PREDICTION OF LOWER EXTREMITY INJURY RISKS DURING AN IMPACT ON MODERN CAR FRONTS WITH A FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR AND THE PEDESTRIAN LEGFORM IMPACTOR ACCORDING TO EEVC WG 17

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ABSTRACT

A legform impactor with biofidelic characteristics (FlexPLI) which is being developed by the Japanese Automobile Research Institute (JARI) is being considered as a test tool for legislation within a proposed Global Technical Regulation on pedestrian protection (UNECE, 2006) and therefore being evaluated by the Technical Evaluation Group (TEG) of GRSP. In previous built levels it already showed good test results on real cars as well as under idealised test conditions but also revealed further need for improvement.

A research study at the Federal Highway Research Institute (BASt) deals with the question on how leg injury risks of modern car fronts can be revealed, reflected and assessed by the FlexPLI and how the impactor can be used and implemented as a legislative instrument for the type approval of cars according to current and future legislations on pedestrian protection. The latest impactor built level (GTα) is being evaluated by a general review and assessment of the certification procedure, the knee joint biofidelity and the currently proposed injury criteria. Furthermore, the usability, robustness and durability as a test tool for legislation is examined and an assessment of leg injuries is made by a series of tests with the FlexPLI on real cars with modern car front shapes as well as under idealised test conditions. Finally, a comparison is made between the FlexPLI and the current european legislation tool, the legform impactor according to EEVC WG 17.

INTRODUCTION

In its final report the EEVC Working Group 17 (2002) gave recommendations for the acceptance levels of shear displacement, bending angle and tibia acceleration for the EEVC legform to bumper test used for the european type approval within the first phase of the European Framework Directive (European Union, 2003) dealing with the protection of pedestrians and other vulnerable road users. Those acceptance levels were on the one hand based on cadaver tests (Kajzer, 1997) where preloaded knee joints that were exposed to bending as well as shearing deformation showed the most common initial damage mechanisms at an average lateral bending angle from 15° on and at an average peak shearing force from 2,4 kN on. Those cadaver tests were reproduced by EEVC WG 17 in order top find a transfer function between cadaver output and impactor output. A lateral bending angle of 15° and 6 mm shear displacement based on a 4 kN shear force were considered to be appropriate acceptance levels. As for the lateral tibia peak acceleration on the other hand, WG 17 did not change the formerly proposed acceptance level of 150 g as they showed a good correlation between cadaver and impactor tests.
Konosu et al. (2001) analysed the influence of rigid bones on the estimation of leg injuries. From a bone bending effect on the bending angle as well as the acceleration varying with the impact conditions they concluded the need for a flexible legform impactor. Therefore, a flexible pedestrian legform impactor (FlexPLI) is being developed by the Japanese Automobile Research Institute and being evaluated by the Technical Evaluation Group (TEG) of GRSP. The present study gives a general review of the latest impactor built level and certification procedure and examines its usability, robustness and durability as a test tool for legislation by a series of tests on real cars with modern front shapes as well as under idealised test conditions.

DEVELOPMENT OF THE FLEX PLI

Flex-G

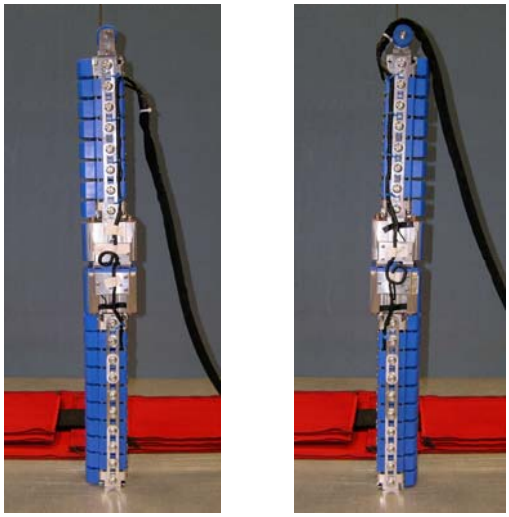
A pedestrian legform impactor with biofidelic characteristics has been developed by the Japanese Automobile Research Institute (JARI) (Konosu et al., 2003) and showed first good results during real car tests in ist version 2004 (Konosu et al., 2005) The Federal Highway Research Institute (BASt) gave an assessment of the impactor in its G-Level showing a good repeatability and reproducibility of test results under idealised test conditions on the one hand but revealing a need for further modification on the other hand (Zander et al., 2006). Tests at an impact speed of 40 km/h could only be performed on cars with modified front

shapes. Even at reduced impact speeds the protection criteria could be met marginally only. Furthermore, an expansion of the limited measurement range that was already partially exceeded within those tests at reduced impact speeds was requested. Finally, the impactor was lacking a continuity between its different built levels - while the requirements for the Flex2004 could be met by a series production car, the same car exceeded the proposed Flex-G limits clearly (Imaizumi, 2005).

Flex-GTα

Those issues were addressed by JARI who developed the Flex-GTα in spring of 2006. The latest impactor built level has a higher knee bending angle limit and modified specifications to improve injury assessment ability. While the femur and tibia lenghts remained the same, the locations of the centers of gravity were moved both towards the knee joint center. The overall impactor mass was reduced by 1,5 kg and is now 12,4 kg. This was mainly done by replacing most of the stainless steel housing by MC-nylon and aluminium. It has to be stated that regarding the weight and CoG characteristics the Flex-GTα differs more from the 50th AM leg than the previous impactor version. At the knee condyle longer knee springs were installed. Furthermore, the femur and tibia impact facing were brought in line with the knee by applying a thicker impact facing over the whole length of the impactor. Additionally, the bone core of both femur and tibia was made thinner and wider in order to obtain a smaller bending stiffness of the long bones. The knee size was changed in order to install longer springs for a higher knee bending limitation (+ 30%). Nine sets of knee ligaments were installed. The knee impact face was given a round shape. All measurement items, their positions and cables remained the same (Fig. 1-4).

Figures 1 and 2. Flex-GTα - impact view and left view.



Figures 3 and 4. Flex-GTα - front view and rear view.

Konosu (2006) justified the main changes between Flex-G and Flex-GTα with a better injury assessment ability. He stated a slightly smaller bending stiffness for the femur and tibia section of the Flex-GTα but still within the PMHS corridors developed by Ivarsson et al. (2004). The knee bending stiffness increased significantly but is still smaller than that of the rigid WG 17 lower leg impactor (Bhalla et al., 2003).

REVIEW OF THE KNEE JOINT BIOFIDELITY AND LEG INJURY CRITERIA

In their 2001 study Konosu et al. reconsidered the injury criteria for the pedestrian subsystem legform with the rigid legform impactor. They took the results of dynamic PMHS tests performed by Kajzer et al. (1997) to obtain the human knee characteristics versus shearing and bending and applied a logistic analysis method (Nakahira et al., 2000) in order to produce an injury risk curve against the bending angle (Figure 5).

