Development and Evaluation of the Advanced Pedestrian Legform Impactor Prototype which can be Applicable to All Types of Vehicles Regardless of Bumper Height - Part 1: Finite Element Model -

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Abstract

The flexible pedestrian legform impactor simulating only a lower limb of a pedestrian, therefore, cannot adequately simulate the bending load generated on a lower limb of pedestrians due to the lack of representation of the upper body in a collision with a vehicle, especially for which has a high-bumper.

However, no one has developed an advanced pedestrian legform impactor (finite element model and/or actual test tool) which can be applicable to all types of vehicles regardless of the bumper height through quantitative validation process using well validated human full-body finite element model and wide variety of low-bumper and high-bumper vehicles.

In this study, we developed an advanced pedestrian legform impactor prototype finite element model by improving specifications of the flexible pedestrian legform impactor finite element model as well as by adding a biofidelic simplified upper body part finite element model. Then, we evaluated its biofidelity by the comparison of injury measures between the advanced pedestrian legform impactor prototype finite element model and a well validated human full-body finite element model quantitatively under the collisions with 18 types low-bumper and 18 types high-bumper simplified vehicles.

As a result, we confirmed its high biofidelity under the above conditions quantitatively.

Keywords computer simulation, influences of the upper body, legform impactor, pedestrian protection test method.

I. INTRODUCTION

Current pedestrian protection test methods try to assess the protection level of vehicle structures to the lower limb of a pedestrian by using a legform impactor simulating only the lower limb of a pedestrian. The flexible pedestrian legform impactor (FlexPLI), which is the latest legform impactor applied to the amendment of Regulation No. 127 of the United Nations (UN-R127 Amendment) [1], has significantly higher biofidelity compared to that of the EEVC pedestrian legform impactor [2]. However, the FlexPLI simulating only the lower limb of a pedestrian cannot adequately simulate the bending load generated on a lower limb due to the lack of representation of the upper body in a collision with a vehicle, especially for which has a high-bumper. Even in the collision with a low-bumper vehicle, it cannot be used without tentatively adding a 50 mm higher impact height compared to that of a human to compensate the influence of the lack of the upper body [3].

Some research attempted to consider the upper body effect by adding a simple mass rigidly at the top of a legform impactor or a lower limb finite element (FE) model [4-6]. However, no quantitative evaluation analyses were made by using a well validated human full-body FE model or full-body post mortem human subject (PMHS) test results under the collision with wide variety of low-bumper and high-bumper vehicles. Consequently, it was unclear if we are able to develop an advanced pedestrian legform impactor (finite element model and/or actual test tool) which can be applicable to all types of vehicles regardless of the bumper height, without any changes of impact height from that of a human.

Based on the above, we have been developing an advanced pedestrian legform impactor (aPLI) which can be applied to any types of vehicle without any changes of impact height from that of a human taking several steps

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as shown in Figure 1.

In the first step, we developed a FE model of a simplified upper body part (SUBP) by simplification of the upper body of a human full-body model that can consider the influences of the upper body part of a pedestrian appropriately [7] (Step 1 in Figure 1).

In the second step, we clarified the need for the improvement of the FlexPLI from the point of view of biofidelity (e.g. mass ratio of long bones and flesh, etc.) by the combination study of the SUBP FE model and the FlexPLI FE model [8] (Step 2 in Figure 1).

However, those studies were only attempts to simplify the upper body of a pedestrian, or clarify any needs for improvements of the FlexPLI specifications under collision with a few vehicles qualitatively. Therefore, so far no studies have been done to develop an aPLI FE model which can be applicable to all types of vehicles regardless of the bumper height without any changes of impact height from that of a human.

In this study, therefore, we developed an aPLI prototype (aPLI PT) FE model by improving specifications of the flexible pedestrian legform impactor as well as by adding a biofidelic simplified upper body part. Then, we evaluated its biofidelity by the comparison of injury measures between the aPLI PT FE model and a well validated human full-body finite element model quantitatively under the collisions with 18 types low-bumper and 18 types high-bumper simplified vehicles.

In the development, we also considered the technical feasibility to develop an actual test tool based on the specification of the aPLI PT FE model in our future study.

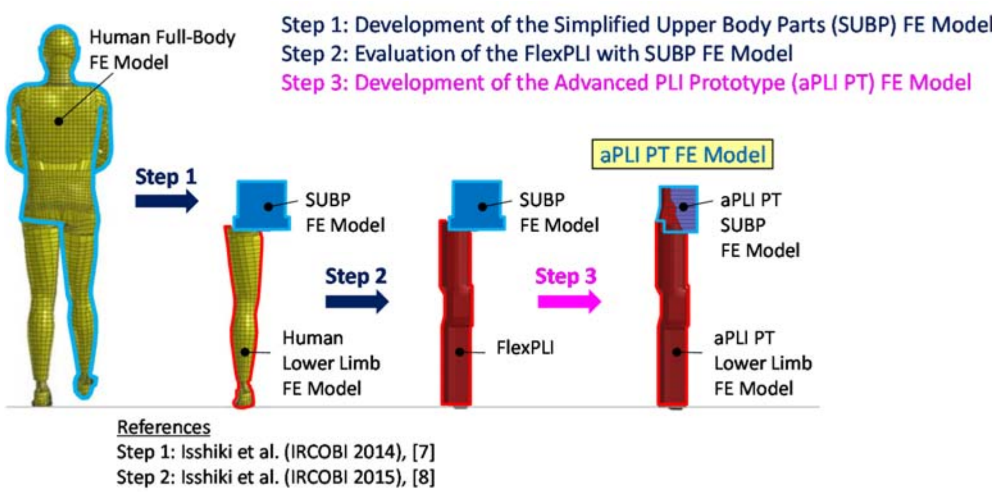


Fig. 1. Overall aPLI development flow.

II. METHODS

We developed the aPLI PT FE model by dividing its SUBP part (aPLI PT SUBP FE Model) and its lower limb part (aPLI PT Lower Limb FE Model) independently using the following procedures, then connected those parts using a hip joint.

Development of an aPLI PT SUBP FE Model

As shown in Figure 2, the aPLI PT SUBP FE model was developed by adding flesh and improving the shape of the flesh and pelvis of the SUBP FE model developed in our preceding study [7] in order to improve its contact characteristics to the vehicle. We determined those specifications using a sensitivity analysis method called the *Taguchi method* [9]. We can find the best specifications using the Taguchi method based on our selected sensitivity analysis parameters and setting levels of each parameter.

Figure 3 and Table 1 shows our selected sensitivity analysis parameters and setting levels of each parameter to conduct the Taguchi method. The parameters were selected based on the results of isolated sensitivity analysis of for each parameter (Appendix Figure A-1 and Table A-1: shape and mass, [7]: other parameters). The levels of each parameter were selected based on the range of relatively linear variation of injury measures of the lower limb as well as the range of existing technical feasibility to develop an actual test tool.

The parameters and the levels were assigned to the L36 orthogonal table of the experimental design method to prepare 36 types of SUBP FE models (Appendix Table A-2: Model 01 to 36). The 36 types of SUBP FE models were attached to a human lower limb FE model [7] respectively as shown in Figure 4. Then we compared injury measures with that of the human full-body FE model [7] under the collision analyses with one averaged high-bumper and one averaged low-bumper simplified vehicle FE model (High-Bumper Avg. FE model and Low-Bumper Avg. FE model) as a representative of the 18 types high-bumper simplified vehicle FE models as well as the 18 types low-bumper simplified vehicle FE models [7] respectively (Appendix Figure A-3 to Figure A-5 and Table A-3).

