Characteristics of the TRL Pedestrian Legform and the Flexible Pedestrian Legform Impactors in Car-front Impact Tests

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ABSTRACT

Pedestrian protection is one of the key topics of discussion in the area of vehicle safety legislation in Europe and Japan. Leg injuries are the most common injuries found in nonfatal pedestrian accidents. The EC regulation and Euro NCAP are evaluating pedestrian leg protection performance in current vehicles. The TRL legform impactor is specified by the EC regulation, where Phase 1 took effect during 2005 and a draft phase 2 is scheduled to take effect in 2013. The global technical regulation (GTR) pedestrian protection test protocol was made basically using the TRL legform impactor. However, a flexible legform impactor has been under development. When the flexible legform impactor development is fully completed and evaluated, it is possible that both legform impactors may be determined to be useful in the GTR. Thus, the objective of this study is to investigate the characteristics of pedestrian leg protection performance of the frontal area of current vehicles using the TRL legform impactor and the flexible legform impactor. Different types of vehicles (sedan, sport utility vehicle (SUV), height wagon, and 1 box car) were used. The center of the bumper and center of the side members (i.e., the vehicles main longitudinal beams) were selected as impact locations for the legform impactors tests. This paper discusses an equivalence of injury assessment between the TRL legform impactor and flexible legform impactor.

INTRODUCTION

Every year, around 78,000 pedestrians are injured in traffic accidents in Japan [1]. Pedestrian protection is one of the key topics of discussion in the area of vehicle safety legislation in Europe and Japan. Leg injuries are the most common injuries found in nonfatal pedestrian accidents [1]; therefore, this investigation focuses on evaluating the protection provided by the bumpers of eight typical cars found in Japan. The basis of the test procedure used in this study for evaluation of bumper performance was developed by the European Enhanced Vehicle-safety Committee (EEVC)/WG17 [2]. The Transport Research Laboratory (TRL) legform impactor [3] approved by the EEVC/WG17 is employed by the EC regulation, where Phase 1 [4] took effect during 2005 and a draft Phase 2 [5] is scheduled to take effect in 2013. The global technical regulation (GTR) pedestrian protection test protocol was made basically using the TRL legform impactor.

On the other hand, a flexible legform impactor which has a greater biofidelic level has been under development [6]. The flexible legform impactor has been evaluated for its technical level as a test tool by the pedestrian legform impactor technical evaluation group (TEG) of GRSP. When the flexible legform impactor development is completed and evaluated, both legform impactors have a possibility to be used in the GTR. Thus, the objective of this study is to investigate the characteristics of the pedestrian leg protection performance of the frontal area of current vehicles using the TRL legform impactor and the flexible legform impactor.

METHOD

Set-up

The current model (2000) of the TRL legform impactor [3] and the flexible legform impactor type GT (2007) [6] were propelled into a stationary vehicle (Figure 2), respectively. The target impact velocity of the legform impactor was 11.1 m/s (40 km/h). The bottom surface of the TRL legform impactor was set to be the same level as the ground line at the moment of contact moment between the legform and bumper surface. The bottom surface of flexible legform impactor was set to be 75 mm higher level from the ground line at the moment of contact, in order to have the flexible legform behavior became similar to that observed in the human body model simulations [6].

The tire pressure in each tested vehicle was adjusted to the pressure recommended by the vehicle manufacturer. To simulate two adult front seat occupants, 75-kg weights were placed on each seat. The temperature in the test facility during the test program was maintained in the range 20 to 21 degrees Celsius. The motion of the legform impactor during its impact with the vehicle was recorded by means of a high-speed digital camera (1000 frames/second).

