DEVELOPMENT OF A BIOFIDELIC FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR Type GT (FLEX-GT)

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Paper Number 07-0178

ABSTRACT

The Japan Automobile Research Institute and the Japan Automobile Manufacturers Association, Inc., have been developing a biofidelic flexible pedestrian legform impactor (Flex-PLI) since 2002, and its the latest version is called Flex-GT, and its prototype (Flex-GT-prototype) is developed in 2006. However, the Flex-GT-prototype is required further evaluation study on its biofidelity.

This study evaluated a biofidelity of Flex-GT-prototype, relationship to the human one using an FE Flex-GT-prototype model which has high fidelity to the actual one and a FE human model which has high biofidelity. This study result shows a good relationship between the Flex-GT-prototype model and the FE human model, especially under the 50 mm or 75 mm lift upped impact conditions.

INTRODUCTION

A study designed to decrease the level of pedestrian injuries when crashing into a car ("study on pedestrian protection") was initiated in the 1960s [1), 2)], and subsequently, test methods to evaluate the pedestrian protection performance of cars ("pedestrian protection test methods") have been frequently discussed.

As a results, several pedestrian protection test methods are developed; the EEVC (European Enhanced Vehicle-safety Committee / European Experimental Vehicles Committee (former name)) Pedestrian Protection Test Method [3), 4)], ISO (International Organization for Standardization) Pedestrian Protection Test Method [5)-7)], and the IHRA (International Harmonized Research Activity) Pedestrian Protection Test Method [8)]. In addition, thus far, regulations and technical standards based on these test methods ("technical standards for pedestrian protection") have been examined by each organization, and the Japanese Technical Standards for Pedestrian Protection [9)], the European Technical Standards for Pedestrian Protection [10), 11)] and the Global Technical Standards (proposal) for Pedestrian Protection [12)] have been developed.

Moreover, in these pedestrian test methods and technical standards for pedestrian protection, impactors imitating major human parts injured when impacting a car (e.g. head impactor and pedestrian legform impactor) are crashed into by a car (see Figure 1) and the pedestrian protection performance of the car is evaluated in terms of the degree of impact/loading levels on the impactors.

Basically, these impactors require a high level of biofidelity (equivalent deformation property under the load of a human body) and high injury evaluation ability (ability to properly evaluate injuries occurring in pedestrians). While the pedestrian legform impactor produced by TRL [13)] which was developed in the 1990s has been used in the EEVC Pedestrian Protection Test Method, European Technical Standards for Pedestrian Protection, and Global Technical Standards (proposal) for Pedestrian Protection, bone parts are made as a rigid body, and moreover, it is considered to be difficult to properly evaluate leg injuries due to the lack of biofidelity and insufficiencies in the measuring instruments incorporated.[14)]

Thus, currently, ECE/WP29/GRSP ("GRSP") of the United Nations has focused its attention on "flexible pedestrian legform impactor" [15)-19)] which have a higher level of biofidelity than conventional impactors, enabling more accurate injury evaluation. As a results, GRSP established the Flexible Pedestrian Legform Impactor Technical Evaluation Subgroup [20)] under GRSP/INF-GR-PS (Informal Group on Pedestrian Safety) to conduct technical evaluation activities on these impactors.

In this article, we report on the status of the development of type GT (Flex-GT), which is the latest model of flexible pedestrian legform impactor.

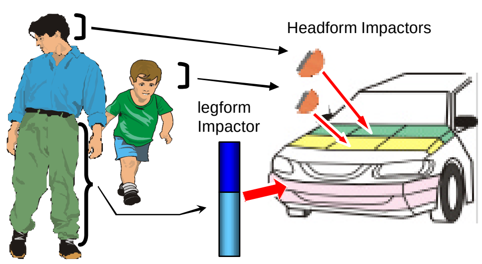


Figure 1. Concept of the pedestrian protection test methods.

DEVELOPMENT OF FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR TYPE GT

Development of a prototype

The flexible pedestrian legform impactor type GT prototype (Type GT prototype) was developed in 2006 (February) (see Figure 2) [21), 22)]. In this version, a) the range of motion of the knee region, b) the light weight of the bone parts, as well as c) the biofidelity are improved. However, a validation of the biofidelity was not completely conducted, so it still needs to be validated.

Thus, to conduct additional validation for the biofidelity of this impactor, analysis with computer simulation was performed in this study.

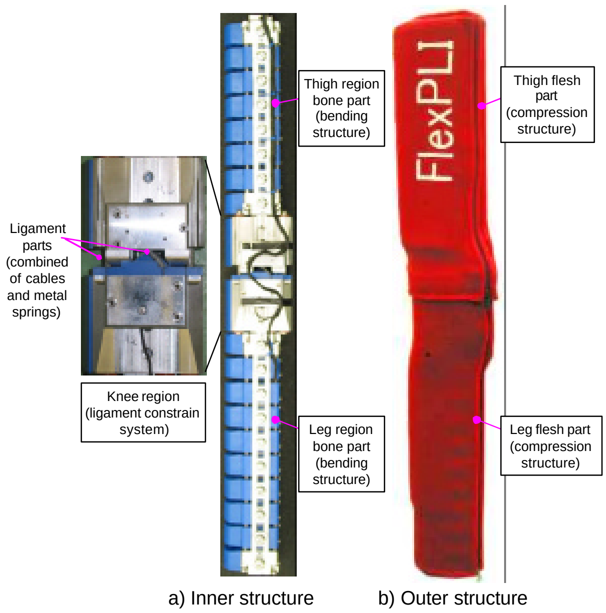


Figure 2. Flexible pedestrian legform impactor type GT prototype (Flex-GT-prototype).

