DEVELOPMENT OF A BIOFIDELIC FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR TYPE GTR PROTOTYPE
Part 1: DEVELOPMENT AND TECHNICAL EVALUATIONS

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ABSTRACT

Prototypes of the latest version of a biofidelic flexible pedestrian legform impactor (Flex-GTR-proto) were developed in November 2008. In this research several technical evaluations on the Flex-GTR-proto were conducted. As a result, fairly good repeatability and reproducibility of the Flex-GTR-proto, and comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts were observed (majorities of CV values are less than 3%).

As for the comparability between the Flex-GT and Flex-GTR proto, some differences were observed between them. Most of the maximum value ratios of Flex-GTR-proto relative to the Flex-GT are less than 1.1. The difference between the Flex-GT and Flex-GTR-proto has a chance to affect the injury threshold values; therefore, a following research has been investigating the threshold values for the Flex-GTR-proto using the ratios of the Flex-GT and Flex-GTR outputs and/or using the correlations between the Flex-GTR-proto and human lower extremities outputs which can be obtained from a computer simulation analysis.

INTRODUCTION

In 1998, the European Enhanced Vehicle-Safety Committee proposed a test procedure to assess the protection vehicles provide to the lower extremity of a pedestrian during a collision [1]. This procedure utilizes a legform impactor composed of rigid long bones.

In order to improve biofidelity of the legform impactor, the Japan Automobile Research Institute (JARI) and the Japan Automobile Manufacturers Association, Inc. (JAMA) have been developing a biofidelic flexible pedestrian legform impactor (Flex-PLI) since 2002 [2]. The Flex-PLI has high biofidelity especially for its long bone parts, which have human-like bending characteristics under a car impact condition, compared to other types of legform impactors, which have rigid long bone parts [3].

The Flex-PLI also provides extended injury assessment capability, including long bone bending moment at multiple locations and knee ligament elongations in comparison to other pedestrian legforms [3].

In 2005, the Flex-PLI Technical Evaluation Group (Flex-TEG) was settled under the UN/ECE/WP29/GRSP/Informal Group on Pedestrian Safety in order to evaluate its performance to adopt the impactor as a regulatory purpose test tool for a Global Technical Regulation on Pedestrian Safety (PS-GTR: gtr 9).

The Ministry of Land, Infrastructure, Transport, and Tourism of Japan (J-MLIT) has been supporting this Flex-TEG activity, taking a task of a chair country of the group and conducting technical evaluation tests on the Flex-PLI.

After the settlement of the Flex-TEG, the Flex-PLI was evaluated and improved its performance under the Flex-TEG activity, and then its design of the final version, type GTR (Flex-GTR), was agreed by the Flex-TEG members in April 2008 [4], and its prototype (Flex-GTR-proto) was released in November 2008.

In the Flex-GTR-proto development, First Technology Safety Systems (FTSS) was involved as a dummy development specialist company.

This paper provides a brief introduction of the Flex-GTR-proto and technical evaluation test results on them under several impact conditions.

TECHNICAL EVALUATION ITEMS

In this research, following technical evaluations were conducted.
E1: Repeatability of the Flex-GTR-proto

E2: Reproducibility of the Flex-GTR-proto
E3: Comparability between the Flex-GT and Flex-GTR-proto
E4: Comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts

MATERIALS

Flexible Pedestrian Legform Impactor type GTR prototype (Flex-GTR-proto)

Figure 1 shows a general construction of the Flex-GTR-proto. Its femur and tibia have flexible long bones which can be bent under the car impact condition. Its knee has a ligament constraint system similar to the human one, and its movement is restrained by four knee ligaments as described in the figure. More detailed information of the Flex-GTR-proto is described in the Part2 of this ESV paper series (Paper Number 09-0146) [5].

In this research three of the Flex-GTR-proto (SN01, SN02, SN03) were used as shown in Figure 2. The three Flex-GTR-protos have the same constructions, and only data acquisition systems (DAS) which can be used are different. The SN01 can implement an off-board DAS only. On the other hand, the SN02 can implement an off-board DAS or on-board DAS (M=BUS, MESSRING, Germany), and the SN03 can implement an off-board DAS or on-board DAS (SLICE, DTS, USA), as shown in Figure 3. More detailed information of the DAS is described in the Part 2 of this ESV paper series [5].

Figure 4 shows the measurement items of the Flex-GTR-protos. In this research mainly injury assessment items and monitoring items were measured.

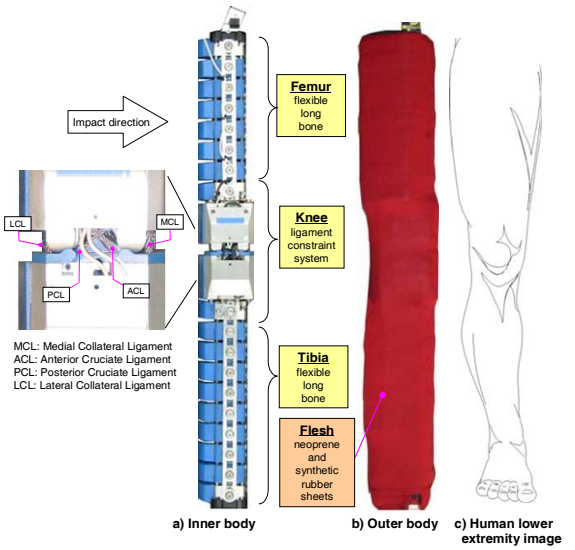

Figure 1. Flexible Pedestrian Legform Impactor type GTR prototype (Flex-GTR-proto).

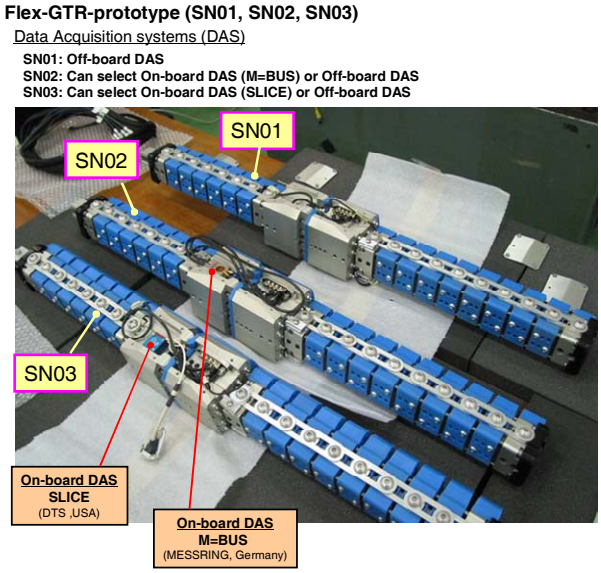

Figure 2. Flex-GTR-proto (SN01, SN02, SN03) and Data Acquisition System (DAS).

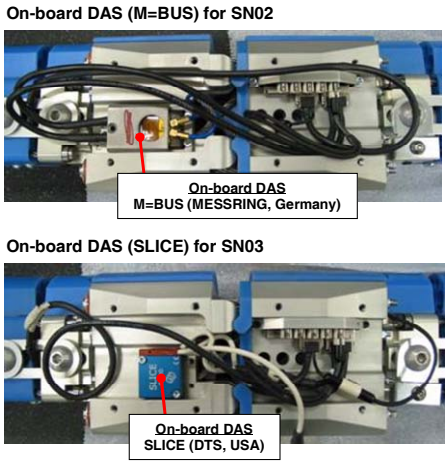

Figure 3. On-board Data Acquisition System (DAS) for the Flex-GTR-proto (SN02 and SN03).

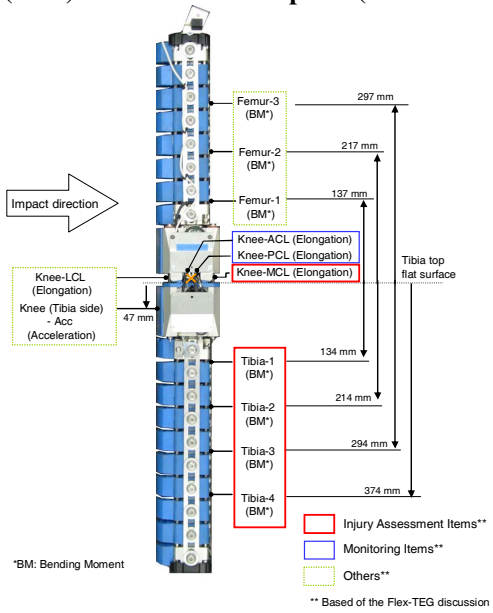

Figure 4. Flex-GTR-proto Measurement Items.

Flexible Pedestrian Legform Impactor type GT (Flex-GT)

Figure 5 shows a general construction of the Flex-GT. Its construction is similar to the Flex-GTR-proto, however, knee ligaments arrangements are different. In the Flex-GTR-proto, the ACL (anterior cruciate ligament) and PCL (posterior cruciate ligament) are located on both sides of the knee, symmetry to the impact and longitudinal axes of the impactor [5]. On the other hand, in the Flex-GT, ACL and PCL are located on different sides of the knee, asymmetry to the impact and longitudinal axes of the impactor. The asymmetric knee ligament location of the Flex-GT tends to generate knee twist motion, therefore it tends to obtain different test results between symmetric left and right bumper corner impacts. As for the DAS of the Flex-GT, only an off-board DAS is available.

Figure 6 shows the measurement items of the Flex-GT. The measurement items are the same except the knee (tibia side) acceleration of the Flex-GTR-proto. In this research, we used the Flex-GT (SN03), and then measured injury assessment items and monitoring items mainly.