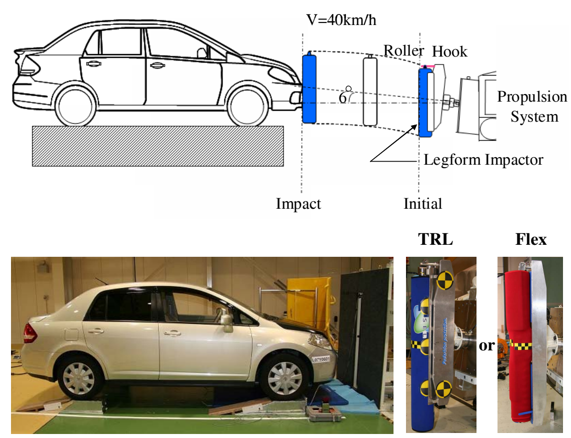


Figure 1. Legform impactor to vehicle bumper impact test setup

Eight different vehicles were tested from the following four categories: sedan, sport utility vehicle (SUV), height wagon, and 1 box car. Their specifications are summarized in Table 1.The height wagon and 1 box car used in this study were classified into the K-car (less than or equal to 660 cc of engine displacement) in Japan.

Table 1. Vehicle specifications

Vehicle type		All length*all width *all height (mm)	Net weight (kg)	Displacement (cc)	Bumper material
Sedan	A	4410*1695*1460	1130	1496	resin
	B	4670*1695*1505	1390	1990	resin
	C	4395*1695*1535	1120	1498	resin
SUV	A	4420*1785*1710	1550	2354	resin
	B	4455*1765*1675	1400	1998	resin
Height wagon	A	3395*1475*1645	840	658	resin
1Box	A	3395*1475*1870	940	658	resin
	B	3395*1475*1880	920	656	resin

The center of the bumper and the center of the side members (i.e., the vehicles main longitudinal beams) were selected as an impact location for both legform impactors tests as shown in Figure 2. The center of the bumper was defined to be on the line of the bonnet lock. It should be noted here that the bonnet lock of the height wagon A was slightly off-set from the vehicle's center line as shown by CI in Figure 2 (6). The location of CII of the height wagon A was 295 mm away from CI.

SI of SUV A is the most outer location in the impact area defined by EC regulation [5]. SII of SUV A is the location in front of the main longitudinal beam.

In front of the 1box A car, there are two cross beams. SI of the 1 box A is the location in front of the main longitudinal beam which is connected to the lower cross beam. SII of the 1box A is the location in front of the longitudinal beam connecting to the upper part of the cross beam. A total of 19 locations from eight vehicles were impacted by the TRL and flexible legform impactors, respectively.

Injury Measures

TRL legform impactor

The lower leg acceleration was used to evaluate tibia fracture risk. The knee shearing displacement (i.e., relative displacement between the leg and thigh at the knee joint level in the lateral direction) was measured to evaluate the cruciate ligament injury risk. The knee bending angle (i.e., angular displacement of the knee joint) was measured to evaluate the collateral ligament injury risk. Each data channel was sampled at 10 kHz, and data processing was done with an SAE Class 180 filter. In this study, the measured criteria were compared to the injury assessment reference values (IARVs), which will be employed by EC regulation phase 2 [5].

Flexible legform impactor

The bending moment was used to evaluate the tibia fracture risk. The anterior cruciate ligament (ACL) elongation and posterior cruciate ligament (PCL) elongation were measured to evaluate each cruciate ligament injury risk. The medial collateral ligament (MCL) elongation was measured to evaluate collateral ligament injury risk. Each data channel was sampled at 10 kHz, and data processing was done with an SAE Class 180 filter. Since the IARVs of flexible legform have not been decided to date, this study used the lowest values employed in the paper [7]. The IARVs used in this study are summarized in Table 2.

Table 2. Injury assessment reference values

	Tibia	Knee ligament		
		ACL	PCL	MCL
TRL	Acceleration	Shear displacement		Bending angle
	170 G [5)]	6 mm [5)]		19 degrees [5)]
Flex	Bending moment	Elongation		
	312 Nm (312-350) [7)]	11.2 mm (11.2 mm) [7)]	11.2 mm (11.2 mm) [7)]	19.5 mm (19.5-21.6 mm) [7)]