Methods

Computer models

The computer models used in this study are shown in Figure 3. The computer models are broadly divided into three, including one imitating a human body ("human model"), one imitating the flexible pedestrian legform impactor type GT prototype ("Flex-GT-prototype model") and one simply imitating a car ("simplified car model").

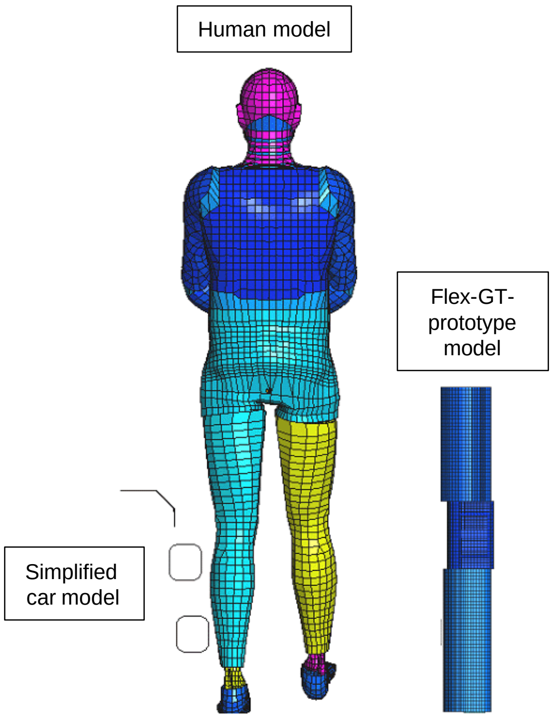


Figure 3. Computer models used in this study (overview).

Human model - The human model is structured based on the MRI (magnetic resonance imaging) scan data of a human body [23), 24)] with fidelic modeling of the inner cross-section structure of the bone part and the ligament structure of the knee region. The bone part of the knee region for this model was validated in detail using various donated body experiment data.

Flex-GT-prototype model - The Flex-GT -prototype model is structured based on the drawing of this impactor with detailed modeling of the structure of the bone part and knee region.[25)] This model was validated per part during the assembly stage, and has high fidelity to the actual impactor.

Simplified car model - The overview shape of the simplified car model is shown in Figure 4. The simplified car model is comprised of three parts including the bonnet leading edge part ("BLE"), the bumper part ("BP") and the spoiler part ("SP").

The structure of the simplified car is shown in Figure 5 - 7. BLE is made of deformable shell elements which can deform upon impact. In addition, the material properties of these elements are provided with the properties of automotive cold-rolled steel plate JSC270C (cold-rolled steel plate, tensile strength: 270 N/mm^2 and over, steel grade: C class).

On the other hand, BP and SP are made of rigid body elements, and the movable property is defined by the properties of the joint bond to each element (see Figure 6 and Figure 7).

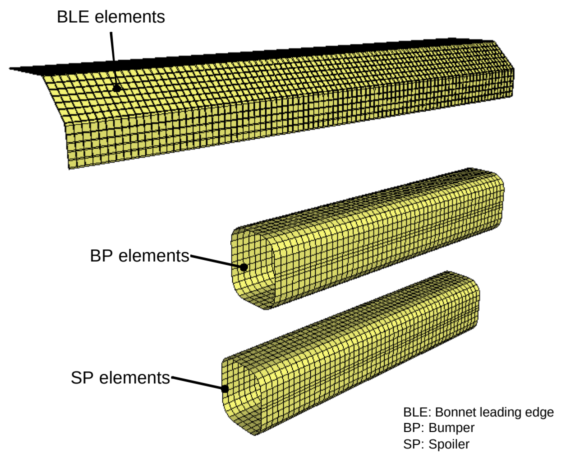


Figure 4. Simplified car model (overview - oblique front projection drawing).

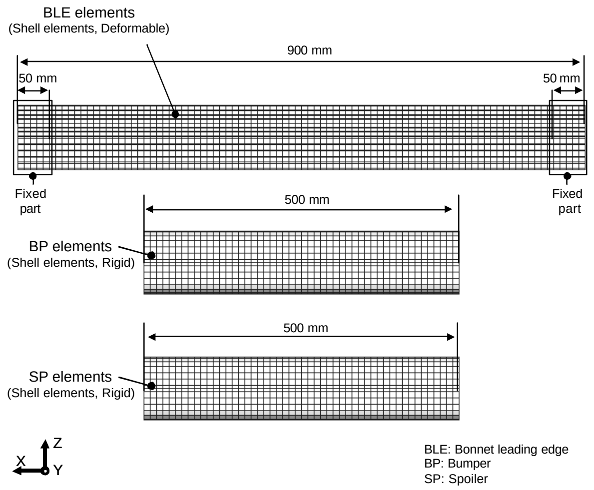


Figure 5. Simplified car model structure (frontal view of the car).

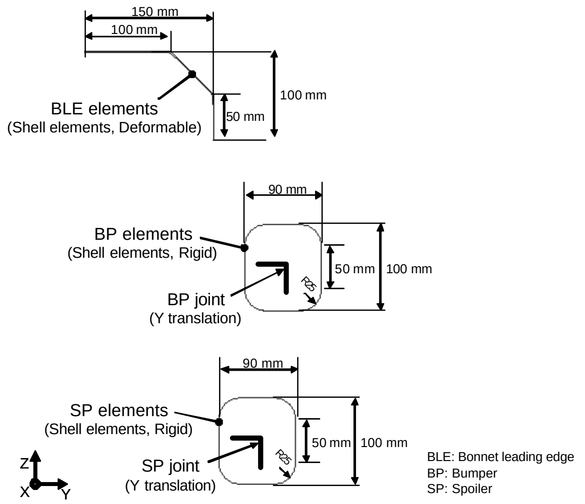


Figure 6. Simplified car model structure (side view of the car).

