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Effect of Seat Condition on Abdominal Injuries to Vehicle Occupants in Frontal Impact Accidents

Yasuhiro Matsui [1,*] and Shoko Oikawa [2]

1 National Traffic Safety and Environment Laboratory, 7-42-27 Jindaiji Higashi-machi, Chofu, Tokyo 1820012, Japan
2 Faculty of Systems Design, Tokyo Metropolitan University, 6-6 Asahigaoka, Hino-city, Tokyo 1910065, Japan; shoko_o@hotmail.com
* Correspondence: ymatsui@ntsel.go.jp; Tel.: +81-422-41-3371

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Abstract: Vehicle occupants were killed in 33% of all traffic accidents in Japan in 2017. Of the vehicles in vehicle-to-vehicle accidents, 54% were impacted from the front. In frontal impact accidents, when the lap belt moves away from the iliac crests of the pelvis of a vehicle occupant, the belt moves directly into the abdomen. Here, we investigated causes of abdominal injuries to vehicle occupants, because the abdomen is associated with the highest rates of severe injury and fatality. The purpose of this study was to clarify the correlation between downward movement of the seat and of the lap belt away from the iliac crests of a human occupant of a car, in the event of a frontal impact. We investigated this phenomenon by conducting simulations using an anthropomorphic 50th percentile male (AM50) human model wearing a three-point seatbelt. We set two deformable seat conditions: Vertical movement and lean forward movement. Our results revealed that the lap belt came off from both of the iliac crests during lean forward movement but only from one of the iliac crests during vertical movement. We concluded that abdominal injuries can be caused by downward movement together with forward rotation in the seat during vehicle-to-vehicle frontal impacts.

Keywords: human model; abdominal injury; frontal impact accidents; simulation

1. Introduction

Vehicle occupants were killed in 33% (1221) of all traffic accidents (3694) in Japan in 2017 [1] (Figure 1). Therefore, countermeasures to reduce fatal traffic accidents are required. In Japan, when road-users are killed or injured in traffic accidents, police officers and medical doctors determine the main body regions associated with severe injuries that led to death. Results of these investigations reveal serious and fatal injury rates for each main body region, presented in Table 1. The abdominal region is associated with the highest rate of severe injury and fatality of vehicle occupants (Table 1) [1]. The same trend has also been observed in France [2]. Therefore, in this study, we focus on causes of abdominal injuries to vehicle occupants.

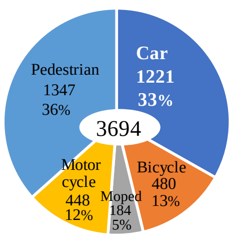

Figure 1. Distribution of traffic fatalities by crash type in Japan in 2017.

Table 1. Severe injury and fatality rates for individual body regions of vehicle occupants involved in traffic accidents in Japan in 2017.

Main Body Region	Number			Rate (%)	
	(a) Minor Injured Occupants	(b) Serious Injured Occupants	(c) Fatality Occupants	Serious Injury Rate b/(a+b)	Fatality Rate c/(a+b+c)
Head	9047	738	305	8	3
Face	3507	304	14	8	0
Neck	302,051	2325	67	1	0
Chest	12,348	2836	444	19	3
Abdomen	1558	511	147	25	7
Back	3009	141	3	4	0
Hip	22,329	937	36	4	0
Arms	8334	985	5	11	0
Legs	7259	1251	28	15	0
Total	369,442	10,028	1049	-	-

Fifty-four percent of vehicles struck in vehicle-to-vehicle accidents in Japan were impacted from the front [3]. A US accident investigation database of occupant injuries in the front passenger seat of impacted vehicles showed that 59% of abdominal injuries were directly caused by seatbelts [4]. Two detailed accident case studies revealed that lap belts caused serious abdominal injuries and residual deformation marks were left behind on seat surfaces, which suggests that the seat moved vertically during the frontal impact [4].

Some studies have attempted to evaluate the relationship between lap belt condition and abdominal injury. Zhu et al. performed simulations using a vehicle cabin model with a rigid-seat model to investigate injury risk, considering the abdomen, for the anthropomorphic 50th percentile male (AM50) and obese male models during frontal impact [5]. In addition, Steffan et al. investigated the relationship between lap belt loading and abdominal response using an AM50 dummy and post mortem human subjects (PMHSs), by employing a rigid seat during frontal impact to facilitate the design and development of seat belt tensioning systems [6]. However, only a few studies have focused on the movement of a seat during frontal impact. Kitamura et al. investigated two accidents in which drivers sustained abdominal injuries owing to car-to-car frontal impacts [7]. These authors indicated the possible cause of abdominal injuries may be due to deformation of the seat during impact. Matsui and Oikawa investigated the relationship between seat height vertical movement and lap belt upward movement, in which an anthropomorphic 50th percentile male Hybrid III dummy model (hereafter referred to as an AM50 Hybrid III model) was seated in a passenger seat model [8]. Results revealed that when the AM50 Hybrid III model moved 150 mm vertically downward, the lap belt exhibited significant upward movement from its initial position on the dummy's waist. This phenomenon resulted in the abdomen being directly compressed, owing to tightening of the lap belt.

