IMPACT RESPONSE AND BIOFIDELITY OF PEDESTRIAN LEGFORM IMPACTORS

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ABSTRACT

The objectives of this research are to propose a new impact response corridor of the ISO legform impactor and to understand the biofidelity of the current legform impactors developed by TRL and JARI.

The latest data obtained from Post Mortem Human Subject (PMHS) knee impact test were analyzed for the proposal, and biofidelity legform impact tests were conducted using current legform impactors.

New normalized biofidelic corridors of impact force correspond to AM50 are proposed. The impact test results indicate the current legform impactors do not have human knee biofidelity.

The current legform impactor design should be improved with respect to the biofidelic response.

PEDESTRIANS are often involved in traffic accidents. In nonfatal pedestrian accidents in Japan, the most commonly injured body region is the leg (40%)[1].

The European Enhanced Vehicle-safety Committee (EEVC), the National Highway Traffic Safety Administration (NHTSA), and the International Standard Organization (ISO) have discussed to improve test methods for evaluating vehicle aggressiveness against pedestrians for many years. EEVC (WG10[2], WG17[3]) and ISO are planning to use a subsystem legform test setup to evaluate bumper aggressiveness against pedestrian lower extremities, particularly against the knee joint. In the subsystem test setup, the legform impactor is propelled into a stationary vehicle as shown in Figure 1. A legform impactor designed by TRL and proposed by EEVC/WG17 consists of the thigh part, the knee joint, and the leg part and weighs 13.4 kg. The impactor should simulate the biofidelic nature of a human leg while having robustness.

To confirm the biofidelity of the mechanical legform impactor, a biofidelic corridor is

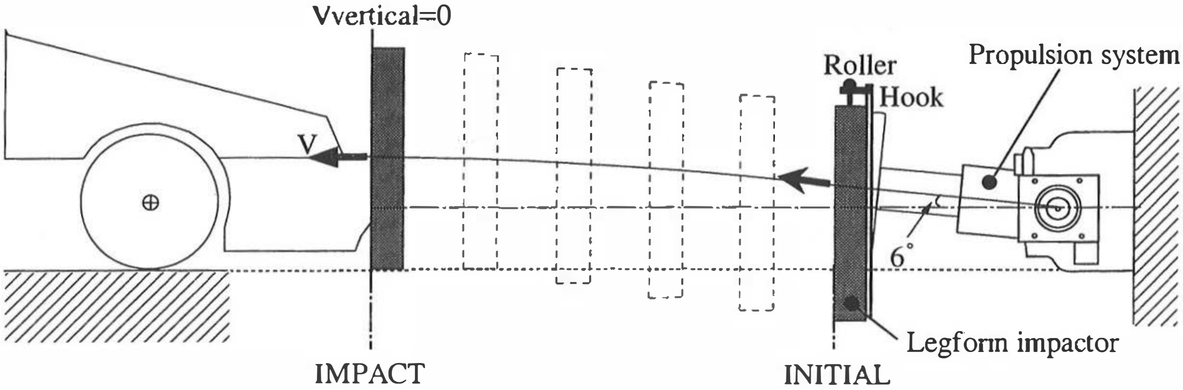

Figure 1 Subsystem legform test setup with ballistic launching conducted by JARI.

needed based on the data obtained from PMHS knee impact tests. ISO/TC22/SC10/WG2[4] discussed the biofidelic corridor and biofidelity test procedure for a legform impactor based on the data obtained by Kajzer et al.[5][6]. The biofidelic corridor and biofidelity test procedure are related to the shearing and bending test setups at low impact velocity level (15 km/h and 20 km/h).

The average knee bending moment at the initial damage induced by the bending setup was 101 to 123 Nm[6], whereas the maximum bending moment of the current EEVC legform impactor is about 450 Nm. Furthermore, the PMHSs used in the studies[5][6] were from an elderly and mainly hospitalized group, whereas the mechanical legform impactor simulates AM50. These contradictions gave us the incentive to further study the biofidelic corridor and the biofidelity test procedure.

In the latest studies[7][8] based on the data obtained from PMHS knee impact tests, the average knee bending moment in a shearing setup at low (20 km/h) and high (40 km/h) impact velocities were 418 to 489 Nm, which are comparable to that in the current EEVC legform impactor. In those studies, the PMHSs came from much younger and not hospitalized group. Accordingly, the data and test setup of the studies[7][8] are useful for establishing the new biofidelic corridor and biofidelity test procedure for the ISO legform impactor.

The objectives of this research are to propose a new impact response corridor of the ISO legform impactor and to understand the biofidelity of the current legform impactors developed by TRL and JARI.

BIOFIDELITY TEST PROPOSED BY ISO/TC22/SC10/WG2

In 1996 ISO/TC22/SC10/WG2 proposed biofidelic corridors and test setups for the legform impactor based on the study conducted by Kajzer et al.[5][6]. The tests are related to shearing setup at an impact velocity of 15 km/h and a bending setup at an impact velocity of 15 and 20 km/h. To understand the biofidelity of the legform impactor, legform impact tests in the setups proposed by the ISO/TC22/SC10/WG2 were conducted using current legform impactors (JARI and TRL).

METHODOLOGY - Figures 2 and 3 show the shearing and bending test setups proposed by the ISO. The impactor used in the shearing setup has a double contact face.