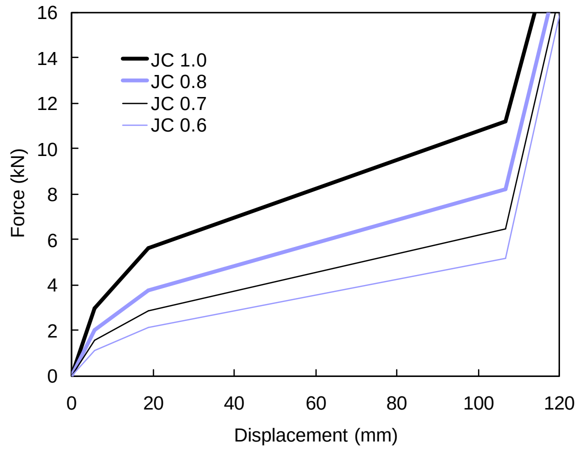


Figure 7. BP and/or SP joint properties of the simplified car model (JC 0.6 – JC 1.0).

Setting conditions

In this analysis, several simplified car models made with varying stiffness and shapes were crashed into the human model and the Flex-GT-prototype model to compare the loading level of each model.

Setting of the human model - As for the human model, to find the correlation with the Flex-GT -prototype model, the model was set to output the load on the tibial part of the leg region and the knee medial collateral ligament (MCL) which are mainly taken as the subject of pedestrian lower limb protection (see Figure 8).

To simply compare the maximum output value on the tibia of the leg region and the knee collateral ligament, the setting of the bone parts fracture (except the fibula) and the setting of the breaking knee ligament parts in the human model are excluded.

As for the legs position of the human model, the initial crash side of the leg was set vertical to the ground, with the other leg casting out at 20 degrees in front of the pedestrian (see Figure 9). This setting is intended to simulate the pedestrian legform impactor impact condition (vertical to the ground, initial crash side of leg) and to prevent interfering with each other of leg.

In crash simulations with the simplified car model, as shown in Figure 10, BP and SP were placed on the leg for the initial crash and the other leg respectively. This is intended to prevent the entire BP and SP from moving backwards from the car due to the impact of the initial crash side of the leg, because it is difficult to imagine that the entire BP and SP backwards movement due to the impact of the initial crash side of the leg under an actual car crash condition.

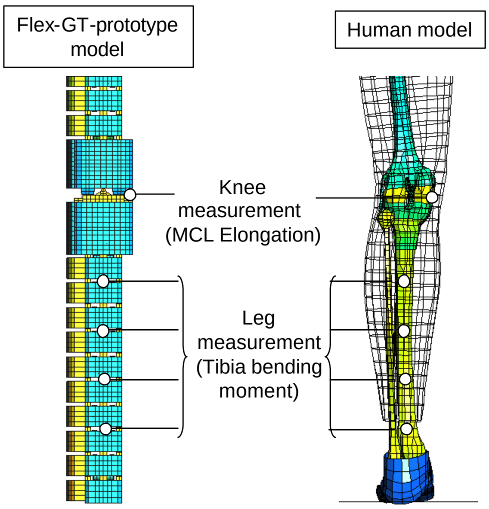


Figure 8. Measurement points of the human model and the Flex-GT-prototype model.

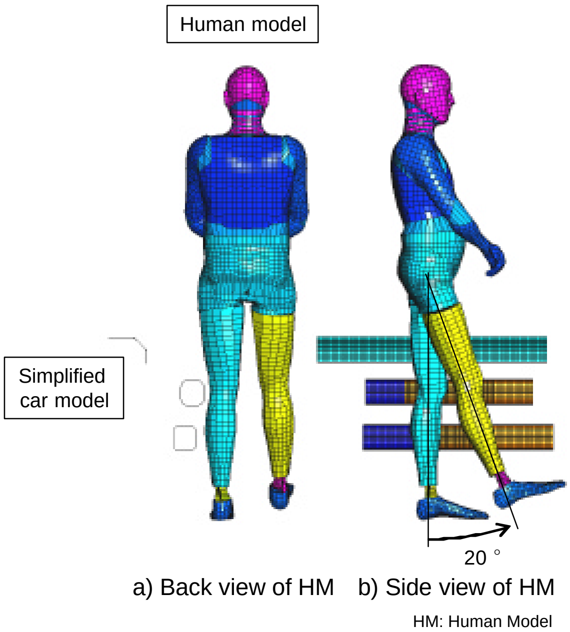


Figure 9. Posture of the human model.

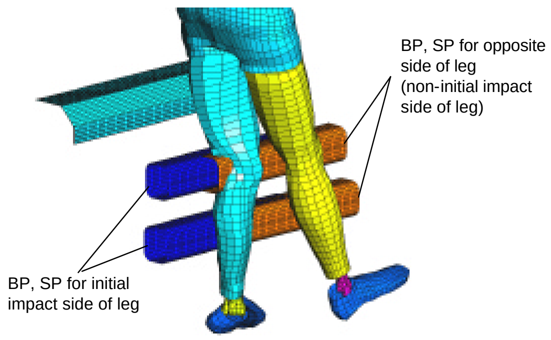


Figure 10. Setting of the simplified car model for the human model.