In the upper body structure of a Hybrid III dummy, there is a space between the thoracic and waist part [9] because the dummy does not have internal organs. Currently, Toyota Motor Corporation and Toyota Central Research and Development Labs. Inc. have jointly developed a finite element model, the total human model for safety (THUMS) version four, which includes an internal organ finite element model [10]. It is possible that dynamic movement of a seatbelt on a Hybrid III dummy may be different from that of a seatbelt worn by a human, i.e., after a lap belt moves away from the iliac crests of the human pelvis it moves deeply into the abdomen.

Thus, the purpose of this study is to clarify the correlation between different downward movement conditions of the seat and those of the lap belt from the iliac crests of a human occupant in the front passenger seat of a car in the event of a frontal impact. We investigate this phenomenon by conducting simulations using an AM50 human model.

Figure 2 shows a photograph of residual deformation of the front passenger car seat after a Japan new car assessment program (JNCAP) full frontal rigid barrier impact test, in which a Hybrid III dummy was seated in the passenger seat during the test. The frontal edge of the seat exhibits residual deformation of 100 mm, which suggests the seat moved downward along with a small forward rotation. Therefore, in this study, we select two conditions: 150 mm vertical downward movement of the seat [8] and 150 mm vertical downward movement in combination with forward rotation.

Figure 2. Photograph of residual deformation of the front passenger seat in a car after a Japan new car assessment program (JNCAP) full frontal rigid barrier impact test.

2. Materials and Methods

An AM50 THUMS ver.4 model (hereafter referred to as the AM50 human model) [10] was placed on a seat fixed to a vehicle cabin model (Figure 3). The AM50 human model is composed of finite elements for all body parts. The height and mass of the AM50 human model were 1.78 m and 74 kg respectively. The thorax and whole-body response of the AM50 human model seated in a vehicle impacted from the front were validated through a comparison with responses of post mortem human subjects (PMHSs) [10]. All simulations were performed using the LS-DYNA commercial finite element software [11]. The vehicle cabin model was fixed to the vehicle coordinate system. Normally, a seat belt is the only system that restrains the upper body of an occupant. The AM50 human model wore a three-point seatbelt. The vehicle cabin model and three-point seatbelt (model number 100112_V1.0) were developed by Livemore Software Technology Corporation (LSTC) [12]. In the National Highway Traffic Safety Administration (NHTSA) New Car Assessment Program (NCAP) test report, load limiters for drivers and front-seat passengers were identical at approximately 5 kN [13]. Forman et al. reported that vehicle occupants with a 5 kN load limiter, without an airbag, could experience multiple rib fractures [14]. Foret-Bruno et al. suggested that a load limiter of 4 kN would provide reasonable safety when used in combination with an airbag [15]. In this study, the upper limit of the force limiter was regulated to 3.3 kN. We excluded the airbag from the current vehicle cabin model in order to investigate potential for abdominal injury under the most severe conditions, where there was a large movement of the hip and lower extremities. The seat-back and floor of the vehicle cabin model were rigid.

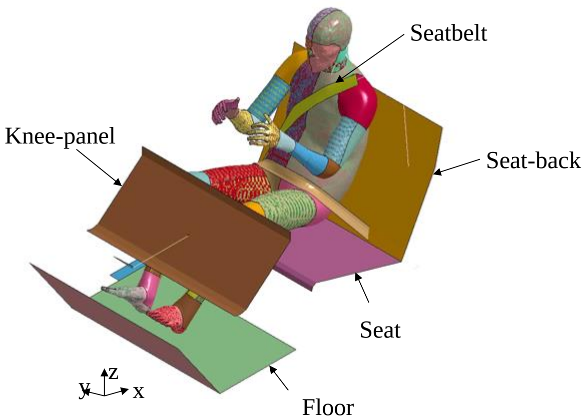

Figure 3. Anthropomorphic 50th percentile male total human model for safety ver.4 (AM50 human model) [10] seated in the vehicle cabin model [12].

The vehicle cabin model used in our research is shown in Figure 4, together with springs representing seat and knee-panel characteristics. The seat was set to move downwards (z-axis) with an increase in applied forces from the thigh and breech. In this study, the center of the seat was moved downward by a maximum displacement of 150 mm, as previously obtained results indicated that this amount of vertical downward movement resulted in upward movement of the lap belt from its initial position at the waist of the AM50 Hybrid III model [8].

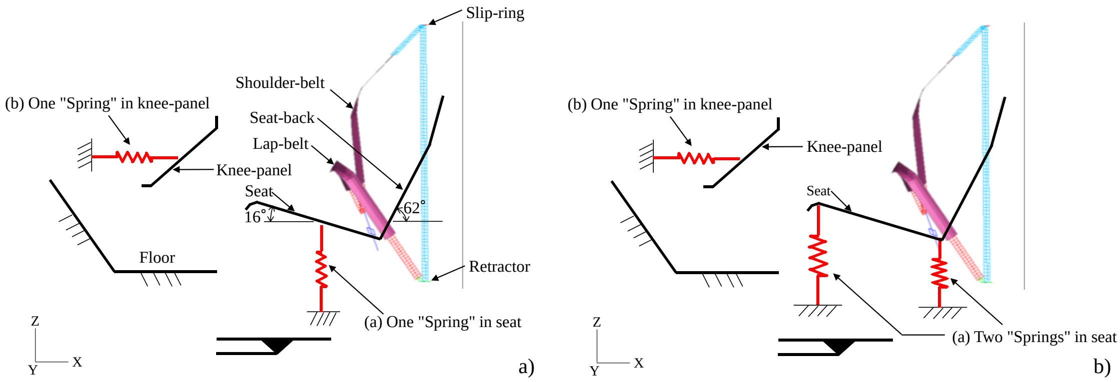

Figure 4. Vehicle cabin model and modified spring model used in this study: (**a**) vertical seat movement and (**b**) lean forward seat movement.

