FE ANALYSES OF THE LAP BELT INTERACTIONS WITH THE PELVIS FOR DIVERSE OCCUPANTS IN VARIOUS SITTING POSTURES

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Paper Number 23-0092

ABSTRACT

Passengers of different body shapes and sizes such as male, female, obese, and lean can sit in a car seat assuming various postures. This study aims to understand the interaction of the lap belt with the pelvis in a vehicle frontal impact scenario for occupants of various shapes, sizes, and sitting postures.

A mid-size male Total HUman Model for Safety (THUMS) was morphed to develop a high and a low body mass index (BMI) human model using computer tomography (CT) images of sitting participants wearing a lap belt. Frontal impact finite element (FE) simulations were conducted for various occupant models (THUMS high-BMI, AM50, low-BMI, AF05, and Hybrid III AM50, AF05) under standard, reclined, and slouched sitting postures in the rear seat. The lap belt interactions with the anterior superior iliac spine (ASIS) were compared using the belt-pelvis angle and the overlap of the lap belt with the ASIS in the lap belt direction (belt-ASIS overlap).

From FE simulations, submarining occurred more in the reclined and slouched postures than in the standard posture because of the large initial rearward pelvis tilt. Submarining occurred in fewer cases in the high-BMI model due to smaller pelvis rotation and larger belt-ASIS overlap than in other models. In the THUMS AF05, even though the belt-ASIS overlap was comparable, the pelvis began to rotate earlier and rotated more than in male models. The pelvis of Hybrid III showed a small initial tilt and rotation angle, resulting in fewer submarine occurrences than human body models. Submarining occurred in more cases in the slouched posture than in the reclined posture. This is because the belt-ASIS overlap was smaller in the slouched posture due to the shallow belt angle.

In this study, a new parameter, the belt-ASIS overlap in the lap belt direction, was proposed to evaluate the belt engagement with the ASIS. The occurrence of submarining in various occupants and postures could be examined by using the lap belt-pelvis angle and the lap belt-ASIS overlap. These two parameters will be useful in designing a restraint system to interact with the pelvis in various conditions.

INTRODUCTION

A seat belt is a key element of the restraint system for occupant protection. During vehicle frontal impacts, the lap belt should engage the anterior edge of the pelvis. Submarining is defined as the lap belt slipping over the pelvis toward the abdomen and can cause serious abdominal injuries [1]. Leung [2] and Horsch [3] proposed a submarining model in which the lap belt starts to slip when the tangential force of the lap belt on the anterior edge of the pelvis exceeds the maximum friction force in the superior direction. Thus, the angle of the lap belt relative to the pelvis is a critical parameter for predicting submarining. Countermeasures for preventing submarining (e.g., occupant position, posture, lap belt anchorage position, seat belt pretensioner, and seat pan design) have been investigated in many studies [4-6].
Reed et al. [7] measured the lap belt location and surface landmark of human subjects sitting on the vehicle seat to investigate the lap belt path around the pelvis. The body mass index (BMI) had a great influence on the belt fit, and the lap belt of obese occupants was located further away from the anterior superior iliac spine (ASIS) in the

anterosuperior directions. Tanaka et al. [8] measured the lap belt fit in the upright and reclined posture using computed tomography (CT). They found that the overlap of the lap belt with the ASIS in the vertical direction depends on the thigh diameter and abdominal shape, and the belt-ASIS overlap was large for females due to a small thigh diameter. Kim et al. [9] have shown that interactions between the lap belt and the pelvis highly depend on the initial location and the initial angle of the lap belt. They demonstrated that the lap belt was likely to intrude into the abdomen when it was positioned high above the ASIS.

In the real world, occupants adopt various postures when sitting in vehicle seats. Especially for seats with limited recline angle, occupants may sit in the slouched posture, moving their hip forward from the normal posture. In future autonomous vehicles, occupants are likely to sit in extreme postures, e.g., highly reclined postures. Hence, the demand for understanding the safety of occupants in various postures is increasing. Reed et al. [10] have shown that the pelvis angle is inclined rearward when assuming a reclined posture. The PMHS tests by Uriot et al. [11] have shown that in the slouched posture, the pelvis tilts backwards and increases the risk of submarining. FE analyses have been conducted for occupants in reclined sitting postures, and the results showed that the pelvis rotated rearward with a large forward excursion, and the lap belt slid over the ASIS [12-14]. The postures of the pelvis and the lap belt fit in the reclined sitting postures are significant parameters in these simulations, but the available information for these parameters on various occupants is still not sufficient.

The purpose of this study is to understand the interaction of the lap belt with the pelvis in a frontal impact for various occupants and sitting postures. The THUMS low-BMI and high-BMI models were developed with morphing based on the CT image of participants. The FE simulations were conducted for THUMS low-BMI, AM50, high-BMI and AF05 as well as Hybrid III AM50 and AF05 seated in the standard, reclined, and slouched postures, and interaction between the lap belt and the pelvis was analyzed.

METHODS

FE Human Model Morphing

THUMS AM50 V4.01 (THUMS AM50) was selected as the baseline model. Tanaka et al. [8] measured 10 male participants wearing a lap belt and sitting upright in a rigid seat using standing CT. The CT images of two participants with BMIs of 33.4 and 17.6 were used to develop the high and low BMI models (THUMS high-BMI and THUMS low-BMI). From these CT images, the shapes of bones and soft tissues were converted to three-dimensional FE models consisting of bones and outer surfaces. The nodes of soft tissue around the pelvis of THUMS AM50 were morphed to have the same outer surface as the referenced models. In THUMS high-BMI, a deep valley shape was formed between the abdomen and the thigh based on the CT image. The soft tissues of the abdomen, the buttock, and the thigh were morphed, but the bones, internal organs, head, upper extremity, and lower legs were not changed.

Sled Tests

Sled tests were conducted using the Hybrid III AF05 in the standard, reclined, and slouched postures to examine the relationship between sitting posture and submarining. The dummy was seated in the rear seat of a mini car body wearing a seat belt without pretensioners and load limiters. For the slouched posture, the hip point was moved forward by 100 mm from the standard posture. The seat back angle was 26°, 29°, 26°, and the pelvis angle was 19.9°, 24.6°, 37.1° in the standard, reclined, and slouched postures, respectively. A crash pulse was based on a full frontal impact test of a minicar at 50 km/h.

FE Simulations

Simulations were conducted using a seat model that represents the environment of the sled tests. A total of 6 models, THUMS high-BMI, THUMS AM50, THUMS low-BMI, THUMS V4.10 AF05 (THUMS AF05), Hybrid III AM50, and Hybrid III AF05, were used in the simulations. The torso of the human and dummy FE model in the standard and slouched postures was rotated to match the pelvis angle with the dummy in the sled tests in the standard and slouched sitting posture, respectively. The pelvis angle in the reclined posture was matched to that in the slouched posture to compare these two postures in the same pelvis angle. The seatback angle was 26° in the standard and slouched posture, and 43° in the reclined posture. Let the segment connecting the ASIS and anterior inferior iliac spine (AIIS) be the anterior edge of the pelvis, then the anterior edge angle of the pelvis (θ_{Pelvis}) is defined as the angle between the horizontal plane and the line that is perpendicular to the anterior edge of the pelvis in the lateral view (Figure 1(a)). The θ_{Pelvis} for THUMS male models, THUMS AF05, Hybrid III AM50, and Hybrid III AF05 were 27.5°, 27.4°, 13.8°, 15.0° in the standard posture and 44.5°, 44.4°, 30.8°, 32.0° in the reclined and slouched postures, respectively. Note that the θ_{Pelvis} defined for Hybrid III AF05 in the FE simulations was smaller than the pelvis angle defined in the sled tests by 5°. The seat and seat belt models were validated by comparing FE simulations with sled tests using Hybrid III and matching the acceleration of each part of the dummy [15].