Setting of the Flex-GT-prototype model - As for the Flex-GT-prototype model, the output setting is same of the human model case as mentioned above (see Figure 8). The front placement position of the Flex-GT-prototype model to the simplified car was set as the center of the car (Figure 11).

In this study, the tibia bending moment values were estimated from the strain values which were occurred in the bone part core part. However, this study did not using the conventional strain to bending moment conversion method (a method using the dynamic three-point leg bending test results) but simply used the three-point bending of the bone part core of leg. This is because the conventional method includes the effects of the inertial force of the bone parts and also includes the effect of the fixed conditions of the bone parts to the three-point bending equipments, which makes it difficult to obtain correct conversion values.

The bending moment conversion method is changed; “RCAL” is indicated in the graph title section to show the differences.

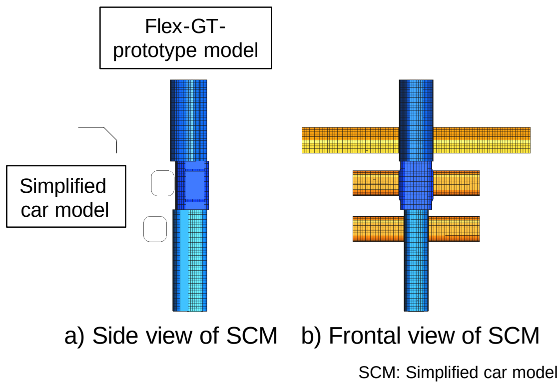


Figure 11. Front placement position of the Flex-GT-prototype model to the simplified car model.

Setting of the simplified car model - The setting parameters of the simplified car model are shown in Table 1. The setting parameters are broadly divided into car stiffness and car shapes (see Figure 12 for the definition of car shapes).

As for car stiffness, BLE stiffness can be changed by altering the plate thickness of the shell elements comprising the car. BP and SP stiffness can be changed by altering the joint properties set for each element. As for car shapes, the shape of the car can be changed by altering the placement of each element.

If simplified car models are created by combining all the setting parameters of car stiffness and car shapes described in Table 1, 4,374 patterns of simplified cars can be created. However, because it takes tremendous time to create 4,374 patterns of simplified cars and perform simulation analyses. In this study, therefore, using a design of experiment method (assignment of setting parameters using L18 orthogonal table), simulations for a total of 18 types of simplified cars representing all setting parameters were conducted (see Table 2).

Table 1. Setting parameters of the simplified car model.

Parameter	Unit	Level 1	Level 2	Level 3
K1 (BLE stiffness*)	mm	0.4	0.6	
K2 (BP stiffness**)	JC***	0.7	0.8	1.0
K3 (SP stiffness**)	JC***	0.6	0.8	1.0
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

* Stiffness is changed by steel plate thickness.
** Stiffness is changed by joint characteristics.
*** JC: Joint characteristics
# BLE: Bonnet leading edge, BP: Bumper, SP: Spoiler

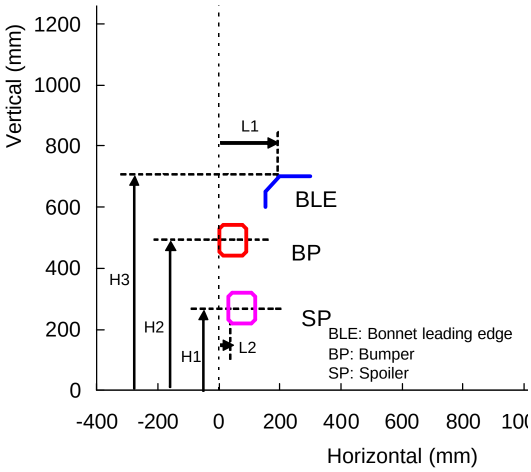


Figure 12. Definition of the car shapes of simplified car models.

Table 2. Specifications of the simplified car models (total 18 types).

Simplified Car Model ID	K1 (BLE stiffness*) mm	K2 (BP stiffness**) JC***	K3 (SP stiffness**) JC***	H1 (BLE height) mm	H2 (BP height) mm	H3 (SP height) mm	L1 (BLE lead) mm	L2 (SP lead) mm
S1	0.4	0.7	0.6	650	450	250	125	-20
S2	0.4	0.7	0.8	700	490	270	200	0
S3	0.4	0.7	1.0	750	530	350	275	30
S4	0.4	0.8	0.6	650	490	270	275	30
S5	0.4	0.8	0.8	700	530	350	125	-20
S6	0.4	0.8	1.0	750	450	250	200	0
S7	0.4	1.0	0.6	700	450	350	200	30
S8	0.4	1.0	0.8	750	490	250	275	-20
S9	0.4	1.0	1.0	650	530	270	125	0
S10	0.6	0.7	0.6	750	530	270	200	-20
S11	0.6	0.7	0.8	650	450	350	275	0
S12	0.6	0.7	1.0	700	490	250	125	30
S13	0.6	0.8	0.6	700	530	250	275	0
S14	0.6	0.8	0.8	750	450	270	125	30
S15	0.6	0.8	1.0	650	490	350	200	-20
S16	0.6	1.0	0.6	750	490	350	125	0
S17	0.6	1.0	0.8	650	530	250	200	30
S18	0.6	1.0	1.0	700	450	270	275	-20

* Stiffness is changed by steel plate thickness.
** Stiffness is changed by joint characteristics.
*** JC: Joint characteristics
# BLE: Bonnet leading edge, BP: Bumper, SP: Spoiler

Impact conditions - A total of 18 types simplified car model were selected as mentioned above, and crashed into the human model and the flexible pedestrian leg impactor type GT prototype model (see Figure 13). The impact speed was set at 11.1 m/s defined in the current GTR proposal.