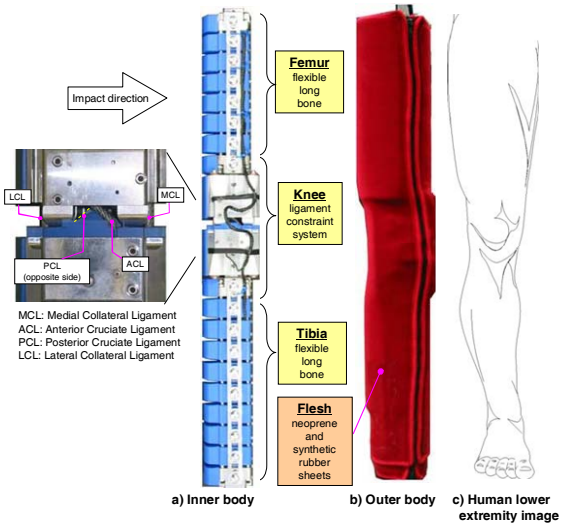

Figure 5. Flexible Pedestrian Legform Impactor type GT (Flex-GT).

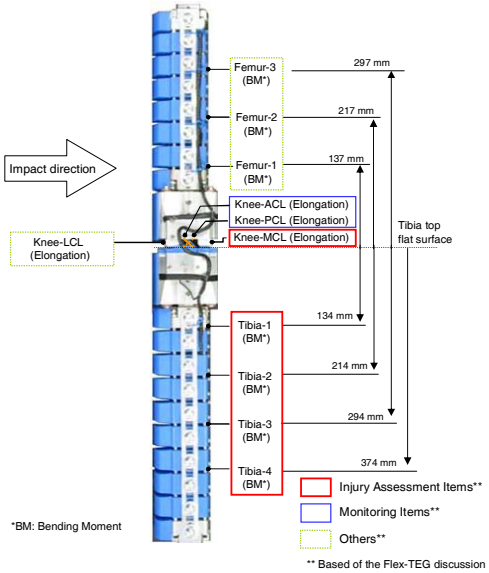

Figure 6. Flex-GT Measurement Items.

Assembly Pendulum Type Calibration Test Rigs

Type 1 – Figure 7 shows the assembly pendulum type calibration test rig (type 1). The rig was developed in order to calibrate the Flex-GT. However, the rig can accommodate not only the Flex-GT but also the Flex-GTR-proto. The test rig therefore was used for investigating E3: Comparability between the Flex-GT and Flex-GTR-proto in this research.

Figure 7. Assembly Pendulum Type Calibration Test Rig (Type 1).

Type 2 – Figure 8 shows the assembly pendulum type calibration test rigs (type 2). The rig was developed in order to calibrate of the Flex-GTR-proto. The rig can accommodate the Flex-GTR-proto only, therefore, the test rig was used for investigating E1: Repeatability and E2: Reproducibility of the Flex-GTR-proto.

Figure 8. Assembly Pendulum Type Calibration Test Rig (Type 2).

Simplified Cars

Type 1 – Figure 9 shows an over view of a simplified car (type 1). The car consisted of bonnet leading edge (BLE), bumper (BP), and spoiler (SP). Figure 10 shows its cross sectional dimensions at the center line of the car. The car was made from steel for automobile; therefore, the car was deformed after an impact test as shown in Figure 11.

This car was used for investigating E1: Repeatability and E2: Reproducibility of the Flex-GTR-proto and E3: Comparability between the Flex-GT and Flex-GTR-proto.

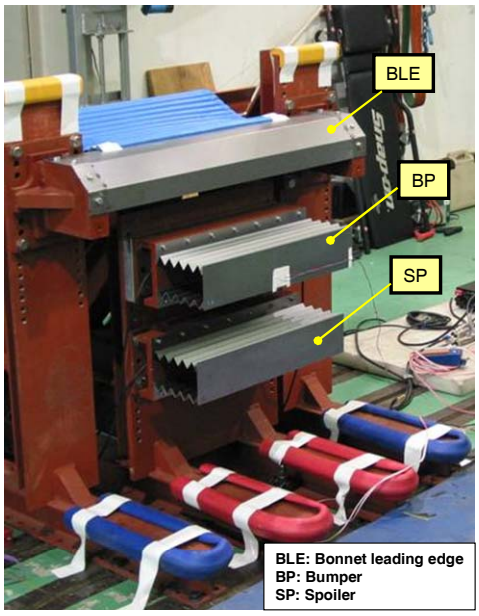

Figure 9. Simplified Car (Type 1).

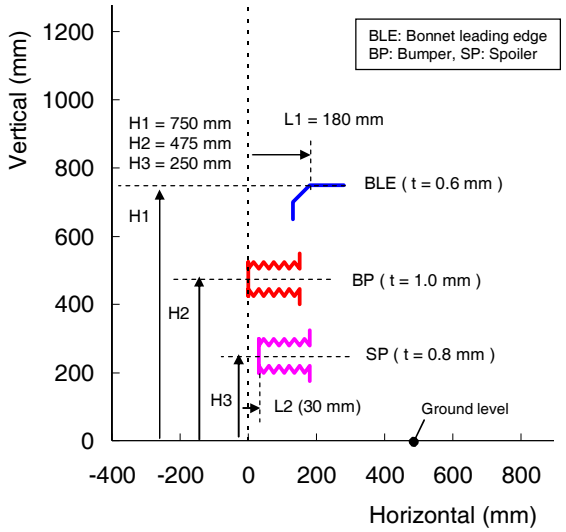

Figure 10. Cross Sectional Dimensions at the Car Center of the Simplified Car (Type 1).

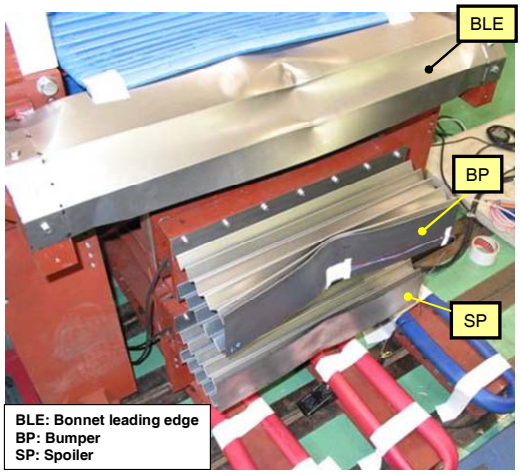

Figure 11. Deformation of the Simplified Car (Type 1) after an Impact Test.

Type 2, –R and -L – Figure 12 shows an over view of the simplified car (type 2, -R and -L). The car had the same configuration as that of the simplified car type 1, consisting of bonnet leading edge (BLE), bumper (BP), and spoiler (SP). Figure 13 shows its cross sectional dimensions at the center line of the car. The type 2 has two versions, –R and –L, by different setting of the car turned 30 degree right or left around the vertical axis, therefore both versions had exactly the same cross sectional dimensions at the car center. The type 2-R simulates right side of the bumper corner, and the type 2-L simulates left side of the bumper corner. The car was made from steel for automobile, which was also used for the simplified car type 1; therefore, the car is deformed after an impact test as shown in Figure 14.

These cars (Type 2, -R and –L) were used for investigating E4: Comparability of the Flex-GTR-proto under the symmetric right and left bumper corner impacts.

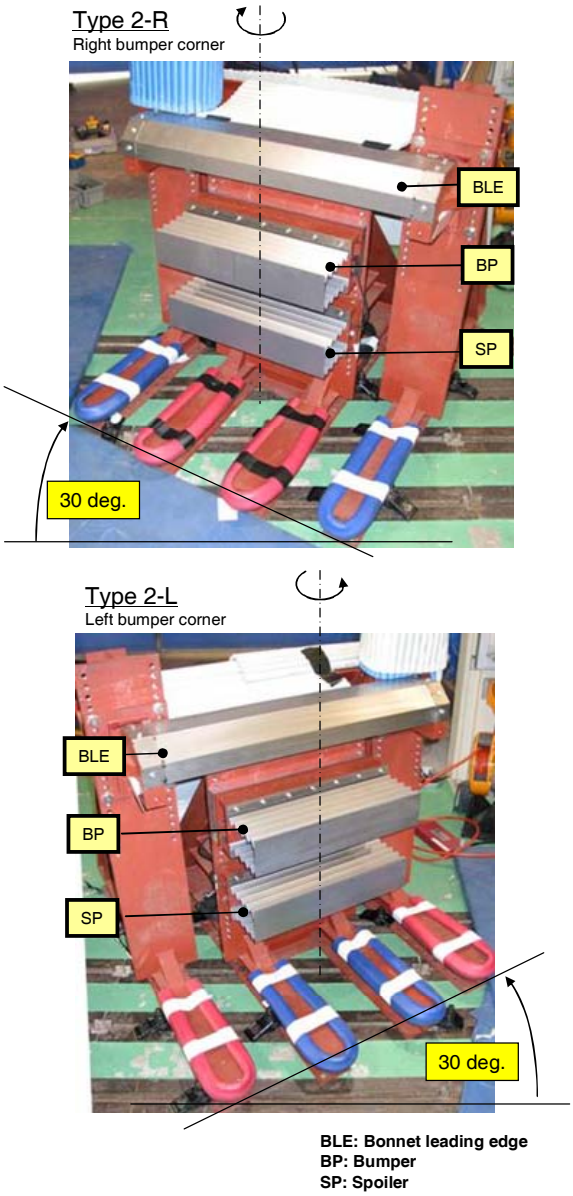

Figure 12. Simplified Car (Type 2, -L and -R).

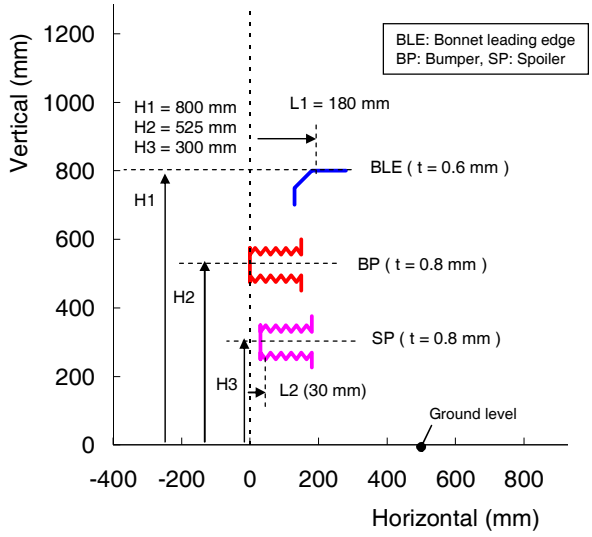

Figure 13. Cross Sectional Dimensions at the Car Center of the Simplified Car (Type 2).