Submarining Assessment

The occurrence of submarining was evaluated based on the relative angle between the pelvis and the lap belt as introduced by Horsch and Herring [3] (Figure 1(a)). Under high loadings, the lap belt fully compresses the abdominal soft tissue, and the lap belt follows the shape of the anterior edge of the pelvis. Considering that submarining is defined as when the lap belt slips over from the anterior edge of the pelvis toward the abdomen, submarining occurrences depend on the angle between the anterior edge of the pelvis and the direction of the lap belt tension. Assuming a two-dimensional problem in the lateral plane, the equilibrium of forces can be expressed as:

$$T\cos\theta_{PB} = T_n\,,\qquad T\sin\theta_{PB} = T_t \qquad (1)$$

where T is the force component of lap belt tension projected to the lateral plane, T_n is the normal force acting on the pelvis, T_t is the tangential force acting on the pelvis. The pelvis-belt angle, θ_{PB} $(= \theta_{Pelvis} - \theta_{Belt})$ is the difference between the pelvis angle (θ_{Pelvis}) and the angle of the direction of lap belt tension from the horizontal plane (θ_{Belt}).

Let the maximum static friction coefficient between the lap belt and the skin be μ_s, then the maximum tangential force T_t is $\mu_s T_n$. For the lap belt to engage the pelvis without slipping, the following equation should be satisfied:

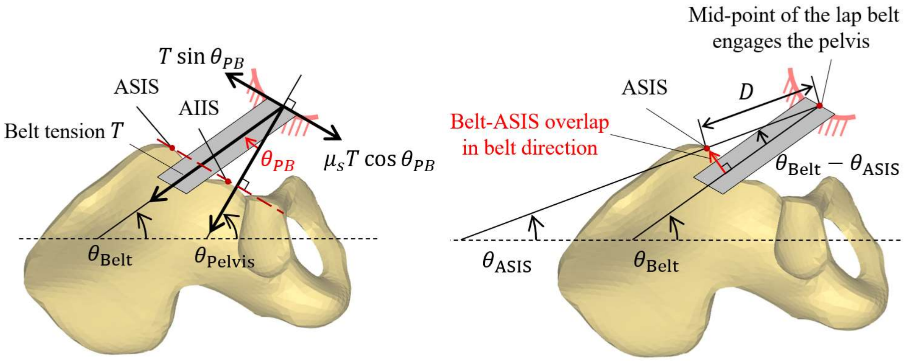
$$\mu_s T\cos\theta_{PB} > T\sin\theta_{PB} \qquad (2)$$
$$\tan\theta_{PB} < \mu_s \qquad (3)$$

The belt can slip on the anterior edge of the pelvis when the belt force is in the superior direction ($\theta_{PB} > 0$). If θ_{PB} exceed θ_{crit} $(= \tan^{-1}\mu_s)$, submarining can occur.

The lap belt overlap with the ASIS can be another parameter to evaluate the submarining occurrence. The lap belt applies force on the pelvis in the direction of the lap belt toward the anchorage. When the lap belt tension is applied to the pelvis closer to the ASIS, the possibility of submarining can be higher. Hence, we defined the belt-ASIS overlap as the distance from the ASIS to the lap belt in the sagittal plane (Figure 1(b)). The belt-ASIS overlap is expressed as:

$$\text{Belt-ASIS overlap} = D\sin(\theta_{Belt} - \theta_{ASIS}) \qquad (4)$$

where D is the distance between the mid-point of the lap belt and ASIS in the sagittal plane that goes across the ASIS, and θ_{ASIS} is the angle of the line connecting the lap belt and ASIS from the horizontal plane. This belt-ASIS overlap is a measure of an effective interaction of the lap belt force with the anterior edge of the pelvis. When the belt applies force over the ASIS (Belt-ASIS overlap < 0), submarining can occur.



(a) Pelvis-belt angle (θ_{PB}) (b) Belt-ASIS overlap in belt direction

Figure 1. Definition of submarining assessment parameters.

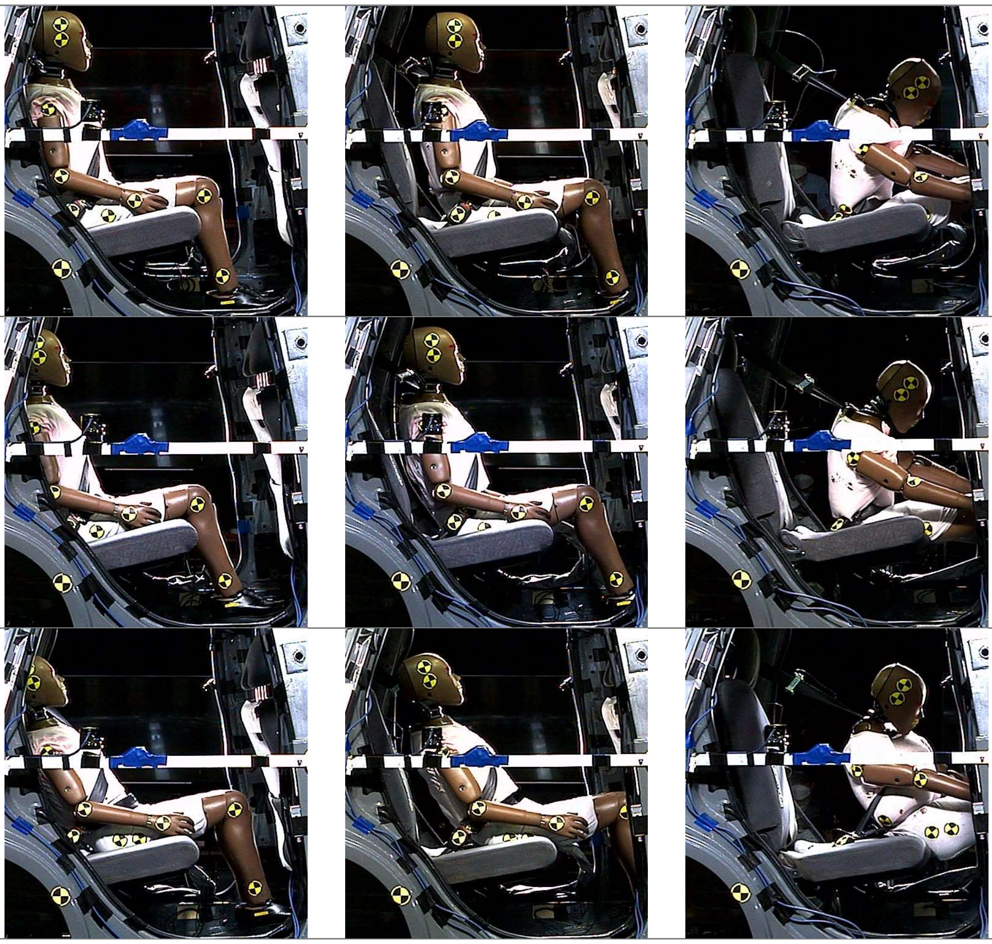
RESULTS

Table 1 presents the occurrence of submarining in sled tests and FE simulations. Submarining occurrences were classified into the following: no-submarining (the lap belt engaged the pelvis the whole time), the lap belt slipped over the pelvis after the pelvis and the sled had a common velocity, and submarining (lap belt slipped over the pelvis before the beginning of rebound phase). As shown in Table 1, submarining tends to occur in the reclined and slouching posture. Submarining was more prone to occur in THUMS models than in Hybrid III dummy models.

Table 1.
Submarining occurrence of sled tests and FE simulations: "++" indicates no submarining occurrence, "+" indicates the lap belt slip over during the rebound phase, and "−" indicates submarine occurrence.

