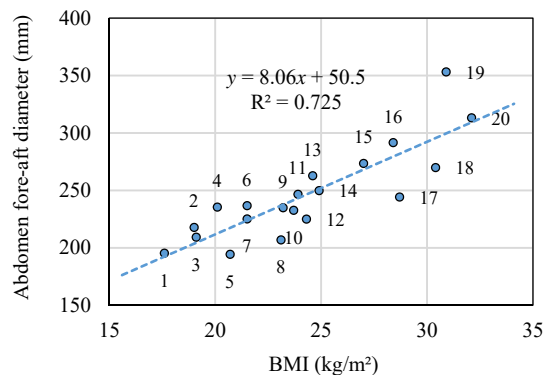


Figure 5. Abdomen fore-aft diameter vs. BMI. The blue circles are volunteers, numbered by increasing BMI.

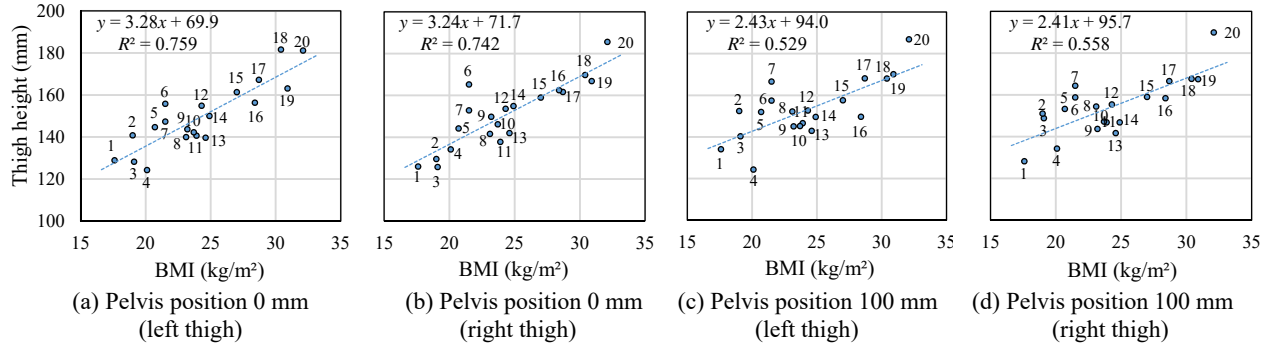


Figure 6. Left and right thigh height vs. BMI

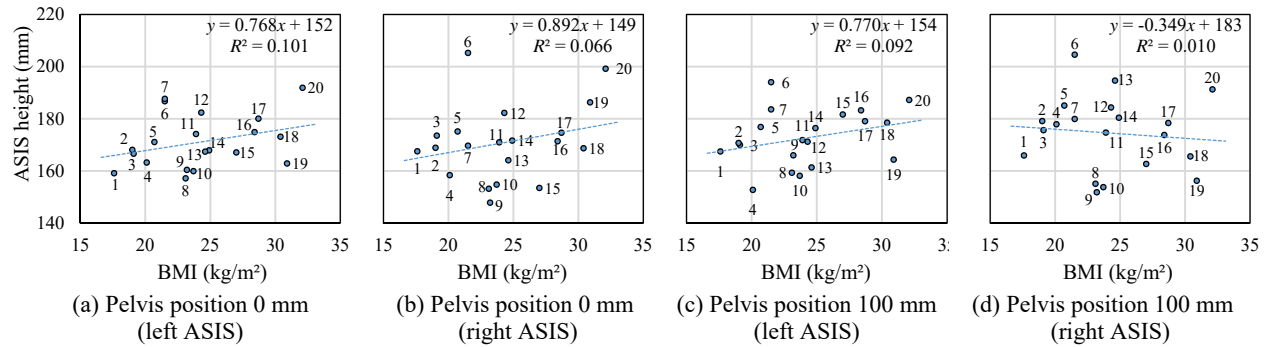


Figure 7. Left and right ASIS height vs. BMI

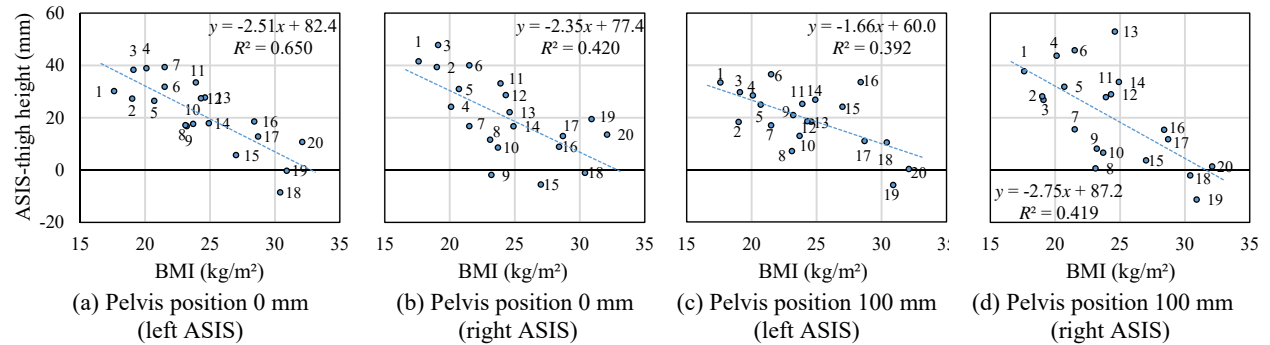


Figure 8. Left and right ASIS height relative to thigh vs. BMI

Lap Belt Path

The surface shape of the 3D body image was developed and modified using Artec Studio 10 Professional and Geo Magic Design X software from a scan of Volunteer 2, 9 and 19. Shell elements were generated on the surface of the body surface in automatic meshing by Altair Hyper Mesh. The shell elements and seat belt elements of the lap belt were made to fit on the shell elements of body surface using a seatbelt fitting interface in LS-PrePost. The shell elements were used in the area where the lap belt fitted the body in curved surface. Five lap belt paths (P1–5) were made with different belt path heights while inboard and outboard anchor points were fixed. Each path was raised by 20 mm in the midsagittal plane: P3 is made to follow the actual lap belt path. P1 and P2 are below—and P4 and P5 are above—the actual path (Figure 9). The distance (error) between the centerlines of the lap belt elements and of the actual