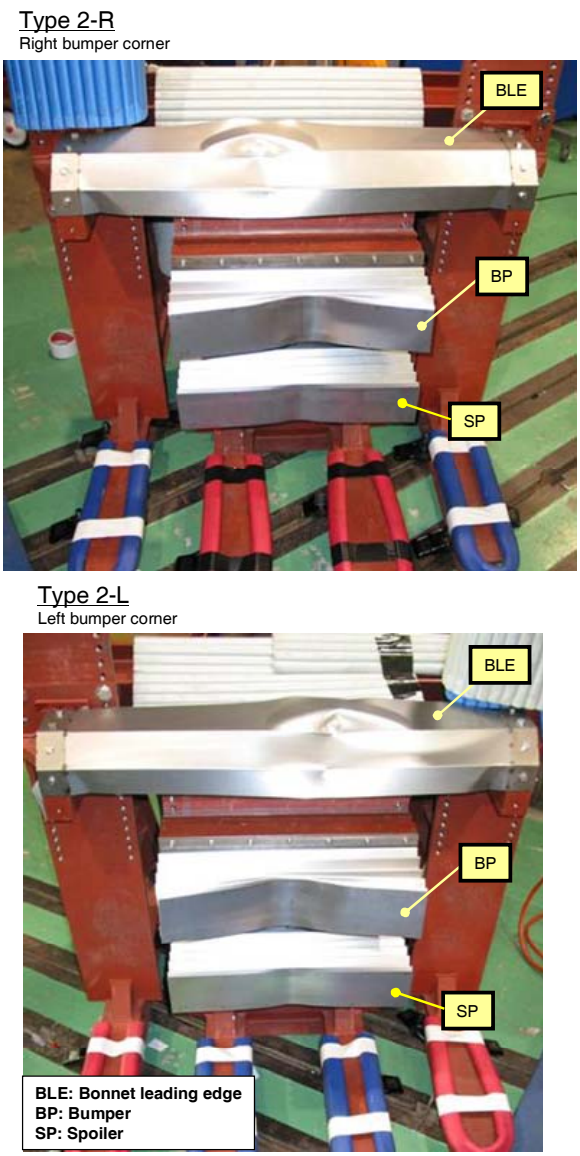

Figure 14. Deformation of the Simplified Car (Type 2, -R and -L) after an Impact Test.

METHODOLOGY

Assembly Pendulum Type Calibration Test Methods

Type 1 – Figure 15 shows the assembly pendulum type calibration test method (Type 1). In the test, the femur top of the Flex-GT or Flex-GTR-proto was attached to the assembly type calibration test rig (Type 1) via a pin joint, and then the tibia bottom was suspended at 15 degrees above the horizontal level. The legform was then released from the suspended position and then impacted the pad attached to the test rig. The same material as that of the flesh part of the Flex-GT and Flex-GTR-proto was used for the pad.

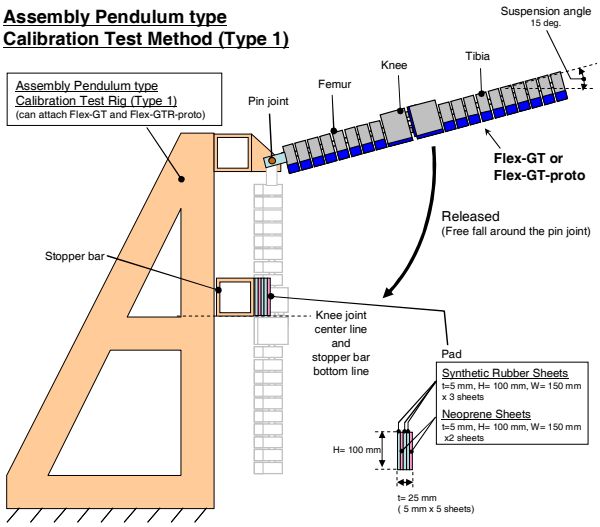

Figure 15. Assembly Pendulum type Calibration Test Method (Type 1).

Type 2 – Figure 16 shows the assembly pendulum type calibration test method (Type 2). In the test, the tibia bottom of the Flex-GTR-proto was attached to the assembly type calibration test rig (Type 2) via a pin joint, and then the top of the femur was suspended with a 5 kg additional mass at 15 degrees above the horizontal level. The legform was then released from the suspended position and then impacted the pad attached to the test rig. The same material as that of the flesh part of the Flex-GT and Flex-GTR-proto was used for the pad.

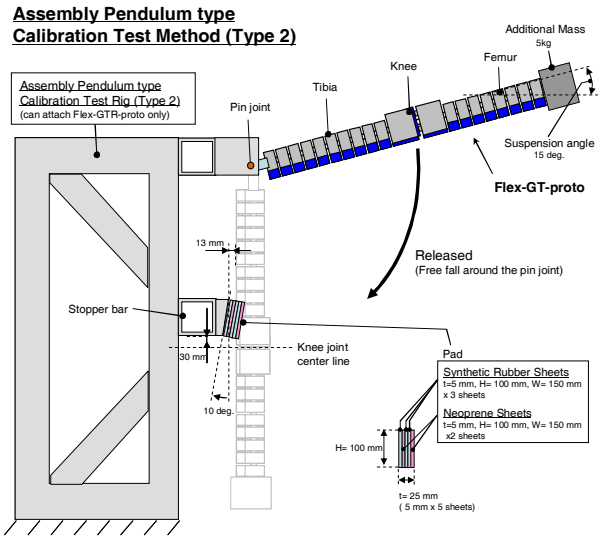

Figure 16. Assembly Pendulum type Calibration Test Method (Type 2).

Simplified Car Test Methods

Type 1 – Figure 17 shows the test method for the simplified car (Type 1). In the test, the Flex-GTR-proto or Flex-GT was propelled to the car under the free flight condition, and then impacted the center line position of the simplified car bumper at 11.1 m/s. The target impact height of the impactor was 75 mm above the ground level, and the target temperature and relative humidity of the test sight were 20 degree Celsius and 40 % respectively. The tolerance of each test condition was settled based on the current global technical regulation on the pedestrian safety (gtr 9).

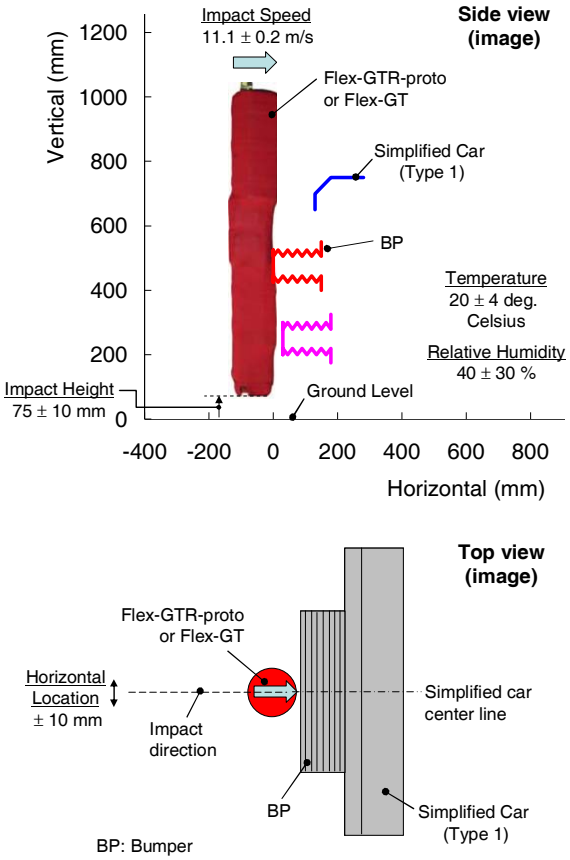

Figure 17. Simplified Car (Type 1) Test Method.

Type 2, -R and -L – Figure 18 shows the test method for the simplified car (Type 2, -R and -L). In the test, the Flex-GTR-proto was propelled to the car under the free flight condition, and then impacted the center line position of the simplified car bumper at 11.1 m/s. The target impact height of the impactor was 75 mm above the ground level, and the target temperature and relative humidity of the test sight were 20 degree Celsius and 40 % respectively. The tolerance of each test condition was settled based on the current global technical regulation on the pedestrian safety (gtr 9).

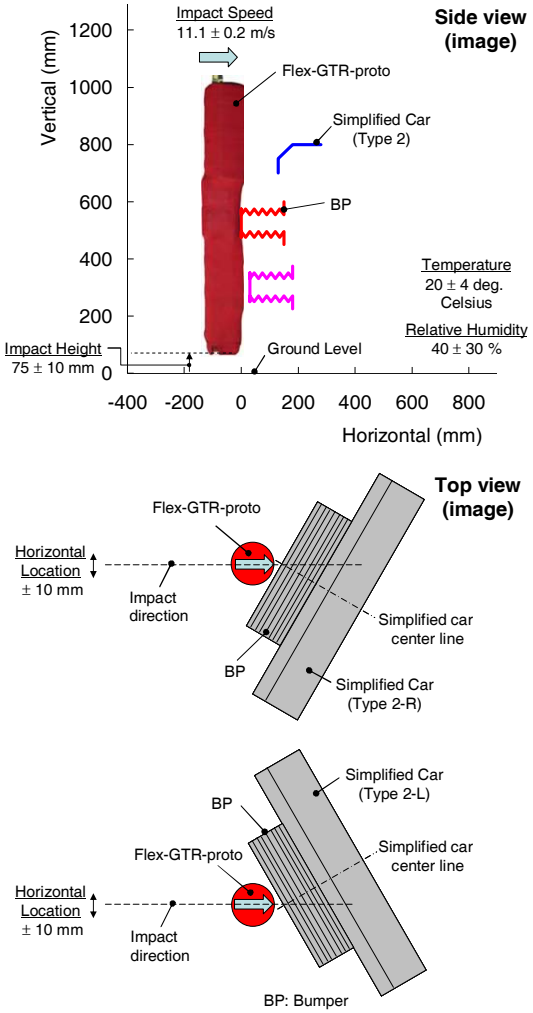

Figure 18. Simplified Car (Type 2, -R and -L) Test Method.