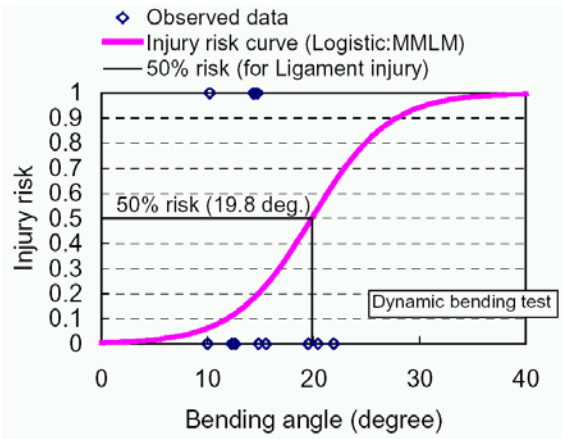


Figure 5. Injury risk curve and 50% injury risk against the bending angle (Konosu et al., 2001).

In an initial study for establishing pedestrian-impact lower limb injury criteria Kerrigan et al. (2003) found within PMHS knee bending and shear tests where the knee joint was isolated from the long bones and within femur and tibia bending tests a significantly lower average lateral failure bending moment for the knee joint than that reported in previous literature as well as that reported in the same study for the femur and for the tibia section. They concluded the importance of realistic boundary conditions and the need for the determination of a statistically valid impact threshold for the knee joint.

Bhalla et al. (2003) made a comparison between PMHS knee joint and mechanical knee joint tests and found a higher stiffness of the rigid EEVC WG 17 legform impactor and the POLAR II knee joint compared to the bending and shear loading stiffness of the PMHS knee, with much smaller differences between the POLAR II and the PMHS knee bending stiffness (Figures 6-8). They also found out pure shear of the knee joint being an extreme case not ocurring in real world pedestrian accidents.

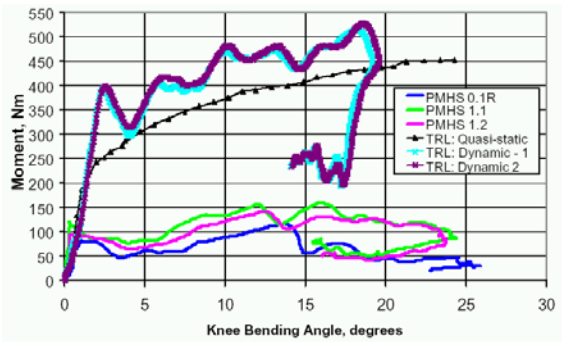


Figure 6. Lateral knee bending stiffnesses of the EEVC WG 17 legform impactor compared to PMHS knee tests (Bhalla et al., 2003).

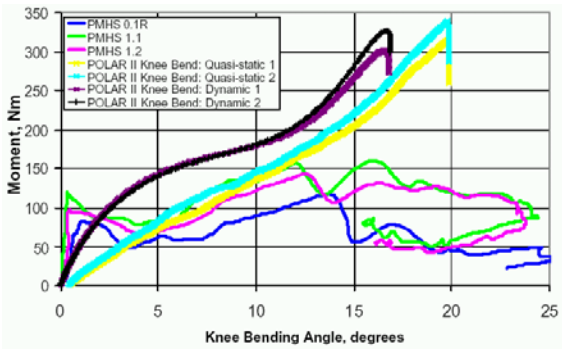


Figure 7. Lateral knee bending stiffnesses of the POLAR II knee compared to PMHS knee tests (Bhalla et al., 2003).

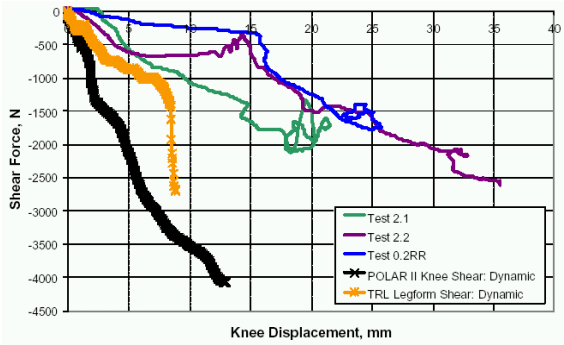


Figure 8. Lateral shear stiffnesses of the EEVC WG 17 legform impactor and the POLAR II knee compared to PMHS tests (Bhalla et al., 2003).

Bose et al. (2004) were analysing the response of the pedestrian knee to the pedestrian impact loading environment in order to determine injury thresholds and to validate computational models and mechanical legform impactors. They tested isolated PMHS knee joints in dynamic lateral-medial valgus loading (4 point bending and 3 point bending and shearing tests) replicating a vehicle-pedestrian impact at 40 km/h with the medial collateral ligament (MCL) as the only major load bearing knee structure being injured in the experiments. They found out a first peak bending moment between about 90 Nm and 150 Nm but assumed a knee shear force of zero within the 4-point pure bending tests. Thus, the four-point bending tests had a moment-shear ratio of infinity. The 3-point bending and shearing tests resulted in peak bending moments between 50 Nm and 80 Nm when inducing a knee angulation rate of 1°/ms and between 230 Nm and 270 Nm when increasing the proportion of the shear force acting at the knee.

Ivarsson et al. (2004) used the 4-point bending results from Bose to develop force-displacement and moment-displacement corridors with localized injury thresholds for the 50th AM femur, tibia and knee when being subjected to latero-medial bending at rates characteristic of the pedestrian impact loading environment. The study resulted in a 50% risk of femur fracture at a bending moment of 447 Nm and a 50% risk of tibia fracture at a bending moment of 312 Nm (Figures 9 and 10).

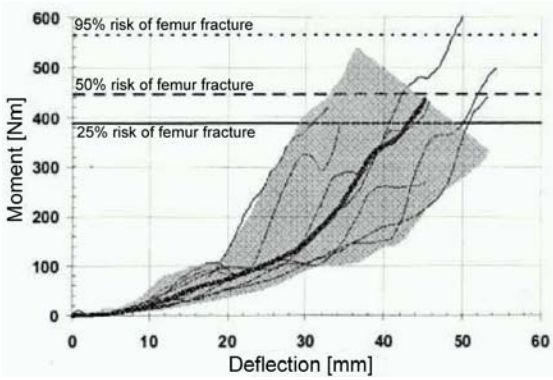


Figure 9. Moment-deflection corridors for the 50th percentile male femur subjected to dynamic latero-medial loading with the point of load application at mid-span (Ivarsson et al., 2004).

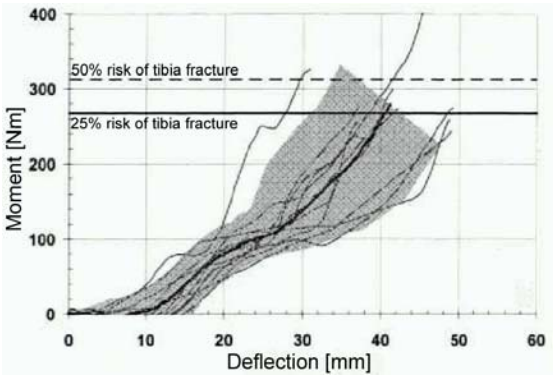


Figure 10. Moment-deflection corridors for the 50th percentile male tibia subjected to dynamic latero-medial loading with the point of load application at mid-span (Ivarsson et al., 2004).

For injuries occuring at the time of the first local moment peak Ivarsson et al. found a 50 % risk of MCL injury in dynamic valgus bending of the knee at a bending moment of 117 Nm or a knee bending angle of 13,9°; for injuries ocurring at the time of the maximum moment the 50 % risk of MCL injury was at 134 Nm or 18,2° (Figures 11 and 12).