	FE simulation						Sled test
Posture	THUMS high BMI	THUMS AM50	THUMS low BMI	THUMS AF05	Hybrid III AM50	Hybrid III AF05	Hybrid III AF05
Standard	++	+	+	+	++	++	++
Reclined	++	–	–	–	++	++	++
Slouching	–	–	–	–	++	–	–

Sled Tests
The dummy kinematics during the impact is shown in Figure 2. In the standard and reclined postures, submarining did not occur, and the pelvis moved downward into the seat cushion while the tibia contacted the lower frame of the front seat. The torso pitched slightly forward in these two postures. On the other hand, submarining occurred in the slouched posture. The pelvis fell from the seat cushion due to the large pelvis excursion, and the torso tilted rearwards and the shoulder belt interacted with the neck.



0 ms 50 ms 80 ms

Figure 2. Kinematic behavior of Hybrid III AF05 in the sled tests: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

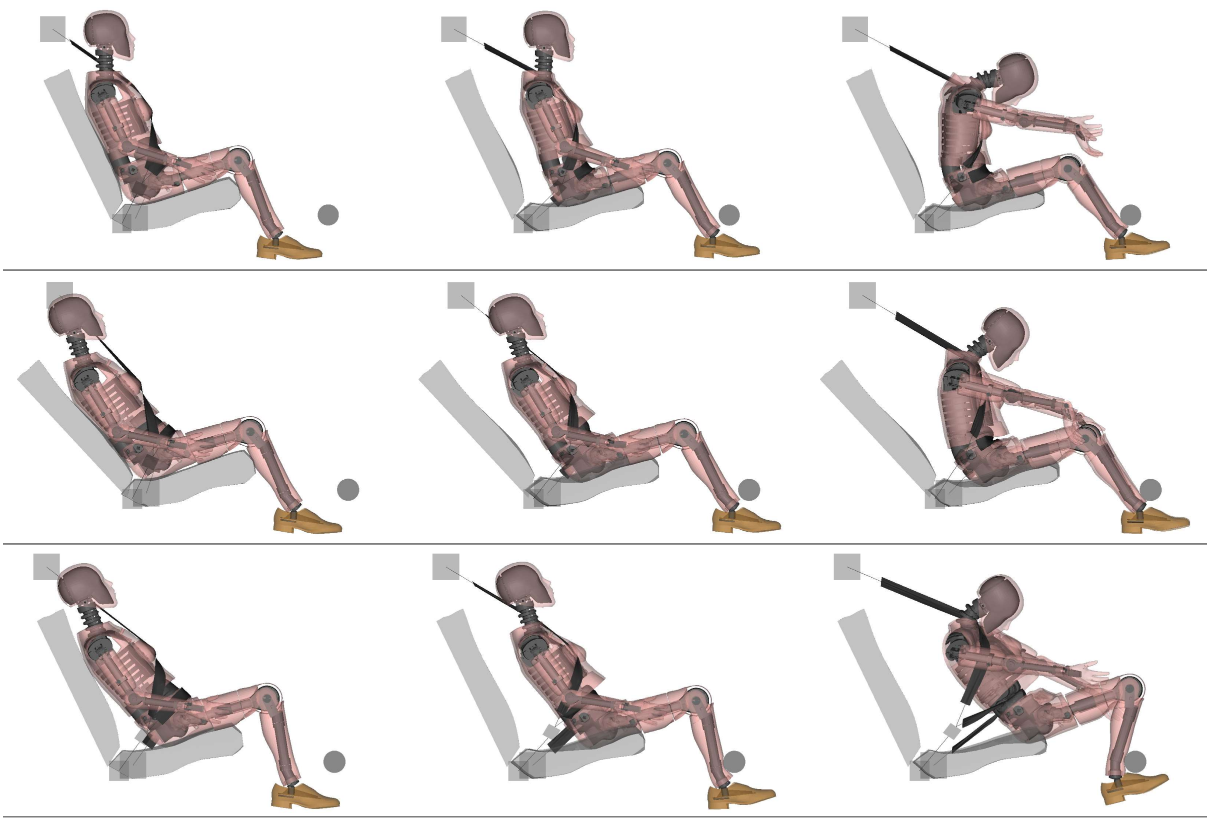
The belt connecting the inboard anchorage to the buckle was initially bent because this connecting belt went through a gap in the seat cushion. A time lag occurred before the bending was removed and tension was generated in the initial stages of the impact. This caused a time delay in increasing the belt tension of the lap belt, resulting in a large pelvis excursion.

FE Simulations

Figures 2, 3, A1, A2, A3, and A4 show the kinematic behavior of models in the standard, reclined, and slouched posture. In the standard posture, submarining did not occur for all models. Note that in this standard posture, for THUMS low-BMI, THUMS AM50, and THUMS AF05, the lap belt slipped from the pelvis during unloading. In the reclined posture, submarining occurred in THUMS low-BMI, THUMS AM50, and THUMS AF05. In the slouched posture, submarining occurred in all models except for the Hybrid III AM50.

Figure 4 shows the trajectories of the head, chest, hip joint, and knee joint for THUMS AM50 and AF05, as well as Hybrid III AM50 and AF05 in the standard posture. The pelvis excursion of the Hybrid III AM50 and AF05 was smaller than THUMS in all postures. The knee excursion, pelvis excursion and rotation were large for THUMS male models. The pelvis, chest, and knee excursion of the THUMS AF05 was smaller with a shorter loading time than THUMS male models. THUMS high BMI showed a larger pelvis and knee excursion than other THUMS male models because the pelvis mass was large, and the lap belt penetrated the valley-shaped gap of the abdomen and compressed the thick soft tissue before the lap belt engaged the pelvis (Figure A1). Due to this large pelvis excursion, the torso of the THUMS high-BMI pitched less than other THUMS models. For THUMS high-BMI in the slouched posture, the pelvis fell from the seat cushion because the initial pelvis position was further forward than in the other postures. In the submarining cases of reclined posture (THUMS AM50, low-BMI, and AF05), the torso of the models tilted rearward.

The pelvis rotated rearward after the lap belt began to apply the restraint force to the pelvis (Figure B1). THUMS models tend to show larger pelvis rotation than Hybrid III, especially in the models with thin abdominal soft tissue (THUMS AF05 and THUMS low-BMI).



0 ms	50 ms	80 ms

Figure 2. Kinematic behavior of Hybrid III AF05: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