TEST MATRIXES

Assembly Pendulum Type Calibration Test Series

Table 1 shows the matrix for the assembly pendulum type calibration test series. In the test series, thirteen tests were conducted, and then the following items were evaluated; E1: Repeatability of the Flex-GTR-proto, E2: Reproducibility of the Flex-GTR-proto, and E3: Comparability between the Flex-GTR and Flex-GT.

Simplified Car Test Series

Table 2 shows the matrix for the simplified car test series. In the test series, eleven tests were conducted, and then the following items were evaluated; E1: Repeatability of the Flex-GTR-proto, E2: Reproducibility of the Flex-GTR-proto, E3: Comparability between the Flex-GTR and Flex-GT, and E4: Comparability of the Flex-GTR-proto under the symmetric right and left bumper corner impacts.

Table 1. Matrixes for the Assembly Pendulum Type Calibration Test Series.

	Test ID	Impactor Type	Impactor SN	DAS	Assembly Pendulum Type Calibration Test Method
E1	P1	Flex-GTR-proto	SN01	Off-board	Type 2
E1	P2				
E1	P3				
E2 E1	P4		SN02	M-BUS	
E2 E1	P5				
E2 E1	P6				
E1	P7		SN03	Off-board	
E1	P8				
E1	P9			SLICE	
E3	P10	Flex-GTR-proto	SN01	Off-board	Type 1
E3	P11		SN02	M-BUS	
E3	P12		SN03	SLICE	
E3	P13	Flex-GT	SN03	Off-board	

E1: Evaluation on the Repeatability of the Flex-GTR-proto
E2: Evaluation on the Reproducibility of the Flex-GTR-proto
E3: Evaluation on the Comparability between the Flex-GT and the Flex-GTR-proto

Table 2. Matrix for the Simplified Car Test Series.

	Test ID	Impactor Type	Impactor SN	DAS	Simplified Car Type
E2 E1	S1	Flex-GTR-proto	SN01	Off-board	Type 1
E2 E1	S2		SN02	M-BUS	
E2 E1	S3				
E2 E1	S4				
E3 E2 E1	S5				
E3 E2 E1	S6		SN03	Off-board	
E3 E2 E1	S7	Flex-GT	SN03	Off-board	
E4	S8	Flex-GTR-proto	SN03	SLICE	Type 2-L
E4	S9				
E4	S10				Type 2-R
E4	S11				

E1: Evaluation on the Repeatability of the Flex-GTR-proto
E2: Evaluation on the Reproducibility of the Flex-GTR-proto
E3: Evaluation on the Comparability between the Flex-GT and the Flex-GTR-proto
E4: Evaluation on the Comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impact

TENTATIVE INJURY ASSESSMENT REFERENCE VALUES

Table 3 shows the tentative injury assessment reference values (t-IARV) in this research. These values were settled based on the proposal or discussion at the 7th Flex-TEG meeting [6-8].

The t-IARV values were used to evaluate standard deviation (St.Dev) levels of the maximum measurement values for injury assessment or monitoring items relative to the injury assessment levels by dividing St.Dev. by t-IARV (i.e. St.Dev/t-IARV).

Table 3. Tentative Injury Assessment Reference Values (t-IARV).

Injury Criteria	Purpose	Proposed/Discussed Injury Assessment Reference Values at the 7th Flex-TEG meeting			Tentative Injury Assessemnt Reference Values (t-IARV) in this research
		TEG-077	TEG-076	TEG-078	
Tibia BM*	Injury Assessment	318 (Nm)	-	-	318 (Nm)
Knee-MCL Elongation		-	23 (mm)	16, 20 (mm)	20 (mm)
Knee-ACL Elongation	Monitoring Only	-	-	12.7 (mm)	12.7 (mm)
Knee-PCL Elongation		-	-	12.7 (mm)	12.7 (mm)

* BM: Bending Moment

TEST CONDITIONS (TARGETS AND RESULTS)

Table 4 shows the test conditions for the simplified car test series. All of the impact conditions are within the targets, except for the horizontal location of the S1. However, the simplified car has a continuous similar shape in the horizontal direction, so the test results were used for our analysis.

As for the assembly pendulum type calibration test series, there were no concerns on the test conditions for the following reasons; 1) well air conditioned test sight is used, 2) not free fright test (well controlled pendulum test).

Table 4. Test Conditions for the Simplified Car Test Series (Targets and Results).

Test ID	Impact Speed (m/s)		Temperature (deg. Celsius)		Relative Humidity (%)	
	Targets	Results	Targets	Results	Targets	Results
S1	11.1 ± 0.2	11.1	20 ± 4	20.6	40 ± 30	40
S2		11.1		21.1		35
S3		11.2		20.5		40
S4		11.1		21.9		42
S5		11.1		21.4		34
S6		11.2		20.7		37
S7		11.1		20.4		48
S8		11.0		22.8		26
S9		11.1		22.2		30
S10		11.1		21.7		29
S11		11.1		22.8		32

Test ID	Impact Height (mm)		Horizontal Locaiton (mm)	
	Targets	Results	Targets	Results*
S1	75 ± 10 above from the ground level	70	Simplified car center line ± 10	28
S2		73		-2
S3		72		-6
S4		71		0
S5		77		-2
S6		75		-10
S7		72		-2
S8		79		5
S9		78		-2
S10		77		-3
S11		80		0

* +: Right, -: Left (from driver's point of view)

TEST RESULTS

The test results are described by each evaluation item.

E1: Repeatability of the Flex-GTR-proto

Assembly Pendulum Type Calibration Test Series – Evaluation test results on the repeatability of the Flex-GTR-proto (SN01-SN03) in the assembly pendulum type calibration test series are shown in Figure 19 through Figure 21 and in Table 5 through Table 7. Each impactor shows repeatable waveforms. The Coefficient of Variation (CV) values with regard to the injury assessment or monitoring items are lower than 7.72% (SN03, Knee-PCL), with the majority of the CV values being less than 3%. When we see the standard deviation values related to the tentative injury assessment reference values (St.Dev./t-IARV), all of the values are lower than 4.52 % (SN03, Knee-ACL), and most of the values are less than 3 %.

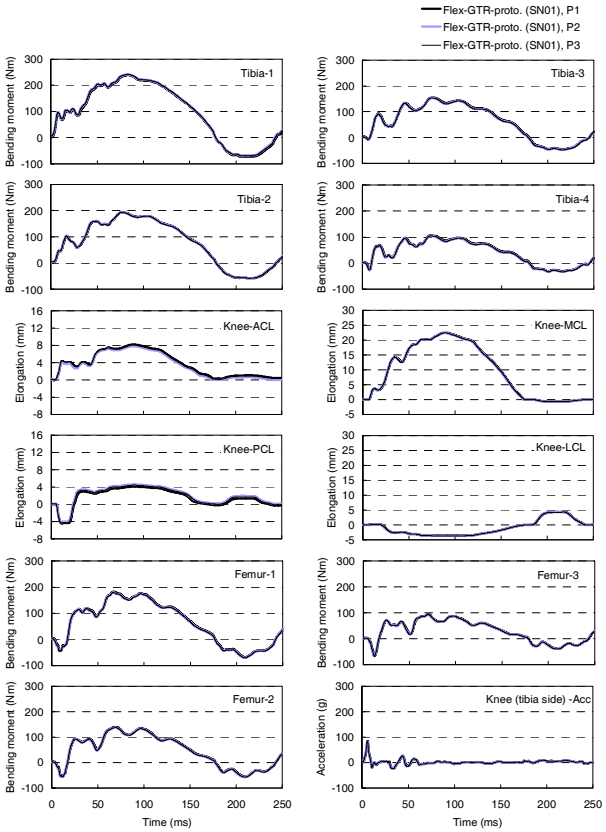

Figure 19. Waveforms (Test ID: P1-P3, Repeatability: Flex-GTR-proto (SN01)).

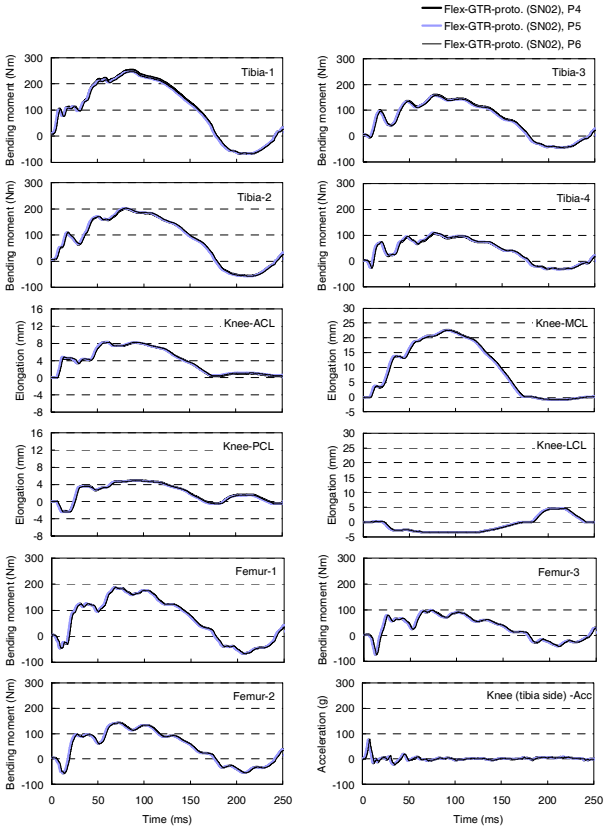

Figure 20. Waveforms (Test ID: P4-P6, Repeatability: Flex-GTR-proto (SN02)).

