

Influence of the Upper Body of Pedestrians on Lower Limb Injuries and Effectiveness of the Upper Body Compensation Method of the FlexPLI

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ABSTRACT

Current legform impact test methods using the FlexPLI have been developed to protect pedestrians from lower limb injuries in collisions with low-bumper vehicles. For this type of vehicles, the influence of the upper body on the bending load generated in the lower limb is compensated by setting the impact height of the FlexPLI 50 mm above that of pedestrians. However, neither the effectiveness of the compensation method of the FlexPLI nor the influence of the upper body on the bending load generated in the lower limb of a pedestrian has been clarified with high-bumper vehicles.

In this study, therefore, two computer simulation analyses were conducted in order to analyze: (1) The influence of the upper body on the bending load generated in the lower limb of a pedestrian when impacted by high-bumper vehicles and (2) The effectiveness of the compensation method for the lack of the upper body by increasing impact height of the FlexPLI for high-bumper vehicles.

The results show that the upper body significantly influenced the bending load generated in the lower limb of a pedestrian. This influence was found to be bumper height dependent. In addition, method of compensation for the lack of the upper body by increasing impact height of the FlexPLI was found not to work for high-bumper vehicles effectively. These results suggest the need to develop a new test method that appropriately incorporates upper body representation regardless of bumper height.

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INTRODUCTION

It is anticipated that the current impact test methods using the Flexible Pedestrian Legform Impactor (FlexPLI) or the EEVC legform impactor, simulating a lower limb of a pedestrian, do not appropriately predict the probability of lower limb injuries of pedestrians in collisions with the vehicles where the lower bumper height is 425 mm and over (high-bumper-vehicle). The reason for this limitation is considered to be that those test methods do not represent the influences of the upper body on the bending load to the lower limb due to the lack of a part corresponding to the upper body or a mechanism reproducing the influences of the upper body.

The latest legform impact test method using the FlexPLI [1] attempts to compensate for the lack of the influences of the upper body by setting the impact height 50 mm higher than that of a pedestrian. However, in the previous study [2], the effectiveness of this compensation was confirmed only in collisions with the vehicles

where the lower bumper height is less than 425 mm (low-bumper-vehicle) mainly focusing on the bending loads generated in the tibia and the knee. In addition, more basic fact that the influence of the upper body on the bending load generated in the lower limb of a pedestrian when impacted by high-bumper vehicles had also not been clarified.

In this study, therefore, we conducted following two computer simulation analyses:

Analysis-1: Influence of the upper body

- In order to clarify the influence of the upper body on the bending load generated in the lower limb of a pedestrian in collisions with high-bumper vehicles, we compared the computer simulation results of the models of the human full-body and an isolated human lower limb.

Analysis-2: Effectiveness of increasing impact height of the FlexPLI

- In order to evaluate the effectiveness of the compensation method for the lack of the upper body by increasing the impact height of the FlexPLI in collisions with high-bumper vehicles, we compared the computer simulation results of the model of the human full-body and FlexPLI at the two different impact heights.

MATERIALS

In this study, a series of Finite Element (FE) models previously developed and validated were used to conduct the two analyses (Analysis-1 and Analysis-2). The models consist of a series of simplified vehicle FE models, a human full-body FE model, an isolated human lower limb FE model, and a FlexPLI FE model as shown in Figure 1. All simulation analyses were performed with the explicit code PAM-CRASH (ESI Group, France).

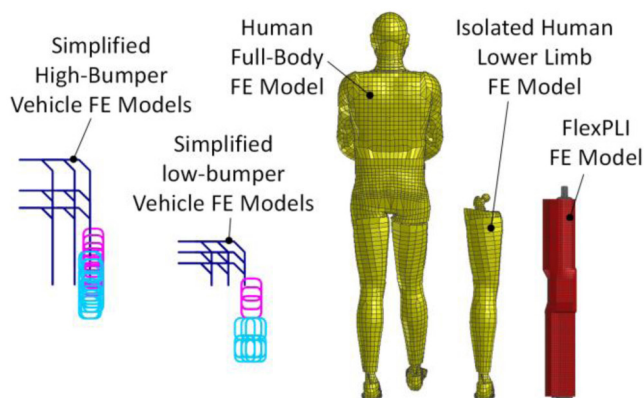


Figure 1. Overview of the simplified vehicle FE models, human full-body FE model, isolated human lower limb FE model, and FlexPLI FE model.