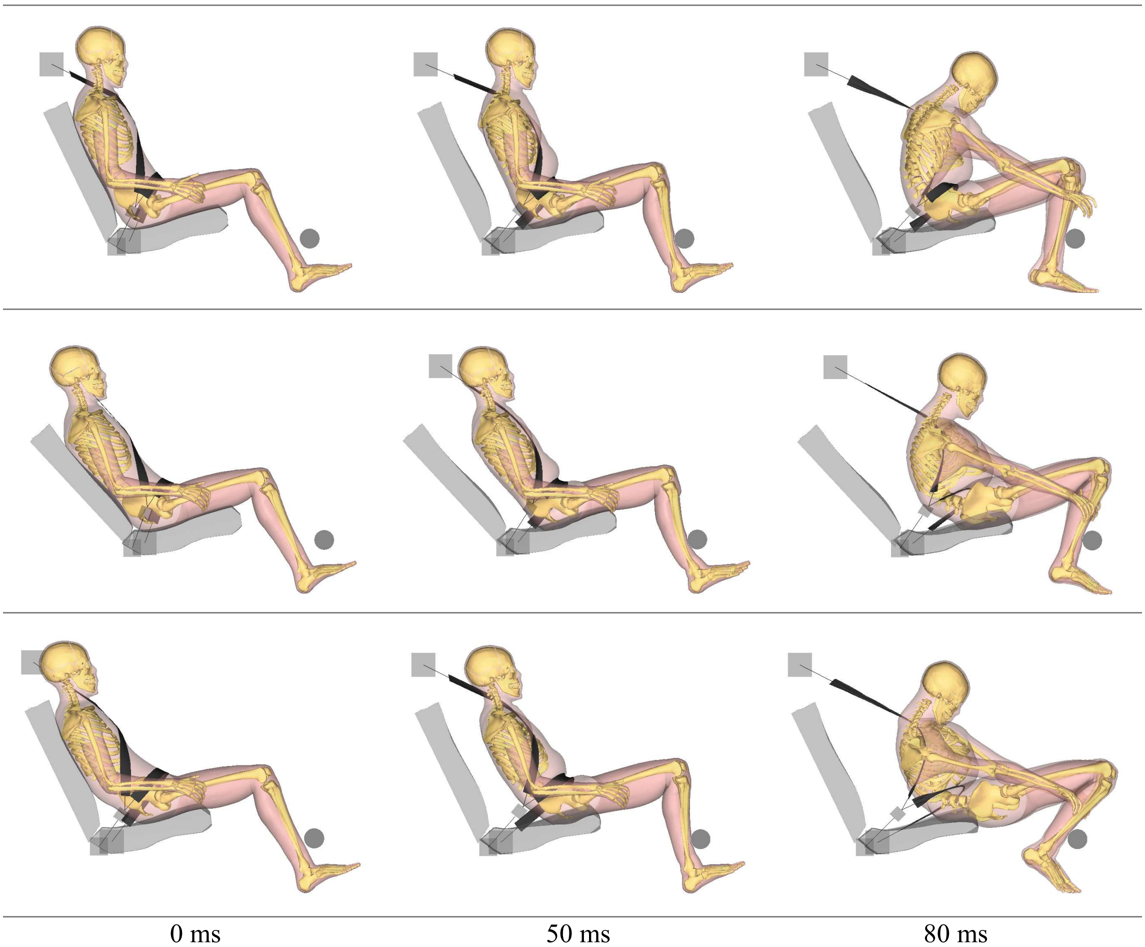


Figure 3. Kinematic behavior of THUMS AM50: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

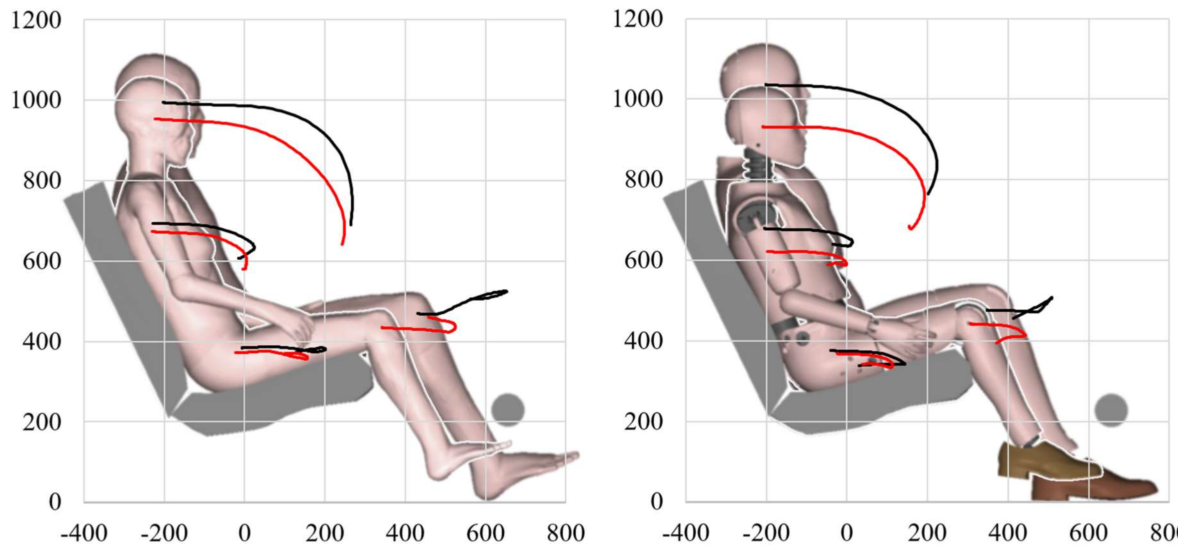


Figure 4. Trajectories of the head, chest (T8), hip joint, and knee joint for THUMS AM50 and AM05 (left), and Hybrid III AM50 and AF05 (right) in the standard posture. Trajectories of male models are shown in black, and those of female models are shown in red.

Figure 5 shows the pelvis-belt angle (θ_{PB}) with time. The time of the occurrence of submarining (the lap belt started to slip over the pelvis), as well as the time of the lap belt slipping over the pelvis during the rebound phase are also indicated in the graph. The maximum static coefficient of friction between the lap belt and skin was set to 0.2, then $\theta_{crit} = 11.2°$ is drawn as a dotted line.

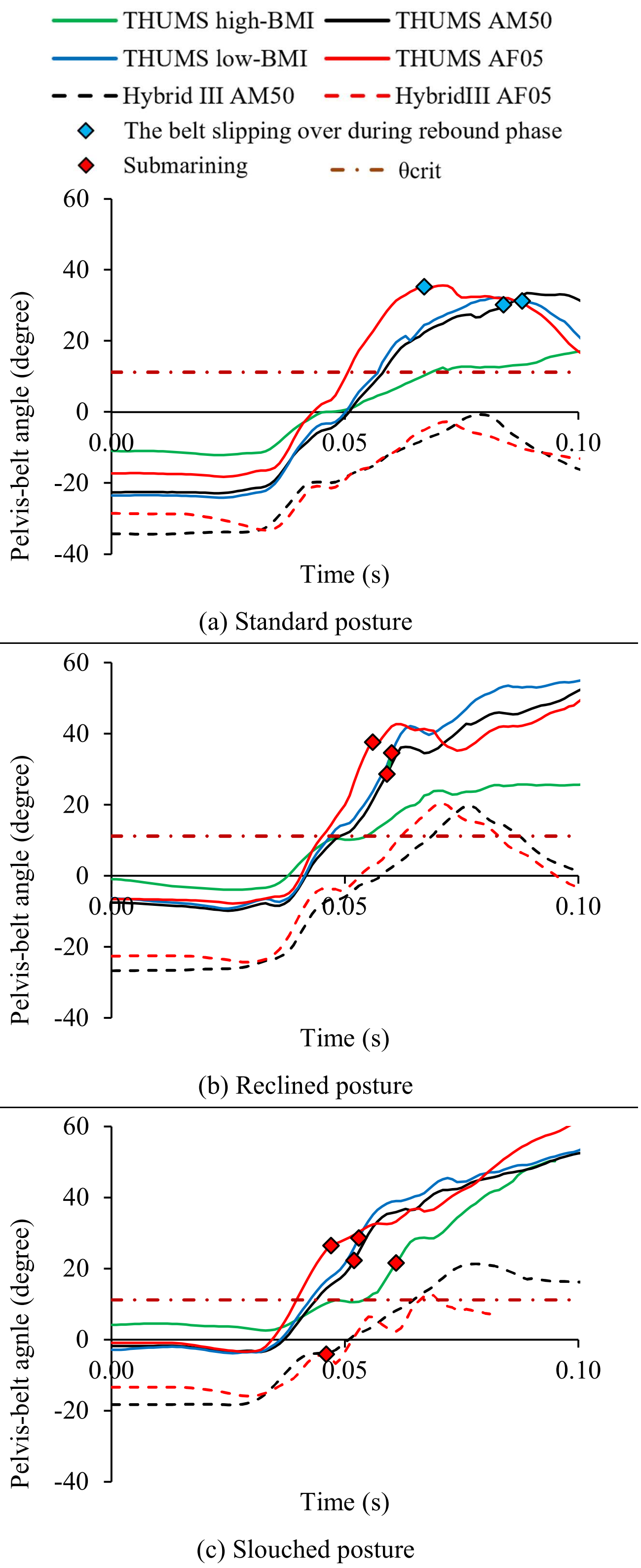


Figure 5. Pelvis-belt angle (θ_{PB}).