We set two seat movement conditions: (a) vertical movement and (b) lean forward movement. For vertical movement, we assigned one spring in the seat to represent vertical seat movement (Figure 4a). The seat moved vertically downwards according to force-displacement characteristics in one spring model of the seat, as shown in Figure 5a. For lean forward movement, we assigned two springs in the seat to reproduce forward rotation of the seat (Figure 4b). The seat moved downwards together with forward rotation according to force-displacement characteristics in the front spring and back spring models of the seat, as shown in Figure 5b.

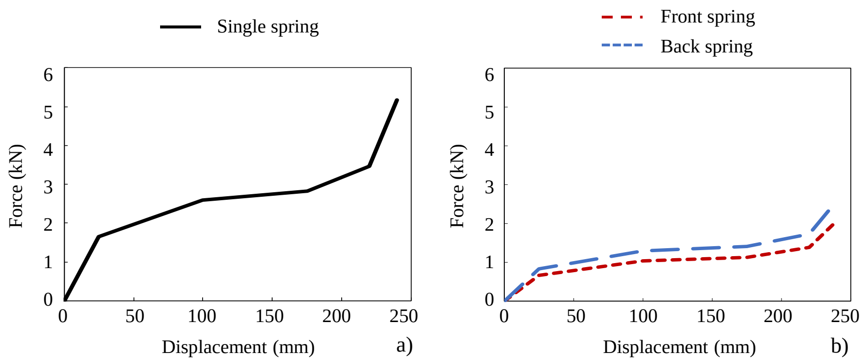

Figure 5. Force-displacement characteristics used in the spring models of the seats: (**a**) vertical seat movement and (**b**) lean forward seat movement.

The knee panel was set to move in the forward direction (x-axis) with an increase in applied forces from the knee through the axial force of the thigh of the AM50 human model. Thus, the knee panel was arranged to move forward, as shown in Figure 6. The initial seat angle and seat-back angle were set to 16° and 62° respectively (Figure 4).

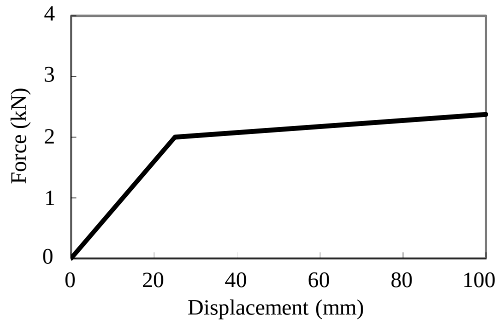

Figure 6. Force-displacement characteristics used in the spring models in the knee panels.

To simulate impact, we used acceleration-time history of the side-sill, which represents the crash pulse of a small-sized sedan—where engine displacement is 1490 cc, curb mass is 1130 kg, and maximum number of passengers is 5—impacting a rigid barrier at 55 km/h according to JNCAP test procedure [16]. Figure 7 shows acceleration and velocity-time-histories applied to the vehicle cabin model in this study. The velocity-time history in Figure 7b was obtained from a single integration of acceleration-time history in Figure 7a. The dummy model was placed in the vehicle cabin model under normal conditions described in the frontal rigid barrier impact test procedure by JNCAP [16]. The vehicle cabin and dummy model are shown in Figure 8. Initial clearance between the knee panel and the AM50 model knee was 70 mm. In this study, the center of the seat height was set 150 mm lower than its original position by force application.

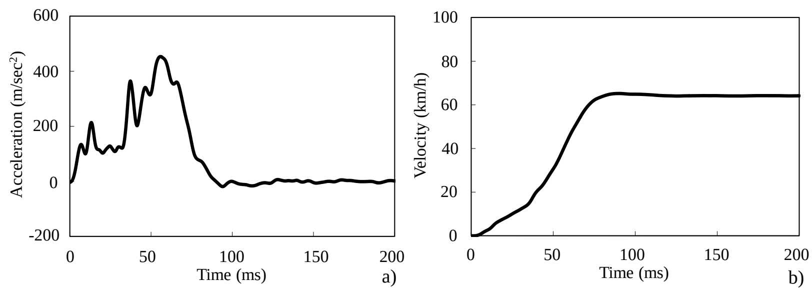

Figure 7. Time-series of (**a**) acceleration and (**b**) velocity applied to the vehicle cabin model.