After the analysis, as shown in Figure 5, we calculated the summation of square measures of the injury measure difference between the SUBP FE model and the human full-body model (S_k). It was calculated in the area which is the injury measure of the SUBP FE model is higher or lower respectively. Then we calculated averaged value for the S_k (S_{avg}).

In order to improve the biofidelity of the SUBP FE model, we have two methods. One method is to minimize the value of the S_k from the S_{avg} (Method 1). It means that we minimize the variation level of the difference of injury measures from that of the human full-body FE model. The other method is to minimize the value of the S_{avg} (Method 2). It means that we minimize the average of the difference of injury measures from that of the human full-body FE model.

In order to conduct the Method 1, at first, we need to calculate the value of the signal noise (SN) ratio using the equation described in Figure 6, then describe a factorial effects diagram with regards to the SN ratio as shown in Figure 7 using the Taguchi Method. Then, we selected a level for each parameter based on the value of the SN ratio by the combination of the largest SN ratio of each parameter, which can minimize the variation level of the difference of injury measures from that of the human full-body FE model.

In order to conduct the Method 2, we need to describe a factorial effects diagram with regards to the S_{avg} as shown in Figure 8 using the Taguchi Method, then select a level for each parameter based on the value of the S_{avg}, by the combination of the lowest value of each parameter, which can minimize the average of the difference of injury measures from that of the human full-body FE model.

In this research, we used the Method 1 at first. Then, if we need further improvement of the biofidelity of the aPLI SUBP FE model, we tried to consider to use the Method 2 additionally.

After the development of the aPLI SUBP PT FE model, its biofidelity was evaluated under collisions with high-bumper (18 types) as well as low-bumper (18 types) simplified vehicle FE models by comparing injury measures between the aPLI PT SUBP FE model attached to the human lower limb FE model and the human full-body FE model (Figure 9).

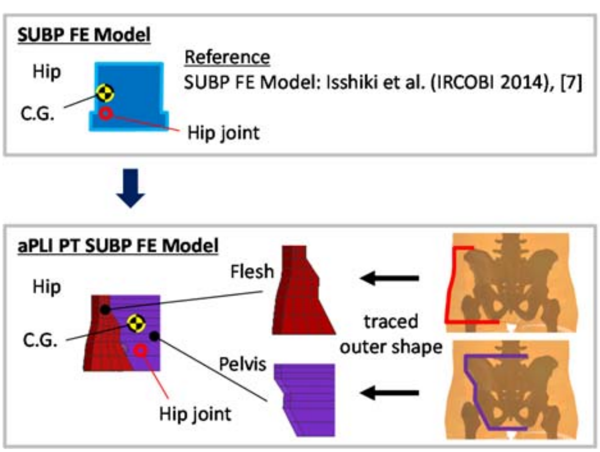


Fig. 2. Overview of the aPLI PT SUBP FE model.

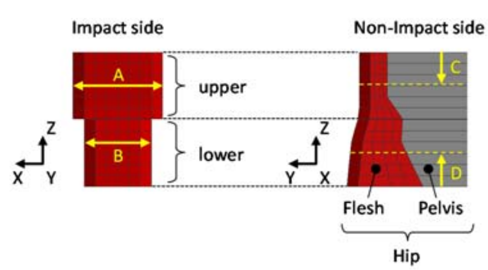


Fig. 3. Definitions of parameters with regards to the shape and stiffness of the SUBP.

TABLE I
PARAMETERS AND LEVELS FOR SENSITIVITY ANALYSIS

Parameters		Symbol	Unit	Level 1	Level 2	Level 3
Shape	Hip (width of impact side face, upper)	A	mm	60	120	180
	Hip (width of impact side face, lower)	B	mm	60	120	180
	Hip (cut of pelvis, upper)	C	mm	20	60	100
	Hip (cut of pelvis, lower)	D	mm	0	40	80
Stiffness	Flesh (base: neoprene)	E	times	1	2	3
Mass	Hip	Mass	kg	13.1	16.1	19.1
Center of Gravity	Hip (y-axis, base: human)	COGy	mm	+80	+40	0
	Hip (z-axis, base: human)	COGz	mm	+50	+25	0
Hip Joint Characteristic	Rotation (x-axis (-), allowance)	Rx(-)a	deg.	0	10	20
	Rotation (x-axis (-), slope, base: human)	Rx(-)s	times	1	1.25	1.5
	Disp. (y-axis (-), slope, base: human)	Dy(-)s	times	0.5	1	100
	Disp. (z-axis (-), slope, base human)	Dz(-)s	times	0.5	1	2
	Disp. (z-axis (+), slope, base: human)	Dz(+)s	times	0.1	1	100

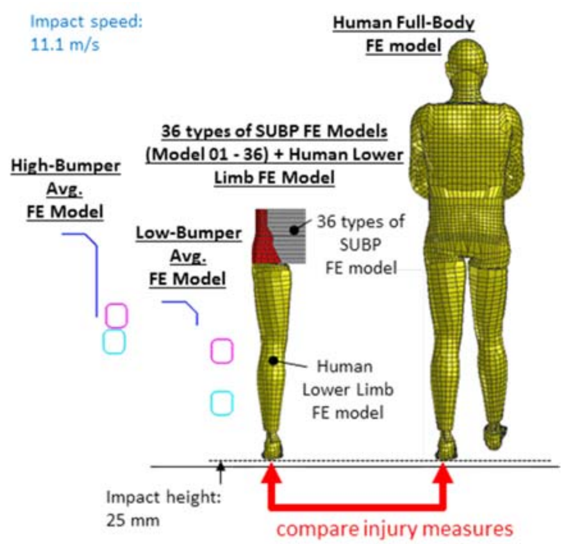
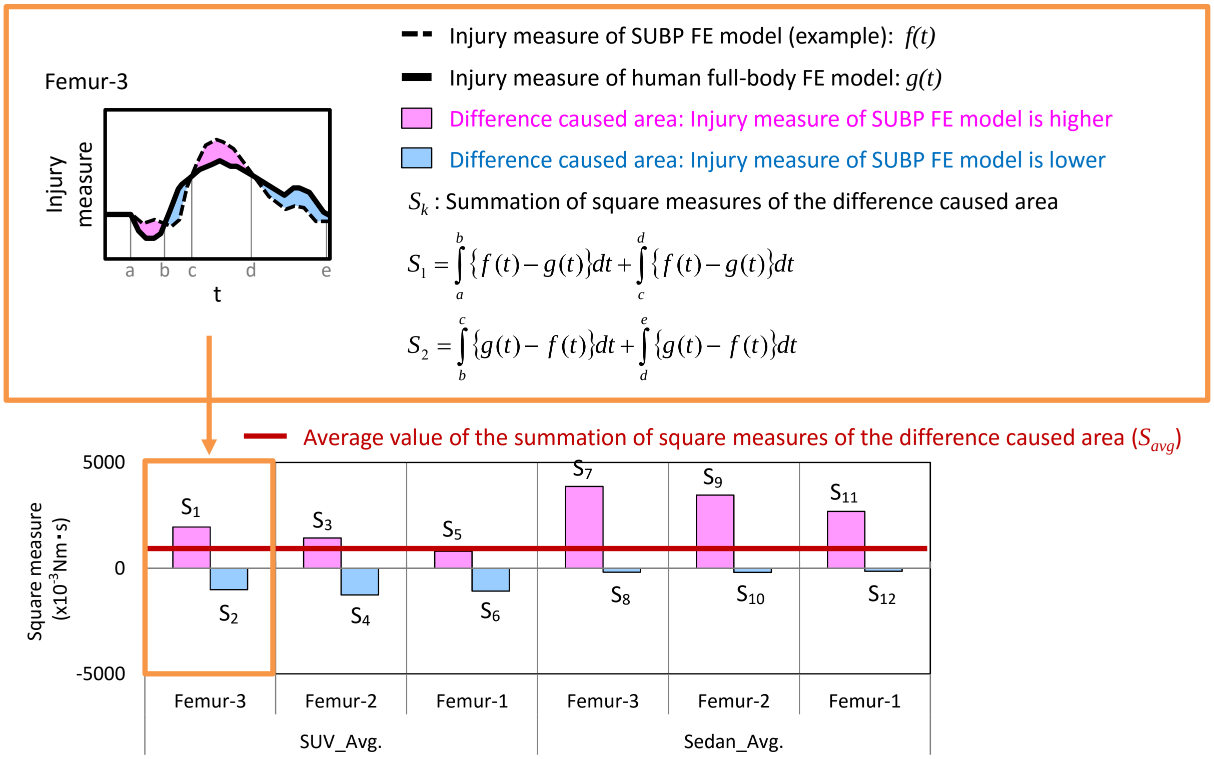