In general, the pelvis rotates with time, and the pelvis-belt angle θ_{PB} becomes large with higher submarining risk. The pelvis-belt angle θ_{PB} does not change until the lap belt interacts with the pelvis, then θ_{PB} increases as the lap belt engage the pelvis and the pelvis rotates rearward (see Figure B1). In the standard posture (Figure 5(a)), the initial θ_{PB} of THUMS is larger than that of Hybrid III due to the large initial pelvis angle. Despite THUMS male models having the same initial pelvis angle (θ_{Pelvis}), THUMS high-BMI has a large initial θ_{PB} due to the shallow angle of the lap belt fit (θ_{Belt}). In the reclined posture (Figure 5(b)), the initial θ_{PB} was larger than in the standard posture by 10.9° on average in all models because the initial pelvis angle was rotated rearward (+17°), whereas the initial lap belt angle θ_{Belt} was steep (+6.1°). In this reclined posture, submarining occurred in the three models (THUMS low-BMI, AM50, and AF05) when θ_{PB} reached around 29° to 38°. In the slouched posture (Figure 5(c)), the initial θ_{PB} was larger than in the reclined posture, because the initial lap belt angle was shallow. Submarining occurred in all THUMS when θ_{PB} reached around 21° to 29°, which was smaller than θ_{PB} at submarining in the reclined posture. In this posture, submarining occurred in Hybrid III AF05 before θ_{PB} reached θ_{crit}.

The thin ASIS flesh margin of THUMS low-BMI and AF05 was fully compressed by the lap belt in the initial stage of restraint, and the pelvis began to rotate earlier. THUMS high-BMI, which has thick abdominal soft tissue, showed fewer submarining occurrences than other THUMS. The thick abdominal soft tissue distributed the force from the lap belt to a wide area of the pelvis (Figure C1) and decreased the pelvis rotation moment. For Hybrid III in the three postures, the initial pelvis angle and the pelvis rotation during loading were small, which led to fewer submarining cases.

Figure 5(b) and Figure 5(c) also suggest that submarining occurred at smaller θ_{PB} in the slouched posture than in the reclined posture. This may have been due to a larger initial θ_{PB} in the slouched posture; however, this may not be the only cause because θ_{PB} of THUMS high-BMI and Hybrid III AF05 at 40 – 50 ms were comparable between the slouched and the reclined postures. This result implies that other parameters are necessary to evaluate the risk of submarining.

Figure 6 shows the lap belt overlap with the ASIS in the lap belt direction (Figure 1(b)). In the standard posture (Figure 6(a)), the belt-ASIS overlap of the THUMS high-BMI is larger than THUMS AM50 and THUMS low-BMI even though the lap belt was fitted in an upper location relative to the ASIS due to the large thigh diameter. Comparing Figure 6(b) and Figure 6(c), the initial belt-ASIS overlap in the slouched posture is smaller than that in the reclined posture due to the shallow lap belt angle in the slouched posture. Submarining occurred when the belt-ASIS overlap reached around -12 to 0 mm in all postures and models.

In the belt-ASIS overlap in the standard posture, three phases of the overlap decrease were observed (Figure 7). In Figure 6(a), phase 1 of the overlap decrease (30 - 40 ms) is caused by soft tissue compression as the occupant moves forward before the lap belt engages the pelvis. Then the lap belt engaged the pelvis (phase 2), and the overlap reaches a plateau. After 50 ms, the overlap decreased again after θ_{PB} exceeds θ_{crit} because the lap belt slid up on the pelvis (phase 3). When the belt-ASIS overlap is negative, submarining occurred. In THUMS AF05, the overlap does not have a plateau because θ_{PB} exceeds θ_{crit} earlier than in other models. In the reclined posture (Figure 6(b)), phase 1 of the overlap decrease was large because the lap belt slid over the skin before the engagement with the pelvis. In the submarining cases, phase 3 of the overlap decrease began earlier after the small plateau area (phase 2). In the slouched posture (Figure 6(c)), phase 3 began even earlier, and there are no plateau areas (phase 2) except for Hybrid III AM50 without submarining.

In THUMS high-BMI, submarining occurred only in the slouched posture whereas it did not occur in the reclined posture. Comparing Figure 6(b) and Figure 6(c), the belt-ASIS overlap of THUMS high-BMI in the slouched posture is always smaller than that in the reclined posture, suggesting that submarining occurred because of small belt-ASIS overlap.

In the Hybrid III AF05 in the slouched posture, the lap belt slipped over the pelvis before θ_{PB} reached θ_{crit}. That suggests submarining occurred in phase 1 of the overlap decrease; in other words, the lap belt slipped over without engagement with the pelvis. Because the initial belt-ASIS overlap of Hybrid III AF05 in the slouching posture was insufficient, the belt-ASIS overlap became negative during phase 1, and submarining occurred (Figure 6(c)).

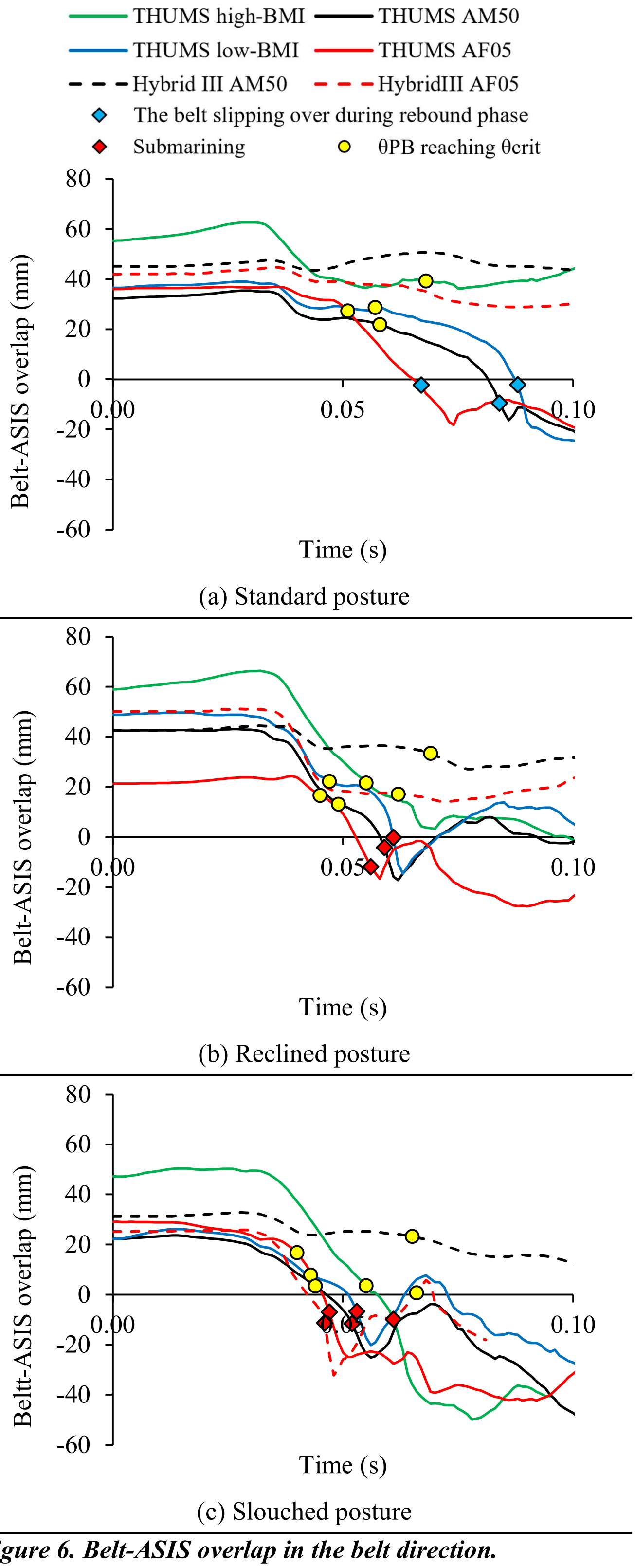
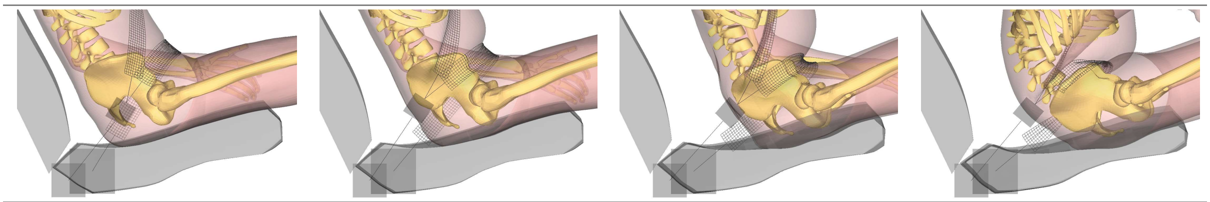


Figure 6. Belt-ASIS overlap in the belt direction.