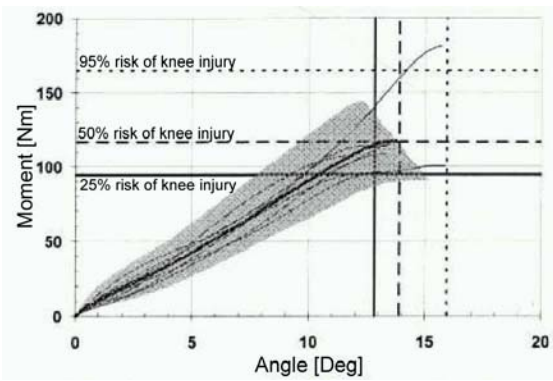


Figure 11. Moment-angle response corridor for the 50th percentile male knee subjected to dynamic 4-point valgus bending for injuries ocurring at the time of the first local moment peak (Ivarsson et al., 2004).

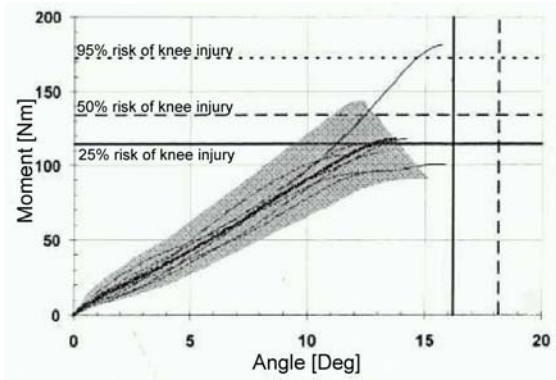


Figure 12. Moment-angle response corridor for the 50th percentile male knee subjected to dynamic 4-point valgus bending for injuries ocurring at the time of the maximum moment (Ivarsson et al., 2004).

In a study going back to 1985 Nyquist et al. subjected human tibias to static and dynamic three-point-bending tests. The applied loads were directed from the anterior to posterior or from lateral to medial and sustained fracture at or near mid-span. The maximum bending moments for seven male cadavers with a lateral load applied at impact speeds between 2,9 and 4,2 m/s were between 224 and 431 Nm with an average of 312 Nm. As a result, an injury threshold of 350 Nm for the maximum tibia bending moment was proposed by the Japanese Automobile Research Institute (Ishikawa, 2004).

For tests on real cars with the Flex PLI version GTα Konosu et al. (2006) derived 50% injury risk levels for the 50th AM for the tibia and knee from the reviewed literature (Table 1).

Table 1.
Proposed 50% injury risk levels for the 50th AM (Konosu et al., 2006)

Leg region	50% injury risk level for 50th AM
Tibia	312 - 350 Nm
MCL	19,5 - 21,6 mm
ACL	11,2 mm
PCL	11,2 mm

Due to the lack of an upper body mass of the FlexPLI the femur test results of the Flex-GTα were considered to be negligible and monitored only in order to check the generated strain of the bone but without any comparison with the injury risk levels derived from the previous studys. Therefore, the proposed injury risk levels are not given in Table 1 and will not be considered further within this study.

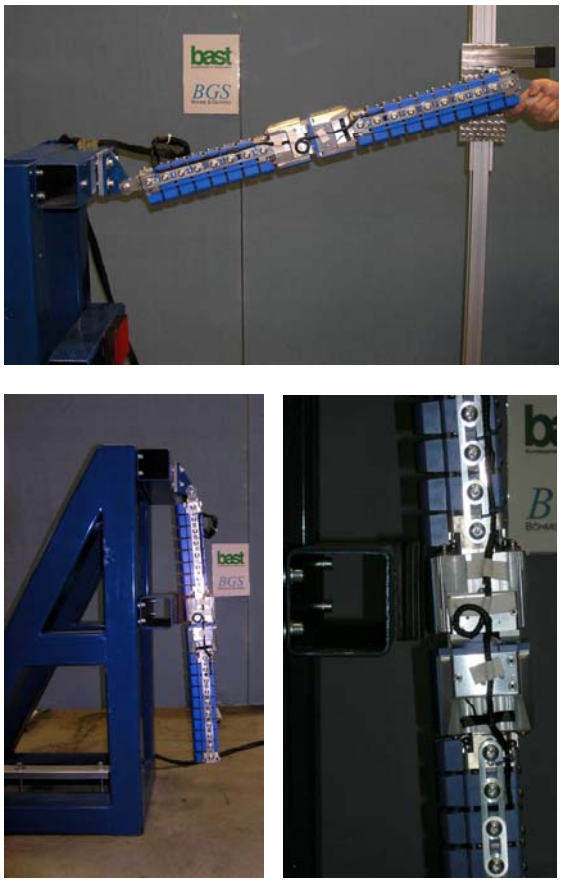
CALIBRATION AND CERTIFICATION

Calibration

As calibration method for tibia, femur and knee the same three point bending method as for the Flex-G has been adopted (Konosu, 2006). Only the strain gauges are calibrated, while the calibration of the sensors and the bones is still not addressed.

Dynamic certification test

The certification procedure for the legform assembly is described in detail in an earlier study of the authors (2006). The impactor is suspended without flesh and skin over a pin joint from a fixed pendulum frame, lifted until it is 15 degrees above the horizontal and then released. A cross beam, covered with two neoprene and three rubber sheets, is fixed at a height such that it is hit by the knee joint of the released legform when reaching the vertical (Figures 13-15), causing bending of the bones and shearing and bending of the knee.



Figures 13, 14 and 15. Dynamic certification test.

Dynamic certification test results

For the present study, in total 21 certification tests were performed. All ligament extensions of the Flex-GTα (medial collateral ligament MCL, anterior cruciate ligament ACL and posterior cruciate ligament PCL) were within the measurement range. (Figures 16 and 17).

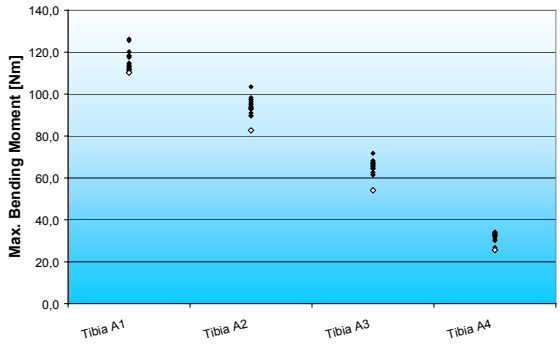


Figure 16. Certification results of the tibia section (◊: full assembly test).

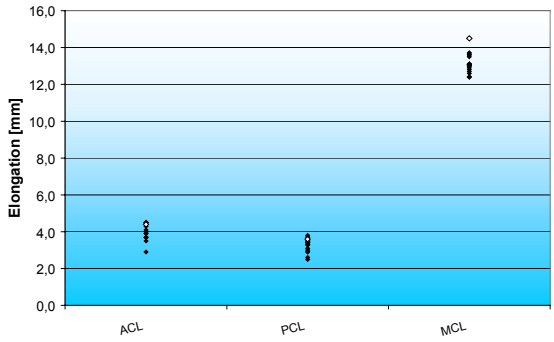


Figure 17. Certification results of the knee ligaments (◊: full assembly test).