Fig. 4. Overview of the sensitivity analysis method of the 36 types of SUBP FE models (Model 01 -36) attached to the human lower limb FE model.



Improvement Method of Biofidelity of SUBP FE model

Method 1: Minimize the value of the S_k from the S_{avg}
(Minimize the variation level of the difference of injury measures from that of the human full-body FE model)

Method 2: Minimize the value of the S_{avg}
(Minimize the average of the difference of injury measures from that of the human full-body FE model)

Fig. 5. Data process method after the CAE analysis.

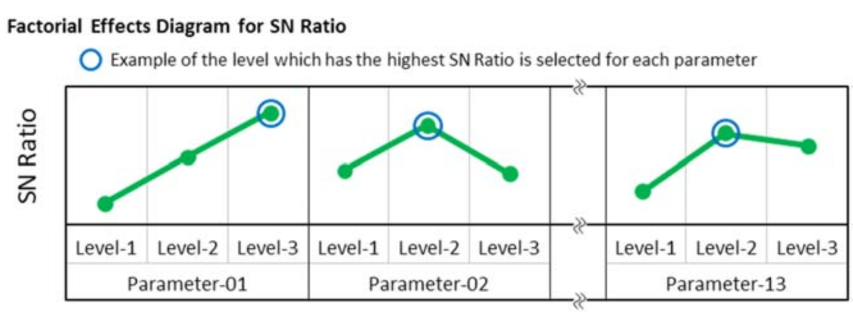


Fig. 6. Level selection method for each parameter to minimize the minimize variation of the differences of injury measures from that of the human full-body FE model (Method 1).

$$\text{SN ratio} = -10\log V_e$$

$$V_e = \frac{1}{n-1}\sum_{k=1}^{n}(S_k - S_{avg})^2$$

where,
V_e : Unbiased variance
S_k : Summation of square measures of the difference caused area
S_{avg} : Average of summation of square measures of the difference caused area
n : Number of the S_k (=12)

Fig. 7. Equation to calculate SN ratio

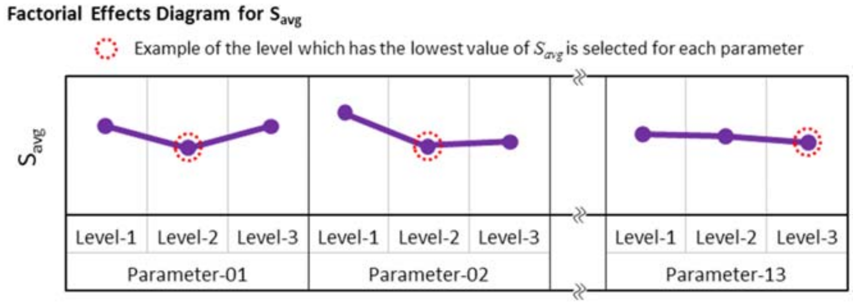


Fig. 8. Level selection method for each parameter minimize the averaged difference of injury measures from that of the human full-body FE model (Method 2).

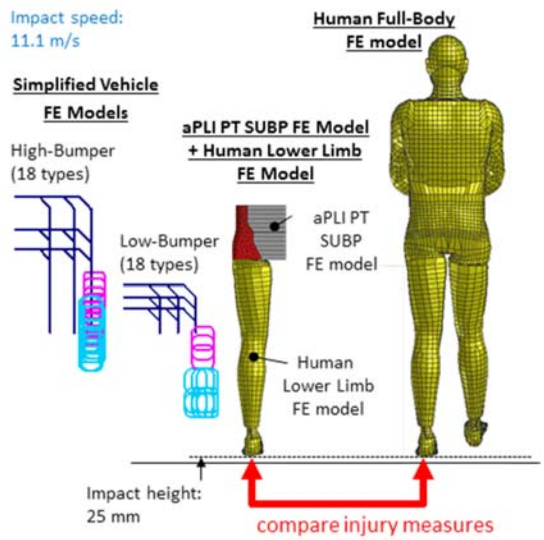


Fig. 9. Overview of the biofidelity evaluation method of the aPLI PT SUBP FE model attached to the human lower limb FE model.

Development of an aPLI PT Lower Limb FE Model

As shown in Figure 10, the aPLI PT lower limb FE model was developed by improving 6 parameters of the FlexPLI (mass distribution of the flesh and the long bones; shape of the impact surface of the long bones; geometric layout of the Anterior Cruciate Ligament (ACL) and the Posterior Cruciate Ligament (PCL); femoral offset; ankle joint representation; femur bending stiffness) which were qualitatively recommended for improvement in the preceding study [7].

Table 2 and Figure 11 to Figure 14 show each specification of the improved parameters for the aPLI PT lower limb FE model compared with those of the human full-body FE model and the FlexPLI FE model. The aPLI PT lower limb FE model has higher biofidelity in each specification compared to those of the FlexPLI.

With regards to the mass distribution of the flesh and the long bones, we considered the technical feasibility to achieve the same as those of a human in the development of an actual test tool based on its FE model, therefore, some differences remain in the specifications.