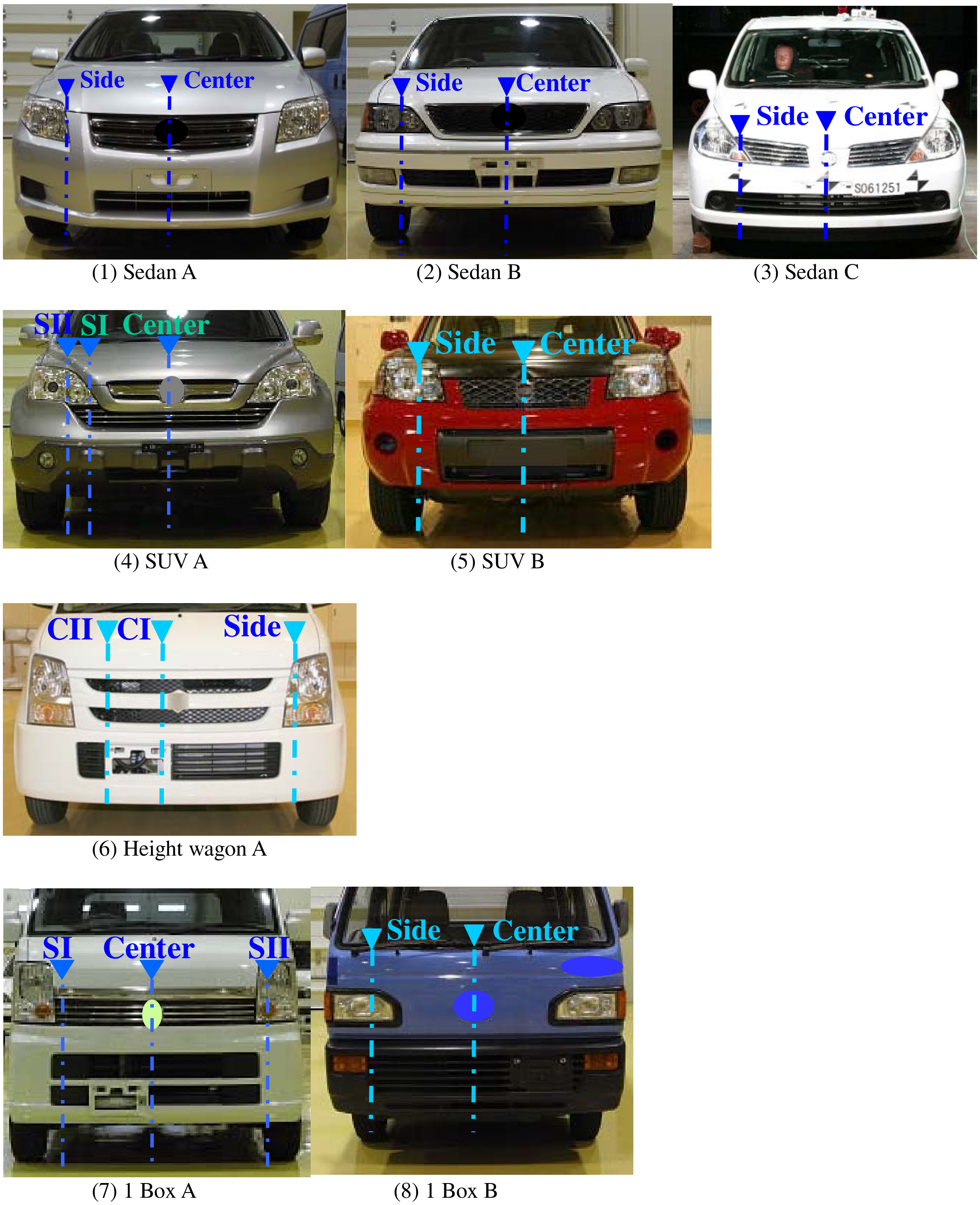


Figure 2. Impact locations on bumper of tested vehicles

RESULTS

Fitting Ratio

The measured injury criteria utilized by the TRL and legform impactors are listed in Table 3. The measured criteria which exceed the IARVs shown in Table 2 are indicated by the yellow shading. The TRL legform impactor impact results which exceed the IARVs [5] did not match the flexible legform impactor impact results which exceed the IARVs [7].