Simplified Vehicle FE Models

A series of 36 simplified vehicle FE models was generated from a simplified vehicle FE model composed of three main parts: A Bonnet Leading Edge (BLE), a Bumper (BP), and a Spoiler (SP) as shown in Figure 2.

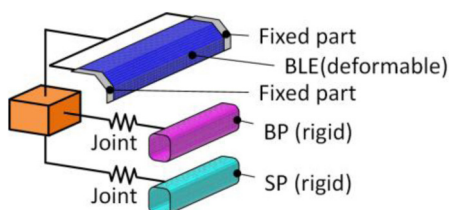


Figure 2. Schematic of the simplified vehicle FE model.

The BLE consists of a deformable shell that simulates the characteristics of a cold rolled steel sheet. This part was designed to reproduce the complicated deformation phenomenon occurring at the BLE of an actual vehicle in longitudinal and vertical directions. The

stiffness of the BLE can be modified by varying the thickness of the shell element. The BP and the SP are composed of a combination of a rigid shell tube with square section connected to a joint element. The joint element restricts motion of the tube to the vehicle longitudinal direction. The stiffness of these components can be modified by varying the mechanical characteristics of the joint elements according to mechanical properties obtained from actual vehicles which were used in the preceding studies [3,4,5]. The vehicle shape can be changed by varying the relative positions of BLE, BP, and SP, according to a vehicle shape corridor provided by the International Harmonized Research Activity for Pedestrian Safety (IHRA-PS) working group [6].

By combining two levels of BLE thickness (0.4 and 0.6 mm), three levels of BP and SP joint element stiffness described in Figure 3, and three layouts of BLE, BP, and SP described in Figure 4 and Table 1, a total of 18 simplified high-bumper vehicle FE models (SUV01 to SUV18) and 18 simplified low-bumper vehicle FE models (Sedan01 to Sedan18) were generated. The models were organized according to an L18 orthogonal table for parametric study design [7] as shown in Table 2.

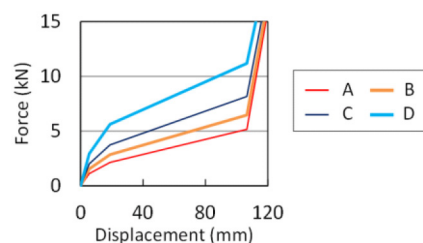


Figure 3. Mechanical characteristics for the BP and SP joint elements.

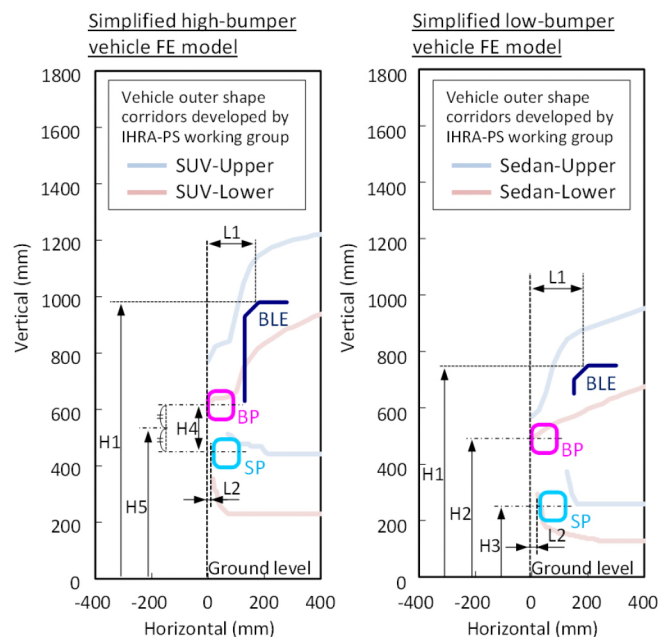


Figure 4. Shape parameters for the simplified vehicle FE models.