In addition, one full assembly dynamic certification test was performed, i.e. that the legform impactor was used as during the real car tests, covered with all neoprene and rubber layers while those layers were removed from the cross beam. As it can be seen in Figures 16 and 17, the results for the maximum bending moments and ligament elongations showed quite similar results. While the maximum bending moments for the tibia segments were the lowest ones from all tests, the ligament peak elongations were comparatively high. Figures 18-21 compare the traces for the tibia bending moments.

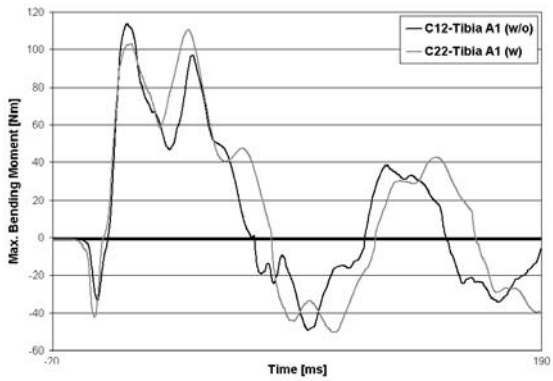


Figure 18. Comparison of the bending moments of the tibia A1 segment with (w) and without (w/o) flesh and skin.

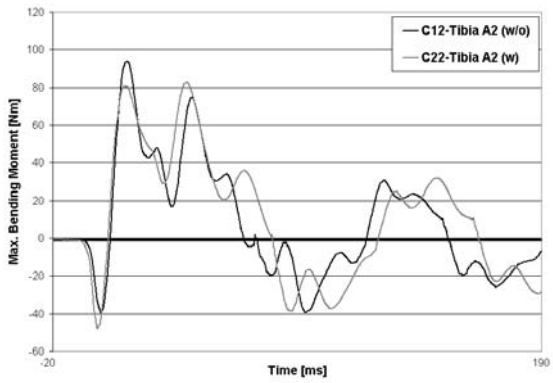


Figure 19. Comparison of the bending moments of the tibia A2 segment with (w) and without (w/o) flesh and skin.

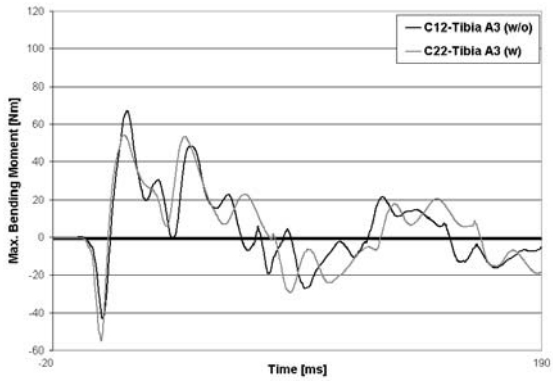


Figure 20. Comparison of the bending moments of the tibia A3 segment with (w) and without (w/o) flesh and skin.

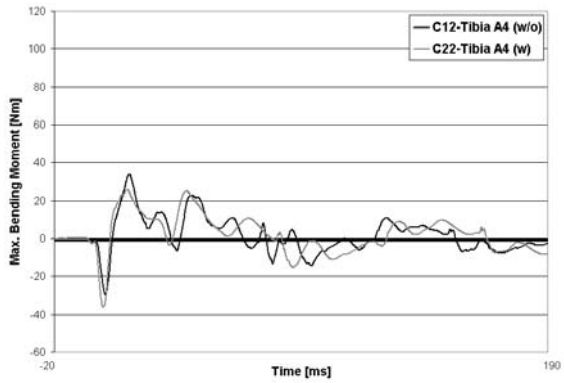


Figure 21. Comparison of the bending moments of the tibia A4 segment with (w) and without (w/o) flesh and skin.

As it can be seen, the legform showed a comparatively similar behaviour for the bending moments. Anyway, within the first peak all tibia segments showed a higher bending moment in the currently proposed certification test (without flesh and skin), while the second peak was higher within the full assembly test.

Figures 22-24 compare the traces of the knee ligament elongations measured within the currently proposed certification test and the full assembly certification test.

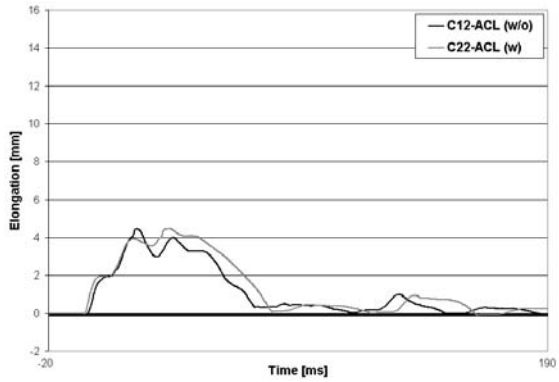


Figure 22. Comparison of the ACL elongations with (w) and without (w/o) flesh and skin.

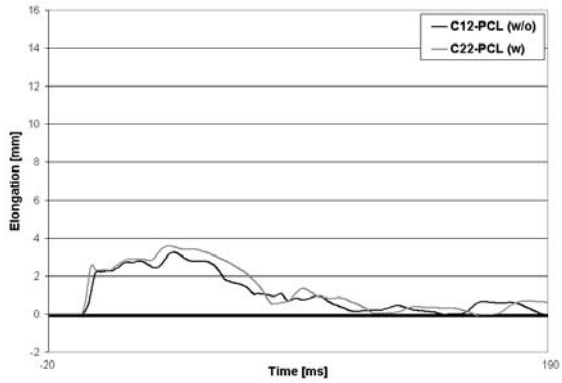


Figure 23. Comparison of the PCL elongations with (w) and without (w/o) flesh and skin.

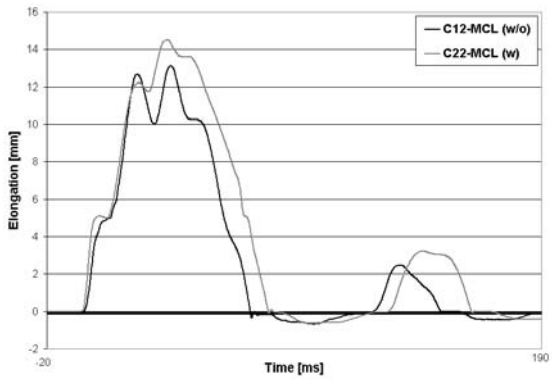


Figure 24. Comparison of the MCL elongations with (w) and without (w/o) flesh and skin.

Also the knee ligaments showed a quite similar behaviour with and without flesh and skin. In general, the knee of the fully assembled impactor (with flesh and skin) gave higher results. This phenomenon can be explained by a higher knee stiffness due to the rubber sheets applied over the whole impactror length and therefore a different energy application.

The standard deviation S of the certification results (tests 1-21) was assessed according to the dummy requirements described by Mertz (2004). The results are given in Table 2.

Table 2.
Repeatability of the certification results

Dynamic certification							
	Max. bending moment [Nm] - Tibia				Elongation [mm]		
	A1	A2	A3	A4	ACL	PCL	MCL
SD	4,41	3,33	2,33	2,16	0,43	0,34	0,41
[%]	3,82	3,53	3,53	6,75	10,44	10,48	3,14
Ass.	A	A	A	A	N	N	A
G: good, A: acceptable, M: marginal, N: not acceptable							

The leg showed acceptable results for the MCL elongation and all bending moments of the tibia. As for the ACL and PCL elongation the certification tests gave unacceptable results.