The measured injury criteria of the TRL and flexible legform impactors, together with the zone indicating whether the measures fulfilled the IARVs, are also shown in Figure 3. For the assessment of the tibia fracture risk, the relation between the acceleration measured by the TRL legform impactor and the bending moment by flexible legform impactor are summarized in Figure 3 (1). For the assessment of the ACL injury risk, the relation between the shear displacement measured by the TRL legform impactor and the ACL elongation measured by the flexible legform impactor are summarized in Figure 3 (2). For the assessment of the PCL injury risk, the relation between the bending angle measured by the TRL legform impactor and the PCL elongation measured by flexible the legform impactor are summarized in Figure 3 (3). For the assessment of the MCL injury risk, the relation between the bending angle measured by the TRL legform impactor and the MCL elongation measured by the flexible legform impactor are summarized in Figure 3 (4). The red shaded areas indicate that the measured criteria exceeded both requirements for the TRL and the flexible legform impactors. The blue shaded areas indicate that the measured criteria met both requirements for the TRL and the flexible legform impactors. For the assessment performance and the injury risk level of the IARVs between the TRL and flexible legform impactors to be completely the same for each injury, the measured criteria both have to be either in the blue area or both in the red area. However, all measured criteria were not in the blue or red area.

In this study, the fitting ratio was defined as the number in the blue or red area divided by the number in the all impact locations (n=19). The fitting ratios corresponding to each injury are listed in Table 4. The fitting ratio for the tibia fracture risk assessment was 63%. On the other hand, the fitting ratios for the ACL, PCL, and MCL injury risk assessments were 84%, 79%, and 84%, respectively. Therefore, the knee ligament injury risk assessment was at a higher level compared to the tibia fracture risk assessment between the TRL and flexible legform impactors.

Table 3. List of measured injury criteria

Vehicle type		Impact location	Impact test result using TRL				Impact test result using Flex				
			Velocity (km/h)	Tibia fracture assessment	Knee ligament injury assessment		Velocity (km/h)	Tibia fracture assessment	Knee ligament injury assessment		
				Acceleration (G)	Shear displacement (mm)	Bending angle (deg)		Bending moment (Nm)	ACL Elongation (mm)	PCL Elongation (mm)	MCL Elongation (mm)
Sedan	A	Center	39.7	138	2.8	4.8	40.7	232	4.2	4.0	11.3
		Side	39.7	291	2.0	20.3	40.5	311	7.7	13.0	25.0
	B	Center	39.8	224	3.7	28.9	39.4	349	9.7	8.5	31.0
		Side	39.9	371	3.9	25.6	40.2	339	17.2	10.2	31.0
	C	Center	40.1	198	1.7	12.6	40.2	178	6.2	4.1	15.4
		Side	39.8	307	3.0	24.3	39.9	307	7.3	8.8	23.2
SUV	A	Center	40.0	81	2.0	2.8	40.1	221	3.7	0.6	9.5
		Side I	40.1	97	2.6	12.6	40.5	238	6.0	5.4	18.1
		Side II	39.9	383	7.5	25.3	40.2	433	13.8	8.7	31.0
	B	Center	40.0	126	1.1	16.5	40.0	356	10.5	6.0	23.5
		Side	40.5	342	6.8	25.3	40.0	435	20.8	9.5	31.1
Height Wagon	A	Center I	40.3	129	1.3	4.0	40.0	279	2.6	1.9	5.6
		Center II	40.3	142	1.7	3.0	40.1	321	2.7	4.1	4.2
		Side	40.4	545	7.8	24.0	40.4	377	10.0	6.7	13.9
1Box	A	Center	39.7	178	2.0	1.6	40.4	236	2.6	5.0	1.4
		Side I	40.1	453	4.0	19.3	40.2	329	9.5	8.3	15.4
		Side II	40.0	399	7.6	24.4	40.3	286	7.2	17.9	27.5
	B	Center	40.3	97	1.8	4.7	39.9	268	4.1	2.7	13.1
		Side	39.9	159	3.0	10.9	39.9	267	6.2	3.8	17.8

:Over injury assessment reference value (IARV)

