Study of Lower Extremity Injury sustained by Passenger in Various Seating Positions during Frontal Collisions

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Abstract In the context of the increasing adoption of virtual testing in various new car assessments, evaluations of diverse crash speeds, dummy types and seating positions during frontal collisions are being considered. In this study, Hybrid III 50th percentile male dummy (Hybrid III dummy) and THUMS 50th percentile male (THUMS) were seated in different seat positions and the behaviour and response of the lower extremity were investigated. Physical sled tests using Hybrid III dummy were conducted at mid seat slide position and rear-most position. CAE analysis was conducted for both Hybrid III dummy and THUMS for different seat positions. The results showed that when the seat was positioned in the rear-most position at the sled test, the Tibia Index (TI) at Hybrid III dummy lower leg, which is an indicator of tibia injury, significantly increased and exceeded the tolerance value compared with the mid position (mid position: TI = 0.26, rear-most: TI=1.10). An increase of the TI was also confirmed for the Hybrid III dummy in the CAE sled model (mid position: TI = 0.35, rear-most: TI = 1.60). In the case of THUMS, while the tibial moment increased from 77 Nm (mid position) to 164 Nm (rear-most position), it remained below the tolerance value (225 Nm). Both Hybrid III dummy and THUMS displayed planter flexion behavior at the ankle. It was found that the occurrence of ankle lock for plantarflexion in the Hybrid III dummy was the reason for the large increase in the Tibia Index in the rear-most seat position. The ankle lock angle in plantarflexion for the Hybrid III dummy (123 degrees) was smaller compared to the human ankle range of motion of 135 degrees. This study shows the necessity for further research on lower extremity evaluation in rearward seating positions where ankle plantarflexion occurs.

Keywords Ankle motion range, frontal collision, human body model, Hybrid III dummy, lower extremity injury.

I. INTRODUCTION

Many studies have been conducted on lower extremity injuries. Begeman *et al.* [1] investigated the tolerance of ankle dorsiflexion during foot impact and found that the maximum dorsiflexion of 45 degrees did not sustain any injuries. Based on this study, the design of the Hybrid III dummy ankle was modified to allow movement up to 45 degrees with soft stop [2]. Currently, the Tibia Index is used as an index to evaluate the risk of injury to the ankle and lower leg. This index is calculated by adding up the tolerance ratios of moment and axial force. Reducing the moment by maintaining the kinematics of leg and foot within the range of ankle tolerance angle during a collision may help reduce the injury risk.

Recently, virtual testing has been making an impact on assessments in the real world. Diverse evaluation conditions are now being considered to supplement existing tests. The European New Car Assessment Program (Euro NCAP) introduced frontal collision virtual testing with diverse crash speed and dummy size [3]. Seat position is also being considered as one of the factors of diversity in various new car assessments. In order to evaluate the injury risk of occupants, it is important to understand how HIII dummy and human body behave in different seat positions. This study aims to investigate occupant kinematics and injury responses of the lower extremity in rearward seating position in frontal collision. Hybrid III 50th percentile male and THUMS 50th percentile male were used to confirm differences between the ATD and HBM.

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II. METHODS

Sled Testing with Hybrid III 50th percentile male dummy

Two sled tests were conducted using the front passenger seat of small SUV with a 56 km/h frontal collision condition. The sled test vehicle consisted of Body In White, passenger seat, three-point seat belt, passenger airbag and instrument panel. Hybrid III dummy was positioned according to China NCAP protocol [4]. A 56 km/h frontal collision pulse was used from an in-house full vehicle test. As shown in Table I, the tests were conducted using two seating positions: (1) Mid and (2) Mid + 120 mm (rear-most). Response of lower extremity and Tibia Index were investigated for both positions. Feet of dummy were placed along the floor, as shown in Fig. 1. In the rear-most position, the dummy was moved 120 mm rearward while maintaining the posture from position (1), and the feet were again placed along the floor, as shown in Fig. 2.

TABLE I
TEST MATRIX

	Sled test 1	Sled test 2
Vehicle	Small SUV	Small SUV
Seat	Passenger	Passenger
Collision pulse	In-house 56 km/h FRB	In-house 56 km/h FRB
Occupant	Hybrid III dummy	Hybrid III dummy
Seat position	Mid	Mid+120 mm Rear-most

Fig. 1. Overview of dummy installation (Sled test 1).

Fig. 2. Overview of dummy installation (Sled test 2).

Sled Simulation Modelling with Hybrid III 50th percentile male dummy

In this study, simulations were performed using Ansys LS-DYNA R11.2 solver and Fujitsu PrimeCX52550M4 hardware. The dummy model used was "HARMONIZED HYBRID III 50M DUMMY LS-DYNA MODEL RELEASE VERSION 1.7" released by Humanetics Innovative Solutions, Inc.. Figure 3 shows an overview of the simulation models. The simulation models were created consisting of Body In White, passenger seat, three-point seat belt, passenger airbag and instrument panel, in the same parts as the sled test. The same 56 km/h frontal rigid barrier collision (FRB) pulse was used, as in the sled test. There were four seating position configurations in the simulations as described in Table II: (1) Mid, (2) Mid + 40 mm, (3) Mid + 80 mm and (4) Mid + 120 mm (rear-most). The dummy maintained the same posture as in the mid-position case, while the seat itself was moved backward without changing the angles of the lower extremities of the dummy. The seatbelt was adjusted after the position change in each case. Detailed posture information is shown in Appendix A. Injuries of head, neck and chest, as well as responses of the lower extremity and Tibia Index, were investigated in order to analyse phenomena of dummy in the sled test in detail.