REAL CAR TESTS

Two cars with pedestrian friendly bumpers according to the EEVC test procedure and limits, a Mercedes A-Class with a Euro NCAP rated green lower leg area, and a VW Golf V with borderline results to a green bumper area were tested with the Flex-G impactor by the authors of this study. (2006). As the test results with reduced impact speeds (24 km/h) already exceeded partially the measuring range for the bending moment as well as for the elongation of the leg, the series production cars were modified by removing the bumper padding and adding a padding at the lower outer contour of the car front. As the Flex-GTα with a significantly higher bending stiffness and a knee bending limitation increased by 30% was expected to deliver usable results with series production cars even at the european regulatory test speed of 40 km/h, the same cars were tested in their unmodified versions at 40 km/h. For comparability reasons an identical impact height of 25 mm above ground level according to the proposed GTR was chosen. An extension of the test series was made to include a car representing the SUV category with a green lower leg test area (Audi Q7) and a car representing the sedan category and designed for compliance with phase 1 of the European Directive. Both cars were tested at an impact height of 75 mm above ground level as this height was used within latest simulations by JARI and resulted in a better knee injury assessment ability.

VW Golf V test results

The impact points to be tested with the Flex-GTα on the VW Golf V were located identically to two green / borderline rated Euro NCAP test points (Figure 25).

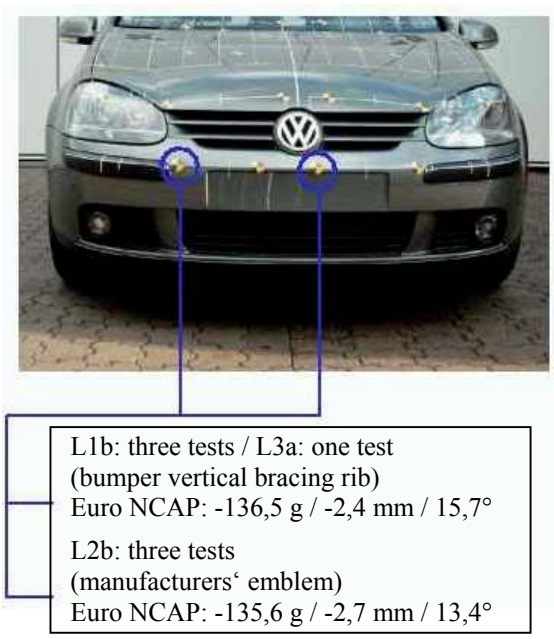


Figure 25. Golf V Euro NCAP impact locations to be tested with the Flex-GTα.

Test point L3a as a symmetrical identical point to L1b according to Euro NCAP was tested one time in order to validate this assumption made by the test laboratory and the sensitivity of the Flex-GTα on mirrored test point.

In total, seven tests at three different impact locations were performed with the Flex-GTα on the Golf V. The results are shown in Figures 26 and 27.

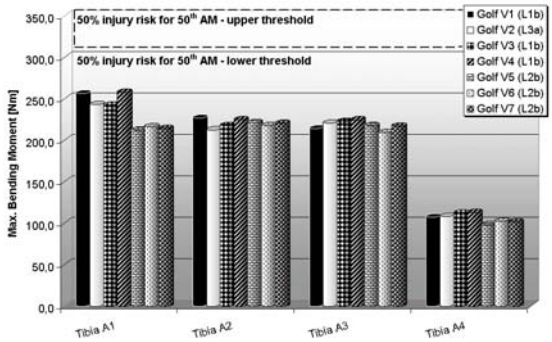


Figure 26. Golf V test results for the tibia segments.

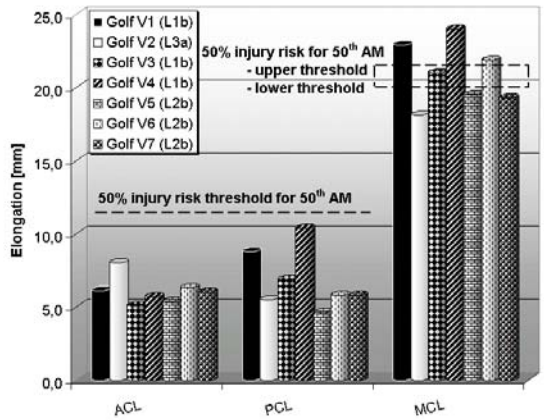


Figure 27. Golf V test results for the knee ligaments.

As it can be seen from the diagrams all three impact locations met the proposed tibia and ACL and PCL knee injury criteria. Only the MCL ligament exceeded the thresholds in half of the tests. Test V2 was performed on a location symmetrical identical to tests V1, V3 and V4, where the PCL peak elongation was permanently higher than the ACL peak elongation. Therefore, the lower PCL than ACL elongation in test V2 initially seemed to confirm the symmetrie. However, the ACL peak elongation in test V2 ocurred at a completely different time and was significantly higher than in the symmetrical identical tests V1, V3 and V4 (Figure 28).

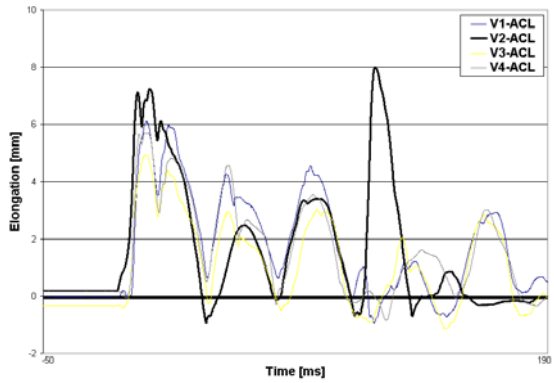


Figure 28. ACL elongations in the Golf V tests (1-4) - examination of the symmetrie.

Besides, also the lower result for the MCL ligament in test V2 could lead to the conclusion of a high knee sensitivity towards structures assumed to be similar. Nevertheless, quite similar characteristics of the MCL elongation traces within the tests 1-4 can be stated, as shown in Figure 29.

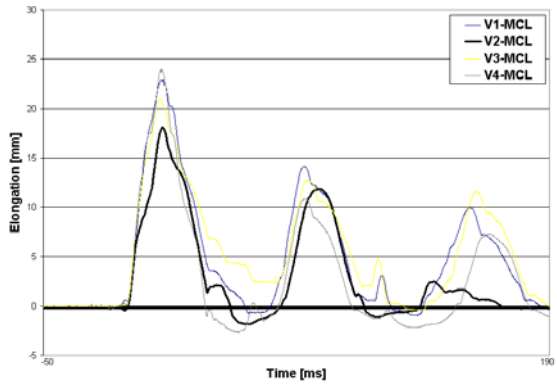


Figure 29. MCL elongations in the Golf V tests (1-4) - examination of the symmetrie.

For the tibia bending moments, all traces of tests 1-4 showed similar tendencies. The tibia section did not show a high sensitivity towards mirrored test points.

In three of the tests the proposed requirements were all met, two of them on a Euro NCAP green rated test point with a knee bending angle of 13,4° in the corresponding Euro NCAP test.