Table 1. Parameters and levels for simplified high-bumper vehicle FE models (above) and simplified low-bumper vehicle FE models (below).

Simplified high-bumper vehicle FE model

Parameter	Unit	Level 1	Level 2	Level 3
K1 BLE thickness	mm	0.4	0.6	-
K2 BP stiffness	-	B	C	D
K3 SP stiffness	-	A	C	D
H1 BLE height	mm	900	980	1120
H4 BP height - SP height	mm	40	110	170
H5 Average height of BP and SP	mm	530	580	670
L1 BLE lead	mm	110	180	280
L2 SP lead	mm	0	10	20

Simplified low-bumper vehicle FE model

Parameter	Unit	Level 1	Level 2	Level 3
K1 BLE thickness	mm	0.4	0.6	-
K2 BP stiffness	-	B	C	D
K3 SP stiffness	-	A	C	D
H1 BLE height	mm	650	700	750
H2 BP height	mm	450	490	530
H3 SP height	mm	250	270	350
L1 BLE lead	mm	125	200	275
L2 SP lead	mm	-20	0	30

Table 2. L18 orthogonal table with the specifications of the 36 simplified vehicle FE models utilized in this study.

Simplified high-bumper vehicle FE models

ID	K1	K2	K3	H1	H4	H5	L1	L2
SUV01	0.4	B	A	900	40	530	110	0
SUV02	0.4	B	C	980	110	580	180	10
SUV03	0.4	B	D	1120	170	670	280	20
SUV04	0.4	C	A	900	110	580	280	20
SUV05	0.4	C	C	980	170	670	110	0
SUV06	0.4	C	D	1120	40	530	180	10
SUV07	0.4	D	A	980	40	670	180	20
SUV08	0.4	D	C	1120	110	530	280	0
SUV09	0.4	D	D	900	170	580	110	10
SUV10	0.6	B	A	1120	170	580	180	0
SUV11	0.6	B	C	900	40	670	280	10
SUV12	0.6	B	D	980	110	530	110	20
SUV13	0.6	C	A	980	170	530	280	10
SUV14	0.6	C	C	1120	40	580	110	20
SUV15	0.6	C	D	900	110	670	180	0
SUV16	0.6	D	A	1120	110	670	110	10
SUV17	0.6	D	C	900	170	530	180	20
SUV18	0.6	D	D	980	40	580	280	0

Simplified low-bumper vehicle FE models

ID	K1	K2	K3	H1	H2	H3	L1	L2
Sedan01	0.4	B	A	650	450	250	125	-20
Sedan02	0.4	B	C	700	490	270	200	0
Sedan03	0.4	B	D	750	530	350	275	30
Sedan04	0.4	C	A	650	490	270	275	30
Sedan05	0.4	C	C	700	530	350	125	-20
Sedan06	0.4	C	D	750	450	250	200	0
Sedan07	0.4	D	A	700	450	350	200	30
Sedan08	0.4	D	C	750	490	250	275	-20
Sedan09	0.4	D	D	650	530	270	125	0
Sedan10	0.6	B	A	750	530	270	200	-20
Sedan11	0.6	B	C	650	450	350	275	0
Sedan12	0.6	B	D	700	490	250	125	30
Sedan13	0.6	C	A	700	530	250	275	0
Sedan14	0.6	C	C	750	450	270	125	30
Sedan15	0.6	C	D	650	490	350	200	-20
Sedan16	0.6	D	A	750	490	350	125	0
Sedan17	0.6	D	C	650	530	250	200	30
Sedan18	0.6	D	D	700	450	270	275	-20

Human Full-Body FE Model

In this study, we utilized a biofidelic human full-body FE model validated in detail against component and full scale experimental data obtained with Post Mortem Human Subjects [8,9,10,11].