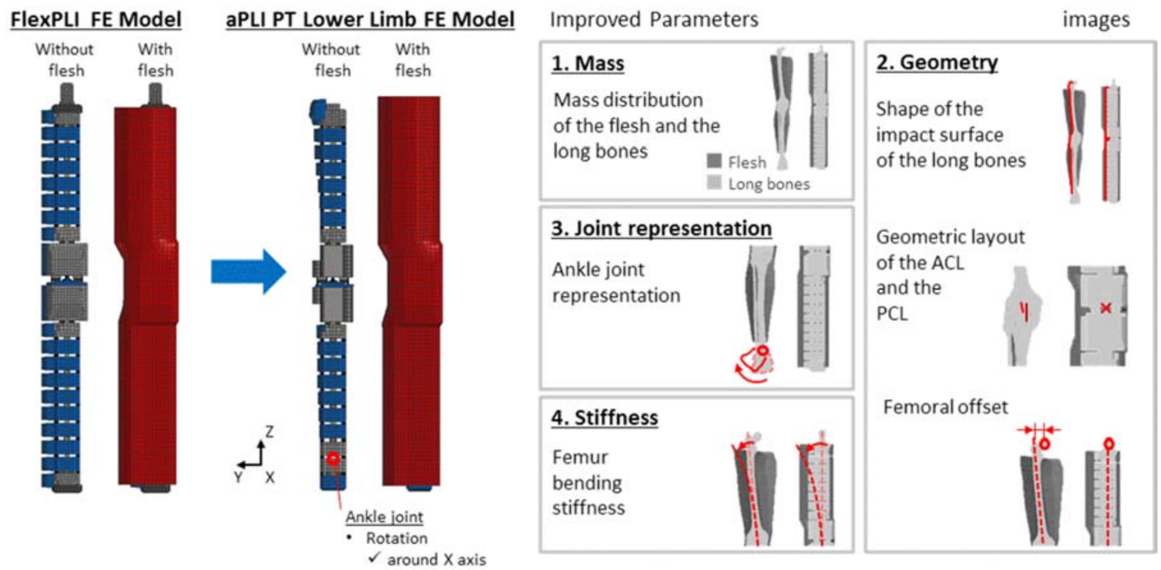


Fig. 10. General information for the aPLI PT lower limb FE model (Improved parameters, images).

TABLE II

SPECIFICATION OF THE IMPROVED PARAMETERS TO DEVELOP THE APLI PT LOWER LIMB FE MODEL

Improved Parameters		Human Full-Body FE model	FlexPLI FE model	aPLI PT Lower Limb FE model
1. Mass				
	Mass distribution of the flesh and the long bones	Flesh: 9.4 kg Long Bones: 2.1 kg	Flesh: 3.8 kg Long Bones: 9.1 kg	Flesh: 6.8 kg Long Bones: 6.1*
2. Geometry				
	Shape of the impact surface of the long bones	Non-Flat	Flat	Non-Flat
	Geometric layout of the ACL and the PCL	Close to Vertical	Angled	Vertical
	Femoral offset	Around 40 mm	0 mm	40 mm
	Shape of the impact surface of the long bones	Non-Flat	Flat	Non-Flat
3. Joint representation				
	Ankle joint representation	Exists	Does not exist	Exists
4. Stiffness				
	Femur bending stiffness	Around 1.4 times of FlexPLI	Same as FlexPLI	1.4 times of FlexPLI

* considered technical feasibility

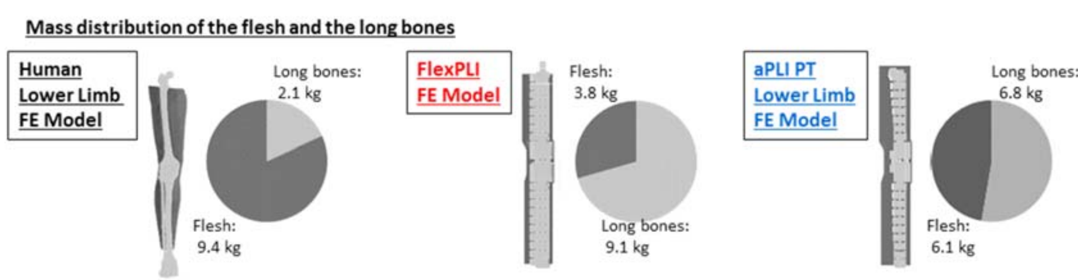


Fig.11. General information of the improved parameters (Mass).

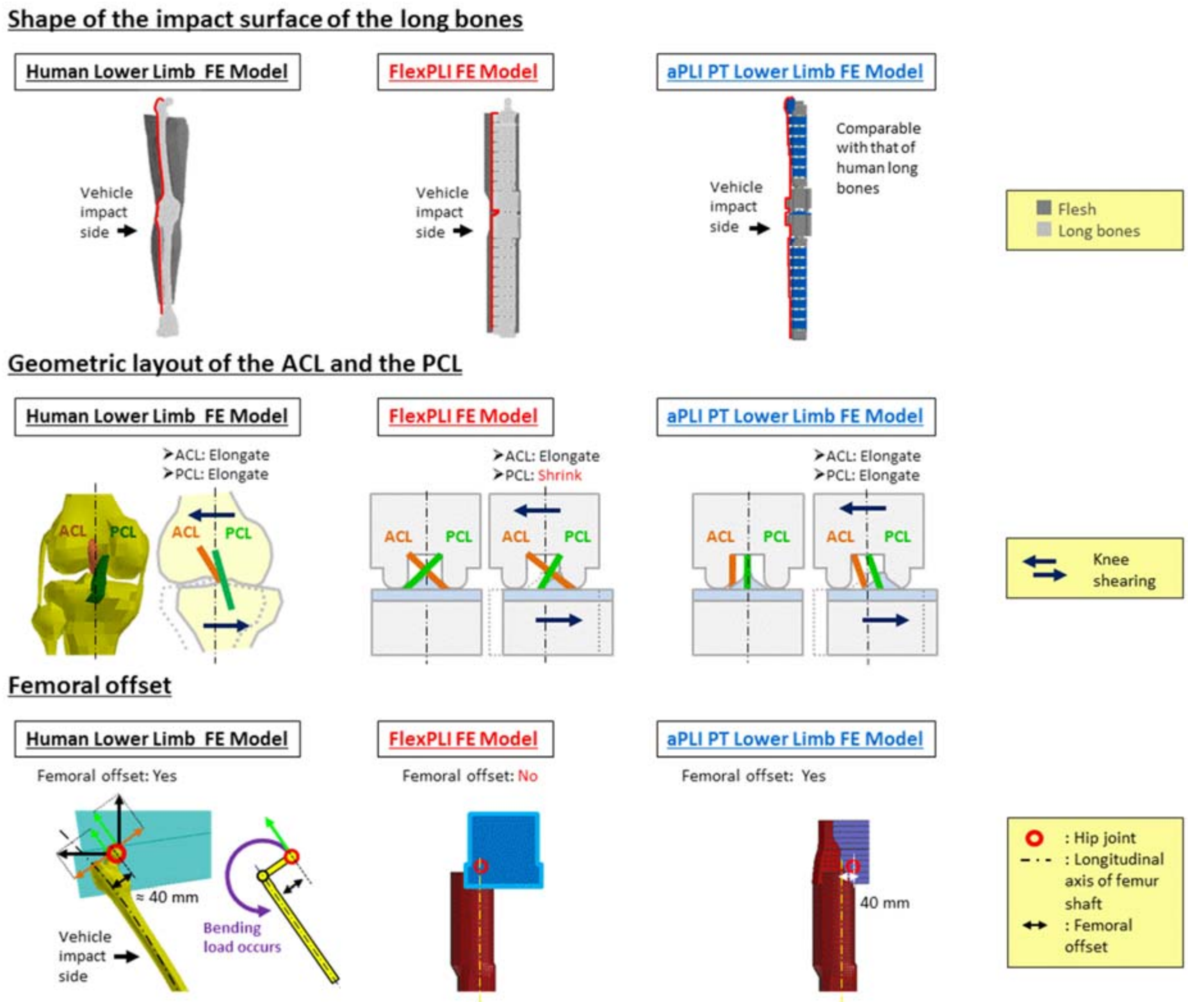


Fig.12. General information of the improved parameters (geometry).