Mercedes A-Class test results

As on the Golf V, also the impact points to be tested with the Flex-GTα on the Mercedes A-Class were located on two green Euro NCAP rated test points (Figure 30).

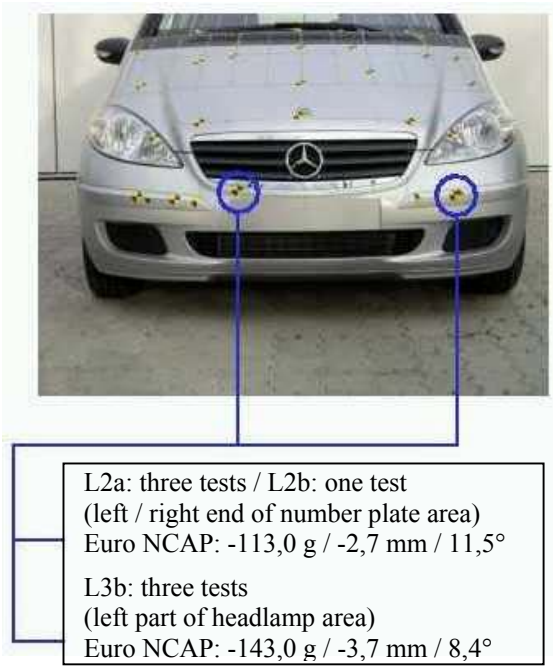


Figure 30. A-Class Euro NCAP impact locations to be tested with the Flex-GTα.

Test point L2b as a symmetrical identical point to L2a according to Euro NCAP was tested one time for validation purposes and in order to analyse the sensitivity of the Flex-GTα towards mirrored test point.

Seven tests at three different impact locations were performed. The results for the tibia and knee are shown in Figures 31 and 32.

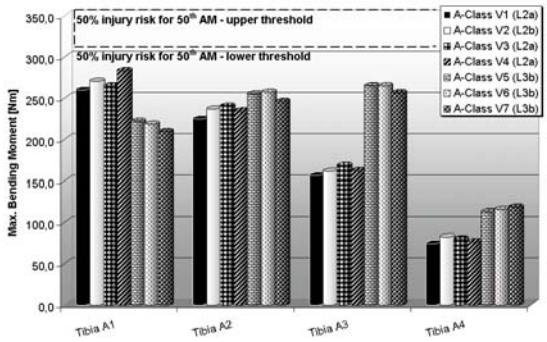


Figure 31. A-Class test results for the tibia segments.

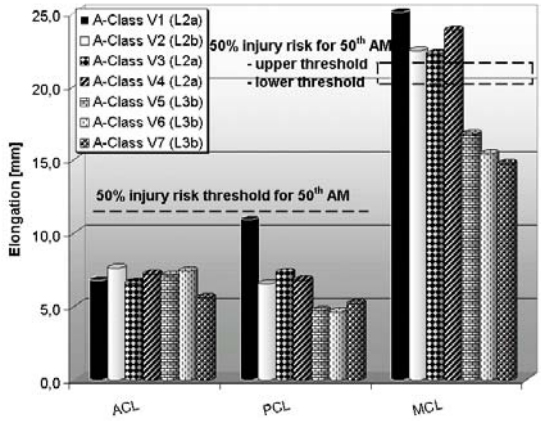


Figure 32. A-Class test results for the knee ligaments.

Again, all three impact locations on the Merceredes A-Class met the proposed tibia and ACL and PCL injury risk thresholds. The MCL ligament exceeded the elongation thresholds at the first and second impact location (Tests V1-V4). Impact point V2 that was mirrored to V1 did not show the tendency of the Golf tests where the ACL and PCL results were the other way around compared to the first impact location. This might also be the case because no clear tendency for the ACL/PCL results of the first impact point can be observed. No tendency can be seen either regarding the MCL sensitivity on mirrored impact points. Despite the quite similar characteristics of the knee elongation traces, test V1 shows quite different peak values and a different behaviour especially for the PCL elongation. Here, also the symmetrical identical point V2 behaves differently (Figure 33).

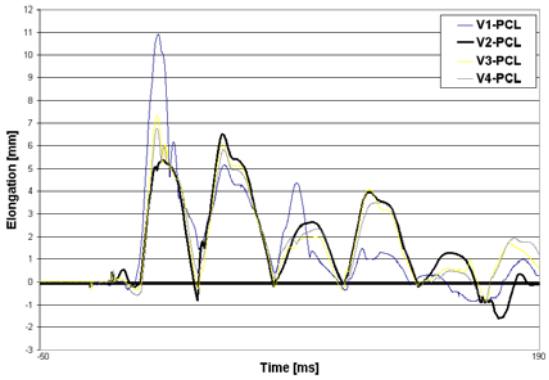


Figure 33. PCL elongations in the A-Class tests (1-4) - examination of the symmetrie.

The traces for the tibia bending moments in tests 1-4 confirmed the Golf V results. Therefore, no sensitivity of the tibia towards mirrored test points could be observed.

The third impact location (L3b) met in all three tests the proposed requirements clearly. Euro NCAP rated this point green and measured a bending angle of 8,4°.

Audi Q7 test results

On the Audi Q7 representing the SUV car category two tests were performed at two different impact locations that were both rated green according to Euro NCAP (Figure 34).

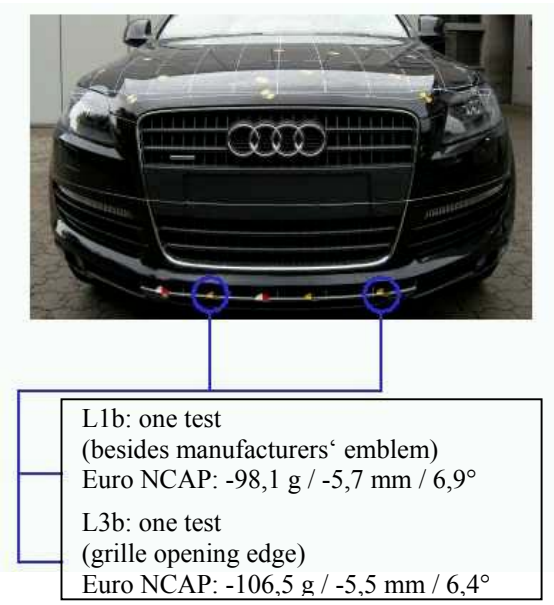


Figure 34. Q7 Euro NCAP impact locations to be tested with the Flex-GTα.

As impact height 75 mm above ground level were chosen. The tibia and knee results are shown in Figures 35 and 36.

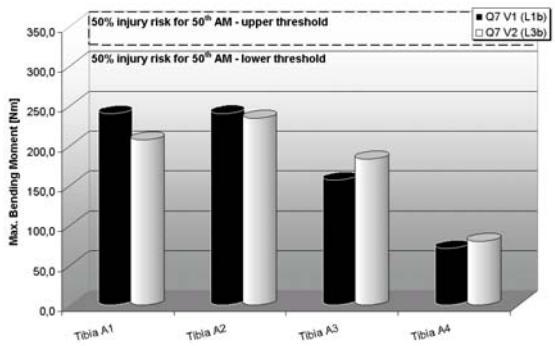


Figure 35. Q7 test results for the tibia segments.