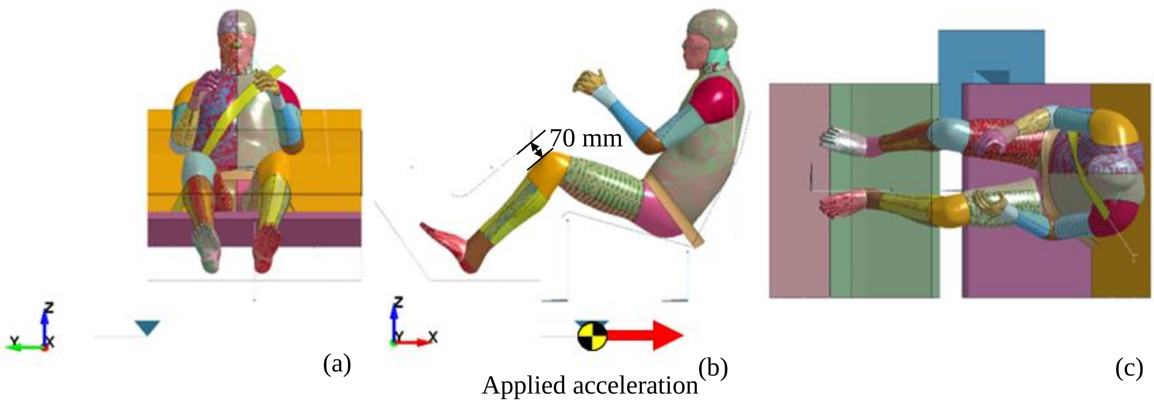

Figure 8. Vehicle cabin and AM50 human models from (**a**) front, (**b**) side, and (**c**) top views.

Under the two seat conditions (vertical movement and lean forward movement), we first investigated dynamic behaviors of the AM50 human model. Next, we observed the instant at which the lap belt detached from an iliac crest. In addition, we investigated movement of the lap belt, as well as tensile force of the lap belt, shoulder belt, and retractor belt (Figure 9) under movable seat height conditions.

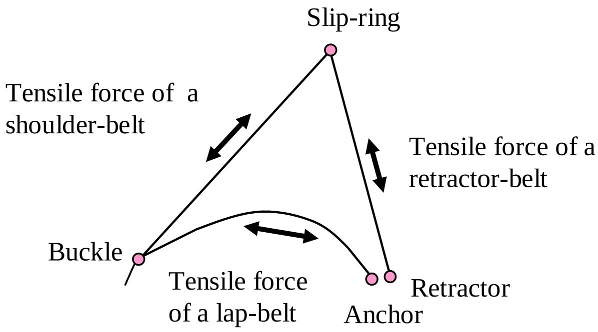

Figure 9. Tensile force activated on various restraining belts.

3. Results

Dynamic behaviors of the AM50 human model under two considered seat conditions are shown in Figure 10. Dynamic movements of the AM50 human model were similar for both seat conditions. Seat angle of the lean forward condition (−4°) was smaller than that of the vertical movement condition (16°) at 90 ms. Dynamic behaviors of the lap belt in the two seat conditions are shown in Figures 11 and 12. In the vertical movement condition, the lap belt detached from the right iliac crest at 80 ms (Figure 12a), but did not detach from the left iliac crest during impact. In the lean forward movement condition, the lap belt detached from the left iliac crest at 75 ms (Figure 12b) and then detached from the right iliac crest at 90 ms (Figure 11b). Thus, the lap belt detached from both iliac crests during the lean forward movement.

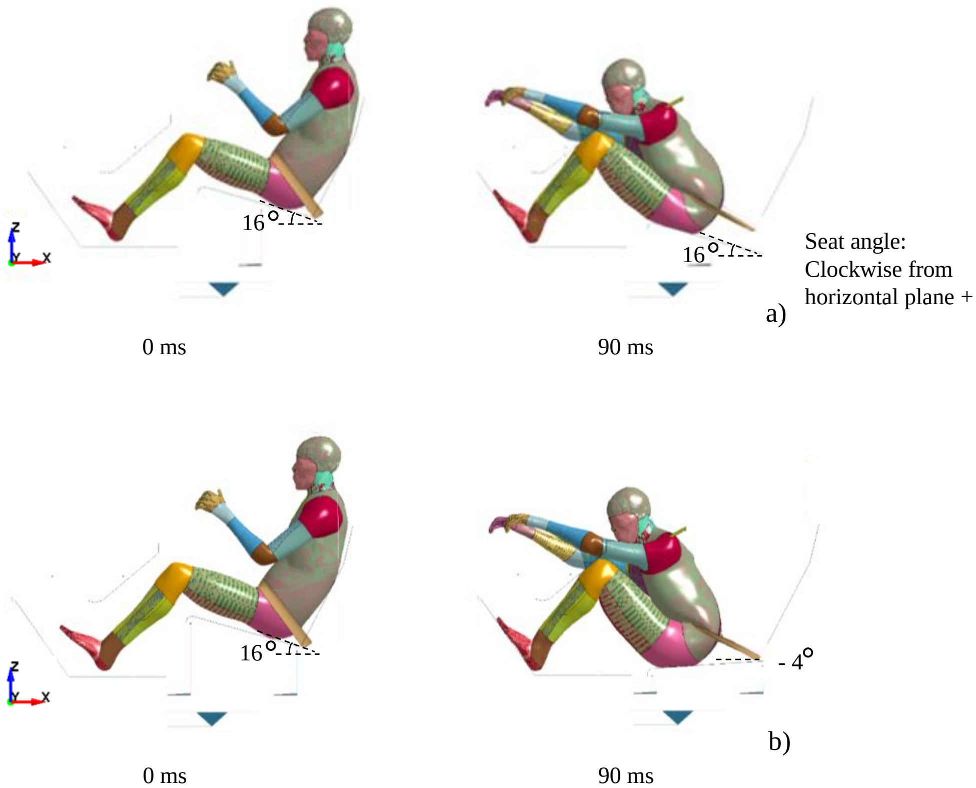

Figure 10. Dynamic behaviors of AM50 dummies under two seat conditions: (**a**) vertical seat movement and (**b**) lean forward seat movement.