lap belt in the same sagittal plane (xz -plane) was calculated. Lap belt length was compared for all five paths in the standard upright position, the slouched position, and the slouched position with both belt anchors moved forward.

Figure 10 shows the average distance between the lap belt fitted on the body surface and the actual lap belt path of Volunteer 2. For the pelvis position 0 mm and the anchor position 0 mm (Figure 10(a)), the farther each path is from the actual, the longer it becomes. That is, P3 is the shortest and the others are all longer. Wearing the lap belt in the shortest path was also true for Volunteer 9 and 19, therefore, many occupants probably fit their lap belt with the shortest total lap belt length, since the actual path was taken from volunteers' freely chosen belt path. However, when the pelvis is positioned 100 mm forward (Figure 10(b)), the total belt lengths for P2, P3, and P4 are comparable, and the lap belt paths are probably unstable. The belts in P3 could slide up to the P4 path on the abdomen. In the forward anchor position with pelvis forward, P2 is shorter than P4, so in the former the lap belt will not be able to slide up to the abdomen, but will remain on the thigh (Figure 10(c)).

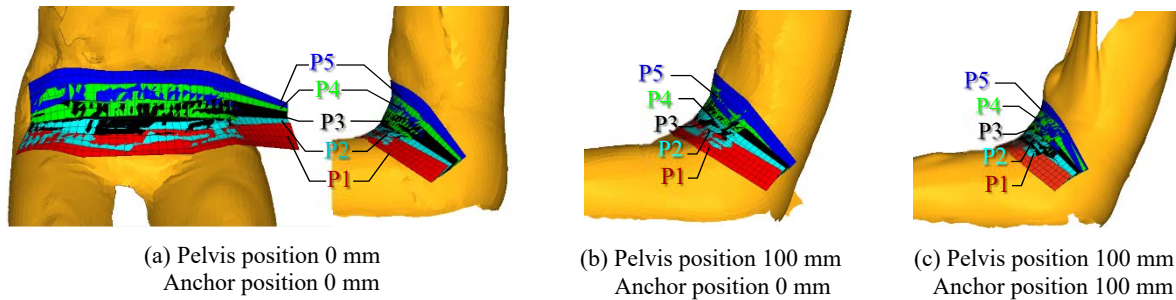


Figure 9. Lap belt fitting on the body surface of Volunteer 2 with a low BMI (19.0 m/kg²)