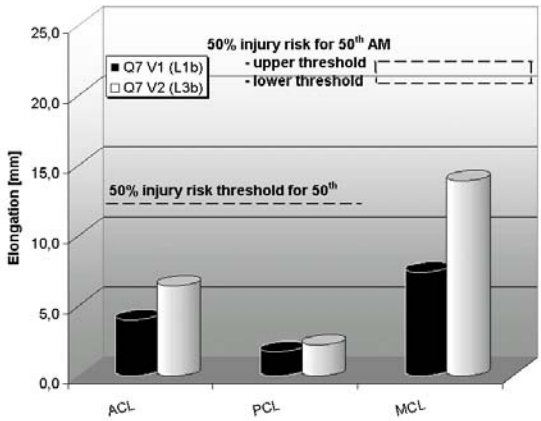


Figure 36. Q7 test results for the knee ligaments.

Both impact locations met all proposed test requirements clearly, whereas the MCL load measured in the second test was significantly higher than that of the first test. This does not confirm the Euro NCAP results where the bending angle of the second test was slightly lower than that of the first test.

Sedan test results

The last car to be tested within this study, a sedan type car MY 2007, has been type approved according to the European Directive on pedestrian protection, i.e. that the bumper area homogeneously met the requirements of phase 1 which are 200 g for the tibia acceleration, 6 mm for the shearing displacement and 21° for the knee bending angle. Three points on the bumper have been tested at an impact height of 75 mm above ground level. The results are given in Figures 37 and 38.

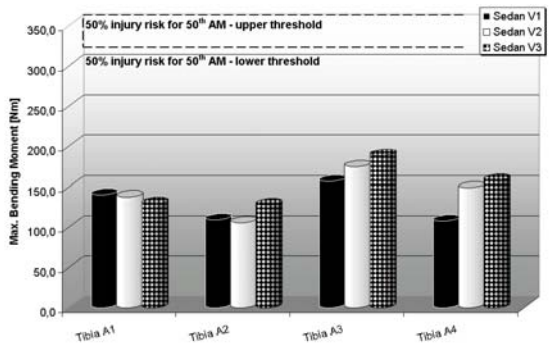


Figure 37. Sedan test results for the tibia segments.

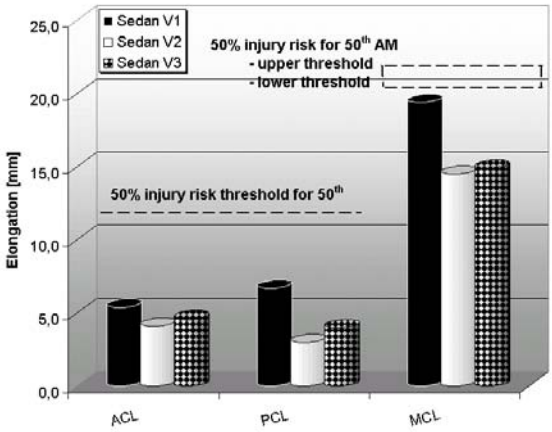


Figure 38. Sedan test results for the knee ligaments.

All three impact locations met the proposed injury criteria clearly. The load on the MCL ligament in the first test was higher than in the following ones but still slightly below the currently proposed lower 50% injury risk threshold of 19,5 mm. These results fully confirm those of the homologation tests where the first test showed the highest bending angle of the rigid WG 17 impactor while the following two tests have met all legform to bumper criteria even of the current phase 2.

REPEATABILITY

Real car tests

For the determination of the repeatability of test results with the Flex-GTα impactor the test values of each of the four impact points being tested three times were taken for the calculation of the standard deviation (SD). Based on the requirements for dummies (Mertz, 2004) the repeatability of the real car tests was assessed according to Table 3.

Table 3.
Repeatability of the real car test results

Golf V							
L1b	Max. bending moment [Nm] - Tibia				Elongation [mm]		
	A1	A2	A3	A4	ACL	PCL	MCL
SD	8,42	4,98	5,39	3,06	0,5	1,75	1,52
[%]	3,34	2,23	2,44	2,76	8,93	20,14	6,71
Ass.	A	G	G	G	M	N	A
L2b	Max. bending moment [Nm] - Tibia				Elongation [mm]		
	A1	A2	A3	A4	ACL	PCL	MCL
SD	1,95	2,07	4,87	2,19	0,46	0,69	1,45
[%]	0,91	0,94	2,27	2,17	7,77	12,83	7,15
Ass.	G	G	G	G	M	N	M
A-Class							
L2a	Max. bending moment [Nm] - Tibia				Elongation [mm]		
	A1	A2	A3	A4	ACL	PCL	MCL
SD	12,00	7,81	6,20	2,64	0,31	2,24	1,45
[%]	4,45	3,35	3,81	3,43	4,45	26,84	6,13
Ass.	A	A	A	A	A	N	A
L3b	Max. bending moment [Nm] - Tibia				Elongation [mm]		
	A1	A2	A3	A4	ACL	PCL	MCL
SD	6,53	5,82	4,71	2,80	0,96	0,32	1,01
[%]	3,01	2,30	1,80	2,41	14,39	6,65	6,51
Ass.	A	G	G	G	N	A	A
G: good, A: acceptable, M: marginal, N: not acceptable							

The calculations for the standard deviation state a repeatability between good and acceptable for all maximum tibia bending moments at all of the four impact locations, while the repeatability results for the knee elongation are in less than half of the cases still acceptable. Here, the PCL ligament shows the highest sensitivity and not acceptable repeatability results at three impact locations. The repeatability of the MCL ligament test results is at least at three impact locations still acceptable. In total, four measurement locations showed inacceptable repeatability results (Figure 39).

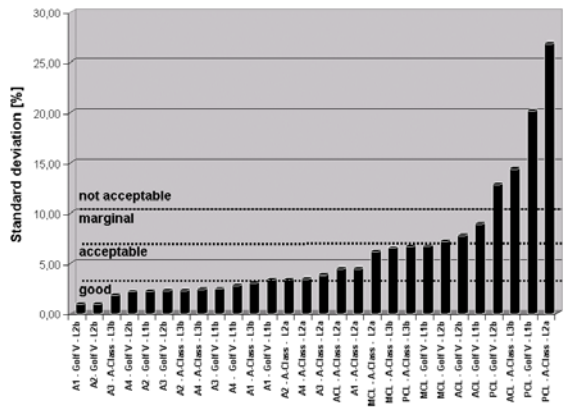


Figure 39. Sensitivity of the measurement locations depending on the impact location.

Inverse tests

In order to obtain more detailed information about the factors causing scatter in the knee elongation test results, three additional tests under idealised test conditions were performed. Therefore, the Flex-GTα legform was impacted by a linearly guided honeycomb impactor with a mass of 8,1 kg at an impact speed of 39 km/h (Zander et al., 2005). During the impact the homeycomb impactor hit the knee center with its upper edge. The test results are given in Figures 40 and 41.

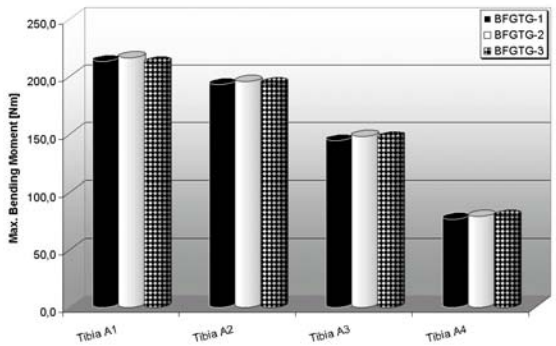


Figure 40. Inverse test results for the tibia segments.