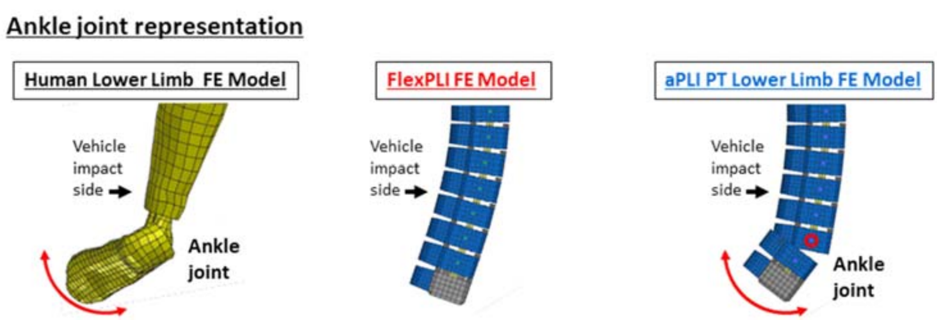


Fig. 13. General information of the improved parameters (joint representation).

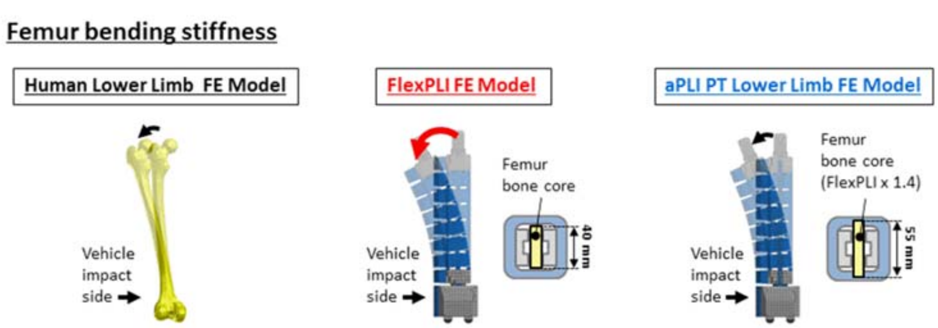


Fig. 14. General information of the improved parameters (stiffness).

Development of the aPLI PT FE Model

The aPLI PT FE model was developed by connecting the aPLI PT SUBP FE model at the top of the aPLI PT Lower Limb FE model via the hip joint. Figure 15 depicts the developed aPLI PT FE model compared to the FlexPLI FE model developed in our preceding study [10]. The aPLI PT FE model consists of the SUBP part and the lower limb part, therefore, its overall height is 168 mm taller than that of the FlexPLI FE model.

Its biofidelity was evaluated under collisions with high-bumper (18 types) simplified vehicle FE models as well as low-bumper (18 types) simplified vehicle FE models by comparing injury measures of the human full-body FE model and the FlexPLI FE model (Figure 14).

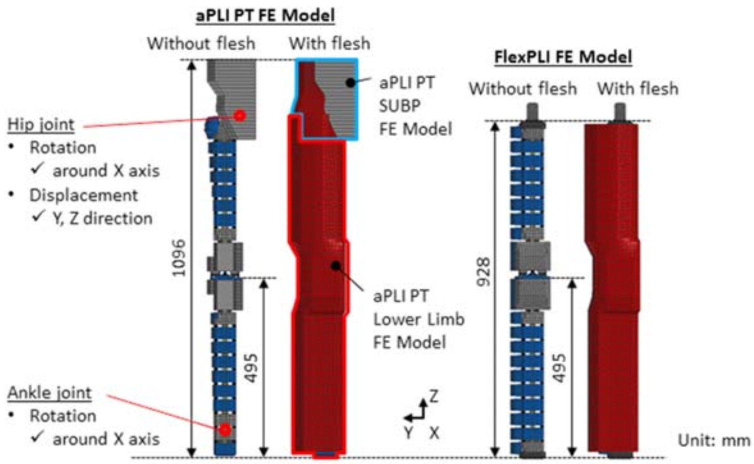


Fig. 15. Overview of the aPLI PT FE model compared to the FlexPLI FE model.

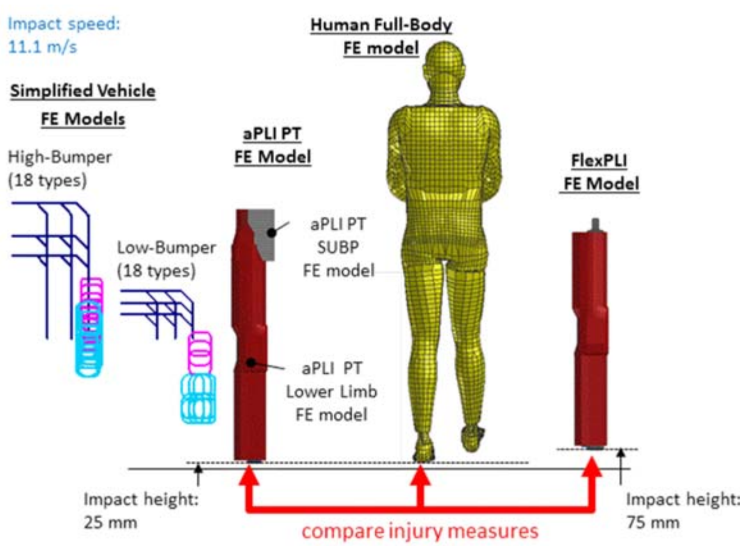


Fig. 16. Overview of the biofidelity evaluation method for the aPLI PT FE model.

III. RESULTS

Selection of the Specification of the aPLI PT SUBP FE Model using the Taguchi Method and Validation of Its Biofidelity

Figure 17 shows the results of the selected level of each parameter in order to develop a biofidelic aPLI PT SUBP FE model using the Method 1. We selected the levels based on the value of the SN ratio by the combination of the largest SN ratio of each parameter, which can minimize the level of the variation of the difference between the injury measures of the aPLI SUBP FE model attached to the human lower limb FE model, and that of the Human full-body FE model.

Figure 18 shows the results of correlation analysis between the injury measures of the aPLI PT SUBP FE model developed using the Method 1 attached to the human lower limb FE model and that of the Human full-body FE model under collisions with high-bumper (18 types) simplified vehicle FE models as well as low-bumper (18 types) simplified vehicle FE models. Based on the results, we can confirm that the aPLI PT SUBP FE model can represent upper body influence on the load at the lower limb appropriately, i.e. the aPLI PT SUBP FE model has high biofidelity with regard to the upper body part of the human full-body FE model.

Figure 19 shows results of the selected level of each parameter if we need to conduct further improvement of biofidelity of the the aPLI PT SUBP FE model by using the Method 2. As a result, more than half of the parameters have the same levels that were selected by using the Method 1. In addition, the influence of the level of the remaining parameters are relatively small or opposite effect that of the Method 1. We already confirmed high biofidelity of the aPLI PT SUBP FE model which was developed using the Method 1, so we decided not to use the Method 2 for the further modifications.