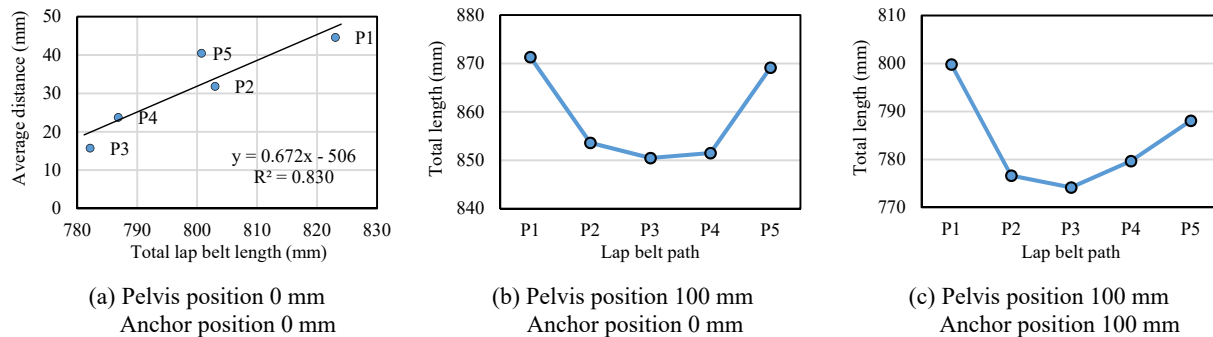


Figure 10.(a) The average distance of the five lap belt paths from the actual lap belt path (pelvis position 0 mm, anchor position 0 mm) for Volunteer 2; (b) & (c) total lap belt lengths for the five belt paths (pelvis position 100 mm and anchor position 0 mm and pelvis position 100 mm and anchor position 100 mm, respectively).

Lap Belt-ASIS Overlap

The height of the lap belt-ASIS overlap (z axis) for each of the 20 volunteers is plotted against BMI in Figure 11, and against ASIS height relative to the thigh in Figure 12. Left and right ASISs are considered separately. Figure 11(a) and (b) show that the lap belt-ASIS overlap decreases as BMI increases for the upright position (pelvis at 0 mm), although the correlation coefficient is small. (Recall that as seen in Figure 8, the ASIS height relative to the thigh decreases with BMI, which indirectly influences the overlap.) However, when the overlaps for the slouching posture are compared (Figure 11(c) & (d)), it is clear that the lap belt-ASIS overlap increases as BMI increases. As shown in Figure 11, the slope of the approximation line of lap belt-ASIS overlap vs. BMI changes from negative to positive when the pelvis is 100 mm more forward, although the correlation coefficient is small. Figure 12(a) and (b) show that, in the upright posture (pelvis position 0 mm), the lap belt-ASIS overlap is proportional to the ASIS height

relative to the thigh. This relation is probably due to the fact that the lower edge of the lap belt is located at the torso-thigh junction. However, for the slouched posture (Figures 12(c) & (d)), there does not appear to be a correlation between the two variables. These results suggest that there is a tendency for the lap belt-ASIS overlap to be sufficient in the upright posture for low-BMI occupants and decrease in the slouching posture. Whereas for high-BMI occupants, the overlap is stable, irrespective of torso angle.