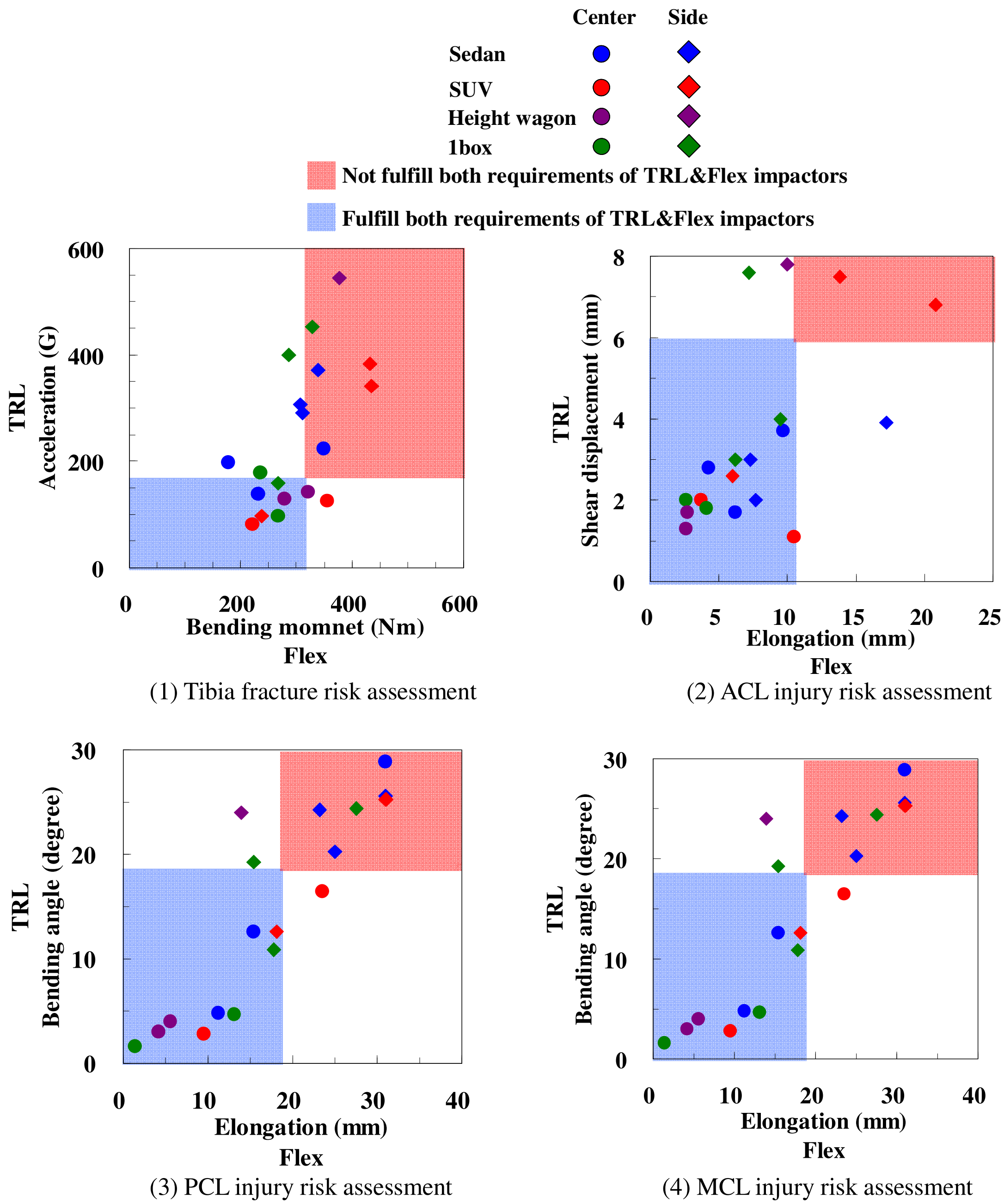
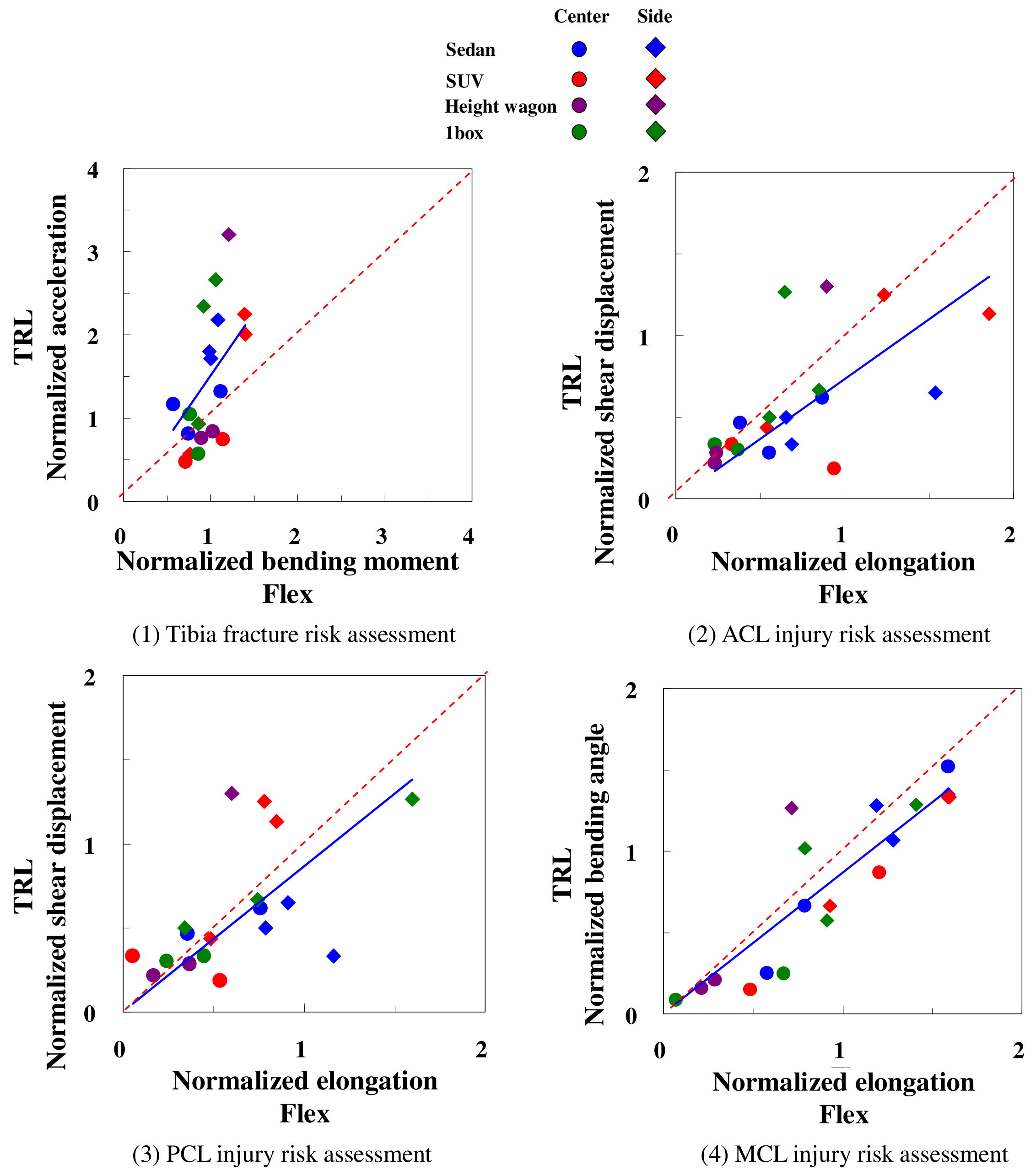