TABLE II
SIMULATION MATRIX OF HIII DUMMY

	Simulation 1	**Simulation 2**	**Simulation 3**	**Simulation 4**
Vehicle	Small SUV	Small SUV	Small SUV	Small SUV
Seat	Passenger	Passenger	Passenger	Passenger
Collision pulse	In-house 56 km/h FRB	In-house 56 km/h FRB	In-house 56 km/h FRB	In-house 56 km/h FRB
Occupant	Hybrid III dummy	Hybrid III dummy	Hybrid III dummy	Hybrid III dummy
Seat position	Mid	Mid + 40 mm	Mid + 80 mm	Mid + 120 mm Rear-most

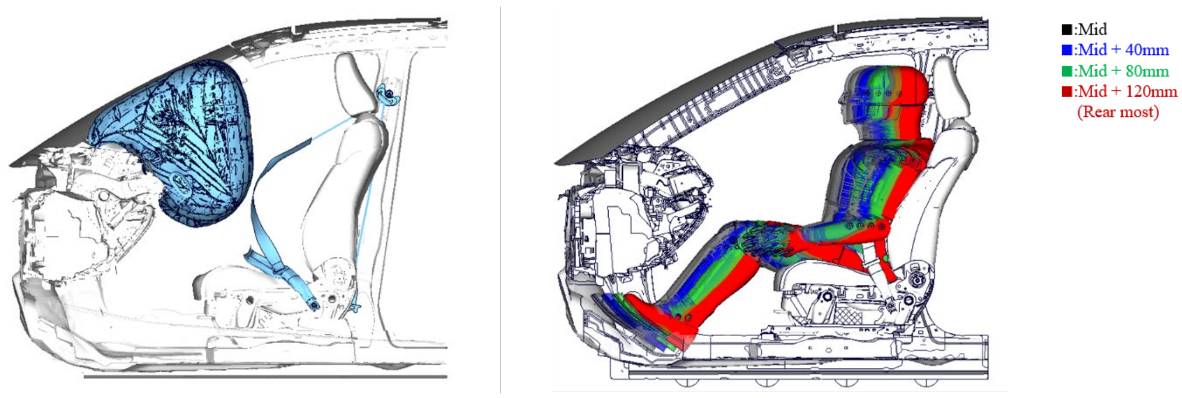


Fig. 3. Overview of simulation model.

Sled Simulation Modelling with THUMS 50th percentile male

To confirm lower extremity behaviour and response of the lower extremity of the HBM, THUMS 50th percentile male version 7 was positioned in the simulation sled model used for the Hybrid III dummy study (Fig. 4). The lower leg moment was used as the injury metric of the THUMS. The moment was extracted from the cross-section of the leg including the tibia, fibula and soft tissue defined at 110 mm upper away from the ankle (distal end of fibula). The location of the cross-section of the THUMS lower leg coincides with the load cell of the HIII dummy lower leg. Positions of hip point, head centre of gravity, heel and knee (lateral position) of THUMS were aligned to those of Hybrid III dummy (Fig. 5). The detailed posture information of THUMS is shown in Appendix A. Simulations were performed with two configurations of seat position as shown in Table III: (1) Mid, and (2) Mid + 120 mm (rear-most).

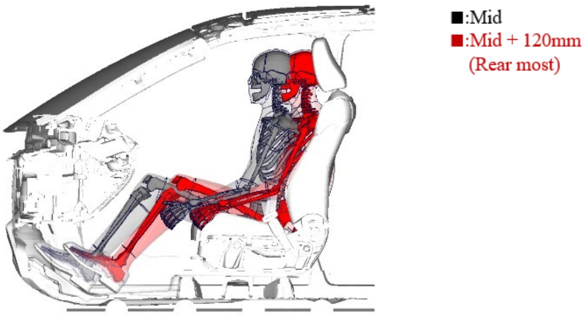


Fig. 4. Overview of simulation model with THUMS.

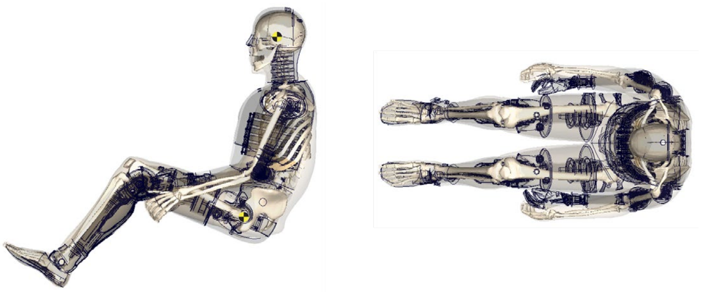


Fig. 5. Posture comparison of dummy and THUMS.

TABLE III
SIMULATION MATRIX OF THUMS

	Simulation 1	Simulation 2
Vehicle	Small SUV	Small SUV
Seat	Passenger	Passenger
Collision pulse	In-house 56 km/h FRB	In-house 56 km/h FRB
Occupant	THUMS	THUMS
Seat postion	Mid	Mid + 120 mm Rear-most

III. RESULTS

Hybrid III 50th percentile male dummy

Results of sled test 1 (Mid) and 2 (rear-most) with Hybrid III dummy are shown. Regarding lower extremity injuries, Tibia Index (Left Lower) is shown in Fig. 6: 0.26 for sled test 1 (Mid) and 1.10 for sled test 2 (rear-most). Sled test 2 (rear-most) indicated a higher value of Tibia Index, which also exceeded 1.0. Additionally, it was confirmed that the main input was Y moment.