With regard to lower limbs posture of the model, the lower limb on the side struck by the vehicle was set in vertical position, and the opposite lower limb was set in 20 degrees ahead from the pedestrian vertical axis (Figure 5). A total of eight “injury measures” were outputted to evaluate the bending load generated in the lower limb: bending moment of the femur at three locations (Femur-1 to 3), elongation of the medial collateral ligament (MCL) of the knee and bending moment of the tibia at four locations (Tibia-1 to 4) as shown in Figure 5. The polarity of the bending moment generated in the femur and the tibia are described in Figure 7. With regards to the polarity of the MCL injury measure, elongation of the MCL was defined as positive.

The elongations of the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) of the knee were not included in this study because ACL or PCL injuries are, when occurring in pedestrian accidents, usually accompanied by MCL injury as shown by the preceding study [12]. The phenomenon is also confirmed from our computer simulation results of the human full-body FE model conducted in this study (Appendix Figure A1).

Isolated Human Lower Limb FE Model

In this study, an isolated lower limb FE model was created from the human full-body FE model. To create the isolated human lower limb FE model, all the parts of the human full-body FE model except the lower limb on the side struck by the vehicle were removed.

FlexPLI FE Model

In this study, a FlexPLI FE model previously developed was utilized. The model has been validated in detail against FlexPLI test data obtained from static and dynamic certifications tests and has a high fidelity to the actual FlexPLI [13,14].

Eight injury measures were outputted as shown in Figure 6. The polarity of the bending moment generated in the femur and the tibia are described in Figure 7. With regards to the polarity of the MCL injury measure, elongation of the MCL was defined as positive. These injury measures of the FlexPLI FE model are from comparable positions to those taken from the human full-body FE model.

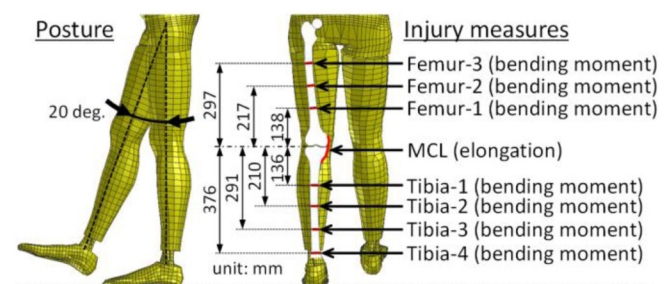


Figure 5. Image of the lower part of the human full-body FE model. Posture and Injury Measures utilized in this study.

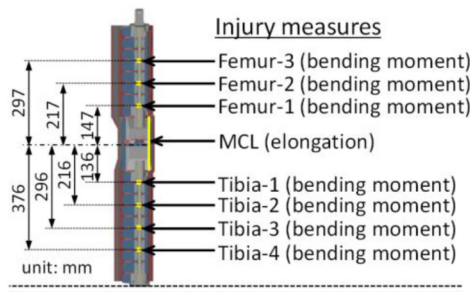


Figure 6. Image of the FlexPLI FE Model and the Injury Measures utilized in this study.

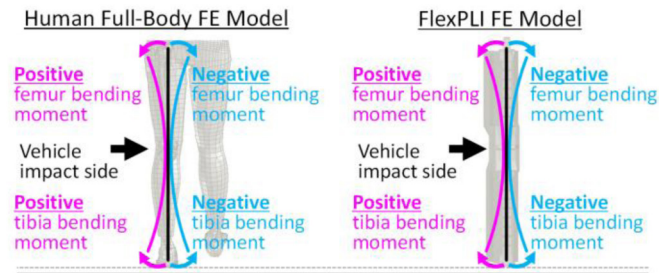


Figure 7. Polarity of the bending moment generated in the femur and the tibia of the human full-body FE model and the FlexPLI FE Model.

METHODOLOGIES

Analysis-1: Influence of the Upper Body

In order to analyze the influence of the upper body on the bending load generated in the lower limb of a pedestrian, a simulation based parametric analysis was conducted. A scheme of the simulation settings for this analysis is presented in Figure 8.