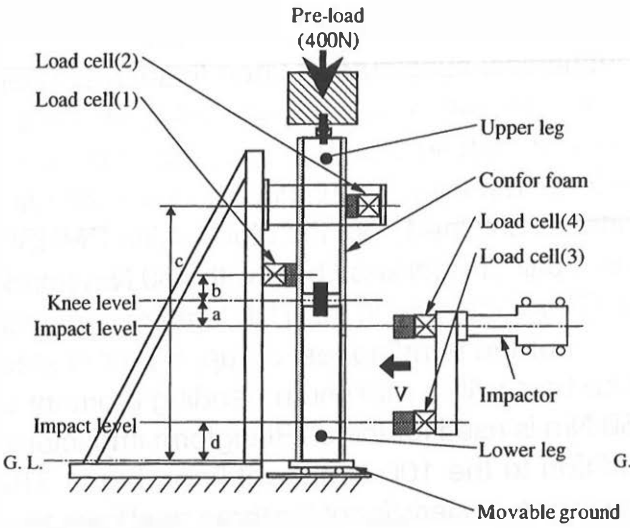

Figure 2 Shearing setup with double impactor proposed by ISO/TC22/SC10/WG2.

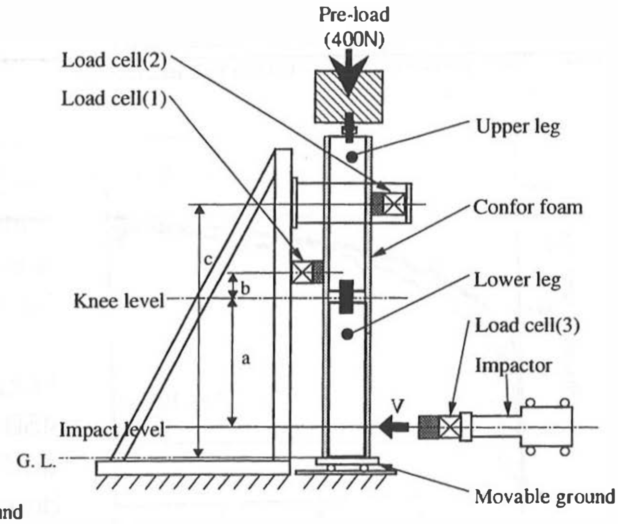

Figure 3 Bending setup with single impactor proposed by ISO/TC22/SC10/WG2.

Two load cells (3)(4) are mounted in front of the impactor to measure the resultant impact force. Two plates of foam padded by Styrodure® (3035S, 50x50x150 mm) are attached in front of the load cells. The impactor used in the bending setup has a single contact face. One load cell (3) is mounted in front of the impactor to measure the impact force. One plate of the foam is attached in front of the load cell. The total mass of the mobile part of the impactor is 40 kg for both setups.

The dimensions of the test setups are described in Table 1. The legform impactor is preloaded with a force of 400 N. Two plates of foam padded by Styrodure® (3035S, 25x50x150 mm) are adjusted to stabilize the upper leg, one for the proximal part (2) and the other for the distal part (1). Each fixation plate is equipped with one load cell to measure the knee force (1) and trochanter force (2). To permit good movement of the lower leg, the legform impactor is placed on a mobile plate.

The motion behavior of the legform impactor is monitored by a high speed video camera. To avoid edge contact at the knee joint, the movement of the legform impactor is restrained by a stopper.

To get the response of the legform impactors, a TRL legform impactor equipped with a shear spring and a JARI legform impactor without shearing mechanism are tested in the both setups. The TRL legform impactor can directly measure the shearing displacement and bending angle. The JARI legform impactor is able to directly measure the shearing force, bending moment, and bending angle.

Table 1 Dimensions of shearing and bending test setups proposed by ISO/TC22/SC10/WG2.

Test set up	Dimension (mm)			
	a	b	c	d
Shearing test	45	45	874	103
Bending test	400	74	904	-

For the shearing test setup, a pair of mechanical substitute of knee ligaments (steel knee bars) with a maximum bending moment of 100 Nm (soft ligament) is installed in the JARI legform impactor, simulating the knee bending stiffness obtained from the study using PMHS[6], and a pair of steel knee bars with 450 Nm (made by TRL) is installed in the TRL legform impactor.

For the bending test setup, a pair of steel knee bars with a maximum bending moment of 450 Nm is used for the JARI legform impactor in addition to the 100 Nm steel knee bars. The bending characteristics of the three steel knee bars are shown in Figure 4.

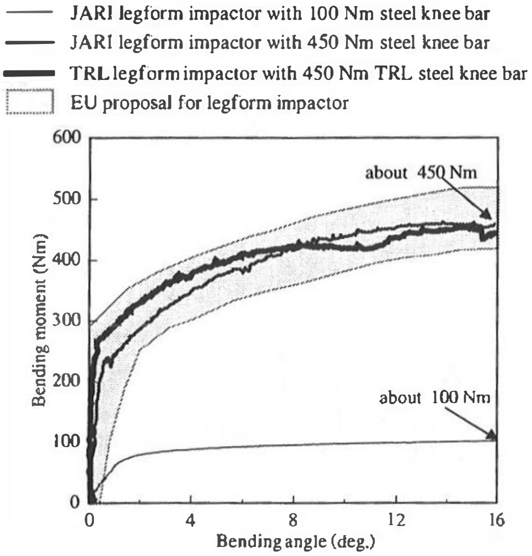

Figure 4 Bending characteristics in three steel knee bars installed in JARI and TRL impactors.

The stationary legform impactor is impacted at a velocity level of 15 km/h for the shearing set up and at 15 and 20 km/h for the bending setup.

RESULTS - Figure 5 shows the time histories of the impact force at 15 km/h obtained from the JARI and TRL legform impactors in the shearing test setup. The time of the peak impact force was adjusted to match the time of the peak force of the corridor. This method was originally proposed by ISO/TC22/SC10/WG2[4]. The impact force obtained from the JARI legform impactor using a pair of steel knee bars with 100 Nm almost satisfied the corridor for the time period from 0 to 40 ms. However, the impact force obtained from the TRL legform impactor was out of the corridor. After 20 ms the impact force obtained by the TRL legform impactor increased significantly due to the secondary contact between the loading impactor and the legform impactor. The movement of the legform impactor was prevented by a stopper to avoid edge contact at the knee joint.