As for the impact height (H_I) of the human model and the flexible pedestrian leg impactor type GT prototype model against the simplified cars, 25 mm above the ground as defined in the current GTR proposal.

In this study, as for the impact height for the flexible pedestrian leg impactor type GT prototype model, in addition to the base height of 25 mm ("base"), base + 50 mm, and base + 75 mm were also conducted.

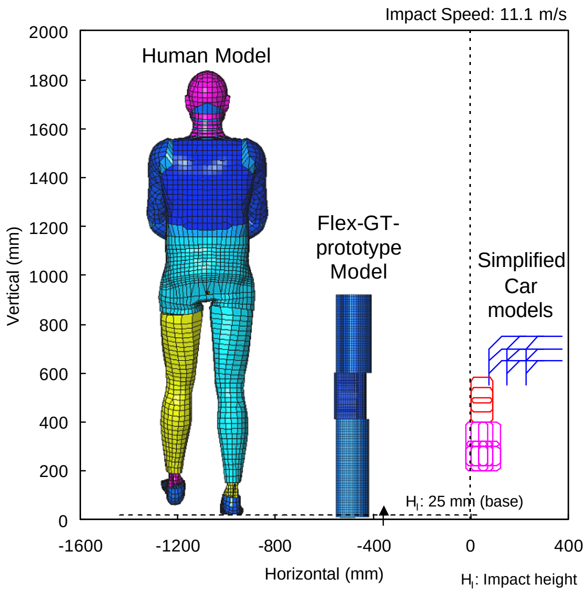


Figure 13. Analysis conditions (image, impact height: 25 mm).

Simulation results

The results of the simulation are shown in Figure 14. This figure shows the relationship between the maximum bending moment occurring in the tibial part of the human model and the flexible pedestrian leg impactor type GT prototype model, as well as the maximum elongation occurring in the knee collateral ligament.

This figure indicates that the Flex-GT-prototype model output and Human model output has generally good relationship. Especially for the maximum bending moment occurring in the tibial part, the results for the impact height of the flexible pedestrian leg impactor type GT prototype model 50 mm higher than the base height best correlate with the output of the human model. As for the maximum elongation of the knee medial collateral ligament, it was found that the results of impact height of the flexible pedestrian leg impactor type GT prototype model which was higher than 75 mm than the base height best correlate with the output of the human model.

Based on correlation coefficient obtained from each result, the tibial fracture evaluation point (R_{tibia}), knee medial collateral ligament breaking evaluation point (R_{MCL}) and total evaluation point ((R_{tibia} + R_{MCL})/2) were calculated and the results are shown in the radar charts in Figure 15. As for total evaluation point, the results of the impact height of the flexible pedestrian leg impactor type GT prototype model 50 mm and 75 mm higher evaluation point (about 0.8) than the base height obtained equivalent evaluation points (about 0.6).

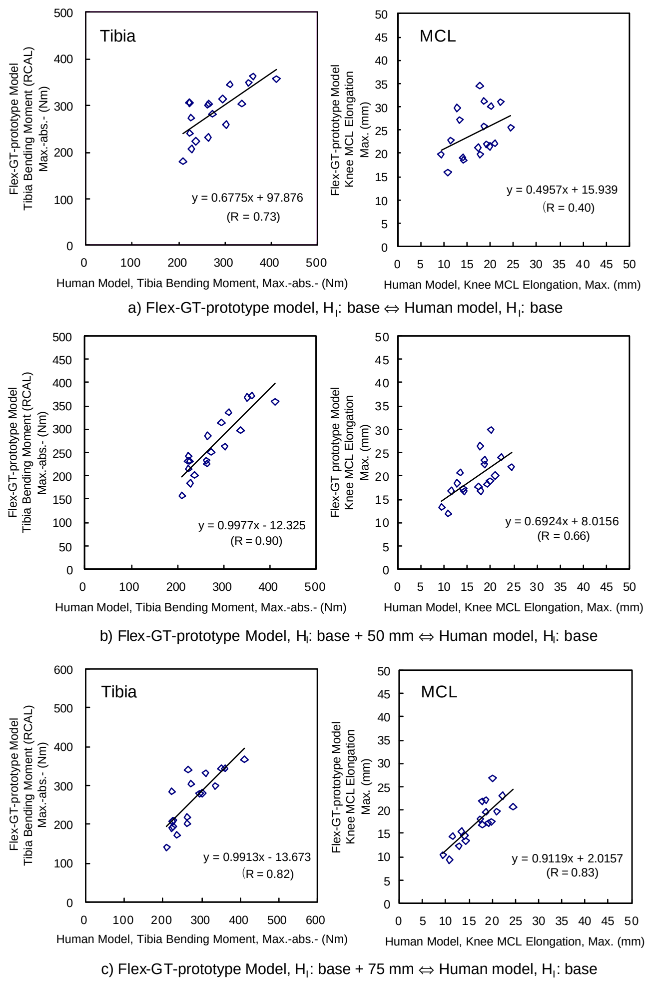
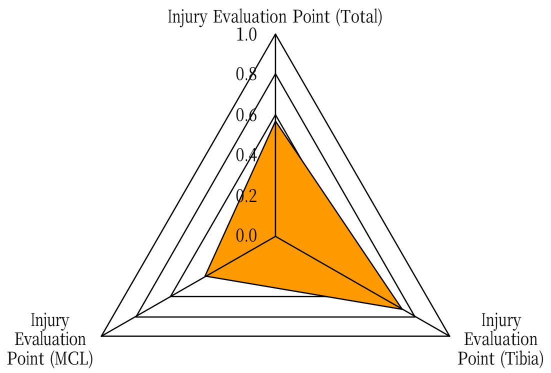
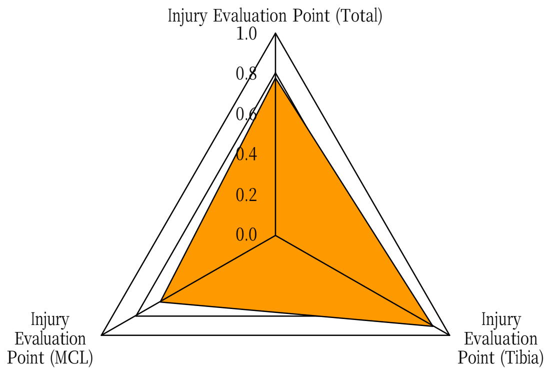