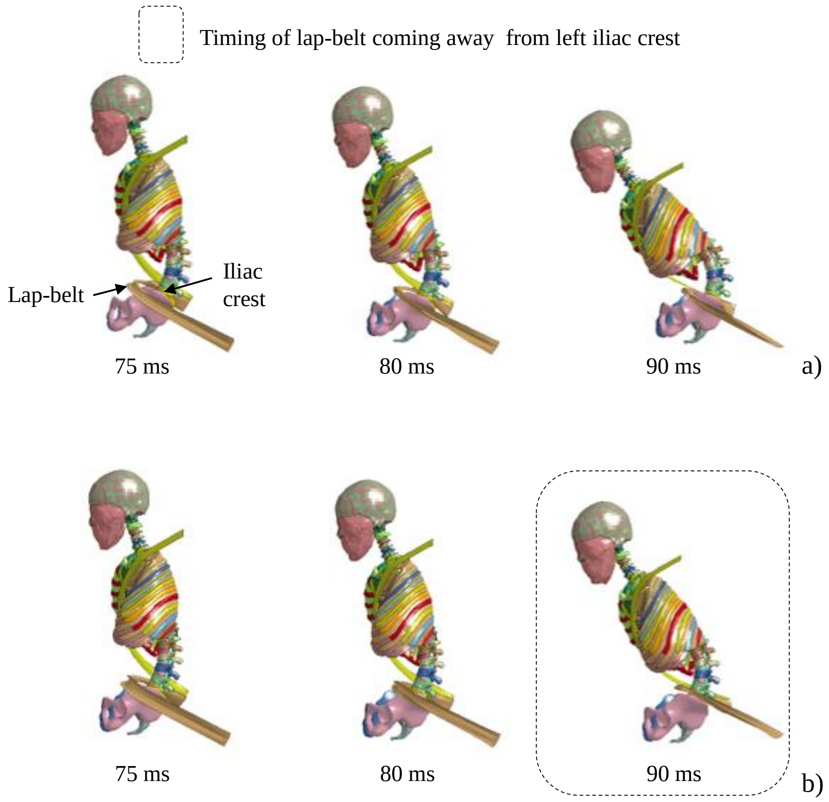

Figure 11. Dynamic behavior of the lap belt under two seat conditions (view from left): (**a**) vertical seat movement and (**b**) lean forward seat movement.

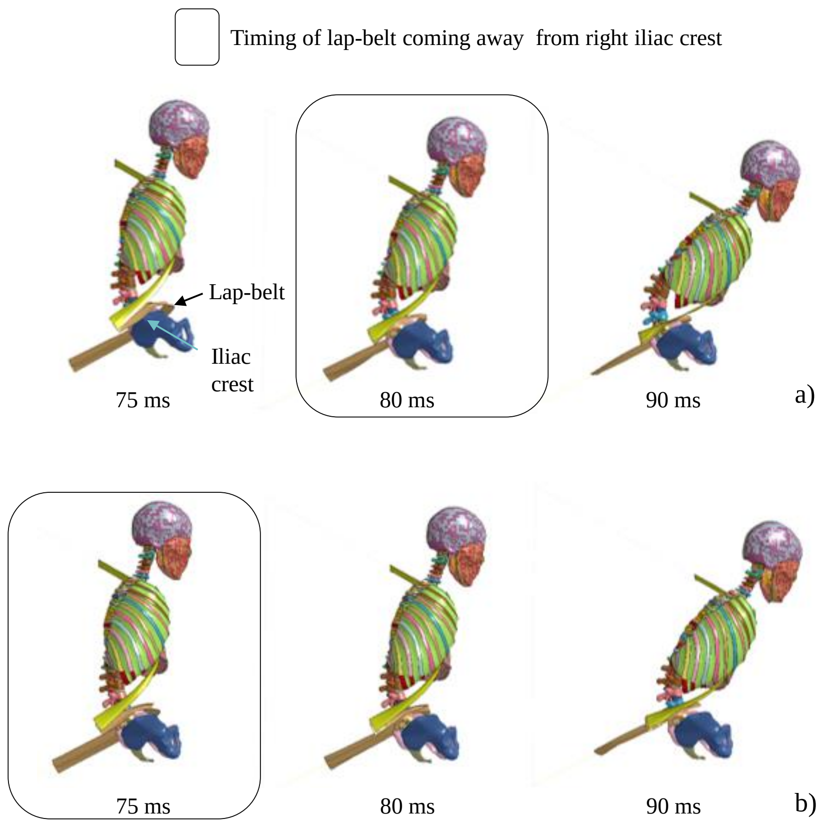

Figure 12. Dynamic behavior of the lap belt under two seat conditions (view from right): (**a**) vertical seat movement and (**b**) lean forward seat movement.