Figure 3. Measured injury criteria

Table 4. Fitting ratio

Injury type	(1) Tibia	(2) ACL	(3) PCL	(4) MCL
Fitting ratio	12/19	16/19	15/19	16/19
	63%	84%	79%	84%



(1) Tibia fracture risk assessment

(2) ACL injury risk assessment

(3) PCL injury risk assessment

(4) MCL injury risk assessment

Figure 4. Injury measures normalized by IARVs

Comparison of Injury Measures Normalized by IARV between TRL and Flexible Legform Impactors

The investigation of an equal possibility of using both the TRL and flexible legform impactors for injury risk estimation is necessary. To assess the injury severity when evaluating the bumper aggressiveness by means of the TRL and flexible legform impactors, the maximum values obtained by both impactors were expressed as injury measures normalized by IARVs (normalized injury measures). The IARVs of the TRL and flexible legforms listed in Table 2 were used. The relationship between the normalized measures of the TRL and the flexible legforms are summarized in Figure 4. The regression line starting from the coordinate origin between the two normalized injury measures was indicated by a blue solid line. The dashed line, corresponding to an 1:1 ratio indicated that the injury risk assessment between the TRL and the flexible legforms is exactly the same. The risk assessment of the tibia fracture using the TRL legform impactor is more severe than that using the flexible legform impactor [see Figure 4 (1)]. The risk assessments of the knee ligament injuries (i.e., the ACL, PCL, and MCL) using the flexible legform impactor are more severe than those using the TRL legform impactor [see Figures 4 (2), 4(3), and 4(4)].