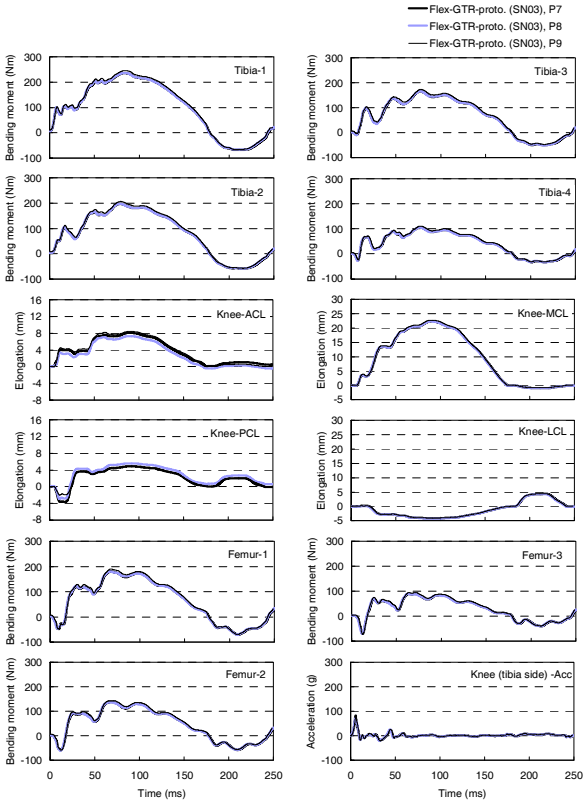

Figure 21. Waveforms (Test ID: P7-P9, Repeatability: Flex-GTR-proto (SN03)).

Table 5. Maximum Values and Variations (Test ID: P1-P3, Repeatability: Flex-GTR-proto (SN01)).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-proto. (SN01), P1	239.7	194.0	154.9	106.4	8.19	4.11	22.4
Flex-GTR-proto. (SN01), P2	241.2	193.6	152.8	104.1	7.85	4.62	22.3
Flex-GTR-proto. (SN01), P3	241.8	193.6	153.4	104.5	8.10	4.41	22.4
Avg.	240.9	193.7	153.7	105.0	8.05	4.38	22.4
St. Dev.	1.08	0.23	1.08	1.23	0.18	0.26	0.06
CV (%)	0.45	0.12	0.70	1.17	2.19	5.85	0.26
Judgement	Good	Good	Good	Good	Good	Acceptable	Good
t-IRAV*	318	318	318	318	12.7	12.7	20
St.Dev./t-IARV (%)	0.34	0.07	0.34	0.39	1.39	2.02	0.29
Judgement	Good	Good	Good	Good	Good	Good	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.

Judgements: Good: < 3%; Acceptable: 3% ≤ and < 7%; Marginal: 7% ≤ and < 10%; Not Acceptable: > 10%

Injury Assessment Items; Monitoring Items

Table 6. Maximum Values and Variations (Test ID: P4-P6, Repeatability: Flex-GTR-proto (SN02)).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-proto. (SN02), P4	253.9	201.1	160.3	106.8	8.28	4.97	22.6
Flex-GTR-proto. (SN02), P5	247.4	203.1	157.4	110.0	8.24	4.90	22.5
Flex-GTR-proto. (SN02), P6	246.7	202.8	157.7	109.9	8.20	4.85	22.5
Avg.	249.3	202.3	158.5	108.9	8.24	4.91	22.5
St. Dev.	3.97	1.08	1.59	1.82	0.04	0.06	0.06
CV (%)	1.59	0.53	1.01	1.67	0.49	1.23	0.26
Judgement	Good	Good	Good	Good	Good	Good	Good
t-IARV*	318	318	318	318	12.7	12.7	20
St.Dev./t-IARV (%)	1.25	0.34	0.50	0.57	0.31	0.47	0.29
Judgement	Good	Good	Good	Good	Good	Good	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.

Judgements: Good: < 3%; Acceptable: 3% ≤ and < 7%; Marginal: 7% ≤ and < 10%; Not Acceptable: > 10%

Injury Assessment Items; Monitoring Items

Table 7. Maximum Values and Variations (Test ID: P7-P9, Repeatability: Flex-GTR-proto (SN03)).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-proto. (SN03), P7	235.8	197.7	165.5	105.9	8.09	4.83	22.3
Flex-GTR-proto. (SN03), P8	236.0	198.5	166.3	105.6	7.31	5.57	22.3
Flex-GTR-proto. (SN03), P9	245.1	206.9	173.4	110.8	8.43	4.96	22.7
Avg.	239.0	201.0	168.4	107.4	7.94	5.12	22.4
St. Dev.	5.31	5.10	4.35	2.92	0.57	0.40	0.23
CV (%)	2.22	2.54	2.58	2.72	7.23	7.72	1.03
Judgement	Good	Good	Good	Good	Marginal	Marginal	Good
t-IARV*	318	318	318	318	12.7	12.7	20
St.Dev./t-IARV (%)	1.67	1.60	1.37	0.92	4.52	3.11	1.15
Judgement	Good	Good	Good	Good	Acceptable	Acceptable	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.

Judgements: Good: < 3%; Acceptable: 3% ≤ and < 7%; Marginal: 7% ≤ and < 10%; Not Acceptable: > 10%

Injury Assessment Items; Monitoring Items

Simplified Car Test Series – Evaluation test results on the repeatability of the Flex-GTR-proto (SN02) in the simplified car test series are shown in Figure 22 through Figure 23 and in Table 8. The Flex-GTR-proto (SN02) shows repeatable kinematics and waveforms. The CV values with regard to the injury assessment or monitoring items are lower than 3.26% (SN02, Tibia-4), with the majority of the CV values being less than 3%. When we see the standard deviation values related to the tentative injury assessment reference levels (St.Dev./t-IARV), all of the values are lower than 1.8 % (SN02, Tibia-1).

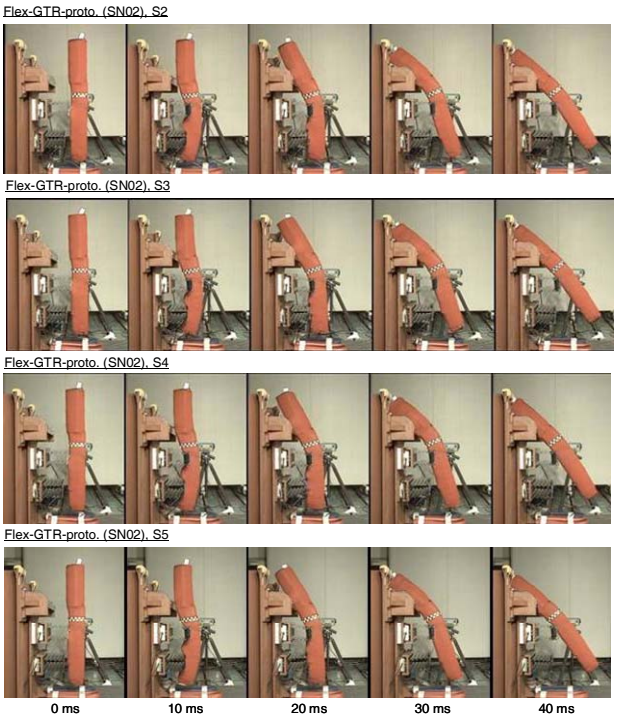

Figure 22. Kinematics (Test ID: S2-S5 Repeatability: Flex-GTR-proto (SN02)).

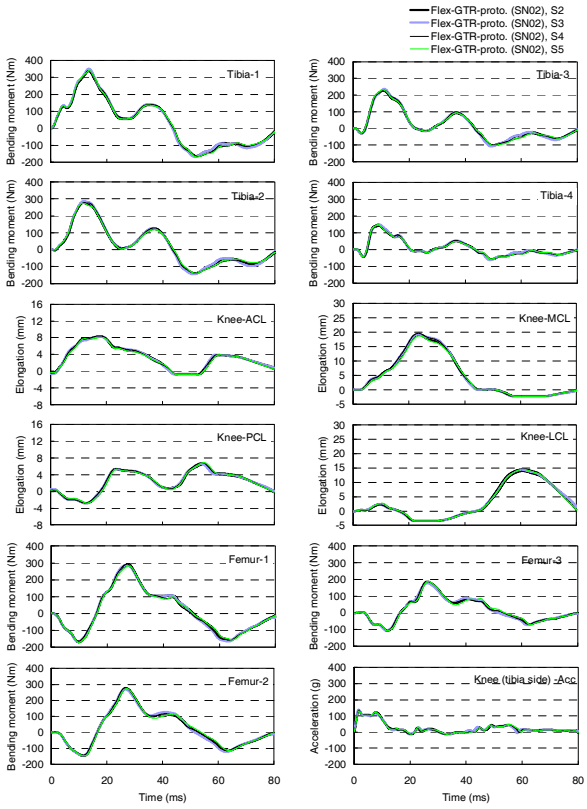

Figure 23. Waveforms (Test ID: S2-S5, Repeatability: Flex-GTR-proto (SN02)).

Table 8. Maximum Values and Variations (Test ID: S2-S5 Repeatability: Flex-GTR-proto (SN02)).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-prot. (SN02), S2	338.2	276.3	227.7	147.7	8.32	6.52	19.3
Flex-GTR-prot. (SN02), S3	350.6	285.5	236.5	148.5	8.28	6.61	19.3
Flex-GTR-prot. (SN02), S4	340.1	276.4	228.1	138.4	8.43	6.85	19.6
Flex-GTR-prot. (SN02), S5	339.4	273.5	231.6	147.3	8.08	6.90	18.8
Avg.	342.1	277.9	231.0	145.5	8.28	6.72	19.25
St. Dev.	5.74	5.23	4.08	4.74	0.15	0.18	0.33
CV (%)	1.68	1.88	1.77	3.26	1.77	2.74	1.72
Judgement	Good	Good	Good	Acceptable	Good	Good	Good
t-IARV*	318	318	318	318	12.7	12.7	20.0
St.Dev./t-IARV (%)	1.80	1.64	1.28	1.49	1.15	1.45	1.66
Judgement	Good	Good	Good	Good	Good	Good	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.