The time-series of seat height at the center of the seat, seat angle, and knee-panel displacement under the two seat conditions are shown in Figure 13. Maximum knee-panel displacement occurred at 75 ms for both vertical movement and lean forward movement (Figure 13c), which occurred 10 ms and 25 ms prior to the maximum seat-height displacement at 85 ms and 100 ms, respectively (Figure 13a). For the lean forward movement condition, the seat angle of 16° at 28 ms decreased to −4° at 102 ms (Figure 13b). For the vertical movement condition, the seat angle remained stable at 16° during impact.

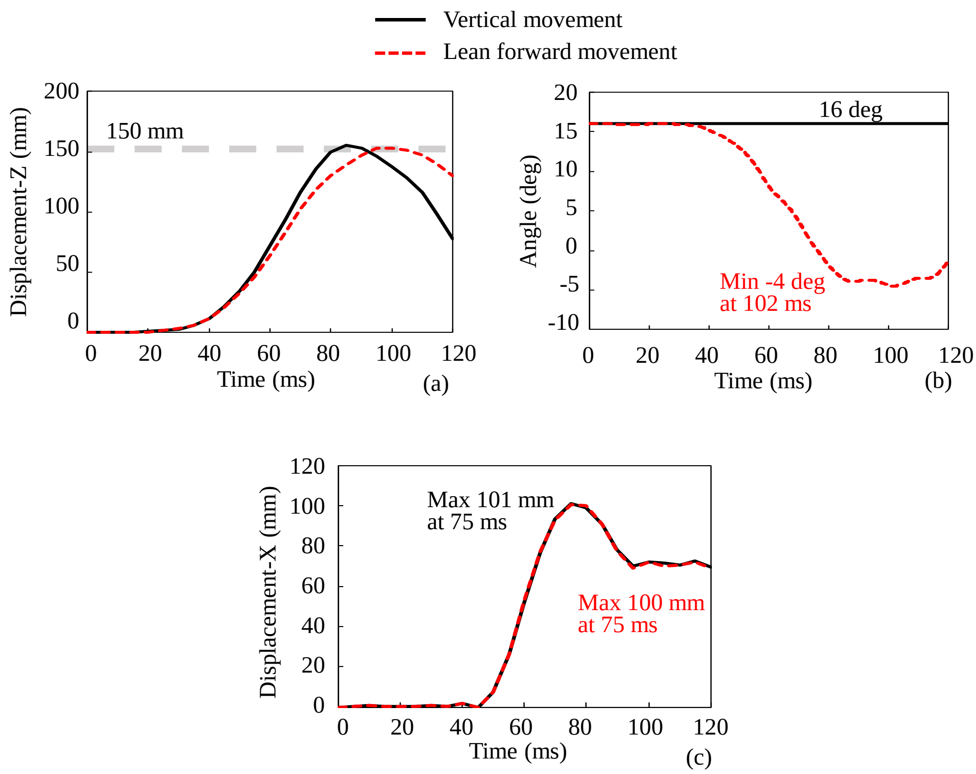

Figure 13. Time histories of (**a**) seat height, (**b**) seat angle, and (**c**) knee-panel displacement under two seat conditions.

Time histories of tensile forces on the retractor belt, shoulder belt, and lap belt are shown in Figure 14. Tensile forces of the retractor belt under two seat conditions were almost consistent (3.3 kN after 51 ms) because the force limiter in the retractor was regulated to 3.3 kN in the three-point seatbelt model. Tensile forces of the shoulder belt in two seat conditions were also almost equal (between 4.2 kN and 4.7 kN after 51 ms) because they were connected to the retractor belt. Tensile forces of the lap belt in two seat conditions were almost consistent prior to 75 ms. Furthermore, maximum tensile forces of the lap belt were similar under the two seat conditions: 9.0 kN for vertical movement and 8.9 kN for the lean forward movement.