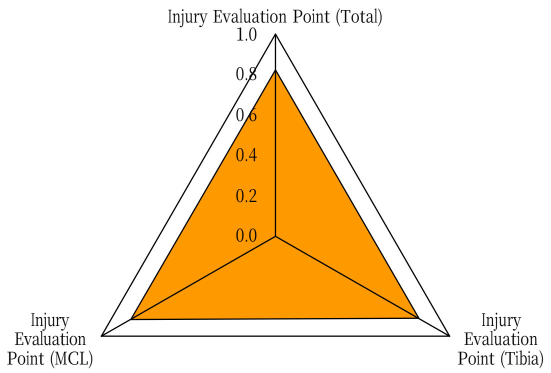
Figure 14. Simulation results (output values and correlation coefficients).



a) Flex-GT-prototype model, H_I: base



b) Flex-GT-prototype Model, H_I: base + 50 mm



c) Flex-GT-prototype Model, H_I: base + 75 mm

Injury Evaluation Point (Total): $(R_{tibia}+R_{MCL})/2$
Injury Evaluation Point (Tibia): R_{tibia}
Injury Evaluation Point (MCL): R_{MCL}

Figure 15. Injury evaluation point.

DISCUSSION

From the results of this analysis, an impact height 50-75 mm higher than the base (25 mm) more correlated with the human model. One of the reasons for this is seemed as to be the effect of the presence or absence of the human upper body.

The human upper body has great inertia force because of its size in mass relative to the leg, which tends to stay relatively at the initial position even after the leg crashes into a car. Therefore, during impact with a car, the upper body tends to lift up the leg overall (see Figure 16).

Figure 17 shows the difference in the knee joint position of the human model and the flexible pedestrian leg impactor type GT prototype (impact height: base) when the maximum bending moment occurs in the tibia in the leg region and when maximum elongation occurs in the knee medial collateral ligament. While in the human model, the knee joint position already rises approximately 20 mm on average when the maximum bending moment occurs in the tibia in the leg region, it only rises less than 5 mm on average in the flexible pedestrian leg impactor type GT prototype. In addition, while in the human model, the knee joint position rises approximately 60 mm on average when maximum elongation occurs in the knee collateral ligament, it rises only about 20 mm on average in the flexible pedestrian leg impactor type GT prototype.

It is highly possible that these differences cause the difference in the loading condition on the tibia and the knee medial collateral ligament, and it is suggested that changing the impact height of the pedestrian legform impactor have effects to correct these differences.

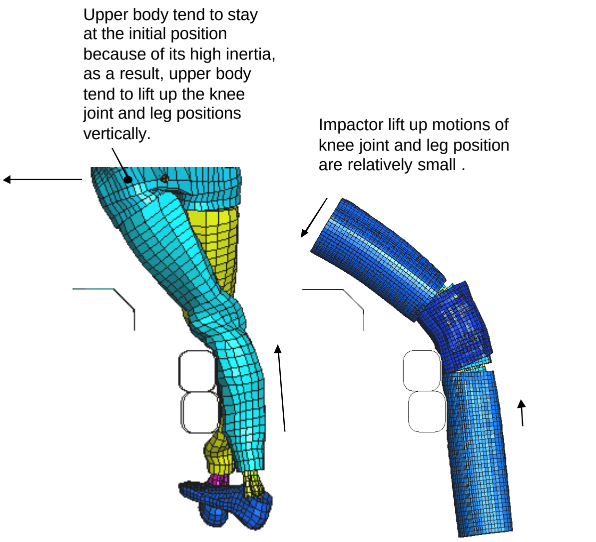
Moreover, the human upper body has the effect of inhibiting thigh movement due to its great inertia force (see Figure 18).

As mentioned above, the human upper body has great inertia force because of its size in mass relative to the leg, which tends to stay relatively at the initial position even after the leg crashes into a car. Therefore, during impact into a car, it inhibits thigh behavior to prevent the thigh from falling against the car. On the other hand, in the pedestrian impactor without an upper body, thigh behavior is not inhibited and the thigh easily falls against the car. These differences become factors which cause significant differences, particularly in the load on the knee collateral ligament.

As shown in Figure 19 and Figure 20, it is considered that shifting the impact position of the pedestrian legform impactor upwards especially facilitates rotation of the leg region of the pedestrian legform impactor, and as a result, the load occurring on the knee part has the same effect as in the human body.