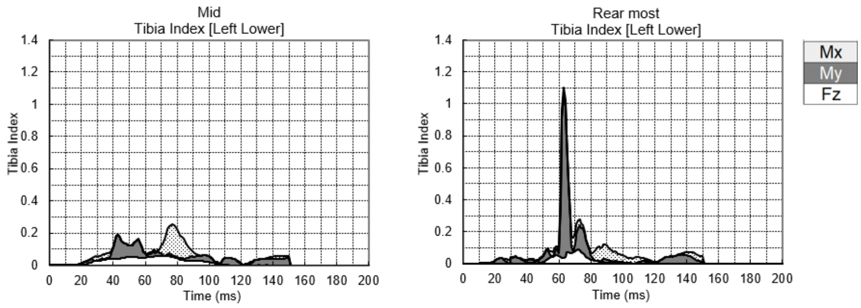


Fig. 6. Tibia index of Hybrid III dummy in sled test.

Detailed analysis of the phenomenon was conducted using the sled simulation results.

Model Validation

Figure 7 (a) and (b) show the comparison between test and CAE response of the head, chest and pelvis G response in the case of mid position (a) and rear-most position (b). The highest peak G and lowest displacement was observed at the pelvis in both test and CAE. The largest displacement was observed at the head in both test and CAE. The change of the seat from the mid position to the rear-most position (+120 mm) resulted in an increase of 25 mm in the test and 42 mm in the CAE in the pelvis displacement. The entire trend of CAE estimation coincided with the test results described above.

Fig. 7 (a) Comparison between test and CAE of G response of Head, Chest and Pelvis in Mid position.

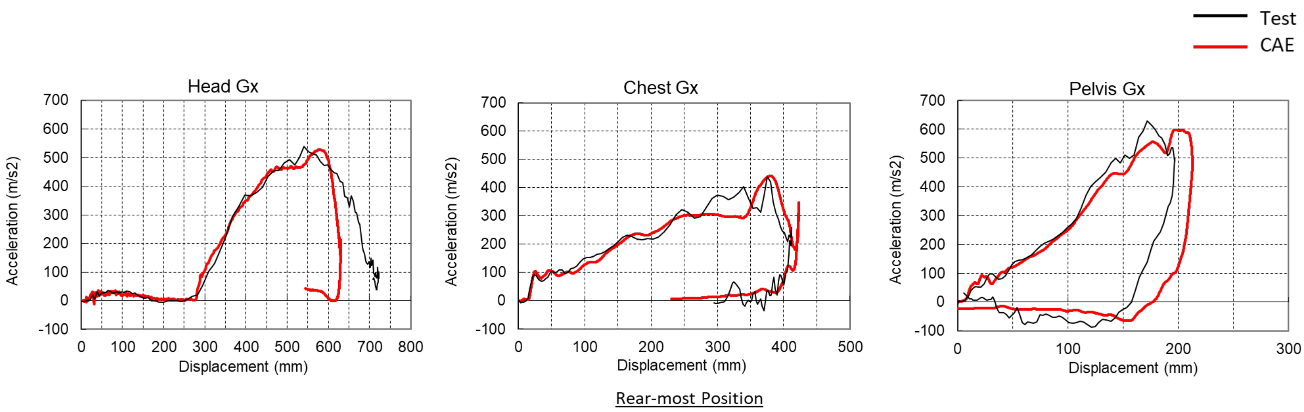


Fig. 7 (b) Comparison between test and CAE of G response of Head, Chest and Pelvis in Rear-most position.

Figure 8 (a) and (b) show the comparison between test and CAE response of the Tibia Index response of the lower legs vs time history in the case of mid position (a) and rear-most position (b). In the case of mid-position, an obvious increase of the Tibia Index was not observed during the impact in the test, while the initiation of the Tibia Index increase was observed at around 50 ms in the CAE. In the case of the rear-most position, a rapid increase of the Tibia Index was observed for left and right legs around 55 ms and reached the peak value exceeding the tolerance value 1.0 in both test and CAE cases. Even though the peak value of Tibia Index estimation of CAE did not coincide with the test result, the CAE model estimated the trend of Tibia Index response in seat position change.

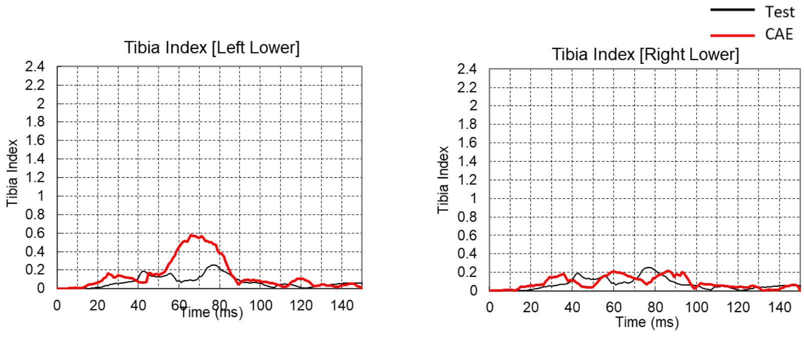


Fig. 8 (a) Comparison between test and CAE of G response of Tibia Index in Mid position.

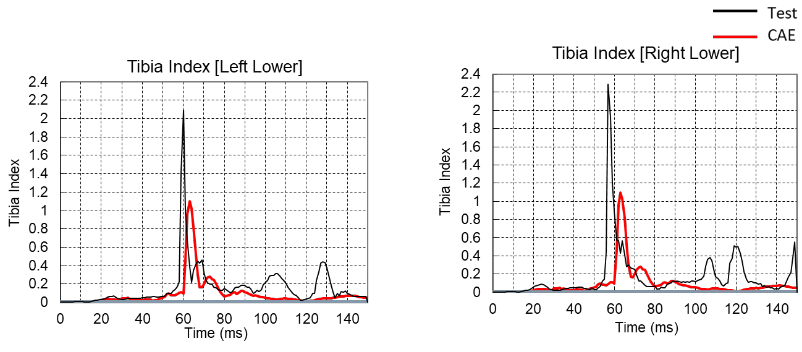


Fig. 8 (b) Comparison between test and CAE of G response of Tibia Index in Rear-most position.