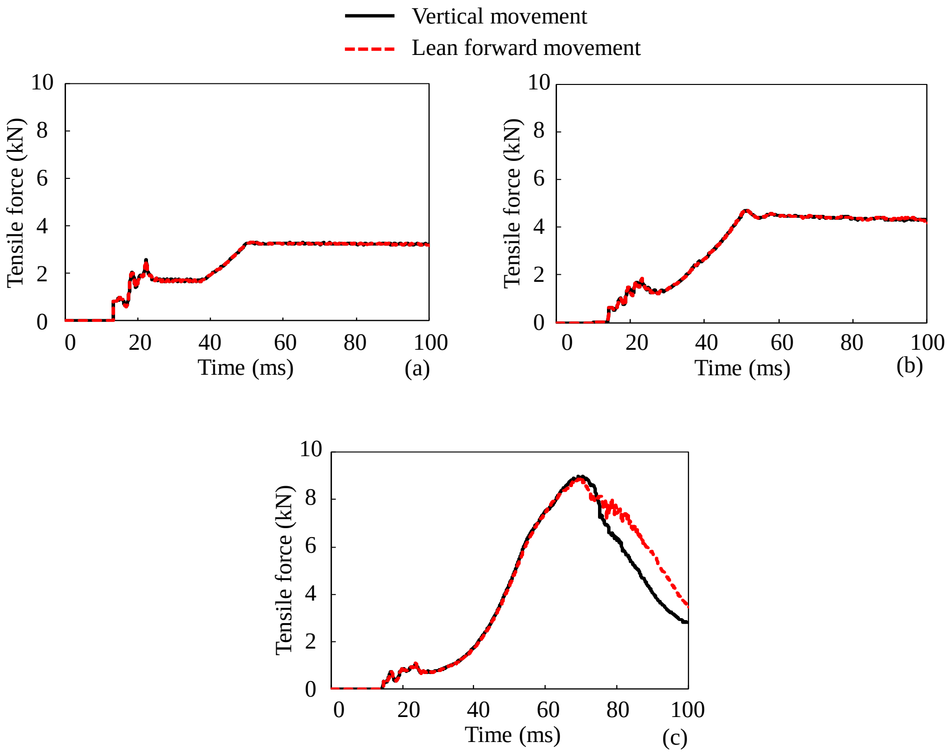

Figure 14. Time histories of the tensile forces on the (**a**) retractor belt, (**b**) shoulder belt, and (**c**) lap belt.

4. Discussion

In this study, we investigated behavior of the seatbelt and AM50 human model under two seat conditions: vertical movement and lean forward movement. Our results indicate that the lap belt detached from both of the iliac crests during the lean forward movement. Under this condition, the lap belt first detached from the left iliac crest at 75 ms and then from the right iliac crest at 90 ms. In addition, under this condition, tensile force of the lap belt reached a maximum (8.9 kN) at 70 ms before decreasing. After the lap belt detached from both of the iliac crests, tensile force of the lap belt reduced more steeply after 90 ms (Figure 15). It was considered that the relatively large contact force would act on the abdomen as a result of the large tensile force generated by the lap belt.

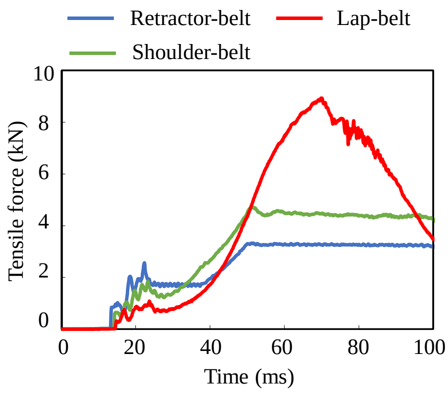

Figure 15. Time history of tensile forces of the seatbelt under the lean forward movement seat condition.

Next, we focused on contact force and deformation to the abdomen of the AM50 human model. In this study, we measured resultant contact force (Fc) applied to the abdomen. Additionally, we measured deformation of the abdomen (D) shown in Figure 16. Deformation of the abdomen is defined as the distance between the abdominal surface corresponding to the center of the lap-belt and the sacrum on the median sagittal plane. The resultant contact force reached a maximum value of 15.0 kN at 70 ms (Figure 17a) and deformation of the abdomen reached a maximum value of 104 mm at 90 ms (Figure 17b). Strain of the deformed abdomen was 68% (=104 mm/154 mm), because the initial distance (D) was 154 mm. These phenomena suggested that a large resultant force was applied to the abdomen, resulting in the lap belt slipping from one iliac crest. After the lap belt slipped from both iliac crests, the abdomen experienced extreme deformation, which indicates possibility for critical abdominal injury.

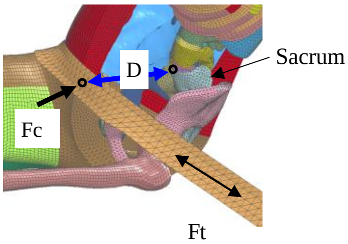

Figure 16. Illustration of the resultant contact force (Fc) between lap belt and abdomen, deformation of the abdomen (D), and tensile force of the lap belt (Ft).

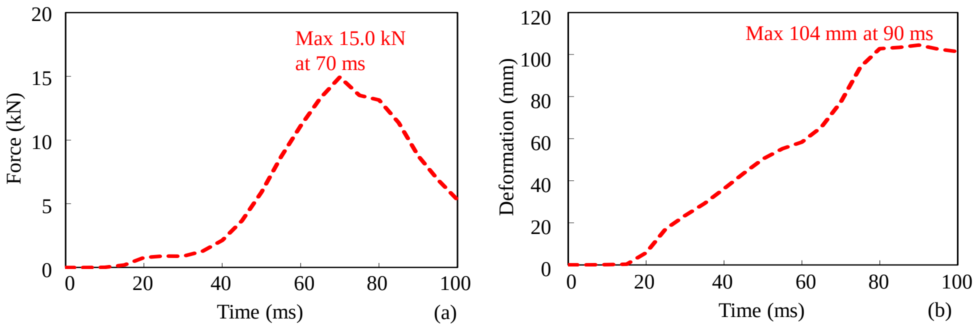

Figure 17. Time history of (**a**) resultant contact force (Fc) and (**b**) deformation of the abdomen (D) under lean forward movement conditions.