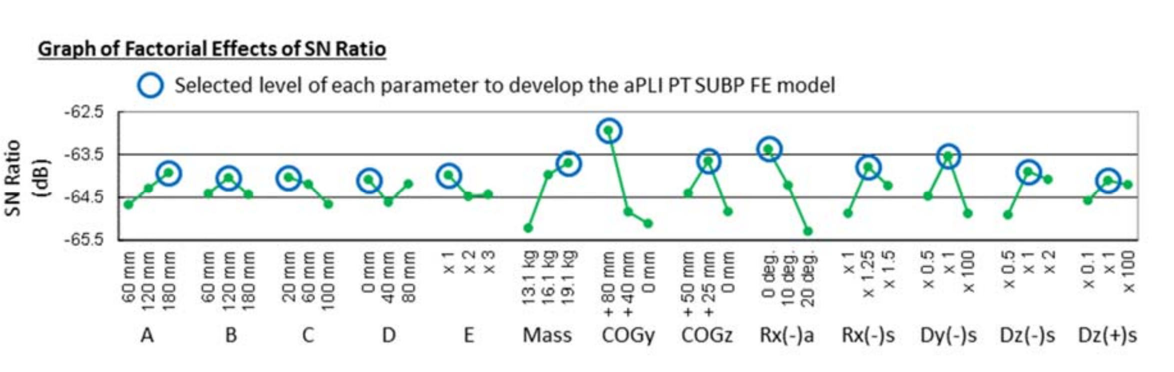


Fig. 17. Selected level of each parameter to develop the aPLI PT SUBP FE model (Method 1).

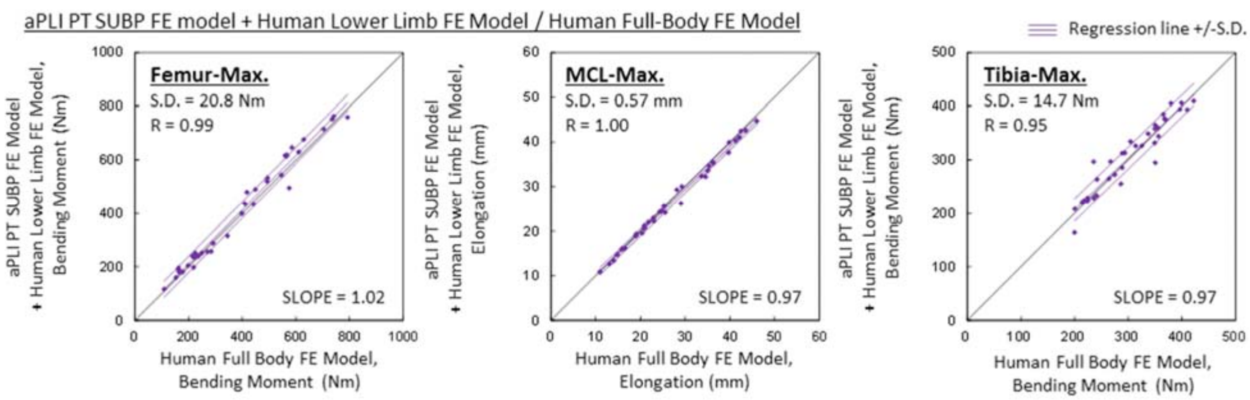


Fig. 18. Biofidelity evaluation results of the aPLI PT SUBP FE model attached to the human lower limb FE model.

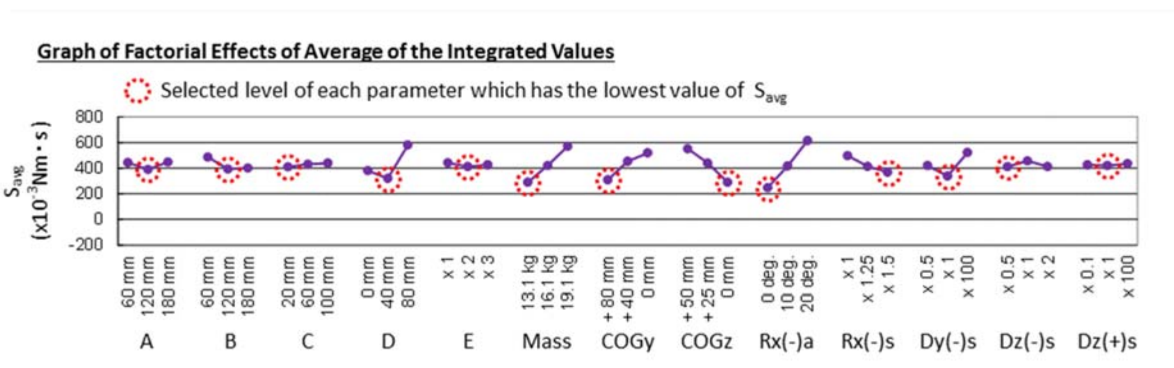


Fig. 19. Selected level of each parameter which has the lowest value of S_{avg} (Method 2).

Biofidelity of the aPLI PT FE Model

Figure 20 shows results of the correlation analysis with regards to the injury measures between the aPLI FE model and the Human full-body FE model under collisions with high-bumper (18 types) simplified vehicle FE models as well as low-bumper (18 types) simplified vehicle FE models. The correlation between the aPLI FE model and the human full-body FE model is significantly high compared to that of the FlexPLI especially for the femur and the MCL outputs.