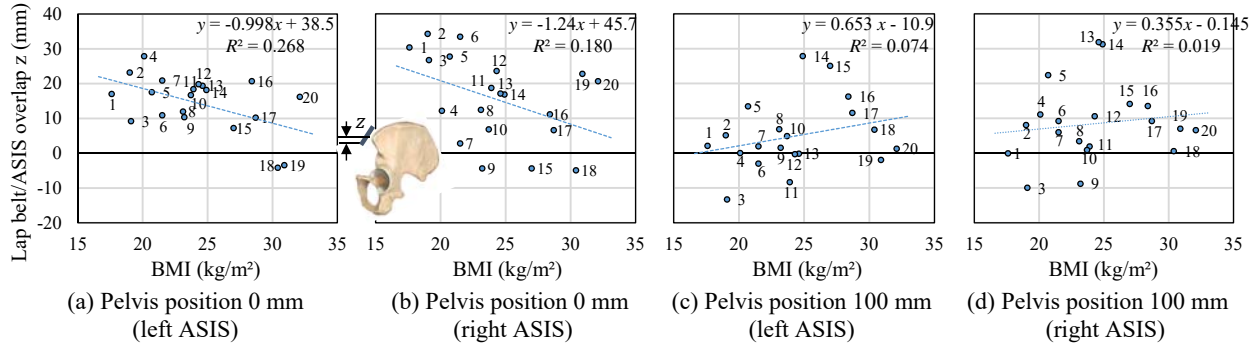


Figure 11. Lap belt-ASIS overlap height (z) vs. BMI

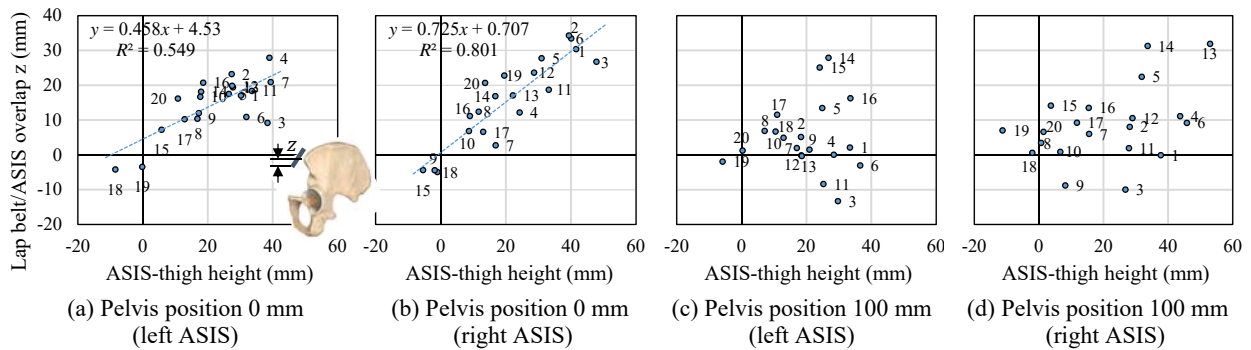


Figure 12. Lap belt-ASIS overlap height (z) vs. ASIS-thigh height

The photographs in Figure 13 show the lap belt paths of Volunteer 1 (low BMI, 17.6 kg/m²) and Volunteer 19 (high BMI, 30.6 kg/m²) for both pelvis positions. In the slouching position, Volunteer 1's lap belt shifted upward onto the flat abdomen, but Volunteer 19's lap belt remained in position under the abdomen. Figure 14 shows the height differences in the lap belt bottom edge for all volunteers in both pelvis positions: the difference is larger for lower-BMI volunteers. All volunteers placed the lap belt around their lower abdomen in the upright posture. However, the low-BMI occupants' belts shifted upward when they slouched. This upward shift probably explains why the lap belt-ASIS overlaps decreased (Figure 11(c) & (d)).

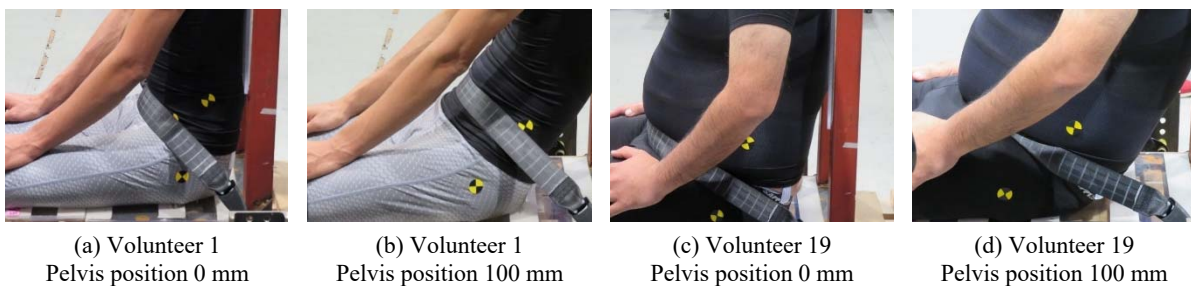


Figure 13. Lap belt path in pelvis position of 0 and 100 mm for thin volunteer and obese volunteer

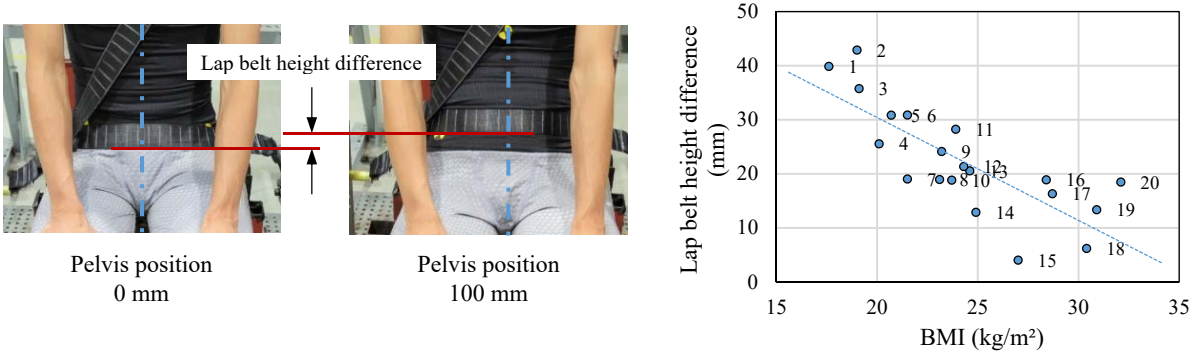


Figure 14. Height differences in lap belt bottom edge from pelvis position of 0 to 100 mm (Volunteer 1)

FE ANALYSIS

The lap belt-ASIS interaction during impact, for occupants with the ASIS locating above and at the torso-thigh junction, was investigated by FE analysis. The model, representing an occupant in the rear seat, consists of a seat, 3-point seatbelt and occupant (Figure 15). THUMS (Total Human Model for Safety) version 3 was used for the human FE model. The friction coefficient between the lap belt and the occupant affects the slip of lap belt on the occupant, and it was 0.3 in this simulation. The crash pulse in the sled was selected to mimic the acceleration of a small car in a full-frontal impact test at a velocity of 50 km/h. Table 2 presents the simulation matrix.