Figures 6 and 7 show the time histories of the impact force at 15 and 20 km/h obtained from the JARI and TRL legform impactors in the bending test setup. After 25 to 35 ms, the impact force obtained by the both legform impactors increased significantly due to the secondary contact against the stopper. When we focus on the time from zero to 25 ms, the impact force obtained from the JARI legform impactor using a pair of steel knee bars with 100 Nm almost satisfied the corridor, whereas the forces from the JARI legform impactor using a pair of steel knee bars with 450 Nm and the TRL legform impactor did not fit the corridor.

The JARI legform impactor using a pair of steel knee bars with 100 Nm satisfied the biofidelity test proposed by ISO/TC22/SC10/WG2. The TRL legform impactor failed this test.

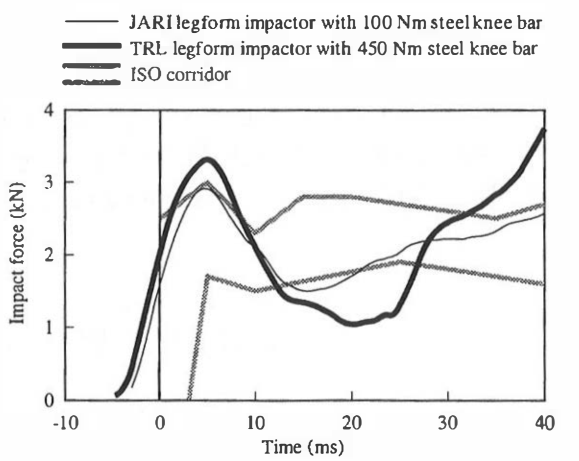

Figure 5 Impact response of TRL and JARI legform impactors in shearing setup at 15 km/h compared with biofidelic corridor.

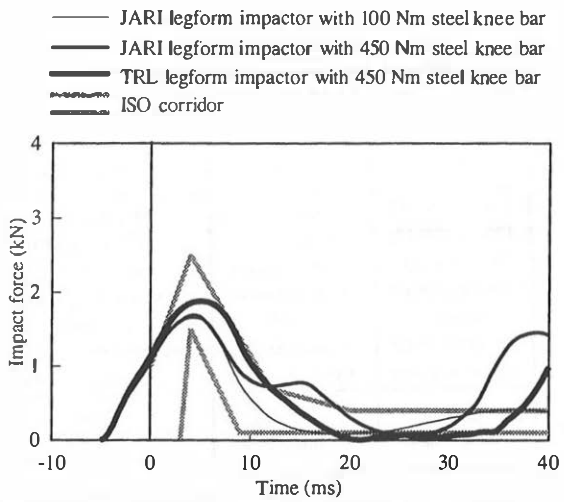

Figure 6 Impact response of TRL and JARI legform impactors in bending setup at 15 km/h compared with biofidelic corridor.

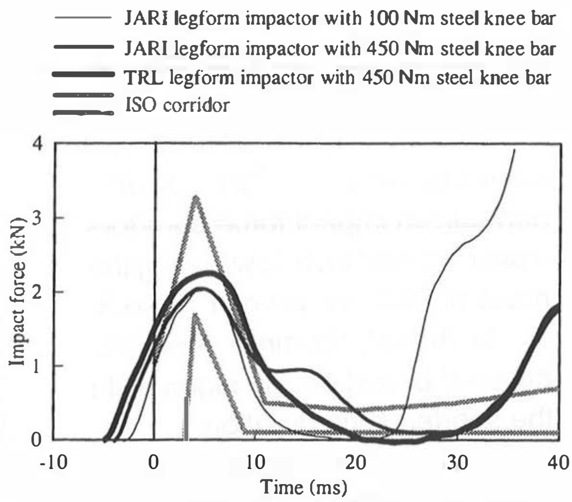

Figure 7 Impact response of TRL and JARI legform impactors in bending setup at 20 km/h compared with biofidelic corridor.

NEW BIOFIDELIC CORRIDOR

The previous biofidelic corridor(4) proposed by ISO/TC22/SC10/WG2 was based on the studies(5)(6) using the PMHSs from an elderly and mainly hospitalized group. Their tests were conducted with the lower extremity amputated. Whereas in the latest studies(7)(8) of PMHS knee impact tests, the PMHSs were not hospitalized. The tests were conducted in shearing and bending setups at low(8) (20 km/h) and high(7) (40 km/h) impact velocities with stable conditions using a complete body as shown in Figures 8 and 9. Table 2 summarizes the test conditions of the previous studies and those of the latest studies.

To propose a new biofidelic corridor, impact forces were normalized in the shearing and bending test setups at low (20 km/h) and high (40 km/h) impact velocities based on the studies(7)(8). In each setup to simulate shearing and bending, results from five experiments were used from the low-impact-velocity tests, and other results from nine (ten) experiments were used from the high-impact-velocity tests, respectively.

The normalizing the impact force considering the difference of the individual subject mass and comparing it to the mass of the standard subject was done according to Mertz(9).