Phase 1 start (33 ms)	Phase 2 start (45 ms)	Phase 3 start (57 ms)	Lap belt slipped over (84 ms)

Figure 7. Interaction between the pelvis and the lap belt at each belt-ASIS overlap decrease stage (THUMS AM50, standard posture, the right arm is not displayed). Phase 1: the ASIS flesh margin is compressed, phase 2: the lap belt engages the pelvis, and phase 3: the lap belt slides up on the pelvis.

DISCUSSION

In this study, the lap belt engagement with the ASIS was examined for various occupant models in the standard, reclined, and slouched postures. The results of this study showed that in the sled tests and FE simulations, the likelihood of submarining increases in the following order: standard, reclined and slouched posture. Hybrid III dummies were less likely to submarine than THUMS.

We proposed a lap belt-ASIS overlap which is the overlap of the lap belt with the ASIS in the belt direction (Figure 1(b)). In previous studies, the position of the lap belt and ASIS of human subjects have been measured [7, 8], and the belt-ASIS overlap has been defined as the vertical distance between the lap belt and the ASIS. While the occupant mainly moves in the forward direction, the lap belt applies a force in the lap belt tension direction toward the anchorage. Hence, the overlap of the lap belt in the vertical direction may not represent the lap belt engagement with the ASIS. For example, the lap belt-ASIS overlap in the vertical direction tends to be small (or no overlap) for high BMI participants because the lap belt locates upward. However, the lap belt engaged with the pelvis for high-BMI occupants [16]. In this study, the lap belt-ASIS overlap in the lap belt direction was large in the high BMI occupant (see Figure 5), and submarining of the high BMI occupant did not occur in the standard and reclined postures. Thus, the belt-ASIS overlap in the lap belt direction is probably appropriate to evaluate the lap belt engagement with the pelvis. Based on this parameter, the layout of the lap belt can be designed to have sufficient overlap with the pelvis.

The combination of the belt-ASIS overlap in the belt direction and the pelvis-belt angle (θ_{PB}) appears to be useful in understanding the process of submarining. The process of change of these parameters with time can be described as follows:

1. The overlap decreases as the lap belt compresses the abdominal soft tissue (phase 1).
2. The overlap becomes constant when the lap belt engages the pelvis, and the pelvis begins to rotate (phase 2).
3. When θ_{PB} reaches θ_{crit}, the lap belt begins to slip on the pelvis, and the overlap begins to decrease again (phase 3). When the overlap is negative, submarining occurs.

Submarining occurred in two scenarios: 1) when the lap belt did not engage the pelvis (e.g., Hybrid III AF05 in the slouched posture), or 2) when the lap belt slips over the pelvis (e.g., THUMS low-BMI in the reclined posture).

This study showed that submarining occurrence is more likely in the reclined posture than in the standard posture. Even though the pelvis angle is the same between the reclined and the slouched postures, the lap belt angle θ_{Belt} was smaller in the slouched posture (Figure 5). Moreover, the smaller belt-ASIS overlap in the slouched posture indicates that submarining is more likely to occur than in the reclined posture (Figure 6).

Rawska et al. [13, 14, 17] have shown that submarining is more likely to occur in a small female FE model than in standard and large male models. Tanaka et al. [8] have shown small females have a large belt-ASIS overlap in the vertical direction because of a low thigh height. However, the result of this study shows that the belt-ASIS overlap in the lap belt direction in the small female model is comparable with that in the male models (see Figure 5). Additionally, due to its small flesh margin, the pelvis of THUMS AF05 began to rotate early in the restraint and rotated largely. This large pelvis rotation is a possible reason that submarining is likely to occur in small female models. Further research is necessary to identify the reasons for the large rotation of the female's pelvis.

A limitation of this study is that it is not clear whether the THUMS can correctly predict submarining. This is because elements of soft tissues around the ASIS became unstable and collapsed under large deformations in some calculations. Sun et al. [18] applied a smoothed particle Galerkin method to a belt-flesh-pelvis interaction for the evaluation of submarining occurrence. Even if submarining prediction in THUMS is not so accurate, the analytical method of the lap belt and pelvis behavior using the belt-pelvis angle and the belt-ASIS overlap proposed in this study will be useful to understand submarining occurrences.

CONCLUSIONS

In this study, sled tests and FE simulations of occupant frontal impact responses were conducted in 3 seating postures. Interactions between the lap belt and pelvis were observed using belt-pelvis angle (θ_{PB}) and belt-ASIS overlap in belt direction.

- The overlap between the lap belt and ASIS in the direction of belt tension may be a better parameter than vertical or lateral overlap to evaluate the risk of submarining in occupants with various body sizes, body shapes, and seating postures.

- In reclined and slouched postures, dummy and human body models tend to show more submarining because of the initially rearward tilted pelvis. In slouched posture, the risk of submarining is higher than reclined posture because of the small belt-ASIS overlap in the belt direction.

- Hybrid III models showed fewer submarining cases because of small pelvis rotation during impact and large belt-ASIS overlap.

- Occupant with high BMI have large belt-ASIS overlap because the lap belt is located forward compared to occupants with lower BMI. The risk of submarining for occupants with high BMI is low because of large belt-ASIS overlap and small pelvis rotation.