To examine the influence of body habitus on the lap belt's interaction with the ASIS, three different habitus were prepared; for simplicity, only thigh diameter and abdominal shape were modified. Five models were created: Models 1–3 differed in habitus, and Models 4 and 5 used the third habitus and made changes to the lap belt. The ASIS of Model 1 (the original THUMS) when seated was higher by 3 mm (measured vertically, along the z axis) than the torso-thigh junction. Model 2 was the habitus with the ASIS at the torso-thigh junction. To achieve the correct dimensions, the upper thigh diameter was made 20 mm larger than that of Model 1. The ASIS was lower than the bottom edge of the lap belt by 9 mm in the vertical direction (z). In Model 3, which represents an occupant with a flat abdomen, the fore-aft diameter of the torso was reduced to 232 mm from Models 1 and 2 (256 mm). Because it is known that the forward location of the lap belt anchor is effective for improving the lap belt's interaction with the ASIS—preventing submarining [1,2,5]—the seatbelt system was changed in Models 4 and 5. In Model 4, the two anchors were moved forward by 100 mm. In Model 5, a pretensioner model was also attached at each anchor, and the lap belt was pulled toward the lap belt direction by 25 mm at 12 ms in Model 5.

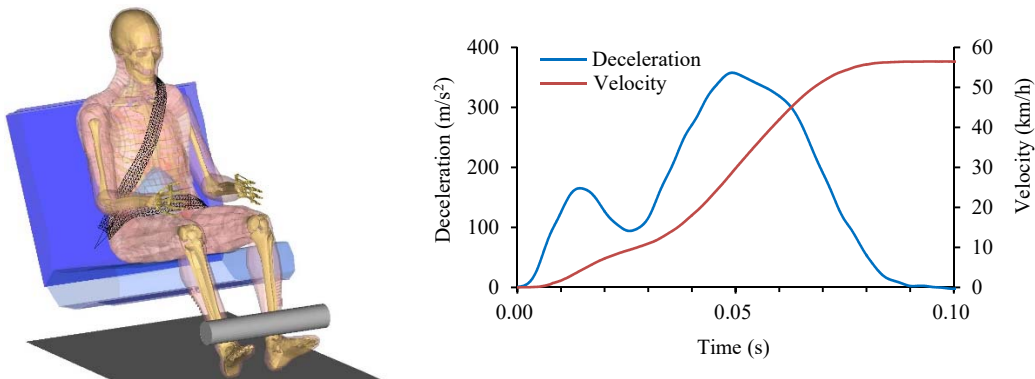
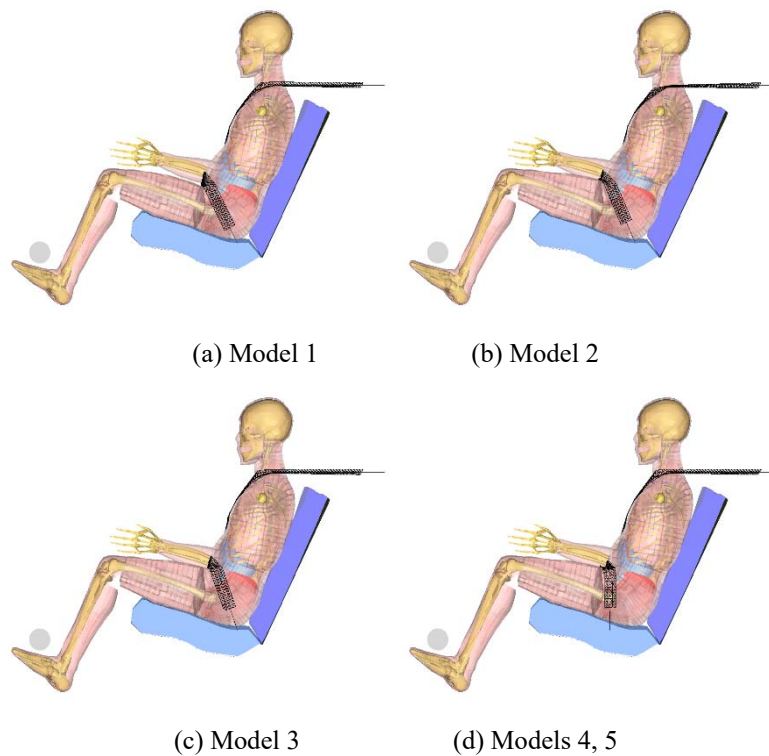