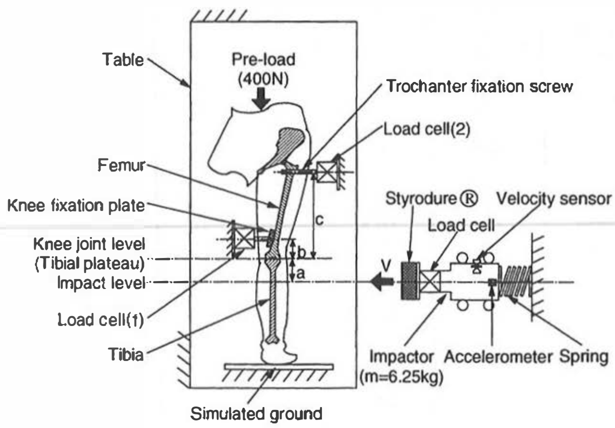

Figure 8 Shearing setup for PMHS(7)(8).

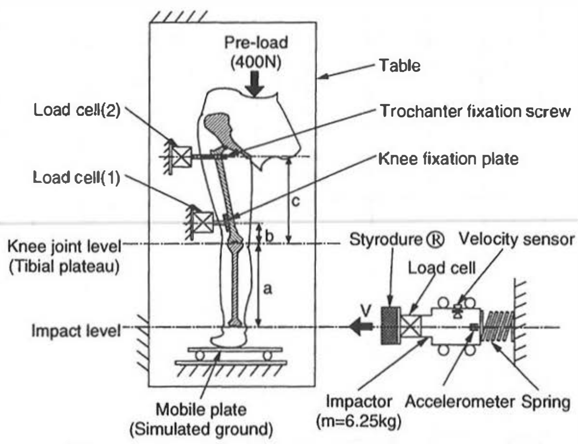

Figure 9 Bending setup for PMHS(7)(8).

For four series of tests with PMHS (shearing test at low speed, shearing test at high speed, bending test at low speed, and bending test at high speed), normalized impact force corridors were obtained as follows using the mass of PMHS shown in Table 3:

1) At first, the time zero was decided based on the signal with the shortest time duration.

2) All other peaks of force curves were aligned in time.

3) The impact forces were normalized according to the following formula:

Table 2 Test conditions in new setups[7][8] and previous setups[5][6].

Study	Kajzer et al.[7]	Kajzer et al.[8]	Kajzer et al.[5][6]
Velocity	40 km/h	20 km/h	15 km/h, 20 km/h
PMHS	51 years (SD 15) 170 cm (SD 12) 76 kg (SD 24) Unhospitalized Fresh Complete body Lying on a table	63 years (SD 15) 172 cm (SD 9) 82 kg (SD 13) Unhospitalized Fresh Complete body Lying on a table	78 years (SD 7)* 165 cm (SD 10)* 66 kg (SD 12)* Mainly hospitalized Preserved Amputated lower extremity Standing position
Impactor	6.25 kg Single face	6.25 kg Single face	40 kg Double face (shearing test) Single face (bending test)

* The age, height and weight of PMHS from shearing test in Kajzer et al.[5].

$$F_N = F \times \sqrt{\frac{M_O}{M}}$$

where: F_N is normalized impact force, F is measured impact force, M is mass of PMHS, and M_o is mass of AM50.

4) The biofidelic corridor was defined by the average impact force with a range of plus or minus one standard deviation.

Table 3 Anthropometric data of PMHS and impact conditions[7][8] from the tests used to calculate the biofidelic corridor and to determine the biofidelic test setup.

Test No.	Anthropometric data of PMHS: Sex	Age (years)	Height (cm)	Weight (kg)	Impact conditions: Configuration	Leg	Impactor velocity (km/h)	Positions from knee joint level: a (mm)	b (mm)	c (mm)
1S	M	36	192	104	Shearing	left	40.3	65	50	420
2B	M	36	192	104	Bending	right	40.3	390	80	460
3B	M	69	170	85	Bending	right	40.2	375	105	355
4S	M	69	170	85	Shearing	left	40.2	60	120	315
6B	M	68	178	96	Bending	right	39.7	415	88	395
7B	M	35	177	75	Bending	right	40.1	390	90	375
8S	M	35	177	75	Shearing	left	-	80	95	350
9S	F	35	161	67	Shearing	left	39.9	65	90	350
10B	F	35	161	67	Bending	right	39.7	345	120	325
11B	M	59	170	66	Bending	right	39.7	399	111	340
12S	M	59	170	66	Shearing	left	39.5	75	125	355
13S	M	44	168	70	Shearing	left	39.6	90	100	285
14B	M	44	168	70	Bending	right	39.9	340	100	300
15B	M	63	177	80	Bending	right	39.7	402	118	338
16S	M	63	177	80	Shearing	left	-	95	135	325
17S	M	68	165	94	Shearing	left	38.8	115	110	240
18B	M	68	165	94	Bending	right	39.7	365	100	300
19B	M	36	166	81	Bending	right	-	345	93	290
20S	M	36	166	81	Shearing	left	-	100	105	267
21S	F	72	159	73	Shearing	left	[21.8]	80	110	300
22B	F	72	159	73	Bending	right	21.3	315	105	325
23B	M	60	177	81	Bending	right	[20.4]	345	95	335
24S	M	60	177	81	Shearing	left	[20.7]	56	115	330
25S	M	56	189	115	Shearing	left	[19.6]	90	115	345
26B	M	56	189	115	Bending	right	[21.6]	326	120	320
27B	F	83	160	53	Bending	right	[20.8]	267	85	320
28S	F	83	160	53	Shearing	left	21.5	86	95	305
29S	F	42	163	56	Shearing	left	[21.7]	85	80	320
30B	F	42	163	56	Bending	right	[21.2]	280	110	335

[ ] : Estimated velocity from film.