Dummy Kinematics

Comparison of acceleration of the dummy's head, chest, and pelvis in simulation is shown in Fig. 9. When the dummy was seated in rearward position, head and chest moved away from airbag. Displacement of the head and chest increased due to delay of contact timing with the airbag after deployment. For the pelvis, distance from the instrument panel to lower extremity increased in rearward position. Displacement of the pelvis increased due to delay of contact timing, or no contact, between the lower extremity and instrument panel.

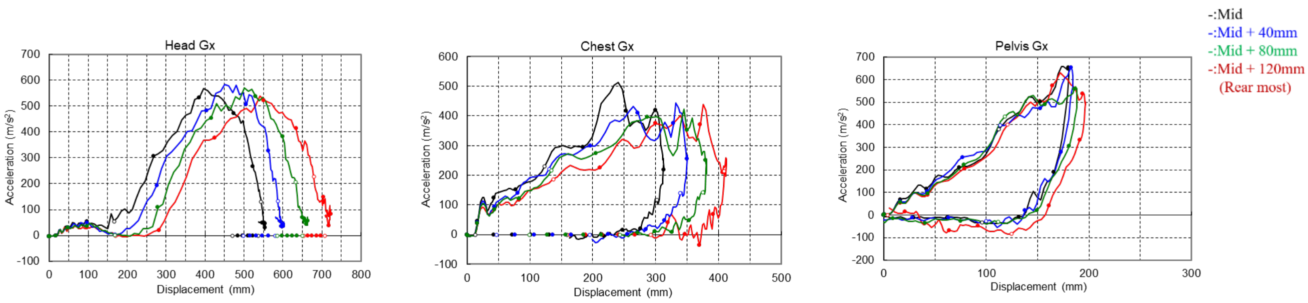


Fig. 9. Comparison of G response of Head, Chest and Pelvis.

Injury Metrics

Results of injury values for four simulation cases are summarised in Fig. 10. Each injury value was compared by dividing it by maximum score limit according to China NCAP protocol. Differences in Tibia Index are significant compared to other metrics. Tibia Index increased when the dummy was seated in rearward position. In the two cases of +80 mm and +120 mm (rear-most), a sharp increase in the Tibia Index was observed, similar to the sled test results. It was confirmed that Y moment was the main component (Fig. 11). The foot behaviour at Tibia Index maximum timing is shown in Fig. 12. In the two cases of +80 mm and +120 mm (rear-most), ankle rotation in plantarflexion direction was observed. It is considered that the cause of the sharp increase of Y moment in these two cases was due to ankle locking in plantarflexion mode. The cause of the plantarflexion mode was that the legs moved forward and knee extended due to sufficient distance before the foot reached the dash panel. Similar foot angles are seen in Fig. 13, while leg angles are different. From the structure of the dummy, it is considered that the ankle lock angle in plantarflexion mode is 123 degrees ± 2 degrees [5]. Two cases of +80 mm and +120 mm (rear-most) reached the lock angle.

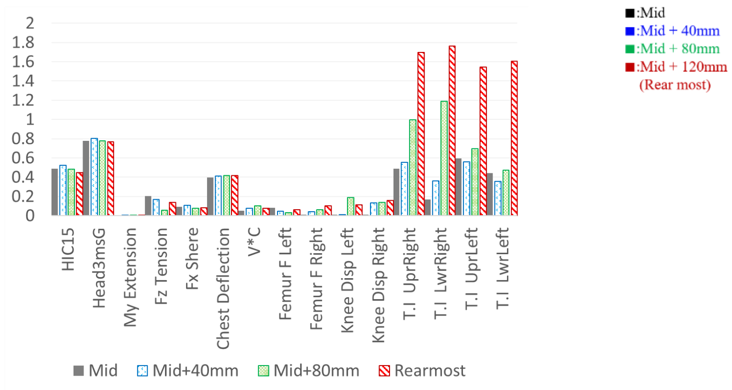


Fig. 10. Summary of injury value.

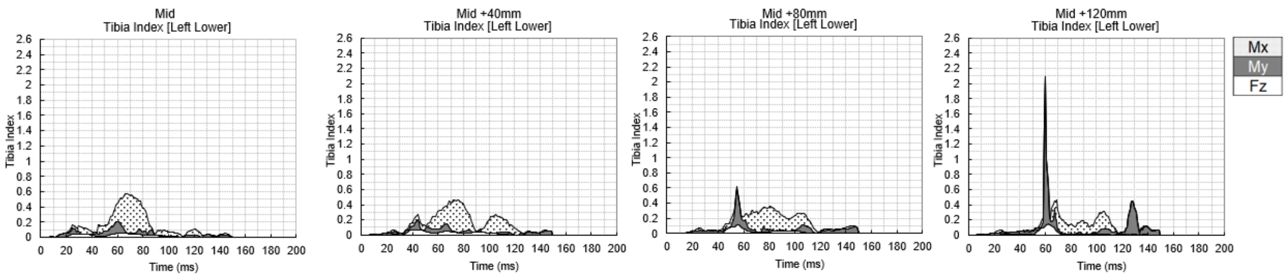


Fig. 11. Tibia Index in simulation with Hybrid III dummy.