Figure 15. Rear seat occupant model (left), and acceleration pulse and velocity change simulating impact velocity of 50 km/h (right)

Table 2. FE occupant model

Model	Human model	Lap belt anchor	ASIS height w.r.t. lap belt bottom (Δz)
Model 1	Original THUMS (protruding abdomen)	Original	3 mm
Model 2	Large diameter thigh, Protruding abdomen	Original	-9 mm
Model 3	Large diameter thigh, Flat abdomen	Original	-12 mm
Model 4	Large diameter thigh, Flat abdomen	Lap belt anchor 100 mm forward	-14 mm
Model 5	Large diameter thigh, Flat abdomen	Lap belt anchor 100 mm forward Buckle and lap belt pretensioners	-14 mm

**Figure 16. Occupant models**

The lap belt-ASIS interaction for the five FE models at 75 ms after impact is shown in Figure 17. The lap belt interacted with the ASIS in the original THUMS (Model 1). Even in Model 2, whose ASIS is located at the torso-thigh junction, the middle of the lap belt in the webbing width direction interacted with the ASIS (Figure 17(b)). Although the overlap was less than in Model 1 (in fact, the lap belt did not overlap with the Model 2's ASIS in the initial condition), during the impact the lap belt interacted with the ASIS. The lap belt, pulled down and rearward, stayed on the lower abdomen while the pelvis moved downward in the seat cushion. On the other hand, in Model 3, with a flatter abdomen (the lap belt was closer to the ASIS), even though the lap belt pulled downward during impact, the lap belt rode over the iliac crest because the thickness of flesh tissue on the ASIS was small: the lap belt was positioned above the ASIS initially and there was not enough time for the lap belt to interact with the ASIS during impact. Notably, the lap belt applied force to the abdomen and the lumbar spine flexed due to the concentrated force of the lap belt.

In Model 4, the lap belt anchors were positioned 100 mm forward compared to previous models. The lap belt applied force to the pelvis in a steep downward angle, interacting with the ASIS. In Model 5, the pretensioned lap belt interacted with the pelvis earlier (in the initial phase of deceleration) and reduced the pelvis' forward displacement, compared to Model 4. The pelvis' rearward posture angle was smaller and the lap belt angle steeper for Models 4 and 5 compared to Models 1 and 2, which indicates that the lap belt with anchor in the forward position is stable to interact with the ASIS compared to the standard anchor position [2].

The forward displacement of pelvis (sacrum) for the five models is shown in Figure 18. That of Model 1 is the smallest (199 mm). The pelvis forward displacement is large for Model 3 (260 mm) since the lap belt did not interact with the pelvis at all. In Model 4, the pelvis forward displacement is also large (263 mm) because the lap belt and buckle anchors were positioned more forward. The lap belt angle is steeper and the force component of the lap belt in the rearward direction is too small to decelerate the pelvis effectively. The forward displacement of the pelvis was reduced to 237 mm by the pretensioners in Model 5.