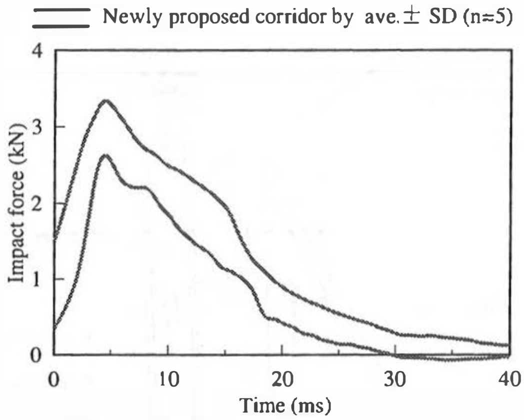

Figure 10 Biofidelic corridor for shearing setup at 20 km/h.

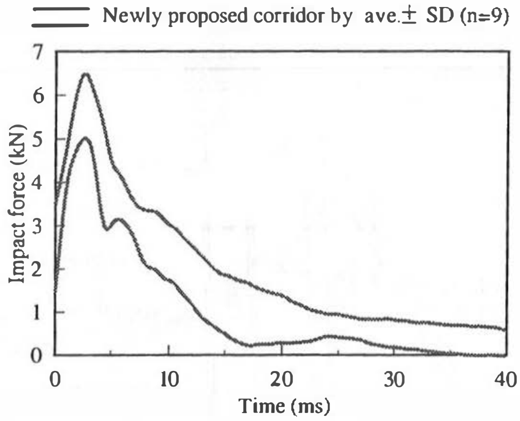

Figure 11 Biofidelic corridor for shearing setup at 40 km/h.

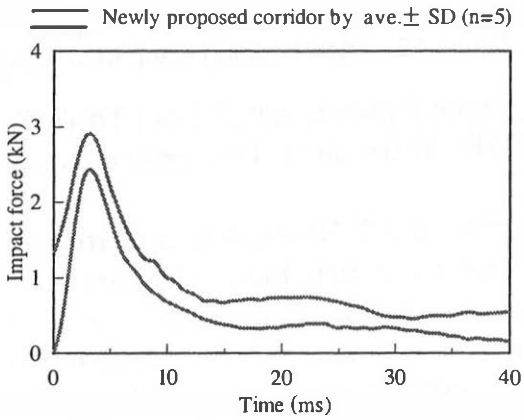

Figure 12 Biofidelic corridor for bending setup at 20 km/h.

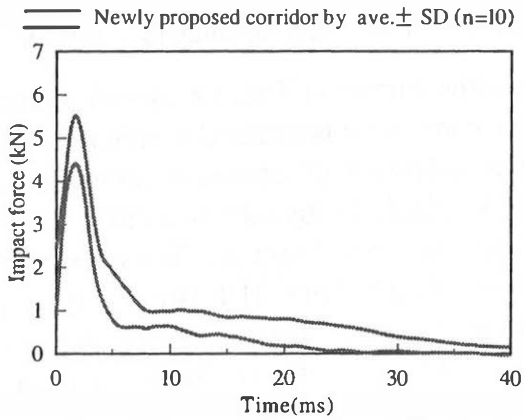

Figure 13 Biofidelic corridor for bending setup at 40 km/h.

Figures 10, 11, 12 and 13 show the calculated biofidelic corridors for the four series (shearing test at low speed, shearing test at high speed, bending test at low speed, and bending test at high speed). The time period of the corridors is defined from 0 to 40 ms, which is the same as in the ISO/TC22/SC10/WG2 proposal.

BIOFIDELITY TEST IN NEW SETUPS

To understand the biofidelity of the legform impactors with respect to the newly obtained biofidelic corridors, legform impact tests using JARI and TRL legform impactors were conducted with the new shearing and bending setups at low (20 km/h) and high (40 km/h) impact velocities based on the studies[7][8].

METHODOLOGY - Figures 14 and 15 show the shearing and bending setups using an impactor with a single contact face. In front of the impactor, Styrodure® (3035S, 100x120x50 mm) is attached as shown in Figure 16. To measure the impact force, an accelerometer and a load cell (3) are mounted on the impactor. The mass of the mobile part of the impactor including the load cell, accelerometer and Styrodure® is 6.27 kg.

The upper part of the legform impactor is fixed by two screws at the levels of the distal part (1) and the proximal part (2). Each fixation screw is equipped with one load cell to measure the knee force (1) and trochanter force (2). The dimensions of both test setups

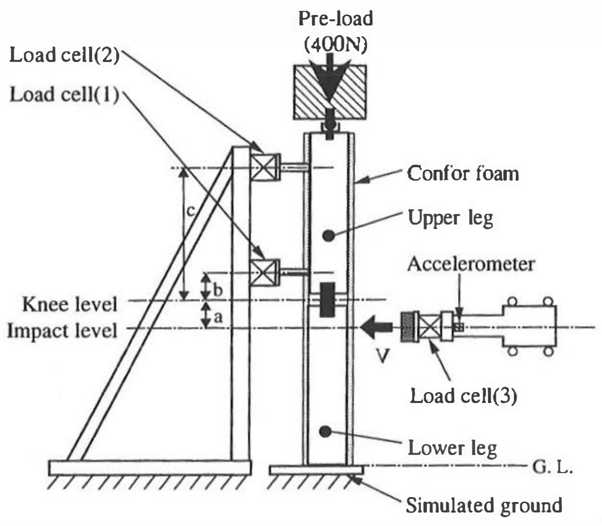

Figure 14 New shearing setup for a legform.