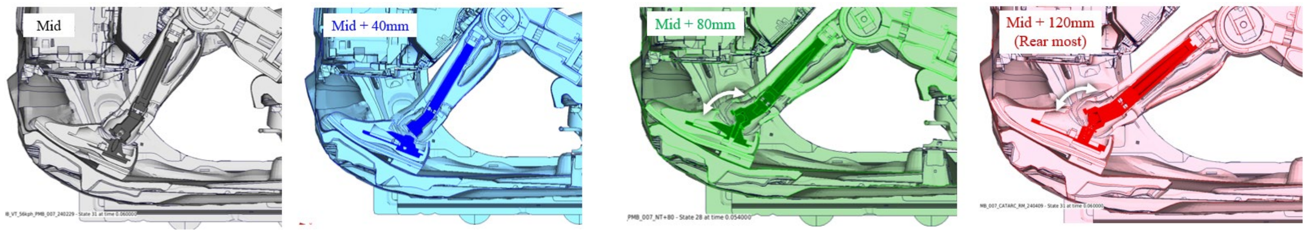


Fig. 12. Behaviour of lower extremity in simulation with Hybrid III dummy.

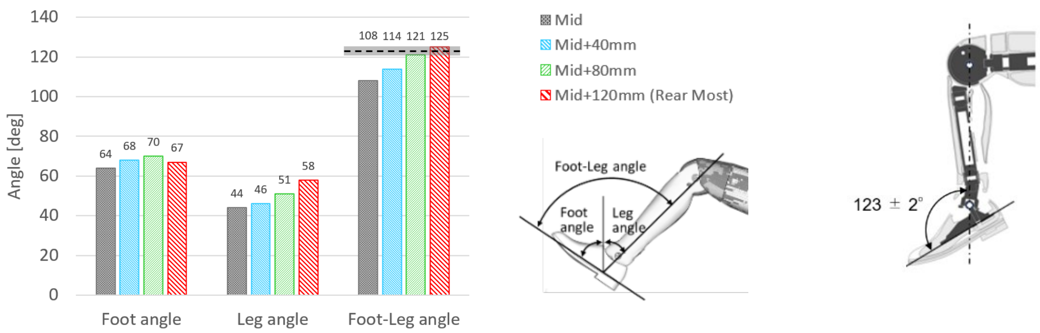


Fig. 13. Summary of foot and leg angles.

THUMS 50th percentile male

Behaviour of THUMS

Comparison of acceleration of the head, chest and pelvis of THUMS is shown in Fig. 14. When THUMS was seated in rearward position, the head and chest moved away from the airbag. Displacement of the head and chest increased due to delay of contact timing with the airbag after deployment. For the pelvis, distance from the instrument panel to the lower extremity increased in the rearward position. Displacement of the pelvis increased due to delay of contact timing between the lower extremity and instrument panel. These results confirm that the same trends of behaviour differences were seen with the dummy.

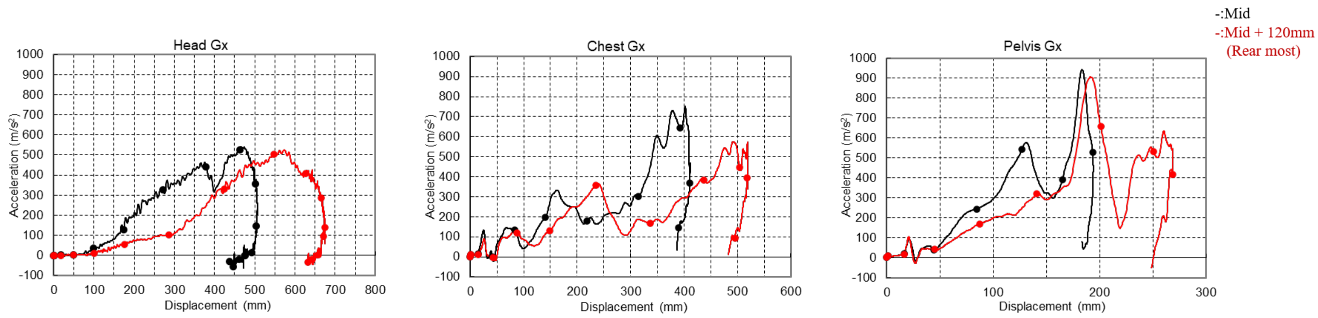


Fig. 14. Comparison of G response of Head, Chest and Pelvis.

Moment of lower extremity

Left lower tibia Y moment, which showed significant changes in the dummy study, was 77 Nm in simulation 1 (Mid) and 164 Nm in simulation 2 (rear-most) for THUMS. The sharp increase in Y moment due to rearward seating was not confirmed (Fig. 15). Foot-leg angle was 108 degrees in simulation 1 (Mid) and 119 degrees in simulation 2 (rear-most), with larger plantarflexion mode occurring in the rear-most position (Fig. 16). While the foot angles were similar, at 69 degrees in simulation 1 (Mid) and 70 degrees in simulation 2 (rear-most), difference was confirmed for the leg angles, at 39 degrees in simulation 1 (Mid) and 49 degrees in simulation 2 (rear-most). Similar to the behaviour observed in the dummy study, increase of distance before the foot contact to dash panel in the rearward seating caused the leg to move forward and the knee to extend. Sharp increase of Y moment was not confirmed as seen in the dummy study, because foot-leg angle of THUMS in both simulations were within range of ankle tolerance angle. The ankle tolerance angle of THUMS is considered to be approximately 135 degrees [6], equivalent to that of human body.