Each of the 18 simplified high-bumper vehicle FE models and 18 simplified low-bumper vehicle FE models designed according to the L18 orthogonal table (Table 2) was set to simulate a collision with the human full-body FE model and with the isolated human lower limb FE model, respectively. Vehicle impact speed was set to 11.1 m/s, which is the vehicle-to-pedestrian impact speed targeted by United Nations pedestrian safety regulations (UN Global Technical Regulation Number 9, UN Regulation Number 127 and 01 series of amendments to UN Regulation Number 127) [1,15,16]. Impact height (H) of the human full-body FE model and the isolated human lower limb FE model was set by adjusting the sole of the foot 25 mm above the ground, which is the vehicle-to-pedestrian impact height targeted by United Nations pedestrian safety regulations (UN Global Technical Regulation Number 9, UN Regulation Number 127 [15,16] to consider the thickness of the sole of the shoe. Kinematics and injury measures from the simulations were analyzed and correlation analysis between the maximum values of the injury measures from the human full-body FE model and the isolated human lower limb FE model was conducted.

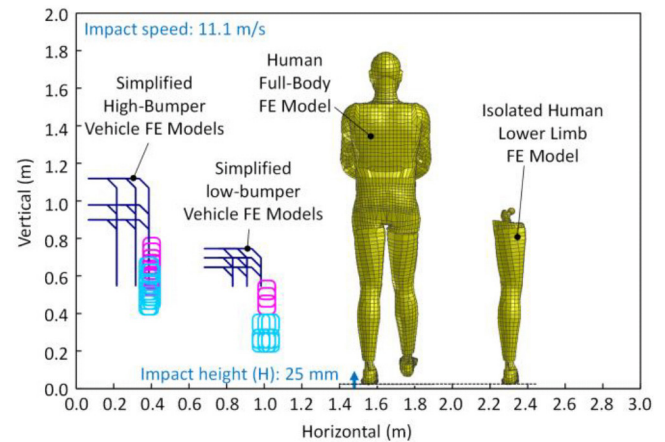


Figure 8. Scheme including models and simulations setup of the parameter study conducted to analyze the influence of the upper body on bending load generated in the lower limb.

Analysis-2: Effectiveness of Increasing Impact Height of the FlexPLI

In order to clarify the effectiveness of the increasing impact height of the FlexPLI, a second simulation parametric analysis was conducted. A scheme of the simulation settings for this analysis is presented in Figure 9.

Each of the 18 simplified high-bumper vehicle FE models and 18 simplified low-bumper vehicle FE models were set to simulate a collision with the human full-body FE model and the FlexPLI. Simplified low-bumper vehicle FE models were also included in this study, in order to clarify the effectiveness of the increasing impact height of the FlexPLI also for femur injury measures, which had not been confirmed in previous studies [2]. Impact speed was set to 11.1 m/s for all cases. The human full-body FE model was set so the sole of the foot on the side struck by the vehicle was 25 mm above the ground. The FlexPLI FE model was set at two different heights of 25 mm and 75 mm. The maximum values of the injury measures from all simulations were extracted and correlation analysis between the human full-body FE model and the FlexPLI FE model at each of the two heights were conducted.

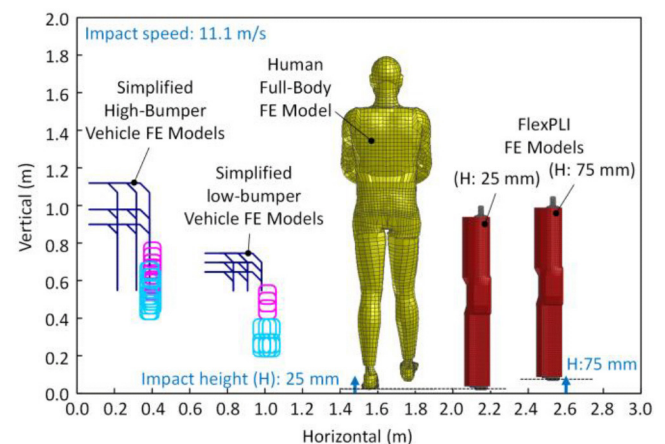


Figure 9. Scheme including models and simulation setup of the parameter study conducted to analyze the effectiveness of increasing impact height of the FlexPLI.