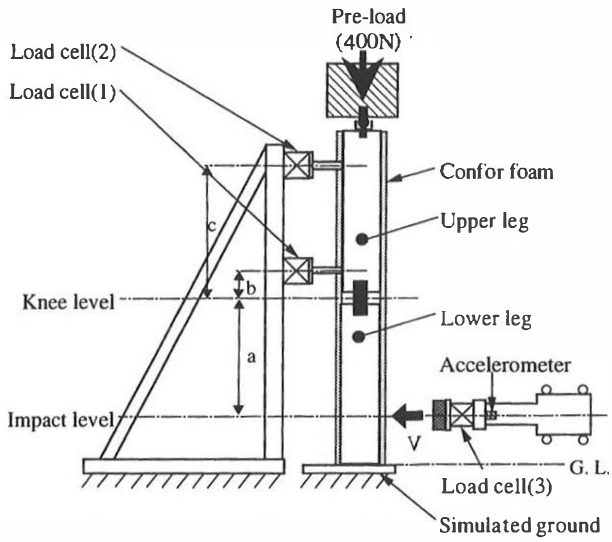

Figure 15 New bending setup for a legform.

are summarized in Table 4 based on the high speed impact data(7) from Table 3. The legform impactor is preloaded with a force of 400 N. The motion of the legform impactor is monitored by a high-speed video camera.

To clarify the biofidelity of the legform impactors, the JARI and TRL legform impactors are used in the test setups. The maximum bending moment of the steel knee bars is 450 Nm for both JARI and TRL legform impactors at a bending angle of 16 degrees as shown in Figure 4. The stationary legform impactor is impacted at velocities of 20 and 40 km/h for both setups. The shearing test using the TRL legform impactor at 40 km/h was not conducted to avoid the damage of the legform impactor.

RESULTS - When we compare the impact responses of the mechanical legform impactors to those of the human leg (newly proposed corridor), the time window of 15 ms is focused.

Results from shearing setup - Figure 17 shows the time histories of the impact forces obtained from the JARI and TRL legform impactors in the shearing test setup at 20 km/h in relation to the newly proposed corridor. The time of the peak impact force was adjusted to match the time of the peak force of the corridor. The impact force obtained from the TRL legform impactor was relatively close to the upper border of the biofidelic corridor.

The difference of the impact forces from the two legform impactors is considered due to their different designing: the TRL legform impactor has a shear spring but the JARI legform impactor does not. The JARI legform impactor does not allow any shearing displacement.

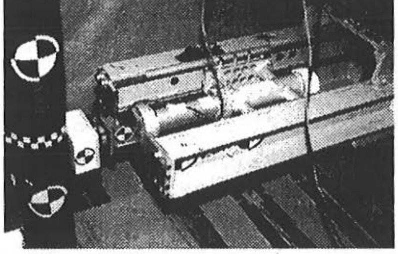

Figure 16 Impactor used in new setups.

Table 4 Geometry of the new biofidelity test setups and referred data(7).

Location	Dimension (mm)			
	Biofidelity tests		Study (7)	
	Shearing setup (Figure 14)	Bending setup (Figure 15)	Shearing setup (Figure 8)	Bending setup (Figure 9)
a	84	377	84 (SD 18)	377 (SD 27)
b	100		100 (SD 20)	
c	335		335 (SD 52)	

Figure 18 shows the time histories of the impact forces obtained from the JARI legform impactor in the shearing test setup at 40 km/h with the newly proposed corridor. The impact force obtained from the JARI legform impactor was completely different from the corridor. Even TRL legform impactor was not tested at high speed, the same result as for JARI legform impactor is expected at high speed because its shear spring is almost bottomed already at 20 km/h (See Figure 21).

Results from bending setup - Figure 19 shows the time histories of the impact forces obtained from the JARI and TRL legform impactors in the bending test setup at 20 km/h with the newly proposed corridor. For the time from 0 to 15 ms, the impact forces obtained by both legform impactors were close to the corridor.

Figure 20 shows the time histories of the impact forces obtained from the JARI and TRL legform impactors in the bending test setup at 40 km/h with the newly proposed

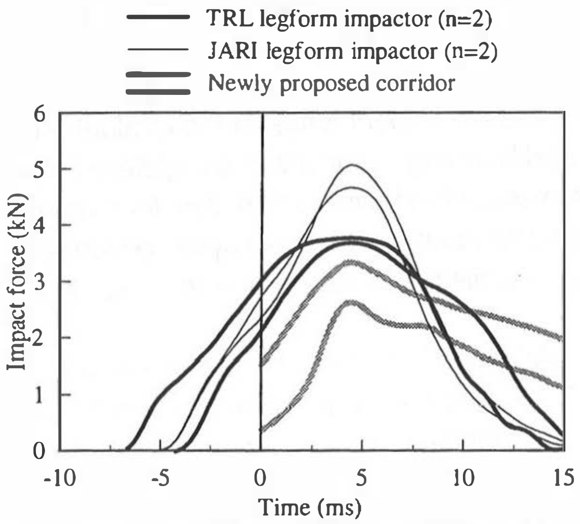

Figure 17 Impact forces of TRL and JARI legform impactors compared with biofidelic corridor in shearing setup at 20 km/h.

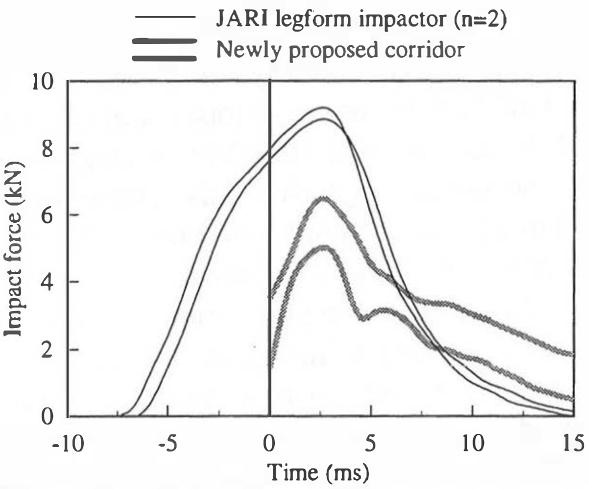

Figure 18 Impact forces of JARI legform impactor compared with biofidelic corridor in sharing setup at 40 km/h.