Analysis of the mechanism for Y moment generation in THUMS tibia showed that Z force from the floor caused the Y moment with offset of the curved tibia as moment arm. Larger Z force increased Y moment in rear-most position compared to mid position. This is because the higher velocity of the foot when contacting the dash panel caused larger contact force from the floor to the foot (Figs 17–19). The comparison between the Hybrid III and THUMS of relative velocity and contact force between the left foot and dash panel for mid position and for rear-most position are shown in Appendix B1. The peak foot velocity of THUMS was higher than that of Hybrid III dummy. (THUMS: 4.1 m/s for mid-position and 10.0 m/s for rea-most position, Hybrid III: 2.4 m/s for mid position and 7.5 m/s for rear-most position). On the other hand, the peak contact force of THUMS was lower than that of Hybrid III dummy. (THUMS: 2.9 kN for mid-position and 4.9 kN for rea-most position, Hybrid III: 3.9 kN for mid position and 8.0 kN for rear-most position). The lower contact force generated in THUMS was presumed due to the flexibility in the lower leg (tibia and fibula), while the Hybrid III dummy's leg behaves more stiffer response.

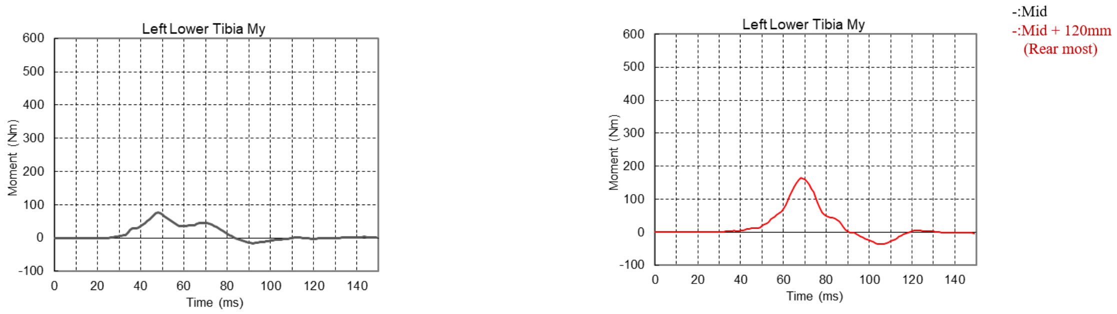


Fig. 15. THUMS tibia moment (My).

Fig. 16. Behaviour of THUMS lower extremity.

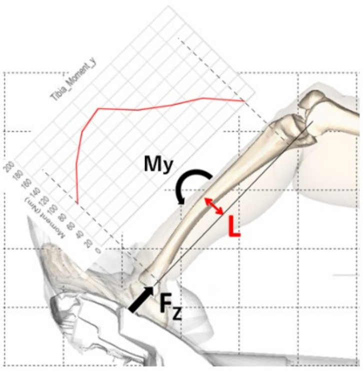


Fig. 17. Mechanism of Y moment generation on THUMS lower extremity.

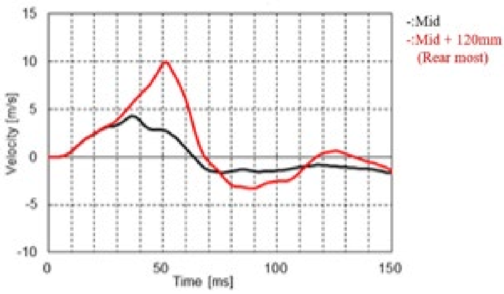


Fig. 18. Comparison of foot velocity

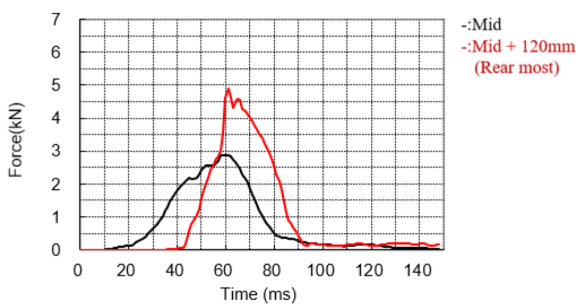


Fig. 19. Comparison of contact force between THUMS foot and floor

IV. DISCUSSION

Hybrid III 50th percentile male dummy vs. THUMS

Figure 20 shows the comparison of Y moment of the lower extremity for Hybrid III and THUMS. In the Hybrid III dummy, the locking of the plantarflexion mode caused high Y moment. By comparison, in THUMS the Y moment was generated as a result of Z force, despite the occurrence of plantarflexion mode. This is because the foot-leg angle of the dummy reached 121 degrees, which caused locking, while the foot-leg angle of THUMS did not reach the maximum angle of ankle motion range. Ankle motion range of THUMS is considered to be approximately 135 degrees, similar to that of human body, which is larger than that of the dummy. Additionally, the foot-leg angle of THUMS (rear-most) is 119 degrees, which is smaller compared to the dummy (rear-most), at 125 degrees, and remaining within the ankle motion range. The foot angles of the dummy and THUMS are comparable, with 67 degrees for the dummy and 70 degrees for THUMS. However, the leg angle of THUMS is 49 degrees, which is smaller compared to the dummy at 58 degrees (Fig. 21). This difference is considered to be due to THUMS having larger pelvis stroke, which reduced knee extension. Deformation of soft tissue of THUMS' pelvis is considered to lead to less restriction of the pelvis by the lap belt (Fig. 22).

These findings show that the rearward seating position is likely to generate plantarflexion of ankle, which might cause high Y moment of lower extremity with Hybrid III dummy due to ankle locking. Therefore, evaluation with rearward seating position may lead to an overestimation of the lower extremity injury risk. This study is limited to the male 50% size occupant and uniaxial frontal sled conditions. Further research is needed on the possibility of lower extremity injuries to occupants at the rear-most position of the passenger seat, as revealed in this study. Parenteau et al. [7] focused on foot-ankle injuries and conducted the accident analysis in the field. The occurrence of lower extremity injuries showed the same trend regardless of the driver's or passenger's seat position, but no mention was made of the seat's fore-aft position. It is important to investigate the actual state of lower extremity injuries to passenger seat occupants in the field accident. Understanding the injury mechanism and injury threshold in plantarflexion of the human ankle is necessary, and for this, bio-fidelity of impact response in plantarflexion is required in ATDs and Human Body Models. This points to the necessity of further research on lower extremity evaluation in rearward seating position.