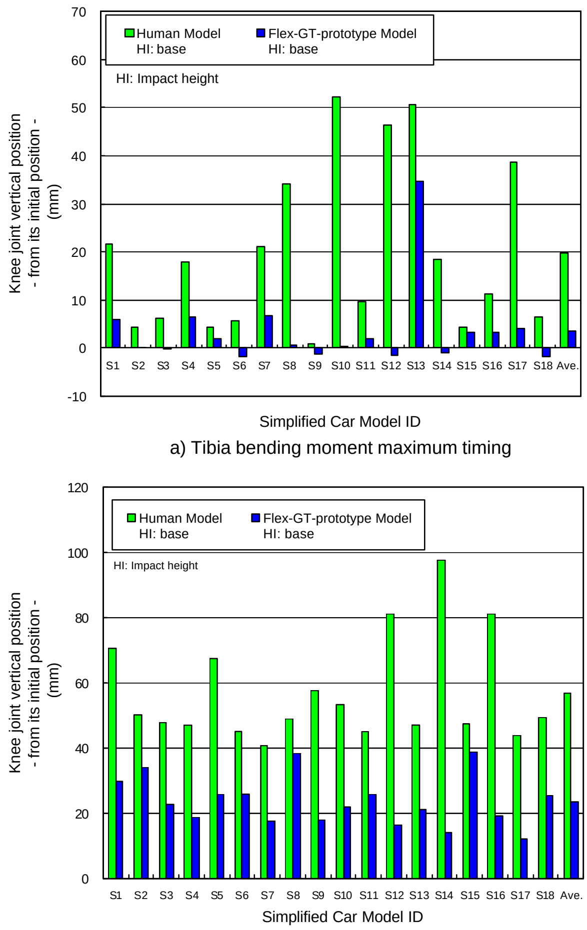
Additionally, it has a chance that the difference in distribution of mass between the human body and the pedestrian legform impactor, while in the human body the bone part is very light in weight and a flesh part covers most of the mass, affects to the human and impactor differences. However, in the pedestrian legform impactor, it is difficult to reduce the mass of the bone part to be equivalent to that of the human body because of various limitations such as incorporation of measuring censors, endurance, and testability. Additionally, the presence or absence of the ankle joint may cause differences in load status.

However, to change the impactor specifications of the pedestrian legform impactor while meeting the basic specifications required for the pedestrian legform impactor (e.g. incorporation of measuring censor, endurance, and testability) is very difficult. Moreover, to change the impactor specification has a high risk for the developments itself (unexpected issue will be happened). To keep the current specification of the impactor and to select best impact heights is therefore one of a good practical method.



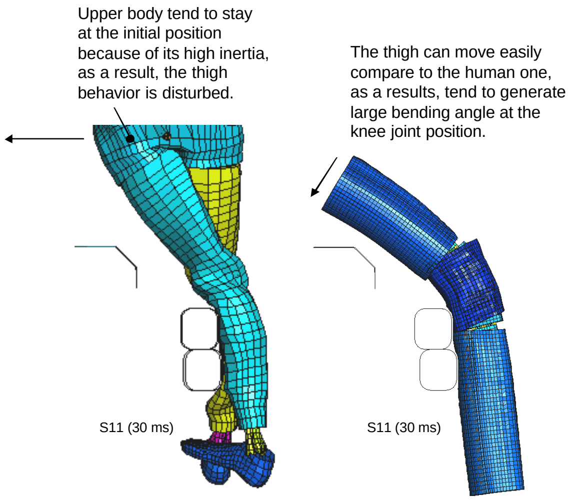
a) Human model, H_I: base   b) Flex-GT-prototype model, H_I: base

Figure 16. Upper body effect (1) - Lifting up the lower limb.



b) Knee MCL elongation maximum timing

Figure 17. Difference in amount of rise of the knee position.



a) Human model, H_I: base   b) Flex-GT-prototype model, H_I: base

Figure 18. Upper body effect (2) – Inhibition of thigh behavior.