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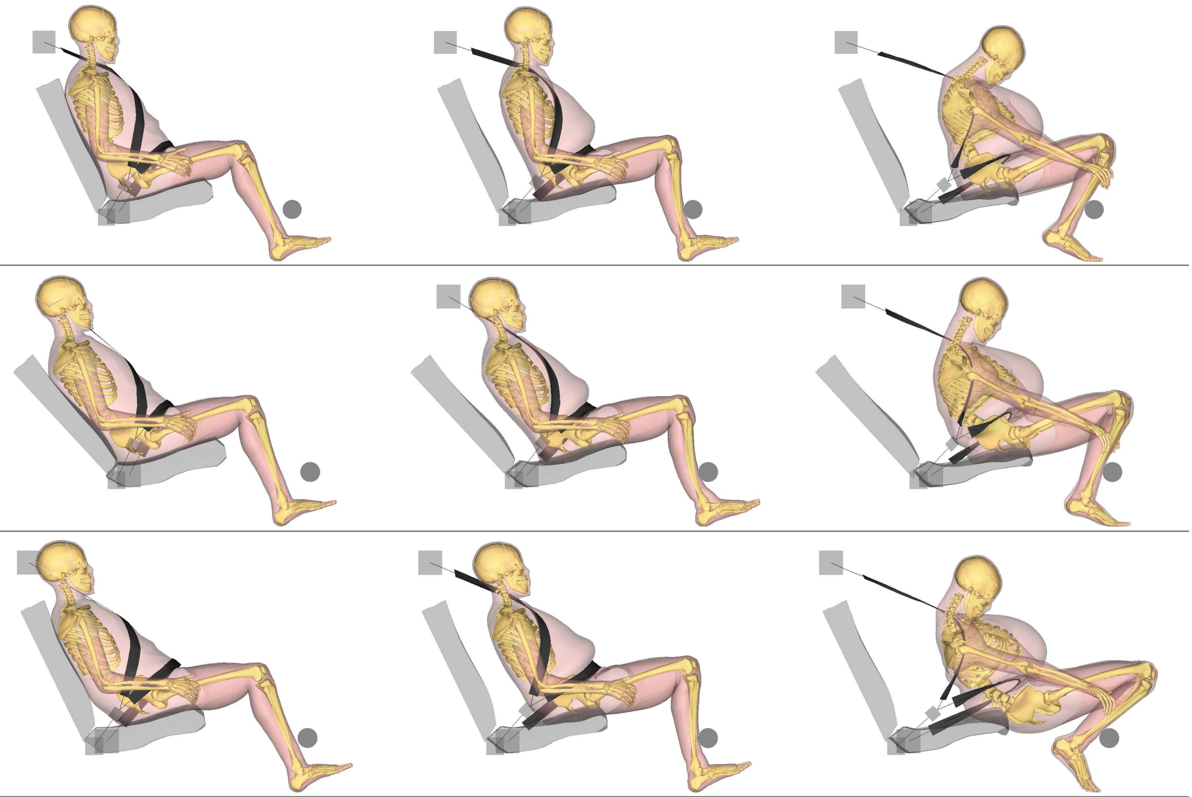
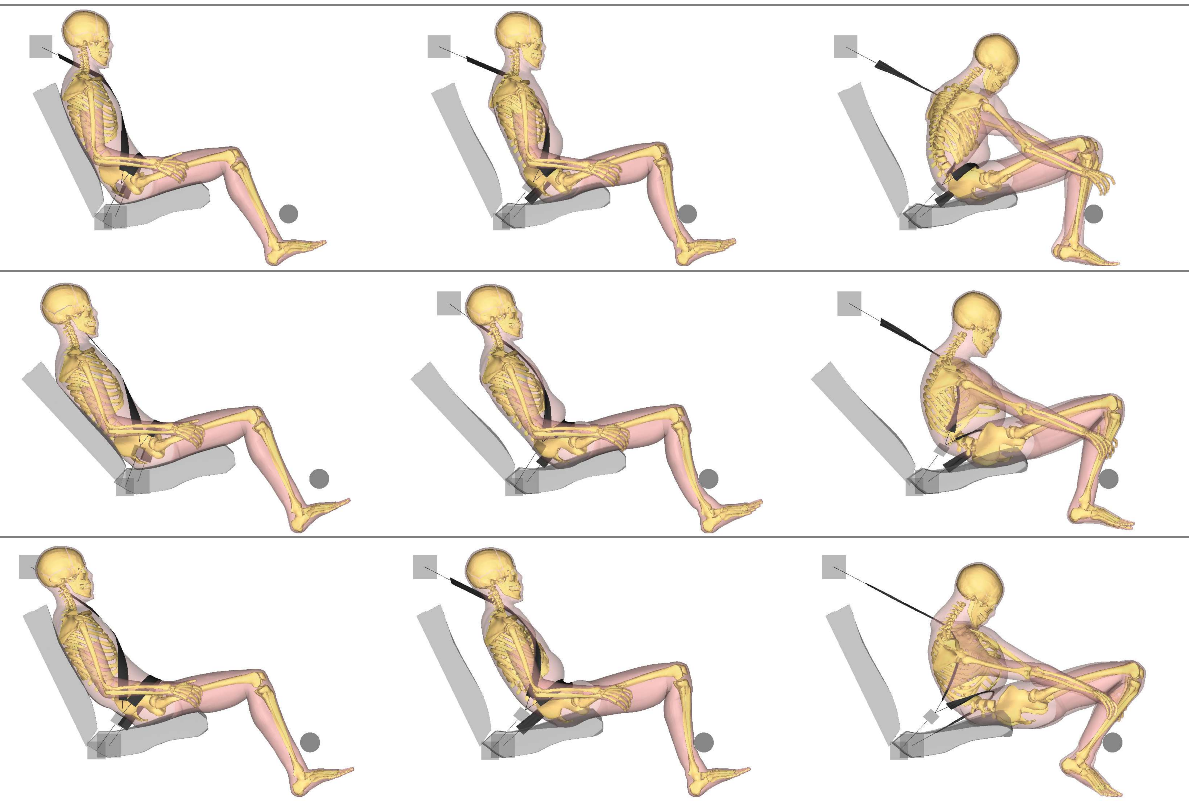
APPENDIX A Kinematic behavior of human body models and dummy models in FE simulations



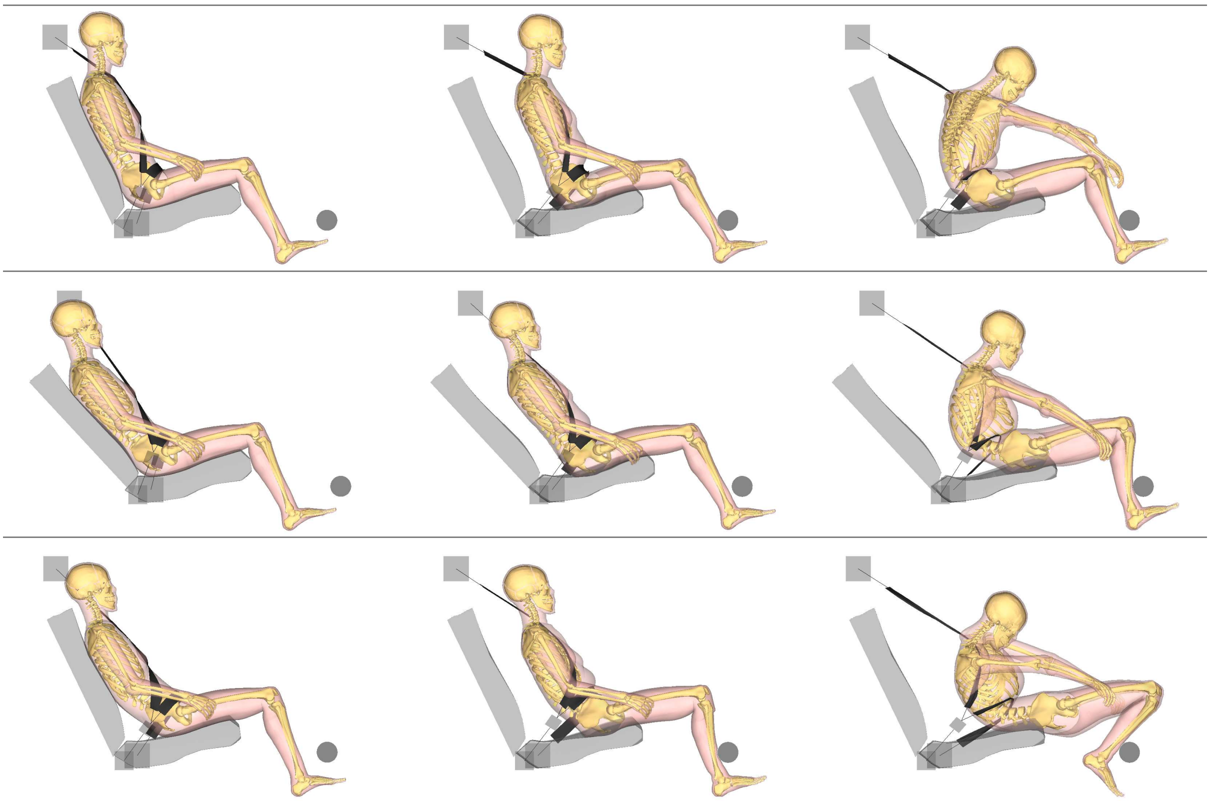
0 ms	50 ms	80 ms

Figure A1. Kinematic behavior of THUMS high-BMI: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).