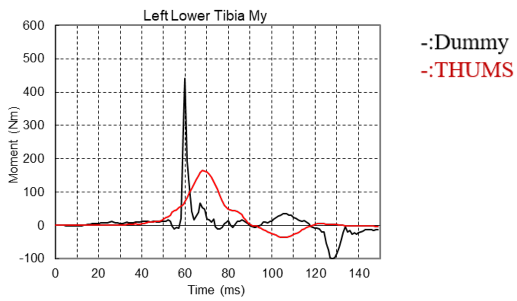


Fig. 20. Moment (My) of lower extremity in rear-most position.

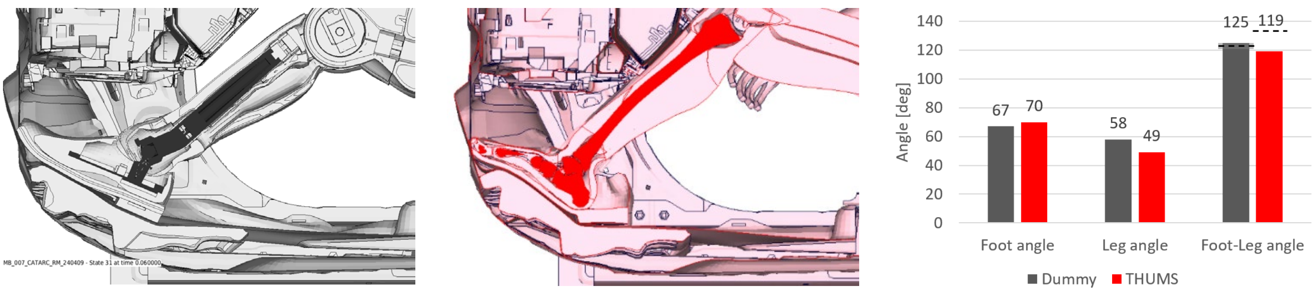
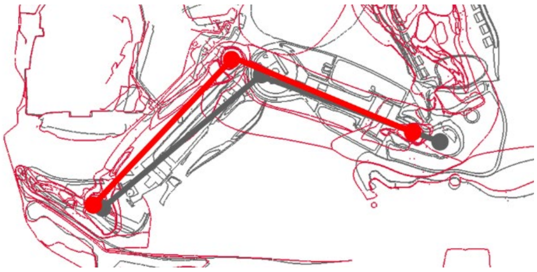


Fig. 21. Behaviour of lower extremity.



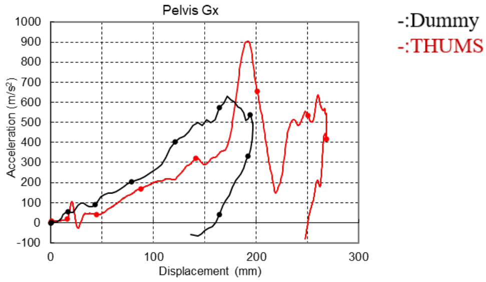


Fig. 22. Comparison of leg and pelvis movement.

V. CONCLUSION

The objective of this study was to focus on differences in passenger seat positions with a 50th percentile male occupant in a frontal collision, investigated through physical sled tests with dummy and simulations with dummy and THUMS. Ankle rotation towards plantarflexion was observed when dummy was seated in rearward seat positions from mid travel position. Study of sled tests at mid +120 mm (rear-most) and simulations at mid +80 mm and mid +120 mm (rear-most) with dummy showed a sharp increase of tibia Y moment and Tibia Index. This is considered to be due to locking of ankle in plantarflexion mode. On the other hand, there was no sharp increase of tibia Y moment although similar plantarflexion mode was observed with THUMS. This is likely due to the difference of ankle motion range and leg angle between dummy and THUMS.

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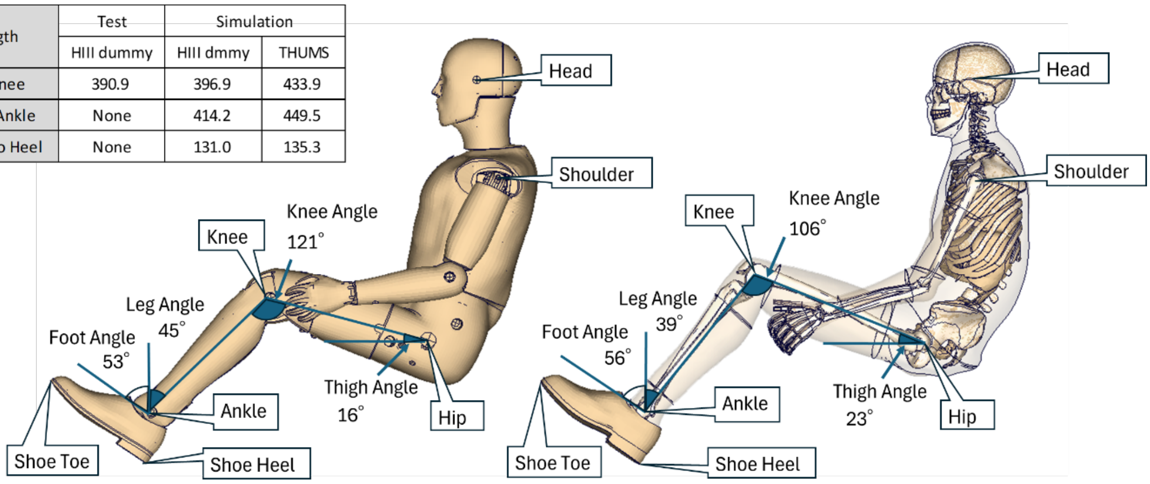
VII. Appendix

A. *Initial Position of Hybrid III Dummy and THUMS*

The hip point of the Hybrid III dummy in the mid-seat position test was used as the reference point. The seat position is horizontally rearward moved from the mid position of the seat. The rear-most seat position was 120 mm rear from the seat mid position. The angles of the thigh, knee, and leg of HIII dummy and THUMS are described in the figure. The length of the thigh and leg of the HIII dummy are shorter than THUMS as shown in the figure. Due to the longer thigh and leg of THUMS, the thigh angle and the knee angle of THUMS are larger than the HIII dummy.