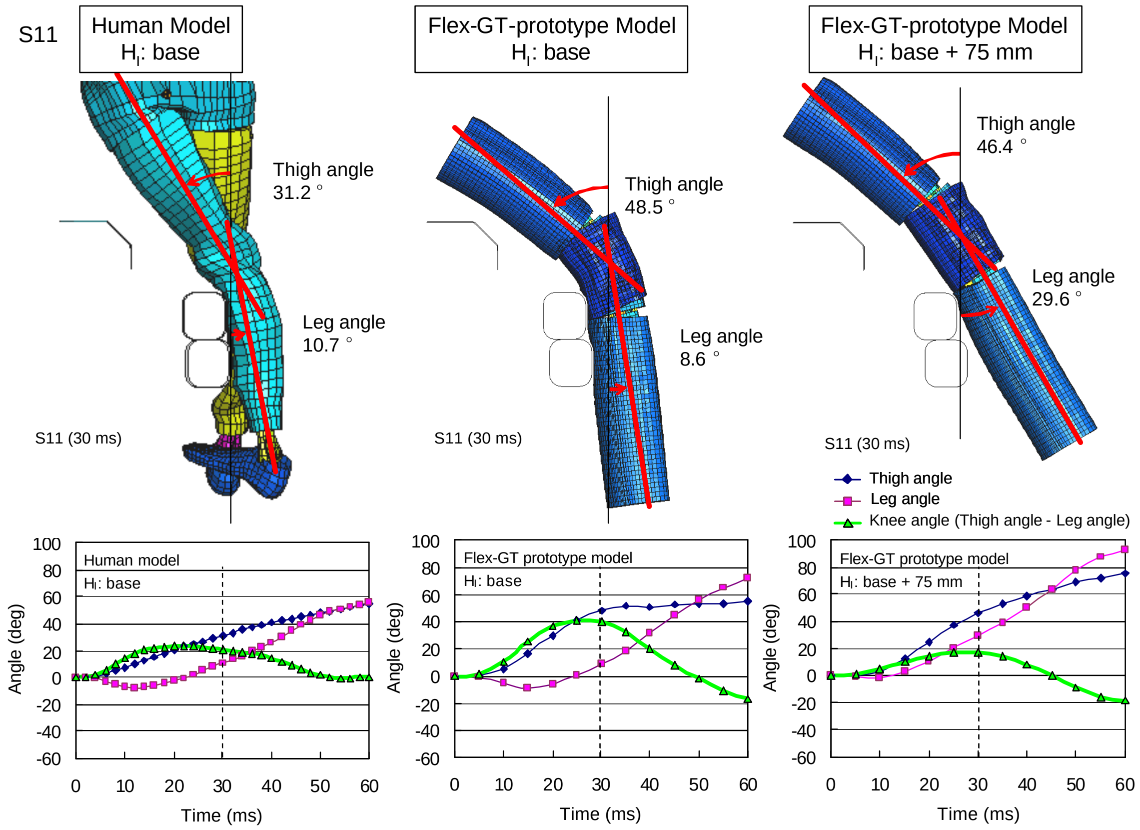


Figure 19. Timely curves for the angle of the thigh, leg and knee (S11) , example.

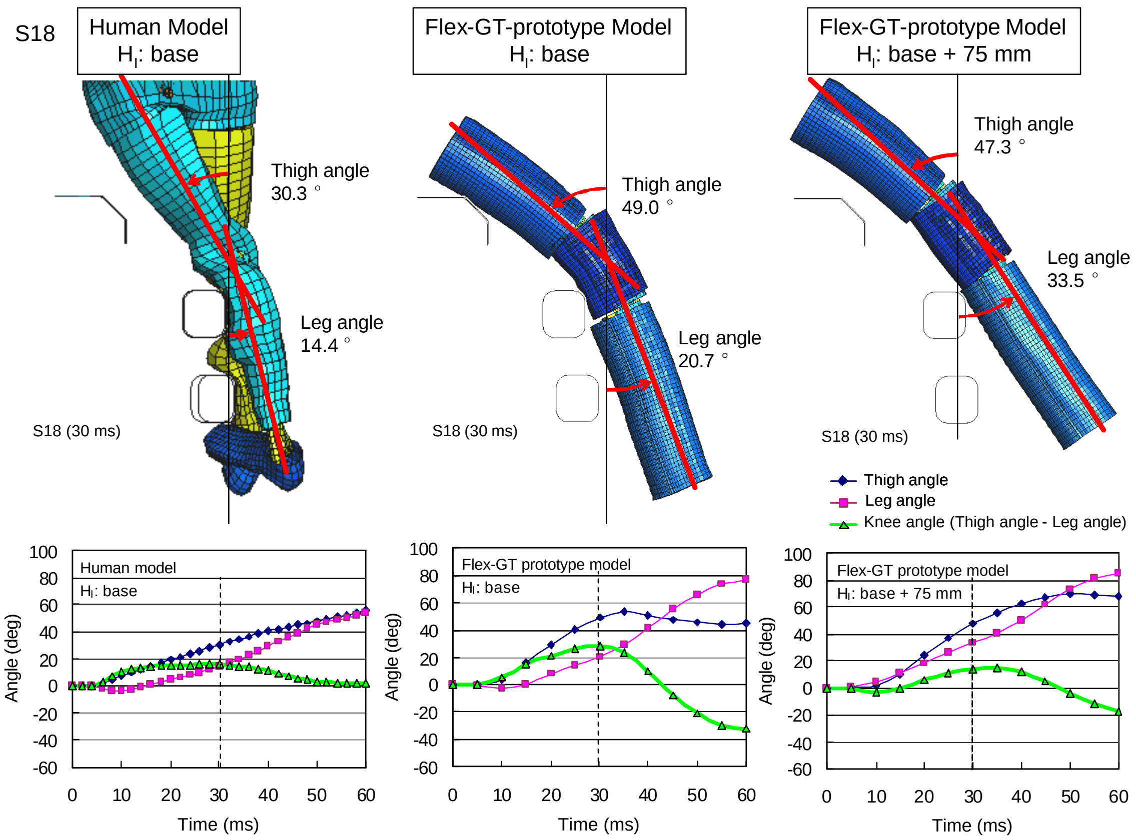


Figure 20. Timely curves for the angle of the thigh, leg and knee (S18), example.

CONCLUSION

In this study, the biofidelity (correlation with the human body) of the flexible pedestrian legform impactor type GT prototype was verified using the Flex-GT-prototype model and the human model.

It was found that correlation with the human body becomes greater by increasing the impact height of the Flex-GT-prototype model by 50-75 mm.

As the main reason for this, it is believed that the human model has an upper body having great mass relative to the leg, affecting the rising of the knee position and the leg region position, and inhibiting thigh behavior, and the lack of these effects is simply corrected by raising the impact height.

Further analysis is required, however, to keep the current impactor specification with selecting a best impact height is one of a good practical method.

ACKNOWLEDGEMENT

We would like to thank Honda R&D Co., Ltd. for their generous supply of a human model and valuable advice required for the analysis of this study.

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