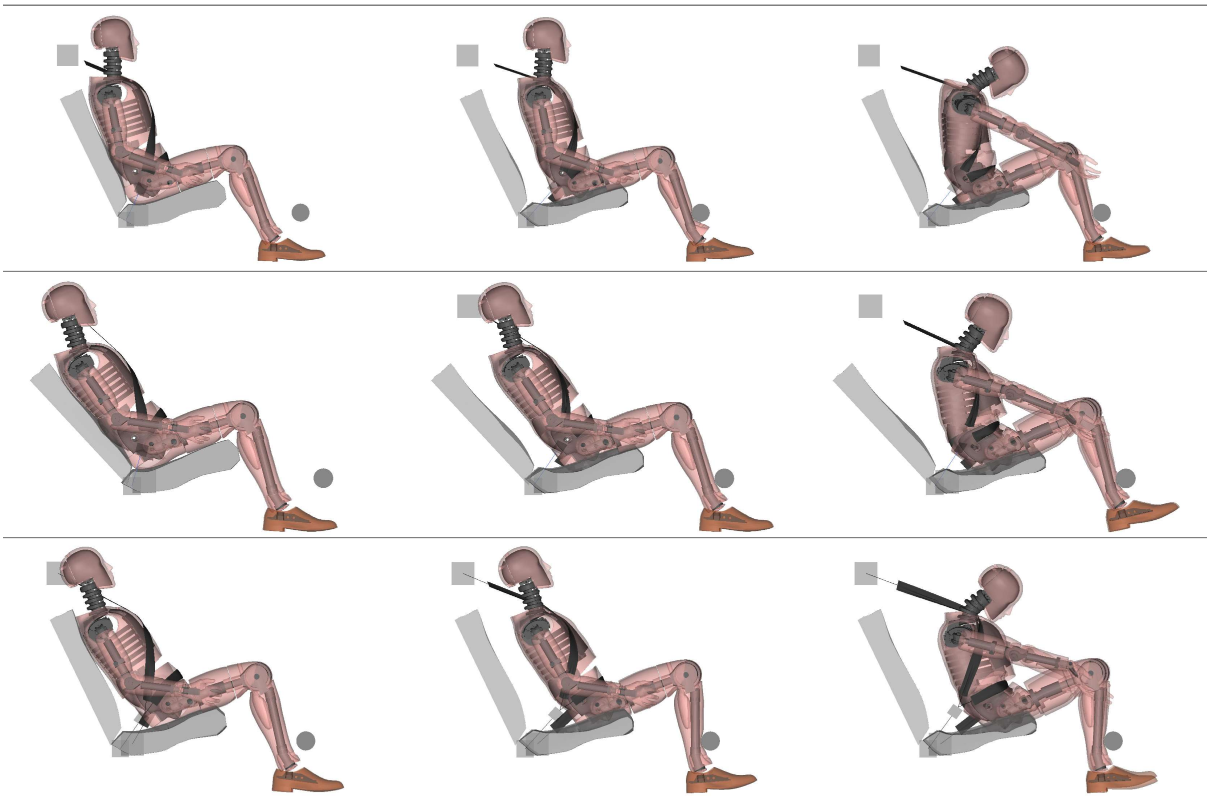
0 ms	50 ms	80 ms

Figure A2. Kinematic behavior of THUMS low-BMI: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).



0 ms 50 ms 80 ms

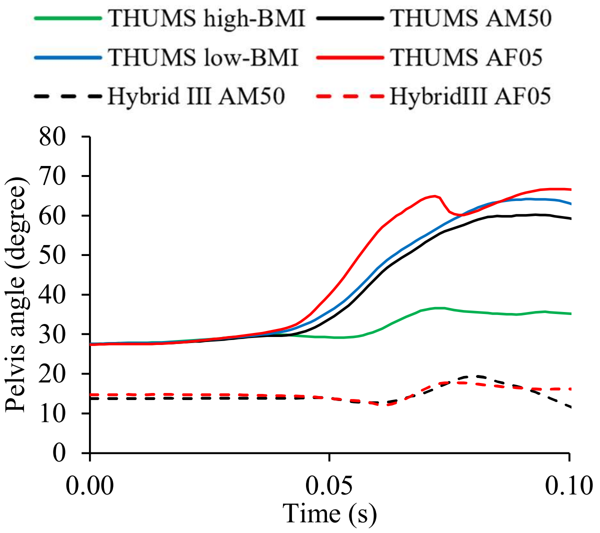
Figure A3. Kinematic behavior of THUMS AF05: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).



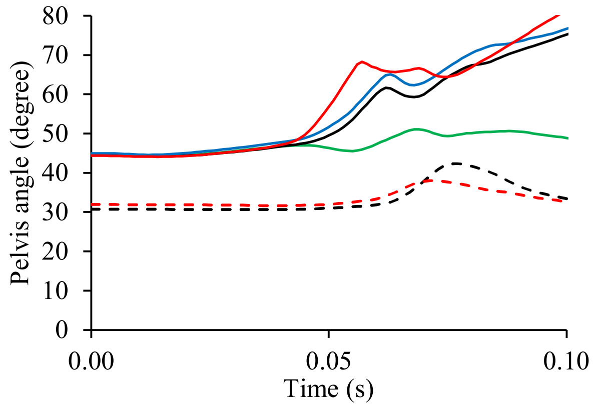
0 ms 50 ms 80 ms

Figure A4. Kinematic behavior of Hybrid III AM50: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

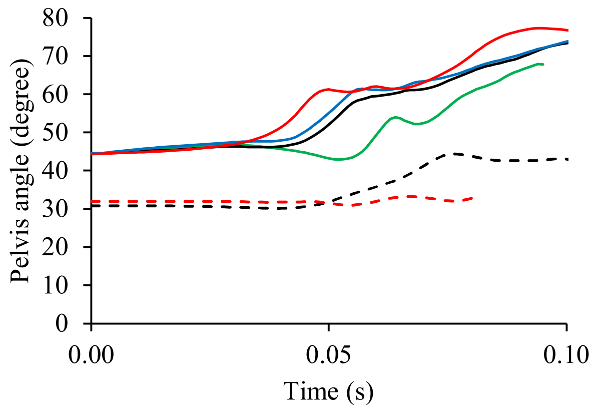
APPENDIX B Pelvis angle (θ_{Pelvis})



(a) Standard posture



(b) Reclined posture



(c) Slouched posture

Figure B1. Pelvis angle (θ_{Pelvis}).

APPENDIX C Stress distribution on the pelvis

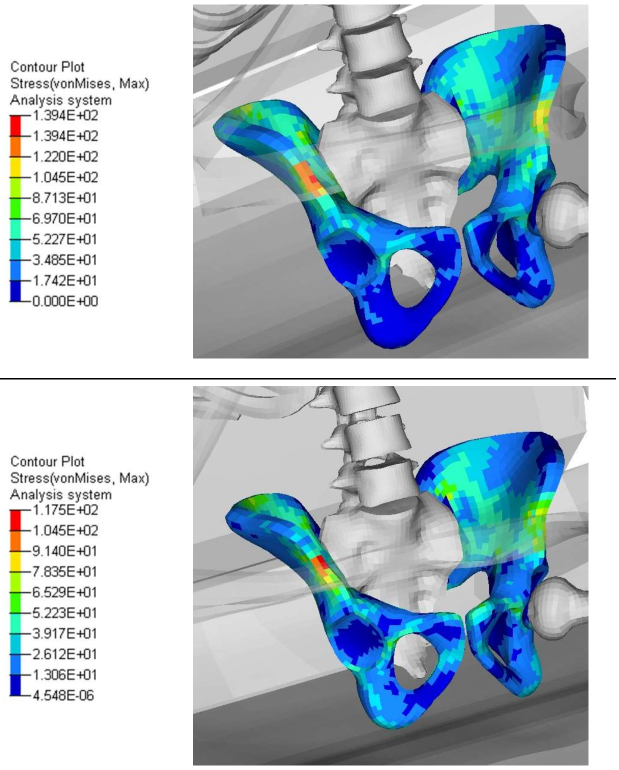


Figure C1. Stress (von Mises) distribution on the pelvis: THUMS AM50 (upper row), THUMS high-BMI (lower row), standard posture, 60 ms.