Judgements: Good: < 3% | Acceptable: 3% ≤ and < 7% | Marginal: 7% ≤ and < 10% | Not Acceptable: > 10%

Injury Assessment Items | Monitoring Items

E2: Reproducibility of the Flex-GTR-proto

Assembly Pendulum Type Calibration Test Series – Evaluation test results on the reproducibility of the Flex-GTR-proto (SN01-SN03) in the assembly pendulum type calibration test series are shown in Figure 24 and Table 9. Each impactor shows very similar waveforms. The Coefficient of Variation (CV) values with regard to the injury assessment or monitoring items are lower than 7.94% (SN01-SN03, Knee-PCL), with the majority of the CV values being less than 3%. When we see the standard deviation related to the tentative injury assessment reference levels (St.Dev./t-IARV), all of the values are lower than 3.0 % (SN03, Knee-PCL), and most of the values are less than 3 %.

Simplified Car Test Series – Evaluation test results on the reproducibility of the Flex-GTR-proto (SN02) in the simplified car test series are shown in Figure 25 through Figure 26 and in Table 10. The Flex-GTR-proto (SN01-SN03) shows comparable kinematics and waveforms. The CV values with regard to the injury assessment or monitoring items are lower than 6.68% (SN01-SN03, Tibia-4), with the majority of the CV values being less than 4%. When we see the standard deviation values related to the tentative injury assessment reference levels (St.Dev./t-IARV), all of the values are lower than 4.12 % (SN01-SN03, Tibia-3).

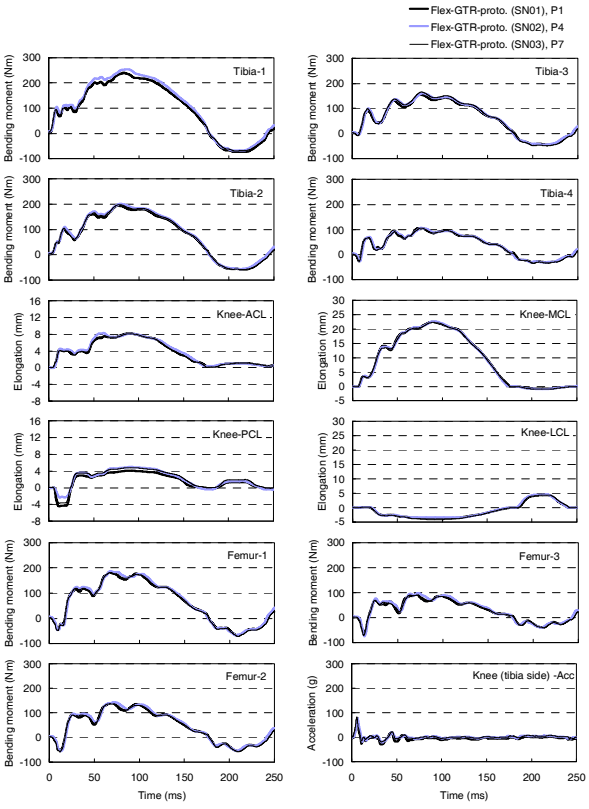

Figure 24. Waveforms (Test ID: P1, P4, P7 Reproducibility: Flex-GTR-proto (SN01-SN03)).

Table 9. Maximum Values and Variations (Data: Avg. of SN01 (P1-P3), S02 (P4-P6), S03 (P7-P9), Reproducibility: Flex-GTR-proto (SN01-SN03)).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-proto (SN01), Avg.***	240.9	193.7	153.7	105.0	8.05	4.38	22.4
Flex-GTR-proto (SN02), Avg.***	249.3	202.3	158.5	108.9	8.24	4.91	22.5
Flex-GTR-proto (SN03), Avg.***	239.0	201.0	168.4	107.4	7.94	5.12	22.4
Avg.	243.1	199.0	160.2	107.1	8.08	4.80	22.4
St. Dev.	5.48	4.64	7.50	1.97	0.15	0.38	0.06
CV (%)	2.26	2.33	4.68	1.84	1.88	7.94	0.26
Judgement	Good	Good	Acceptable	Good	Good	Marginal	Good
t-IARV*	318	318	318	318	12.7	12.7	20
St.Dev./t-IARV (%)	1.72	1.46	2.36	0.62	1.20	3.00	0.29
Judgement	Good	Good	Good	Good	Good	Acceptable	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.
*** Flex-GTR-proto (SN01), Avg.: Average data of P1-P3
Flex-GTR-proto (SN02), Avg.: Average data of P4-P6
Flex-GTR-proto (SN03), Avg.: Average data of P7-P9

Judgements: Good: < 3% | Acceptable: 3% ≤ and < 7% | Marginal: 7% ≤ and < 10% | Not Acceptable: > 10%

Injury Assessment Items | Monitoring Items

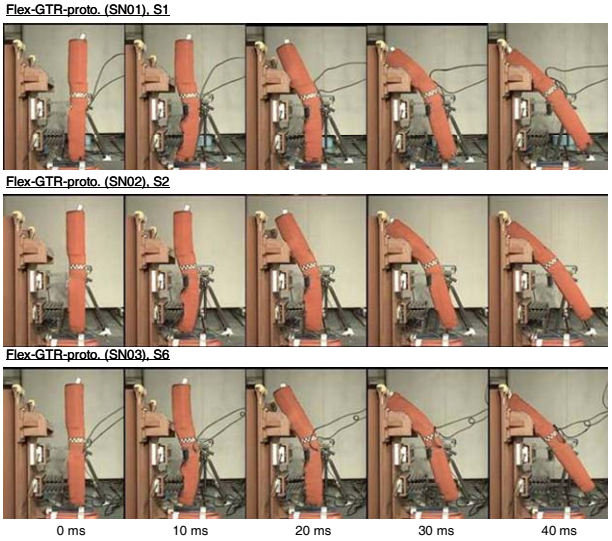

Figure 25. Kinematics (Test ID: S1, S2, S6 Reproducibility: Flex-GTR-proto (SN01-SN03)).

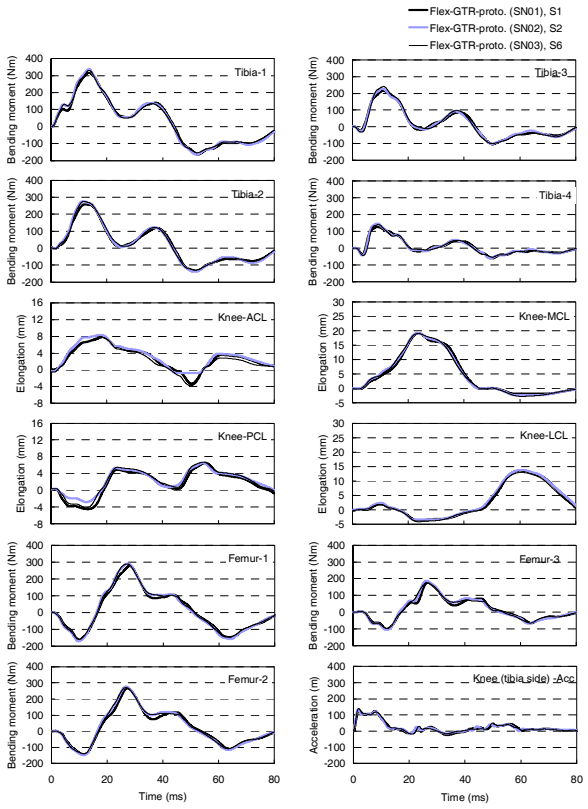

Figure 26. Waveforms (Test ID: S1, S2, S6 Reproducibility: Flex-GTR-proto (SN01-SN03)).

Table 10. Maximum Values and Its variations (Data: S1, Avg. of SN02 (S2-S5), S6, Reproducibility: Flex-GTR-proto (SN01, SN02, SN03)).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-prot (SN01), S1	317.2	258.5	214.7	127.7	7.81	6.54	19.2
Flex-GTR-prot (SN02), Avg.***	342.1	277.9	231.0	145.5	8.28	6.72	19.3
Flex-GTR-prot (SN03), S6	330.9	275.6	240.6	140.8	7.80	6.71	19.1
Avg.	330.1	270.7	228.8	138.0	7.96	6.66	19.2
St. Dev.	12.47	10.60	13.09	9.22	0.27	0.10	0.10
CV (%)	3.78	3.92	5.72	6.68	3.44	1.52	0.52
Judgement	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Good	Good
t-IARV*	318	318	318	318	12.7	12.7	20
St.Dev./t-IARV (%)	3.92	3.33	4.12	2.90	2.16	0.80	0.50
Judgement	Acceptable	Acceptable	Acceptable	Good	Good	Good	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.
*** Flex-GTR-proto (SN02), Avg.: Average data of S2-S5

Judgements: Good: < 3%; Acceptable: 3% ≤ and < 7%; Marginal: 7% ≤ and < 10%; Not Acceptable: > 10%

Injury Assessment Items | Monitoring Items

E3: Comparability between the Flex-GT and Flex-GTR-proto

Assembly Pendulum Type Calibration Test Series – Evaluation test results on the comparability between the Flex-GT and the Flex-GTR-proto in the assembly pendulum type calibration test series are shown in Figure 27 and Figure 28. Several measurement values of the Flex-GTR-proto are slightly higher than the Flex-GT (SN03), however, most of the Flex-GTR-proto outputs are within the Flex-GT corridor [9], which is tentatively settled to calibrate the Flex-GT by using the assembly pendulum type calibration test method (Type 1).

The average ratio of the measurement values of the Flex-GTR-proto to the Flex-GT corridor (center) are shown in Figure 29. All of the average ratios are lower than 1.36 (Knee-PCL, Avg.), and most of the average ratios are less than 1.1.