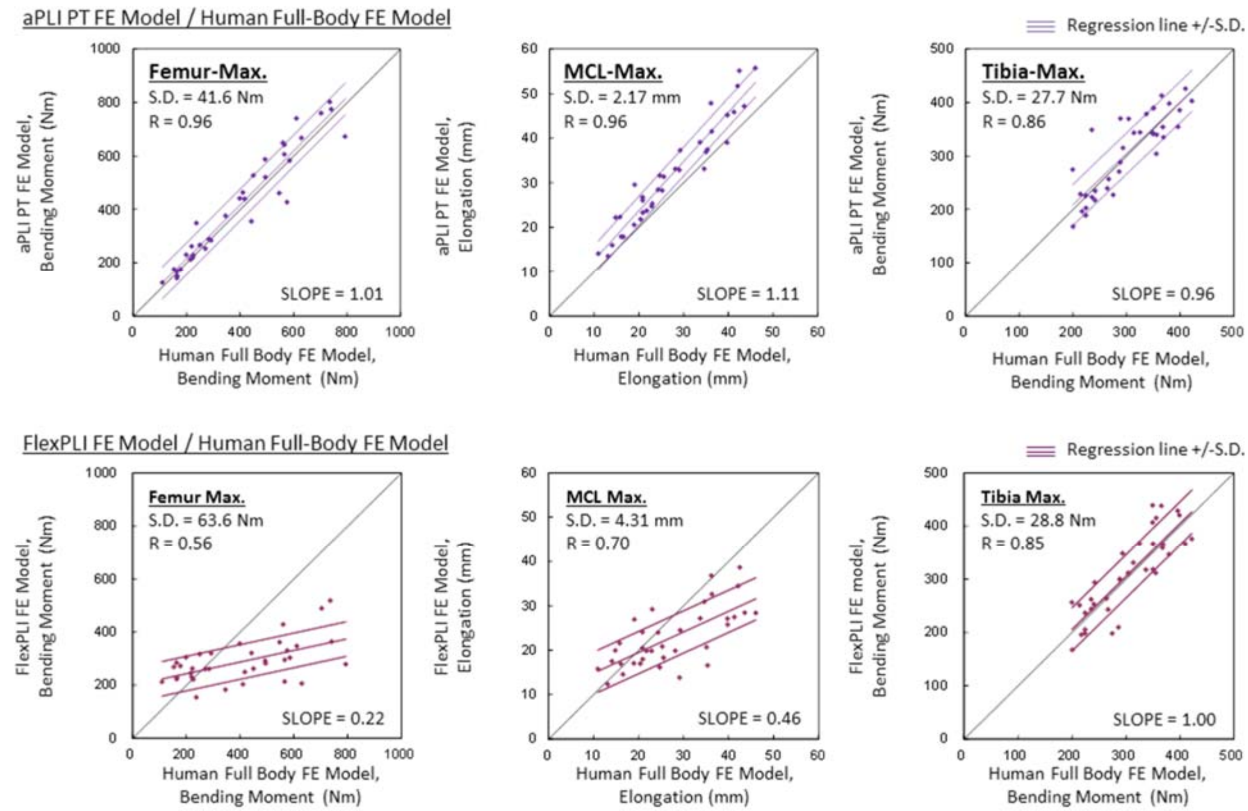


Fig. 20 Biofidelity evaluation results of the aPLI FE model and FlexPLI FE model under collisions with the 36 types of simplified vehicle FE models.

IV. Discussion

We developed the aPLI PT FE model by dividing its SUBP part (aPLI PT SUBP FE Model) and its lower limb part (aPLI PT Lower Limb FE Model) independently, then connected those parts using a hip joint.

The aPLI PT SUBP FE model was developed by using the Taguchi method, then it shows high biofidelity by the combination of the human lower limb FE model. However, the Taguchi method can only set 2 or 3 levels of each parameter, then it just selects the best level among them. Therefore, strictly speaking, we still have room to improve its biofidelity using an optimization technique which can treat more levels for each parameter, then its selects the best level among them by making a response surface of each parameter.

The aPLI PT lower limb FE model part was developed based on the knowledge of our previous analysis of what kind of improvement of the FlexPLI specifications are effective to improve its biofidelity [7]. Biofidelity was confirmed under the combination with the aPLI PT SUBP FE model, i.e. as a aPLI PT FE model, then it showed higher biofidelity compared to that of the FlexPLI. However, the aPLI PT lower limb FE model was not developed by using any optimization technique as well as the aPLI PT SUBP FE model, so we also have room to improve its biofidelity.

In addition, we considered the technical feasibility to develop an actual test tool based on the specification of the aPLI PT FE model, however, no one has confirmed the technical feasibility to develop the aPLI PT actual test tool. Therefore, to develop an aPLI PT actual test tool based on its FE model is necessary.

V. Conclusions

In this study, we developed an advanced pedestrian legform impactor prototype finite element model by improving specifications of the flexible pedestrian legform impactor finite element model as well as by adding a biofidelic simplified upper body part finite element model. We confirmed its high biofidelity under collisions with the 18 types high-bumper simplified vehicles as well as the 18 types low-bumper simplified vehicles by the comparison of injury measures between the advanced pedestrian legform impactor prototype finite element model and a human full-body FE model quantitatively.

This result demonstrated us that we are able to develop a high biofidelic advanced pedestrian legform impactor finite element model which can be applicable to all types of vehicles regardless of the bumper height.

VI. References

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VII. APPENDIX

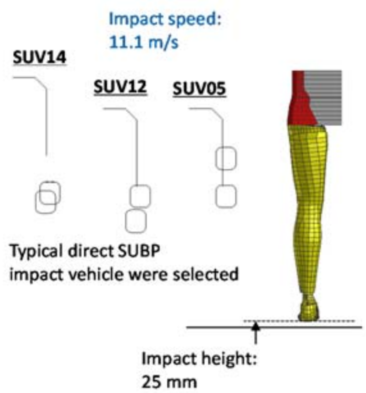

Fig. A-1. Overview of the isolated sensitivity analysis with regards to the shape and stiffness of the SUBP.

TABLE A-I
PARAMETERS AND LEVELS FOR ISOLATED SENSITIVITY ANALYSIS WITH REGARDS TO THE SHAPE AND STIFFNESS OF THE SUBP

Parameters	Symbol	Unit	Levels								
Hip (width of impact side face, upper)	A	mm	40	60	80	100	120	140	160	180	200
Hip (width of impact side face, lower)	B	mm	40	60	80	100	120	140	160	180	200
Hip (cut of pelvis, upper)	C	mm	0	20	40	60	80	100	120	-	-
Hip (cut of pelvis, lower)	D	mm	0	20	40	60	80	100	120	-	-
Flesh (base: neoprene)	E	times	0.1	0.5	1.0	1.5	2.0	3.0	4.0	-	-

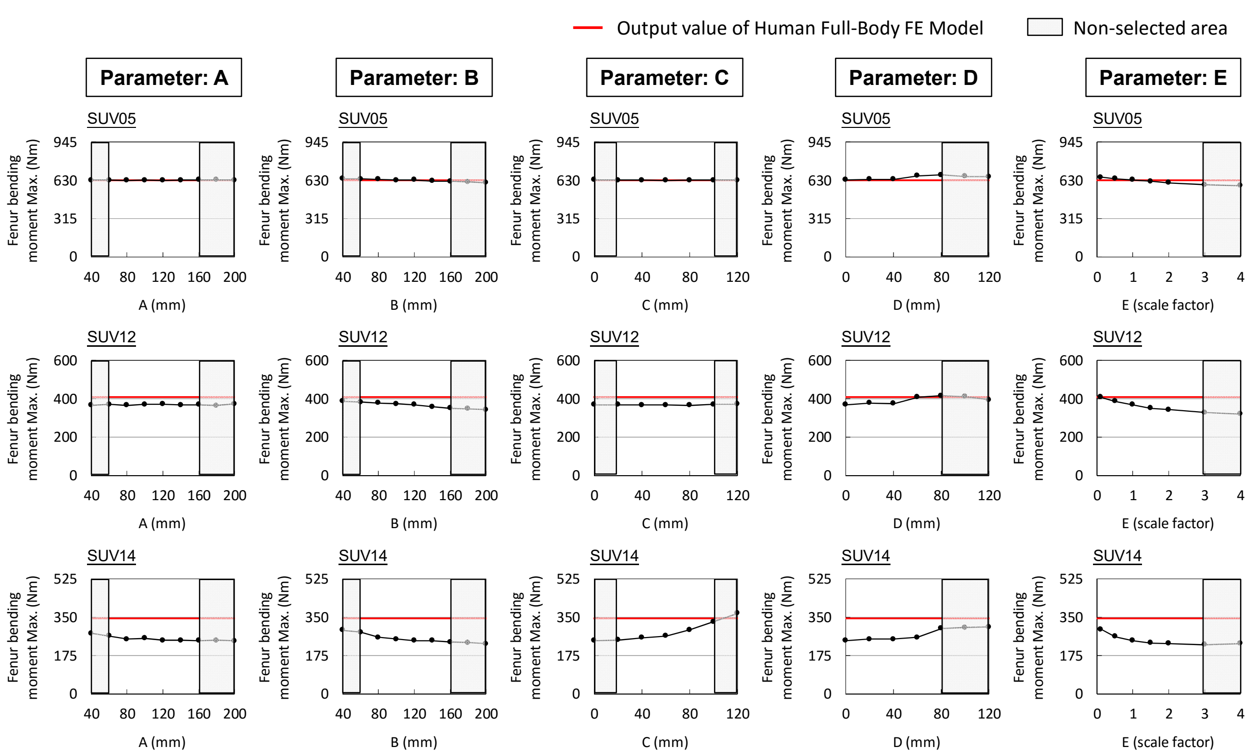

Fig. A-2. Results of the isolated sensitivity analysis with regards to the shape and stiffness of the SUBP.