Length	Test	Simulation	
	HIII dummy	HIII dmmy	THUMS
HP-Knee	390.9	396.9	433.9
Knee-Ankle	None	414.2	449.5
Ankle to Heel	None	131.0	135.3



	Test				Simulation											
Occupant	Hybrid III dummy												THUMS			
Seat slide	MID		Rear-Most		MID		MID + 40mm		MID + 80mm		Rear-Most		MID		Rear-Most	
	X	Z	X	Z	X	Z	X	Z	X	Z	X	Z	X	Z	X	Z
Head CG	108	666	230	648	117	658	157	658	197	658	237	656	120	657	248	655
Shoulder	140	400	251	388	135	403	175	403	-231	403	255	401	136	410	264	408
H point	0	0	107	-5	-2	0	38	0	78	0	118	-2	9	2	137	0
Knee	-382	83	-280	83	-385	107	-345	107	-305	107	-265	105	-392	169	-269	171
Ankle	None	None	None	None	-681	-182	-641	-182	-601	-182	-561	-184	-674	-181	-554	-181
Shoe Heel	None	None	None	None	-690	-313	-650	-313	-610	-313	-570	-315	-672	-316	-556	-317
Shoe Toe	None	None	None	None	-924	-103	-884	-103	-844	-103	-804	-105	-915	-112	-796	-105

Fig. A 1. Initial Position of Hybrid III dummy and THUMS

B. *Comparison between HIII dummy and THUMS in Velocity and Contact Force of Foot*

The comparison between the Hybrid III and THUMS of relative velocity and contact force between the left foot and dash panel for mid position and for rear-most position are shown in Appendix B1. The peak foot velocity of THUMS was higher than that of Hybrid III dummy. (THUMS: 4.1 m/s for mid-position and 10.0 m/s for rea-most position, Hybrid III: 2.4 m/s for mid position and 7.5 m/s for rear-most position). On the other hand, the peak contact force of THUMS was lower than that of Hybrid III dummy. (THUMS: 2.9 kN for mid-position and 4.6 kN for rear-most position, Hybrid III: 3.8 kN for mid position and 8.0 kN for rear-most position).

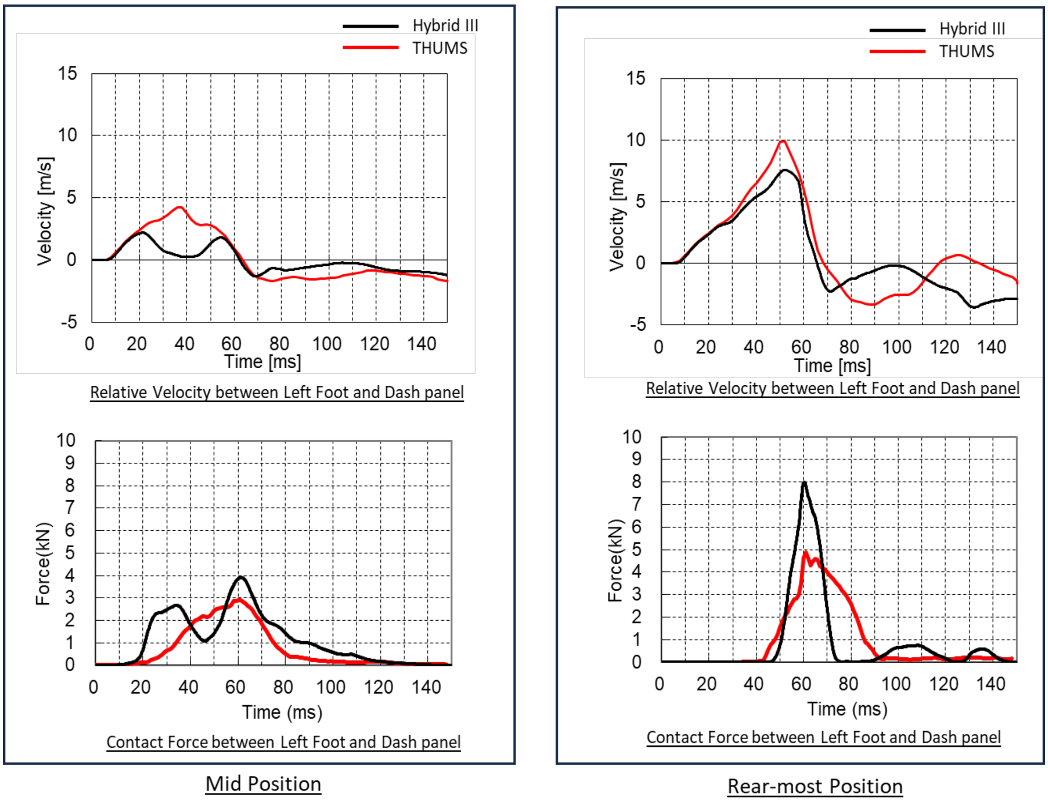


Fig. B 1. Comparison between HIII dummy and THUMS in Relative Velocity and Contact Force of Foot