The coefficients of linear regression and the correlation coefficients are listed in Table 5. The correlation coefficient between the normalized injury measures of the TRL legform and the normalized injury measures of the flexible legform were over 0.51 for all injury types. Specifically, the correlation coefficient between the normalized bending angle of the TRL legform and the normalized MCL elongation of the flexible legform was 0.89. The coefficient of linear regression between the two normalized injury measures was 0.87. These coefficients indicate that both normalized injury measures could predict a similar risk of medial collateral ligament injury.

Table 5. Coefficient of linear regression and correlation coefficient

Injury type	(1) Tibia	(2) ACL	(3) PCL	(4) MCL
Coefficient of linear regression	1.50	0.73	0.87	0.87
Correlation coefficient	0.57	0.52	0.51	0.89

DISCUSSION

In this study, the criteria measured by TRL legform impactor and the criteria measured by flexible legform impactor were compared. Ideally, when comparing both results, the impact conditions such as impact velocity should be completely same. However, in this study, the impact velocity ranged 39.7 km/h to 40.7 km/h. One of the limitations of this study is that the analyzed results might be affected by the variation in impact velocity. In the future, the effect of impact velocity on the injury measures should be investigated. Then, the current results possibly could be improved by the elimination of the velocity effect.

The measured injury criteria in each tested vehicle were shown in Figure 3. When focusing on the tibia for its fracture risk assessment against a vehicle center impact, all tested vehicles except three cases fulfilled the requirements for both legform impactors [see Figure 3(1)]. In contrast, for the tibia fracture risk assessment against a vehicle side member, the measured injury criteria indicated extremely high levels compared to those obtained at the vehicle center impact. The stiffness of the bumper in front of the main longitudinal vehicle beam in current vehicles is relatively high, and the distance between the inner surface of the bumper cover and frontal edge of the main longitudinal vehicle beam is too short to allow absorption of the impact energy exerted by the legform impactor. Some countermeasures, including attachment of energy absorbing structures in front of main longitudinal vehicle beam, might be necessary in terms of providing future pedestrian leg protection.

When focusing on the MCL injury risk assessment, the measured bending angles of an 1 box car by the TRL legform impactor were relatively smaller than those of a sedan or an SUV [see Figure 3(4)]. The frontal shape of the 1 box car could contribute to the reduction of the possibility of an MCL injury.

In this study, eight different vehicles including two 1 box cars were used. The 1 box cars were classified into the K-car (less than equal to 660 cc of engine displacement) in Japan. On the other hand, larger 1 box cars (such as more than or equal to 2000 cc engine displacement) are also popular in Japan. Since the difference in the car front design between the K-car and the relatively large engine displacement car is not understood, the pedestrian lower leg safety performance of the large engine displacement 1 box car should be investigated.

In Figure 4, linear regression was applied by the least square method for the injury measures normalized by the IARVs. The distances between each injury measure data point and the linear regression line are summarized in Table 6. The distances over 0.5 are marked by the yellow shaded areas. Table 6 indicates that the distances were over 0.5 in all injury types at the side of the height wagon. It implies that there is a possibility that the car front structure at the side of the height wagon is different than the structure of other vehicles.