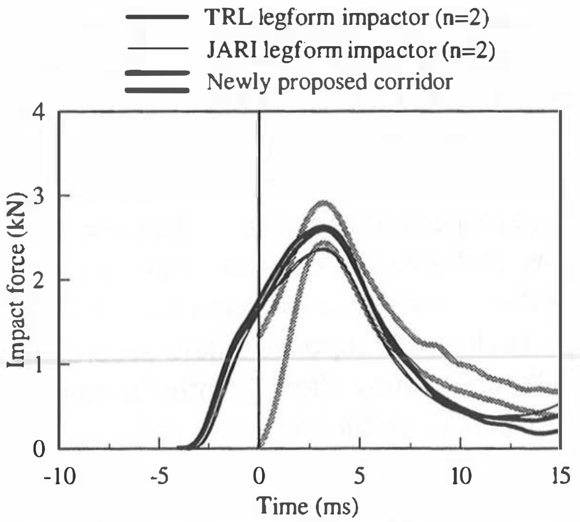

Figure 19 Impact forces of TRL and JARI legform impactors compared with biofidelic corridor in bending setup at 20 km/h.

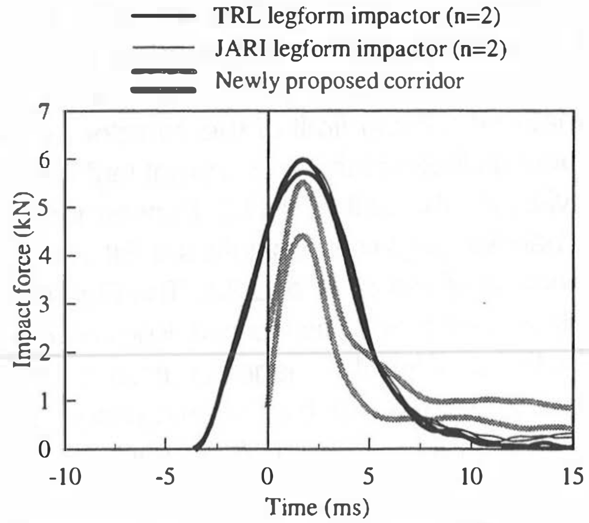

Figure 20 Impact forces of TRL and JARI legform impactors compared with biofidelic corridor in bending setup at 40 km/h.

corridor. The peaks of the impact forces obtained from both legform impactors were relatively close to that of the upper limit of the corridor. However, the impact forces obtained from both legform impactors did not fit the newly proposed corridor for the time from 0 to 15 ms.

Based on the results from the both setups, the JARI and TRL legform impactors do not have a biofidelity of the human leg with knee. The current legform impactors should be improved with respect to the biofidelic response especially at high speed.

DISCUSSION

Impact force can be relevant to evaluate the biofidelity of deformable knee system under the assumption that mass distributions and moment of inertias are similar in both systems, mechanical legform impactor and lower extremity of PMHS. In this case, unknown dynamic property of the knee joint can be determined by the impact force applied at the same place on the both systems. We decided to use the impact force for the evaluation of the biofidelity because we found that shearing and bending deformations registered from PMHS test were influenced by the complex movement of the lower extremities, for example rotation around longitudinal axis. Those parameters were also influenced by the occurrence of damages of ligaments and bones. Therefore, reliability of these parameters evaluating the biofidelity is strongly limited.

In the shearing and bending setups, the JARI and TRL legform impactors do not have a biofidelity of the human leg with knee. These mechanical legform impactors are designed according to the physical parameters (dimensions, mass distributions, moment of inertia, soft tissue stiffness, etc.) of a human leg (AM50, static condition). However, in the PMHS impact tests[7][8], we could see significant movement of muscles especially at 40 km/h. It may be necessary to consider the effective mass and the effective moment of inertia in designing a human like legform impactor used for high speed (40 km/h) impact tests.

Impact forces of the TRL and JARI legform impactors are outside the new proposed corridor. At the high speed bending impact test, the peak value is slightly outside the corridor but the impulse (area under the force curve) is almost two times bigger compared to that of the lower limit of the corridor for the time period from 0 to 5 ms. The impact responses indicate that the current legform impactors are stiffer and its effective mass is heavier than that of the PMHS. Furthermore, the knee responses of shearing displacement and bending angle show significant differences between the legform impactors and PMHS as shown in Figures 21 and 22. The Figures also indicate the importance to define a time window when proposing the biofidelic corridor since the impact response differs according to the timing of initial damage occurrence. These differences may affect the measurement of the injury criteria such as bending angle, shearing displacement and acceleration. The injury thresholds of the EEVC legform test are proposed based on the available PMHS test results. Accordingly, if we continue to use the current legform impactors, some transfer functions are needed to interpret the data measured by the current legform impactors as injury criteria.