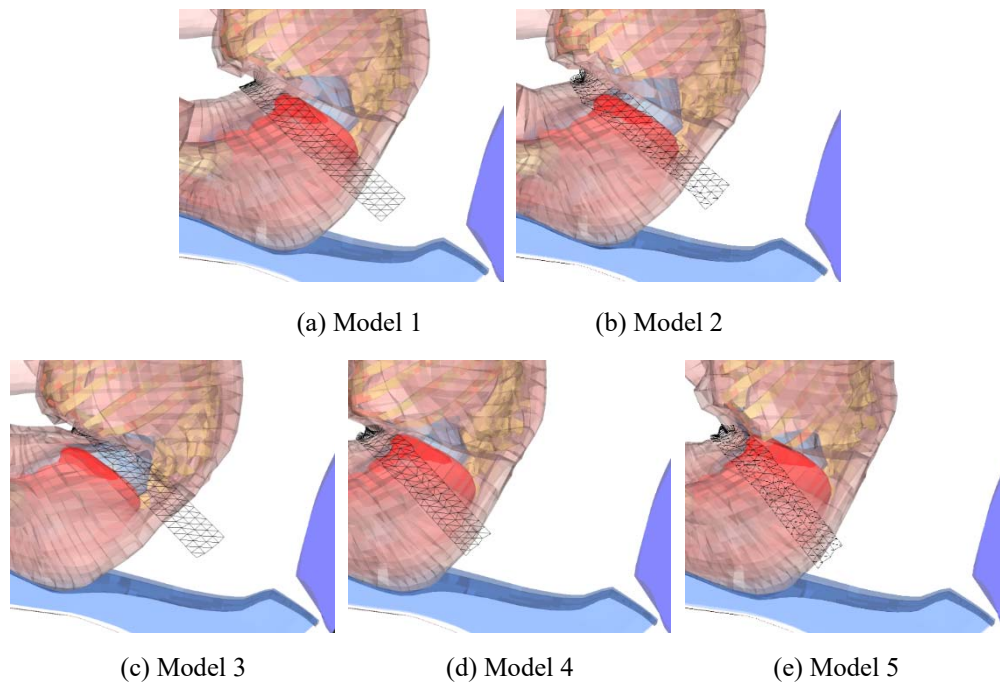


Figure 17. Lap belt interaction with the ASIS (75 ms)

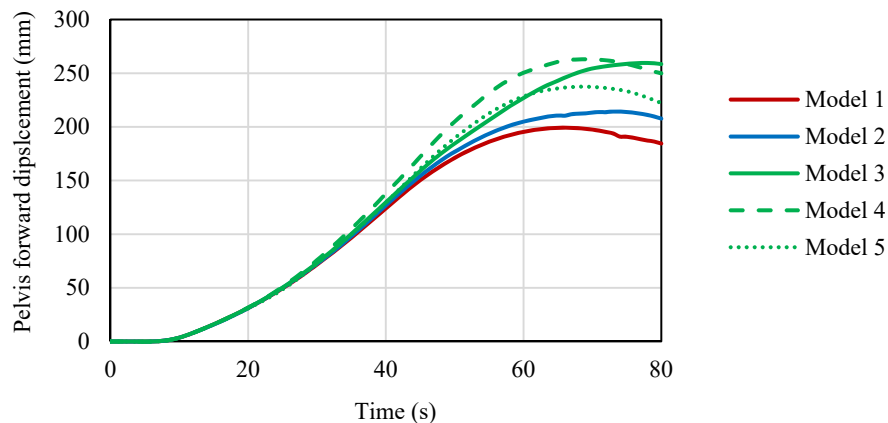


Figure 18. Pelvis forward displacement of FE models

DISCUSSION

In this study, the lap belt-ASIS overlap was examined for ten volunteers sitting in the rear seat of a small car and on a rigid seat. The overlap was relatively small for four out of ten occupants. The overlap tended to be large for low-BMI volunteers in the upright posture, while it decreased in the slouching posture (forward pelvis position). Several volunteers participated in both the rear-seat and the rigid-seat measurements. Figure 19 compares a volunteer (BMI 23.2 kg/m²) seated in the rear seat of a small car and in the rigid seat. In the 100-mm pelvis forward position in the rigid seat, the pelvis inclines rearward under the lap belt because of the slouched torso. The lap belt path when the volunteer is in the rear car seat is similar to that of the rigid seat with the pelvis forward position. This is probably why low-BMI volunteers tended to have poor lap belt-ASIS overlap both in the rear seat of a small car and in the rigid seat in the pelvis forward position. Some low-BMI occupants sit on the seat with kyphosis of the lumbar spine and the rear-inclined pelvis (Figure 19 (a) & (c)). This posture was pointed out for thin occupants by Izumiya et al. [6]. Thus it is likely that low-BMI occupants rotate their pelvis rearward under the lap belt in the rear seat, and the lap belt-ASIS overlap decreases, as was observed in this study.

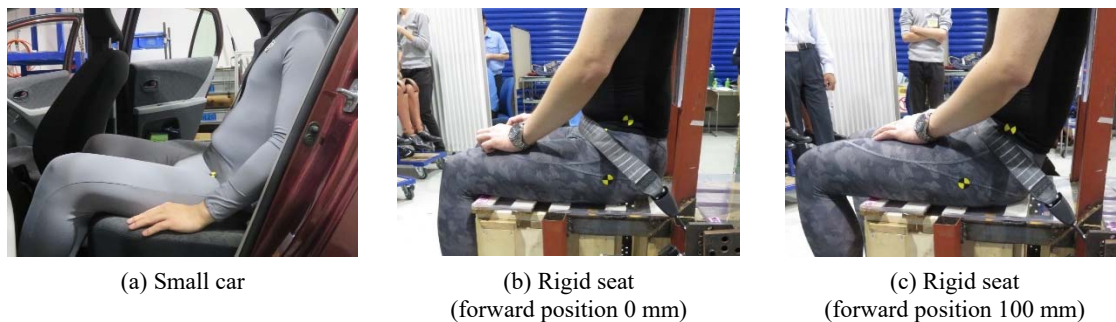


Figure 19. Volunteer 9 (BMI 23.2 kg/m²) seated in the rear seat of a small car and in the rigid seat