TABLE A-II

SPECIFICATIONS OF THE 36 TYPES OF SUBP (MODEL 01 TO 36) FE MODEL

Model ID	Parameters												
	A	B	C	D	E	Mass	COGy	COGz	Rx(-)a	Rx(-)s	Dy(-)s	Dz(-)s	Dz(+)s
	mm	mm	mm	mm	times	kg	mm	mm	deg.	times	times	times	times
Model01	60	60	20	0	1	13.1	80	50	0	1	0.5	0.5	0.1
Model02	120	120	60	40	2	13.1	40	25	10	1.25	1	1	1
Model03	180	180	100	80	3	13.1	0	0	20	1.5	100	2	100
Model04	120	180	100	80	3	13.1	80	50	0	1	1	1	1
Model05	180	60	20	0	1	13.1	40	25	10	1.25	100	2	100
Model06	60	120	60	40	2	13.1	0	0	20	1.5	0.5	0.5	0.1
Model07	180	60	60	40	3	13.1	80	50	10	1.5	0.5	1	100
Model08	60	120	100	80	1	13.1	40	25	20	1	1	2	0.1
Model09	120	180	20	0	2	13.1	0	0	0	1.25	100	0.5	1
Model10	180	120	20	80	2	13.1	80	50	20	1.25	0.5	2	1
Model11	60	180	60	0	3	13.1	40	25	0	1.5	1	0.5	100
Model12	120	60	100	40	1	13.1	0	0	10	1	100	1	0.1
Model13	180	180	60	0	2	16.1	80	25	20	1	100	1	0.1
Model14	60	60	100	40	3	16.1	40	0	0	1.25	0.5	2	1
Model15	120	120	20	80	1	16.1	0	50	10	1.5	1	0.5	100
Model16	120	180	100	40	1	16.1	80	25	20	1.25	0.5	0.5	100
Model17	180	60	20	80	2	16.1	40	0	0	1.5	1	1	0.1
Model18	60	120	60	0	3	16.1	0	50	10	1	100	2	1
Model19	120	120	20	40	3	16.1	80	25	0	1.5	100	2	0.1
Model20	180	180	60	80	1	16.1	40	0	10	1	0.5	0.5	1
Model21	60	60	100	0	2	16.1	0	50	20	1.25	1	1	100
Model22	60	60	100	80	2	16.1	80	25	10	1.5	100	0.5	1
Model23	120	120	20	0	3	16.1	40	0	20	1	0.5	1	100
Model24	180	180	60	40	1	16.1	0	50	0	1.25	1	2	0.1
Model25	60	180	20	40	2	19.1	80	0	10	1	1	2	100
Model26	120	60	60	80	3	19.1	40	50	20	1.25	100	0.5	0.1
Model27	180	120	100	0	1	19.1	0	25	0	1.5	0.5	1	1
Model28	180	120	100	0	3	19.1	80	0	10	1.25	1	0.5	0.1
Model29	60	180	20	40	1	19.1	40	50	20	1.5	100	1	1
Model30	120	60	60	80	2	19.1	0	25	0	1	0.5	2	100
Model31	120	60	60	0	1	19.1	80	0	20	1.5	1	2	1
Model32	180	120	100	40	2	19.1	40	50	0	1	100	0.5	100
Model33	60	180	20	80	3	19.1	0	25	10	1.25	0.5	1	0.1
Model34	60	120	60	80	1	19.1	80	0	0	1.25	100	1	100
Model35	120	180	100	0	2	19.1	40	50	10	1.5	0.5	2	0.1
Model36	180	60	20	40	3	19.1	0	25	20	1	1	0.5	1

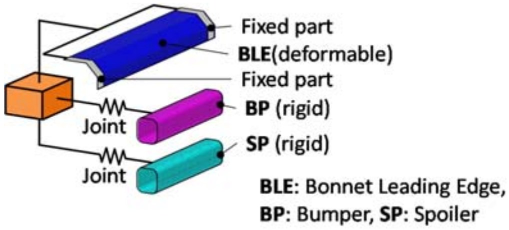

Fig. A-3. General Information for the simplified vehicle FE model [3].

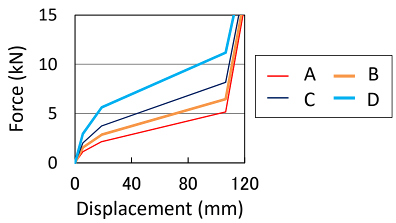

Fig. A-4. Joint characteristics of BP and SP of the simplified vehicle FE model.

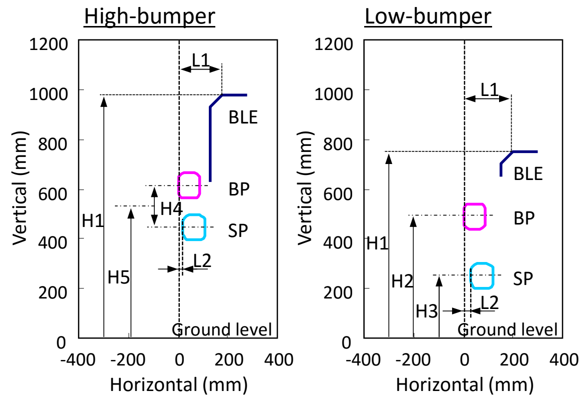

Fig. A-5. Definition of shape of the simplified vehicle FE model.

TABLE A-III
GENERAL INFORMATION FOR THE SIMPLIFIED VEHICLE FE MODEL (HIGH-BUMPER AVG. AND LOW-BUMPER AVG.)

High-bumper						
Parameters		Unit	Level 1	Level 2	Level 3	High-bumper Avg.
K1	BLE thickness	mm	0.4	0.6	-	0.5
K2	BP stiffness	-	B	C	D	C
K3	SP stiffness	-	A	C	D	C
H1	BLE height	mm	900	980	1120	980
H4	BP height - SP height	mm	40	110	170	110
H5	Average height of BP and SP	mm	530	580	670	580
L1	BLE lead	mm	110	180	280	180
L2	SP lead	mm	0	10	20	10
Low-bumper						
Parameters		Unit	Level 1	Level 2	Level 3	Low-bumper Avg.
K1	BLE thickness	mm	0.4	0.6	-	0.5
K2	BP stiffness	-	B	C	D	C
K3	SP stiffness	-	A	C	D	C
H1	BLE height	mm	650	700	750	700
H2	BP height	mm	450	490	530	490
H3	SP height	mm	250	270	350	270
L1	BLE lead	mm	125	200	275	200
L2	SP lead	mm	-20	0	30	0