Simplified Car Test Series – Evaluation test results on the comparability between the Flex-GT and the Flex-GTR-proto in the simplified car test series are shown in Figure 30 through Figure 32. Several measurement values of the Flex-GTR-proto are slightly higher than the Flex-GT (SN03).

The average ratio of the measurement values of the Flex-GTR-proto to the Flex-GT (SN03) are shown in Figure 33. All of the average ratios are lower than 1.16 (Femur-3, Avg.), and most of the average ratios are less than 1.1.

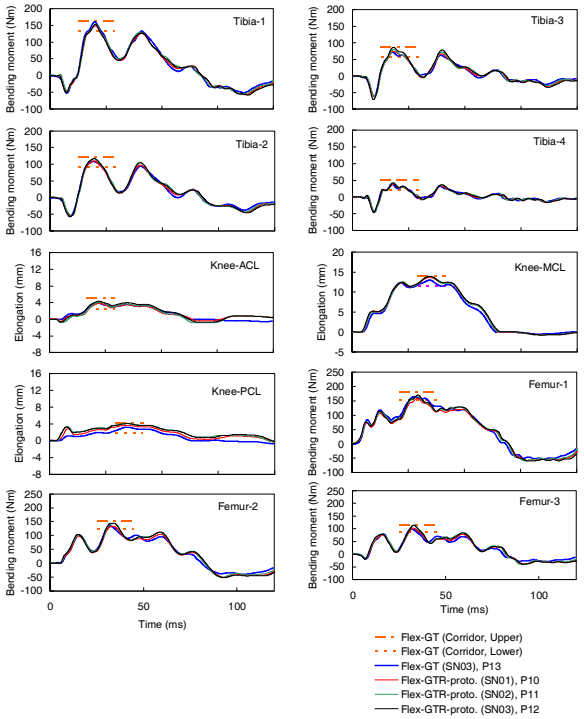

Figure 27. Waveforms with Flex-GT Corridor (Test ID: P13, P10-P12, Comparability: Flex-GT and Flex-GTR-proto).

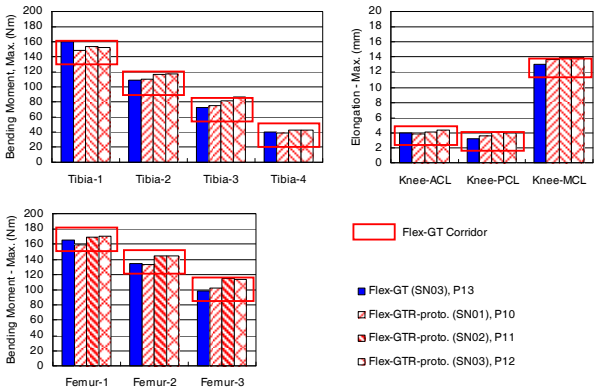

Figure 28. Maximum Values with Flex-GT Corridor (Test ID: P13, P10-P12, Comparability: Flex-GT and Flex-GTR-proto).

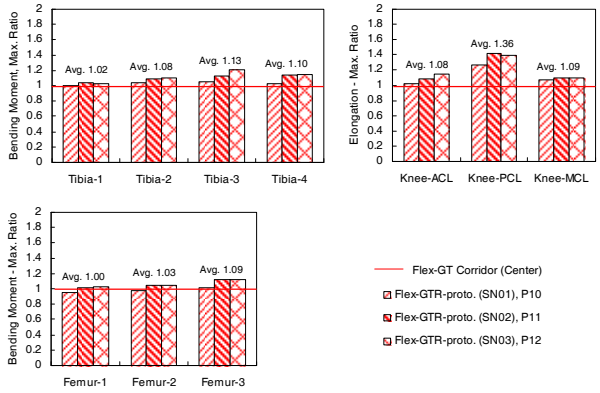

Figure 29. Maximum Value Ratio to the Flex-GT Center Corridor (Test ID: P10-P12, Comparability: Flex-GT and Flex-GTR-proto).

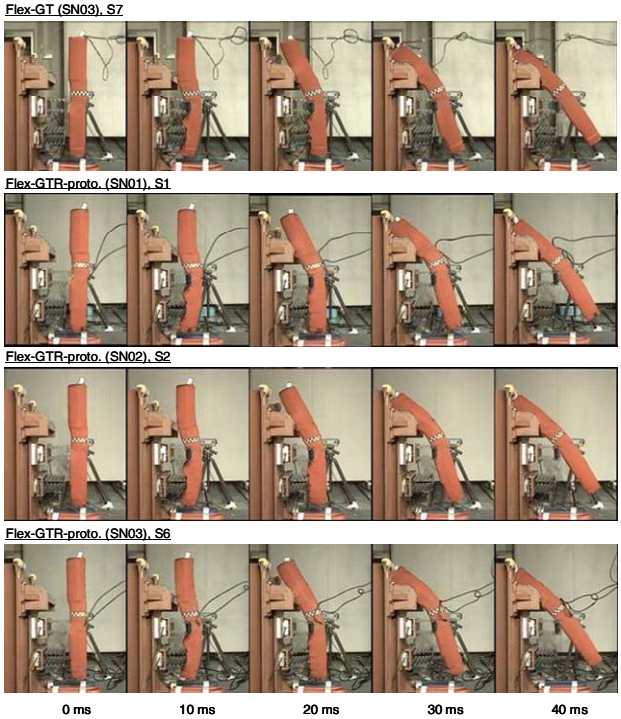

Figure 30. Kinematics (Test ID: S7, S1, S2, S6, Comparability: Flex-GT and Flex-GTR-proto).

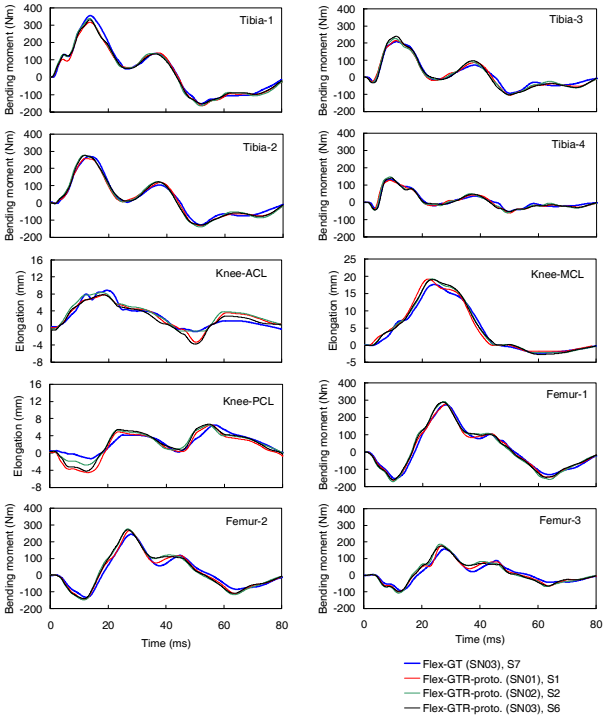

Figure 31. Waveforms (Test ID: S7, S1, S2, S6, Comparability: Flex-GT and Flex-GTR-proto).

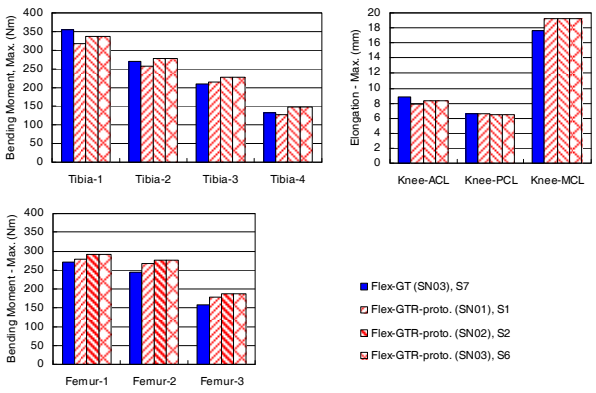

Figure 32. Maximum Values (Test ID: S7, S1, S2, S6, Comparability: Flex-GT and Flex-GTR-proto).

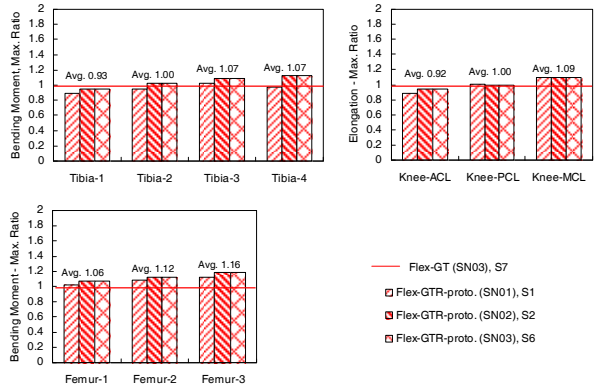

Figure 33. Maximum Value Ratio to the Flex-GT (SN03) (Test ID: S7, S1, S2, S6, Comparability: Flex-GT and Flex-GTR-proto).

E4: Comparability of the Flex-GTR-prototype output under the symmetric right and left bumper corner impacts

Evaluation test results on the comparability of the Flex-GTR-proto (SN03) output under the symmetric right and left bumper corner impacts are shown in Figure 34, Figure 35, and Table 11. The Flex-GTR-proto shows comparable kinematics and waveforms under the symmetric right and left bumper corner impacts. The Coefficient of Variation (CV) values with regard to the injury assessment or monitoring items are lower than 4.94% (Knee-PCL), with the majority of the CV values being less than 3%. When we see the standard deviation values to the tentative injury assessment reference values (St.Dev./t-IARV), all of the values are lower than 2.98 % (Knee-PCL).