Based on accident analysis by Hartka et al. [13], the lap belt caught the ASIS for obese occupants in collisions, even though the lap belt overlap with the ASIS of obese occupants are poor in Reed's study [9]. Their results might be consistent with the interaction behavior of the lap belt and ASIS for the original THUMS with protruding abdomen during impact in this study: the protruding abdomen meant the lap belt was further from the ASIS, and thus took more time to move downward as the pelvis rotated, so the lap belt could interact with the ASIS. As shown in Figure 1(c), the lap belt of the THOR dummy is in front of the ASIS because of the protruding abdomen. The lap belt can interact with the ASIS during impact even though the ASIS is located at the torso-thigh junction [7]. In contrast, for the flat abdomen occupant (Model 3), since the abdomen fore-aft diameter is small and the thickness of flesh tissue on the ASIS is small, there was not enough time for the lap belt to catch the ASIS. Model 3 has a thick thigh like a sport man with strong muscle of thigh such as Volunteer 4 sitting in the rear seat (Figure 1(b)). The geometrical relation between the lap belt and the ASIS for Model 3 can be applied for low-BMI occupants with flat abdomen and the bottom of the lap belt placed above the ASIS.

The static measurement in the rigid seat showed that the lap belt can shift up to the abdomen (above the ASIS) in low-BMI occupants in the pelvis forward position, with the standard belt-anchor location (Figure 10(a) & (b)). However, the lap belt will not shift to the abdomen of low-BMI occupants if the lap belt anchor is positioned forward (see Figure 10(c)). On impact, the forward anchor position could cause the lap belt to catch the ASIS, because the lap belt pulled steeply downward during impact. Thus, the anchor-forward position provides a benefit for the lap belt-ASIS interaction. On the other hand, the pelvis displacement is large. Insufficient pelvis restraint can also increase the deflection of the lower chest on the buckle side, since the large lap belt force in the final stage of a crash is transmitted to the shoulder belt through the slit of the tongue plate [7]. In the FE analysis, the lap belt and buckle pretensioners effectively reduced the pelvis forward displacement. However, it should be noted that the forward lap belt anchor locations can worsen the accessibility of rear car seats.

In this study, low-BMI occupants tended to have small lap belt-ASIS overlap in the initial posture; further, FE analysis indicated that the lap belt did not catch the ASIS for these occupants during impact. According to Izumiya's study [6], even though the lap belt interacted the ASIS, submarining inclined to occur for low-BMI occupants because of their initial reclined posture of pelvis. Consequently, the initial overlap—and, more critically, the lap belt-ASIS interaction during impact—can be insufficient for the pelvis restraint of low-BMI occupants.

LIMITATION

The ASIS locations were identified by medical doctors. However, it is difficult to determine the correct position of ASIS because the ASIS has a rounded shape and the high BMI occupants have thick soft tissue on the ASIS. Thus, the ASIS positions can include errors in measurements. The geometry and material properties of the soft tissue of THUMS and its modified FE model were not validated to investigate the movement of the lap belt over the ASIS.

CONCLUSIONS

In this research, the bottom edge of the lap belt relative to ASIS (anterior superior iliac spine) point overlap for volunteers seated in the rear seat of a small car and in the a simple rigid seat was measured. FE analysis was also conducted for the rear seat occupant whose ASIS was located at the torso-thigh junction.

- The bottom edge of the lap belt did not overlap with the ASIS for four of ten volunteers seated in the rear seat of a small car. Three of them had BMIs lower than the volunteer average.
- When volunteers sat in an upright posture in a simple rigid seat, the overlap of the lap belt increased with the vertical height of the ASIS relative to the thigh height. For low-BMI volunteers in the slouched 100 mm forward pelvis posture, the lap belt moved up to the flat abdomen and the lap belt-ASIS overlap tended to decrease.
- FE simulations, using morphed THUMS model, of the occupant with the morphed flat abdomen and ASIS locating at the torso-thigh junction by morphed thighs showed that the lap belt did not interact with the ASIS at all during impact. For the occupant with the protruding abdomen, although the lap belt did not initially overlap with the ASIS, it did during impact since the lap belt was pulled downward and the extra distance provided by compression of the thigh tissue meant there was time for the lap belt to interact with the ASIS.

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