The definition and time history of the vertical distance of lap belt movement are shown in Figure 18. The lap belt slipped upwards by a maximum distance of 4 mm at 50 ms and maintained this upward movement until 80 ms. We consider that although slipping distance was small, the pelvis could be rotated forward along with the lean forward movement of the seat from the initial seat angle of 16°. Time history of the seat angle indicates that it reached 0°, i.e., a horizontal condition, at 76 ms and 4° at 90 ms (Figure 13b). During these periods, the iliac could be rotated forward, leading to slipping of the lap belt from the iliac crests.

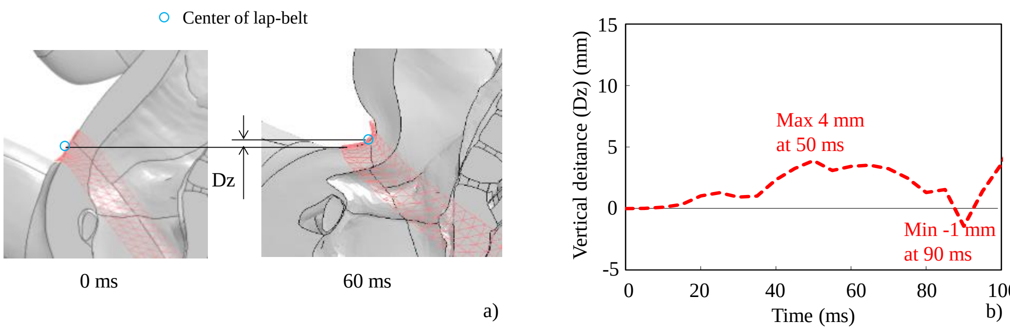

Figure 18. Definition and time history of vertical distance (Dz) of lap belt movement: (**a**) definition and (**b**) time history.

Results indicated that the lap belt detached more easily from the iliac crests during the lean forward movement. A photograph of the front passenger seat after the full-frontal rigid barrier impact test exhibits residual deformation of the frontal edge of the seat (Figure 2). A similar residual seat deformation was observed in car-to-car real-world frontal impact accidents [7]. Based on this residual seat deformation, a seat would be rotated during frontal impact to a car. Thus, the lean forward movement condition is estimated to be similar to the deformation situation generated by real-world accidents. Findings of the present study suggest that to evaluate an occupant's behavior in detail in future work, a seat model considering rotation should be incorporated into the vehicle cabin model when simulations are performed.

In this study, we noted that the lap belt detached from both iliac crests during lean forward movement when two springs were used in the seat model and one spring used in the knee-panel model. We believe that our results derived using springs are consistent with those obtained using finite element models of the seat and knee panel. Finite element models of the seat can represent deformation of the cushion and framework structure in detail and can be compared with force-displacement spring characteristics. In the same manner, finite element models of the knee panel can represent details of deformation of the rib structure with relatively more or less rigid parts. Thus, in the future, finite element analyses of the seat and knee panel should be performed to understand these phenomena in more detail.

In our method, we employed limited conditions: only two seat deformable conditions (vertical movement and lean forward movement), one frontal impact situation (full-frontal rigid barrier impact test at 55 km/h), one passenger car (engine displacement of 1490 cc), without airbag deployment, and an AM50-sized human model. However, for the case of airbag deployment, correlation between pelvis and lap belt movement would be different than that obtained in this study, because airbag deployment may prevent movement of the head and upper body of a human during impact. In addition, when we consider an initial seating condition, an occupant may wear a seatbelt with some amount of looseness. Under such conditions, the lap belt may detach from the iliac crests. In the future, simulation must be carried out considering a combination of factors such as forward rotation and looseness of the seat belt, by employing a wide variety of crash types and occupant seating conditions. Subsequently, a statistical analysis can be applied to develop the extracted results.

Another limitation of the present study is that we performed simulations considering only an AM50-sized human model because current safety assessment tests usually involve performance of the full frontal rigid barrier impact test of the Japanese type approval test, using an AM50 dummy. However, people of several different sizes and body shapes may ride in vehicles. In the future, in combination with the AM50 sized human model, data of 95 percentile males and 5 percentile females should be used to represent large male and small female occupants when conducting such simulations in studies focusing on lap belt movement.

5. Conclusions

We investigated the correlation between downward movement conditions of the seat and movement of the lap belt away from both iliac crests of a human occupant in the passenger seat during a frontal impact, by using an AM50 human model. We employed two deformable seat conditions: vertical movement and lean forward movement. The major finding was that the lap belt detached from both of the iliac crests during the lean forward movement of a seat, whereas the lap belt detached from only one of the iliac crests during vertical movement. We conclude that abdominal injuries can be caused by downward movement together with forward rotation in the seat during vehicle-to-vehicle frontal impacts. The finding of the present study suggests that when simulations are performed to evaluate the occupant's behavior in detail, in the future, a seat model considering rotation should be incorporated into the vehicle cabin model. Abdominal injury simulations considering different model sizes of vehicle occupants must be considered along with various crash types and occupant seating conditions. Furthermore, in the future, it is necessary to develop a design of a seat or a seat belt, such that the seat does not rotate during frontal impact.

Author Contributions: Conceptualization, Y.M.; investigation, S.O.; writing-original draft, Y.M.; writing-review and editing, S.O.

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Conflicts of Interest: The authors declare no conflict of interest.

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