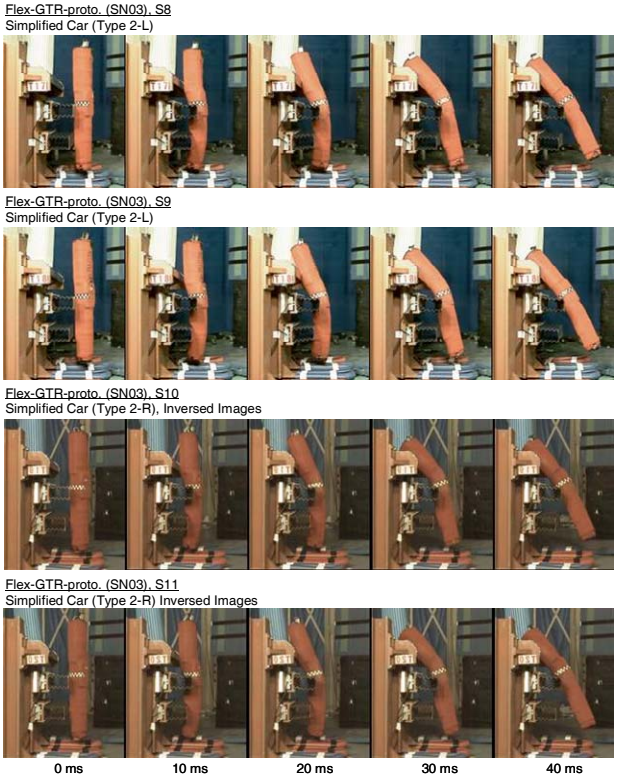

Figure 34. Kinematics (Test ID: S8-S11, Comparability: Flex-GTR-proto output under Symmetric Right and Left Bumper Corner Impact).

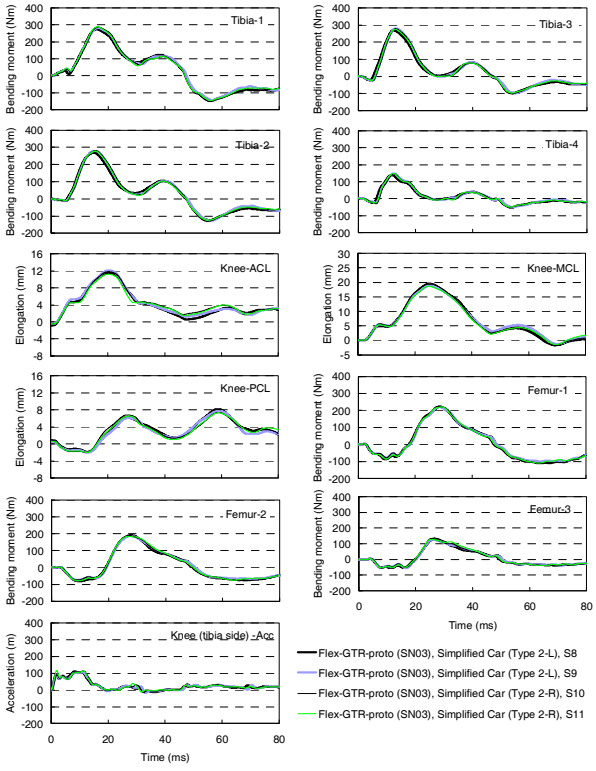

Figure 35. Waveforms (Test ID: S8-S11, Comparability: Flex-GTR-proto output under Symmetric Right and Left Bumper Corner Impact).

Table 11. Maximum Values and Variations (Test ID: S8-S11, Comparability: Flex-GTR-proto output under Symmetric Right and Left Bumper Corner Impact).

	Max. values**						
	Tibia-1 (Nm)	Tibia-2 (Nm)	Tibia-3 (Nm)	Tibia-4 (Nm)	Knee-ACL (mm)	Knee-PCL (mm)	Knee-MCL (mm)
Flex-GTR-prot. (SN03), S8	273.7	269.6	269.8	139.5	11.61	8.18	19.3
Flex-GTR-prot. (SN03), S9	282.1	280.0	281.1	149.2	12.11	7.72	18.8
Flex-GTR-prot. (SN03), S10	285.6	281.5	278.7	146.5	11.81	7.38	19.8
Flex-GTR-prot. (SN03), S11	285.6	281.5	278.7	146.5	11.81	7.38	19.8
Avg.	281.8	278.2	277.1	145.4	11.84	7.67	19.43
St. Dev.	5.61	5.74	4.98	4.15	0.21	0.38	0.48
CV (%)	1.99	2.06	1.80	2.85	1.74	4.94	2.46
Judgement	Good	Good	Good	Good	Good	Acceptable	Good
t-IARV*	318	318	318	318	12.7	12.7	20.0
St.Dev./t-IARV (%)	1.77	1.81	1.57	1.31	1.62	2.98	2.39
Judgement	Good	Good	Good	Good	Good	Good	Good

* t-IARV: Tentative Injury Assessment Reference Values
** Injury assessement items and monitoring items were evaluated.

Judgements
Good: < 3%
Acceptable: 3% ≤ and < 7%
Marginal: 7% ≤ and < 10%
Not Acceptable: > 10%

Injury Assessment Items | Monitoring Items

DISCUSSIONS

In this research the following items were evaluated.
E1: Repeatability of the Flex-GTR-proto
E2: Reproducibility of the Flex-GTR-proto
E3: Comparability between the Flex-GT and Flex-GTR-proto
E4: Comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts

The evaluation results of each item are discussed bellow.

E1: Repeatability of the Flex-GTR-proto

Technical evaluations on the repeatability of the Flex-GTR-proto were conducted in the assembly pendulum type calibration test series as well as in the simplified car test series. As a result, the Coefficient of Variation (CV) values with regard to the injury assessment or monitoring items are lower than 7.72% (SN03, Knee-PCL, Assembly pendulum type test series), with the majority of the CV values being less than 3%. When we see the standard deviation values to the tentative injury assessment reference values (St.Dev./t-IARV), all of the values are lower than 4.52 % (SN03, Knee-ACL, Assembly pendulum type test series), with the majority of the values being less than 3 %.

The acceptance level of the CV values for a regulatory tool is less than 10% based on a BASt proposal [10]; therefore, the test results show fairly good repeatability of the Flex-GTR-proto relative to the proposed acceptance level.

E2: Reproducibility of the Flex-GTR-proto

Technical evaluations on the reproducibility of the Flex-GTR-proto were conducted in the assembly pendulum type calibration test series as well as in the simplified car test series. As a result, the Coefficient of Variation (CV) values with regard to the injury assessment or monitoring items are lower than 7.94% (SN03, Knee-PCL, Assembly pendulum type test series), with the majority of the CV values being less than 3%. When we see the standard deviation values to the tentative injury assessment reference values (St.Dev./t-IARV), all of the values are lower than 4.12 % (Tibia-3, Simplified car test series), and most of the values are less than 3 %.

The results of the CV value evaluations show fairly good reproducibility of the Flex-GTR-proto relative to the proposed acceptance level.

E3: Comparability between the Flex-GT and Flex-GTR-proto

Technical evaluations on the comparability between the Flex-GT and Flex-GTR-proto were conducted in the assembly pendulum type calibration test series as well as in the simplified car test series. As a result, the maximum measurement values of the Flex-GTR-proto are slightly higher than the Flex-GT in general. The ratios of the maximum measurement values of the Flex-GTR-proto to the Flex-GT are lower than 1.36 (Knee-PCL, Avg., Assembly pendulum type test series), and the majority of the ratios are less than 1.1.

In particular, the difference of the Knee-PCL output under the assembly pendulum type test series, 1.36, is larger than the differences of the other outputs. This is because the absolute Knee-PCL output during the test is very small, 4 mm or less, therefore, even a very small difference of 1 mm or less (the differences are within the Flex-GT corridor, besides its t-IARV is 12.7 mm, i.e. relative difference to the t-IARV is very small), appears exaggerated when expressed in ratio.

E4: Comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts

Technical evaluations on the comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts were conducted in the simplified car test series. As a result, the Coefficient of Variation (CV) values with regard to the injury assessment or monitoring items are lower than 4.94% (Knee-PCL), and the majority of the CV values is less than 3%. When we see the standard deviation values to the tentative injury assessment reference values (St.Dev./t-IARV), all of the values are lower than 2.98 % (Knee-PCL).

The results of the CV value evaluations show fairly good comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts relative to the proposed acceptance level.

Overall

Technical evaluations on the Flex-GTR-proto were conducted in this research. As a result, fairly good evaluation results were obtained. The results were lead by the improvement of the knee construction from an asymmetric construction of the Flex-GT to symmetric construction of the Flex-GTR-proto. The symmetric construction prevents the knee twist motion around the longitudinal axis of the impactor, which leads to stable outputs and a comparable output at the symmetric right and left bumper corners. Additionally, from the Flex-GTR-proto version, FTSS, a company specialized in manufacturing crash dummies, joined the development to assure that the Flex-GTR is produced under high quality control conditions.

The difference between the Flex-GT and Flex-GTR-proto outputs may alter appropriate threshold values for each injury criterion; therefore a following research has been investigating the threshold values for the Flex-GTR-proto using ratios of the Flex-GT and Flex-GTR-proto outputs in this study, and/or using the correlation between the Flex-GTR-proto and human lower extremities which can be obtained from a computer simulation analysis.

CONCLUSIONS

In this research, the following items were evaluated.

- Repeatability of the Flex-GTR-proto
- Reproducibility of the Flex-GTR-proto
- Comparability between the Flex-GT and Flex-GTR-proto
- Comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts

As a result, fairly good repeatability and reproducibility of Flex-GTR-proto, and comparability of the Flex-GTR-proto output under the symmetric right and left bumper corner impacts were observed (majorities of CV values are less than 3%).

As for the comparability between the Flex-GT and Flex-GTR proto, some differences were observed between them. Most of the maximum value ratios of the Flex-GTR-proto relative to the Flex-GT are less than 1.1.

The difference between the Flex-GT and Flex-GTR-proto has a chance to affect the injury threshold values; therefore, a following research has been investigating the threshold values for the Flex-GTR-proto using the ratios of the Flex-GT and Flex-GTR-proto outputs and/or using the correlations between the Flex-GTR-proto and human lower extremities which can be obtained from a computer simulation analysis.

The Flex-TEG members have been conducting further technical evaluation after our initial technical evaluations. The results are going to be put together and used for the Flex-GTR finalization.

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