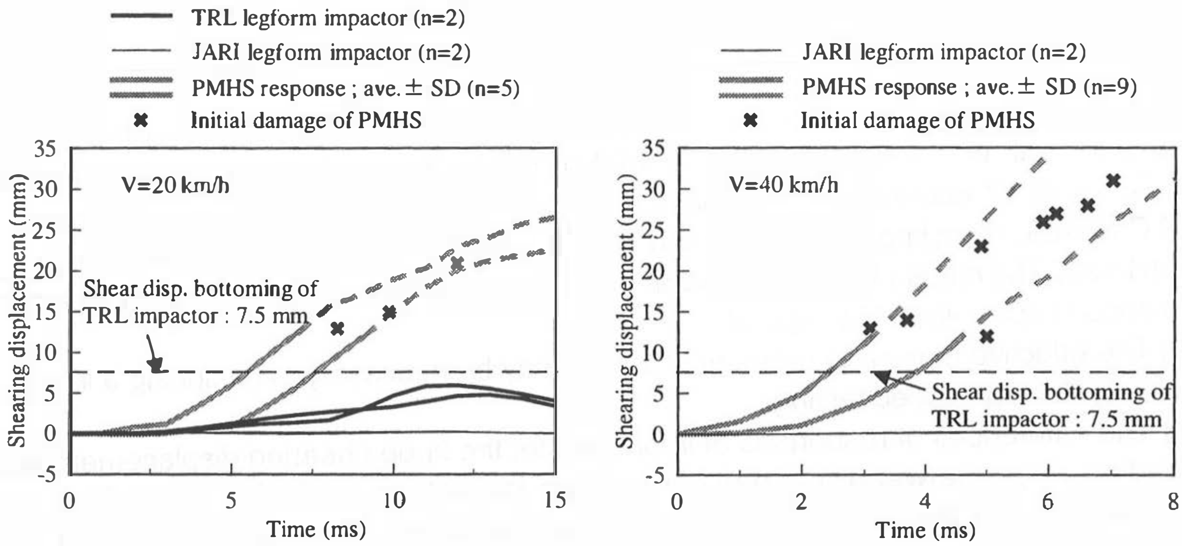

Figure 21 Knee shearing displacement of TRL and JARI legform impactors compared with that of PMHSs in shearing setup.

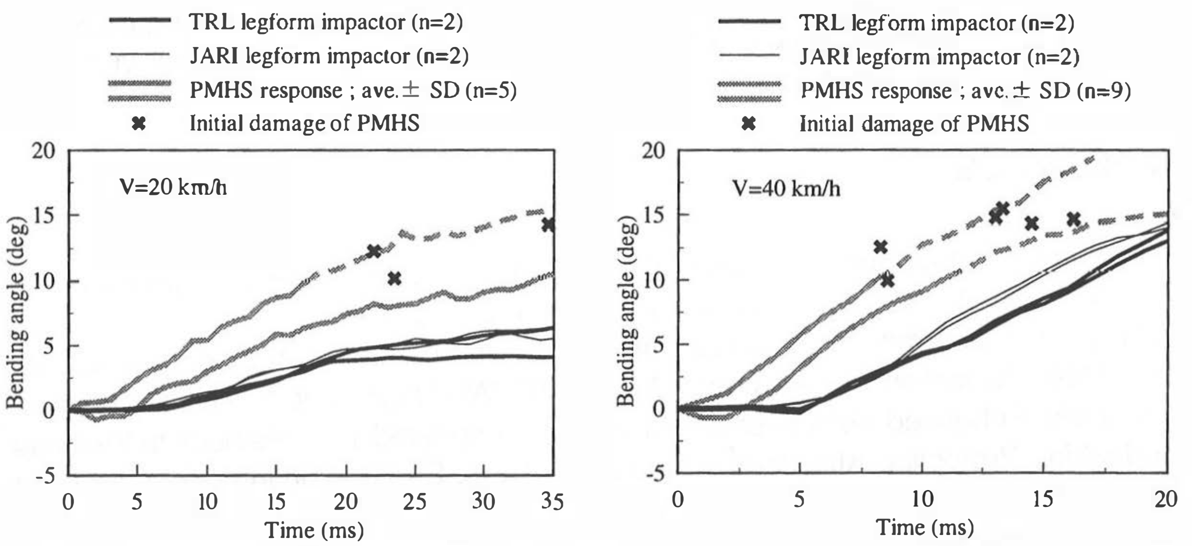

Figure 22 Knee bending angle of TRL and JARI legform impactors compared with that of PMHSs in bending setup.

This is important to point out that the scope of the paper is to discuss the methodology to evaluate the biofidelity of the legform impactor with deformable knee system. Legform impactor itself can evaluate the risk of knee injury by measurement of physical parameters related either to deformation or loads in the knee region. However, in the PMHS test of shearing and bending setups, in which the impact level differs strongly from that of an average car, the risk of knee injury can be evaluated only for certain point or certain area of impact. When evaluating the aggressiveness of car front to pedestrian, the criteria based on the combination of shearing and bending effects should be developed because the injury to the knee can occur either at small bending with large shearing or at large bending with small shearing.(7)(8)

CONCLUSIONS

PMHS knee impact test data were analyzed to propose a biofidelity test of the legform impactor with biofidelic corridors. Biofidelity tests were conducted to understand the biofidelity of the current legform impactors. The conclusions are summarized below.
(1) Current legform impactors (JARI and TRL) do not have the biofidelity of the human leg with knee. The current legform impactors should be improved with respect to the biofidelic response especially at high speed.
(2) The effective mass and moment of inertia may be necessary in designing a legform impactor for high-speed testing.
(3) The differences of responses of impact force, the knee shearing displacement and bending angle between mechanical legform impactor and PMHS may affect the measurement of the injury criteria such as bending angle, shearing displacement and acceleration. Accordingly, some transfer functions are needed to interpret the data measured by the current legform impactors as injury criteria.
(4) New biofidelic corridors based on impact forces are proposed corresponding to AM50.
(5) The JARI legform impactor using a pair of steel knee bars with a maximum bending moment of 100 Nm satisfied the biofidelity test proposed by ISO/TC22/SC10/WG2. The TRL legform impactor failed this test.

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