Table 6 The distances between injury measures and the linear regression line

Vehicle type		Distance from linear regression line			
		Tibia fracture	ACL injury	PCL injury	MCL injury
Sedan A	Center	0.21	0.26	0.18	0.29
	Side	0.13	0.23	0.78	0.05
Sedan B	Center	0.25	0.03	0.05	0.17
	Side	0.35	0.65	0.16	0.03
Sedan C	Center	0.20	0.17	0.04	0.02
	Side	0.21	0.03	0.21	0.29
SUV A	Center	0.39	0.12	0.33	0.32
	Side I	0.39	0.06	0.02	0.16
	Side II	0.10	0.47	0.67	0.05
SUV B	Center	0.65	0.69	0.32	0.20
	Side	0.07	0.31	0.46	0.06
Height wagon	Center I	0.39	0.06	0.08	0.04
	Center II	0.48	0.15	0.04	0.03
	Side	0.90	0.88	0.90	0.74
1Box A	Center	0.07	0.22	0.06	0.03
	Side I	0.70	0.06	0.03	0.38
	Side II	0.63	1.08	0.13	0.07
1Box B	Center	0.48	0.04	0.11	0.39
	Side	0.24	0.13	0.24	0.25

The time history of the MCL elongation for the flexible legform impactor impacting against the center of Sedan A and the behavior of the flexible legform impactor at the time of maximum elongation are shown in Figures 5 and 6, respectively. According to Figure 5, 31.7 ms is the time when the maximum elongation was observed; however, the legform impactor was not in complete contact with the car front at this time (see Figure 6). Since the injury measures should be evaluated during the contact to the car front, the duration for the injury risk evaluation due to contact to a car front should be investigated in the future.

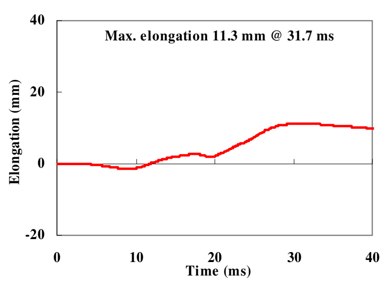


Figure 5 Time history of MCL elongation

Figure 6 Flexible legform behavior at 32 ms

For the assessment of tibia fracture, the TRL legform impactor has a simplified design such that it can measure the acceleration at 66 mm below the knee level. In contrast, strain gauges were attached at four different levels in vertical locations on the tibia of the flexible legform to measure bending moments. An analysis of the maximum bending moment was employed for this study. If the lower part of the bumper in a tested car is more rigid, the measured bending moment at the corresponding location of the flexible legform could be the highest. Thus, there is a possibility to have lower correlation coefficients when comparing the relationship between the normalized acceleration of the TRL legform and the normalized bending moment of the flexible legform at the similar level to 66 mm below the knee.

CONCLUSIONS

This study investigated the equal possibility of injury risk estimation using both the TRL and the flexible legform impactors. Nineteen locations of eight different Japanese vehicles (including sedan, sport utility vehicle (SUV), height wagon, and 1 box cars) were impacted by the TRL and the flexible legform impactors, respectively.

In this study, the fitting ratio was defined as the number in an area where the measured criteria either fulfilled both requirements or exceeded both requirements of the TRL and the flexible legform impactors divided by the number in the all test cases (n=19). The fitting ratio for the tibia fracture risk assessment was 63%. In contrast, the fitting ratios for the ACL, PCL and MCL injury risk assessments were 84%, 79% and 84%, respectively. Therefore, the knee ligament injury risk assessment was at a higher level as compared to the tibia fracture risk assessment between the TRL and the flexible legform impactors.

The measured injury criteria were normalized by the injury assessment reference values (IARVs) (normalized injury measures). In this study, the IARVs which are to be employed by EC regulation Phase 2 were used for the normalized criteria for the TRL legform impactor. Since the IARVs of the flexible legform have not been decided to date, this study used the values employed in an ESV paper. The relationship between normalized measures of the TRL and the flexible legforms were investigated. The risk assessment of tibia fracture using the TRL legform impactor is more severe than that using the flexible legform impactor. The risk assessments of knee ligament injuries (ACL, PCL, MCL) using the flexible legform impactor are more severe than those using the TRL legform impactor. The coefficients of linear regression and correlation coefficients were investigated. The correlation coefficients between the normalized injury measures of the TRL legform and normalized injury measures of the flexible legform were over 0.51 for all injury types. Specifically, the correlation coefficient between the normalized bending angle of TRL legform and the normalized MCL elongation of the flexible legform was 0.89. The coefficient of linear regression between the two normalized injury measures was 0.87. These coefficients indicate that both normalized injury measures could predict a similar risk of medial collateral ligament injury.

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