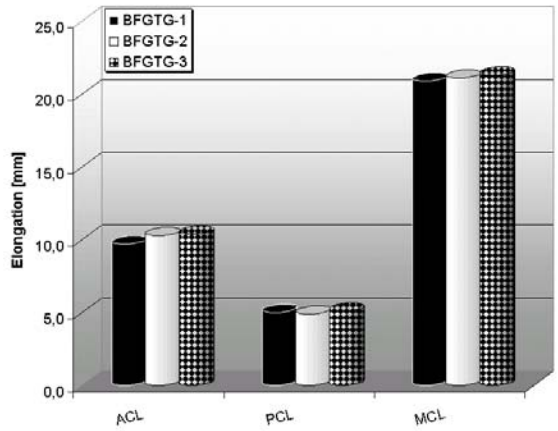


Figure 41. Inverse test results for the knee ligaments.

For the assessment of the repeatability of the test results the standard deviation was calculated and the results compared with the dummy requirement criteria (Table 4).

Table 4.
Repeatability of the inverse test results

Al honeycomb							
	Max. bending moment [Nm] - Tibia				Elongation [mm]		
	A1	A2	A3	A4	ACL	PCL	MCL
SD	2,57	1,42	1,76	1,27	0,38	0,10	0,20
[%]	1,20	0,73	1,20	1,62	3,74	2,00	0,95
Ass.	G	G	G	G	A	G	G
G: good, A: acceptable, M: marginal, N: not acceptable							

The standard deviation that was between good and acceptable for the maximum tibia bending moments obtained during the real car tests could be confirmed by the inverse tests. Here, all test results showed a high repeatability for all tibia segments and the PCL and MCL ligament. Only the repeatability of the ACL ligament was assessed not better than acceptable.

The results of the tests under idealised impact conditions reveal the sensitivity of the Flex-GTα towards marginally changed impact parameters as impact height and x,y and z-rotation. When eliminating these parameters the Flex-GTα-impactor itself shows a very high repeatability. A study on the variation of different impact parameters under otherwise constant impact conditions could be carried out to obtain a conclusion about the influence on the test results with the aim to define tolerances within a test procedure to be drafted.

DISCUSSION

Several improvements have been incorporated within the development of the Flex-GTα impactor. It is now robust enough to be tested at a regular impact speed of 40 km/h on cars with modern front shapes without any modification. In general, good test results according to Euro NCAP could be confirmed by tests with the Flex-GTα on real cars. Only the MCL ligaments exceeded partly the currently proposed 50% injury risk thresholds for the 50th AM. However, it has to be stressed that newest developments of cars with modern front shapes tested in this study like the Audi Q7 or being designed for the european type approval like the sedan type car met all test requirements clearly. On the other hand, good test results with the FlexPLI have already been confirmed by tests with the rigid EEVC WG 17 legform impactor in an earlier study of the authors (Zander et al., 2006). In case of the parallel introduction of the Flex PLI as a test tool within regulations on pedestrian protection this might give car manufacturers a certain reliability which is imperatively needed during the car design and development process.

In real car tests, the Flex-GTα shows a good to acceptable repeatability of the maximum bending moment results, whereas the knee seems to be very sensitive towards car front modifications and different impact parameters like impact height or the impactor rotation. This can be stated by tests under idealised impact conditions, where the impactor shows a high repeatability of test results also for the knee ligaments. A study on the variation of impact parameters should be carried out and impact tolerances should be defined.

Regarding the knee elongations the Flex-GTα sometimes reveals a high sensitivity towards mirrored test points. Therefore, the question on symmetrical identical car front structures needs to be analysed in detail.

Like previous versions of the FlexPLI also the Flex-GTα is lacking an upper body mass. Therefore, test results of the femur loadings have not been considered within this study. Further research on the influence of an upper body mass on

femur loads during collisions of pedestrians with car fronts is needed.

The handling and usability of the Flex-GTα legform impactor are good. No expendables like foam or ligaments are needed. No changes were made within the calibration procedure of the strain gauges which therefore still needs to be re-defined, as it is influenced by mechanical aspects.

The dynamic certification test is still performed without flesh and skin. A full assembly dynamic certification test that was additionally performed showed quite similar peak results, even though the traces show some differences regarding the knee stiffnesses and peak value times. Therefore it currently seems to be the more appropriate certification procedure.

For the ACL and PCL ligament the dynamic certification test showed an unacceptable repeatability. These results were likely being influenced by a rotation of the impactor around its vertical axis due to the suspension method at the pendulum frame as well as the existing clearance of the knee. Therefore, the certification procedure still requires a revision.

CONCLUSIONS

Even though tests with the current version of the FlexPLI and the EEVC WG 17 legform impactor are still not comparable in a full extent, good test results with the rigid WG 17 impactor according to the EEVC limits could be confirmed by the results with the biofidelic Flex-GTα according to the currently proposed injury thresholds. Furthermore, good results with the FlexPLI were confirmed by WG 17 results in an earlier development level already. It can be concluded that on the one hand former car front developments for meeting the EEVC criteria were already beneficial for the protection of pedestrians, and that on the other hand the introduction of the new biofidelic impactor would not necessarily have an influence on the design of already started developments. These aspects might give car manufacturers a reliability regarding their design and development process.

The comparatively lower repeatability of the knee test results within real car tests especially for the ACL and PCL ligament reveals the high sensitivity of the knee towards even minor modifications of the car front as well as a variation of impact parameters like impact height and impactor rotation. Further research in this field is needed. Nevertheless, the information obtained by the FlexPLI on the protection potential of car fronts can help to show a broader variation of possible design changes needed to meet the requirements of the biofidelic impactor and herewith to improve the protection of pedestrians and other vulnerable road users during a collision with a modern car front.

REFERENCES

Bose D., Bhalla K., Rooij L., Millington S., Studley A., Crandall J. 2004. „Response of the knee joint to the pedestrian impact loading environment.“ SAE World Congress, SAE paper no. 2004-01-1608.

Bhalla K., Bose D., Madeley N., Kerrigan J., Crandall J. 2003. „Evaluation of the response of mechanical pedestrian knee joint impactors in bending and shear loading.“ Paper no. 429 of ESV conference proceedings 2003.

EEVC Working Group 17. 2002. „Improved test methods to evaluate pedestrian protection afforded by passenger cars.“ December 1998 report with September 2002 updates.

European Union. 2003. „Directive 2003/102/EC of the European Parliament and of the Council of 17 November 2003 relating to the protection of pedestrians and other vulnerable road users before and in the event of a collision with a motor vehivle and amending Council Directive 70/156/EEC.“ Official Journal of the European Union, 06.12.2003.

Imaizumi, I: “Report on Flex-G car test results.” 2nd Meeting of GRSP technical evaluation group. Bergisch Gladbach, Germany, 2005.

Ishikawa H. 2004. „Discussion on injury thresholds for pedestrian legform test.“ 6th Meeting of GRSP informal group on pedestrian safety. Paris, France, 2004.

Ivarsson J., Lessley D., Kerrigan J., Bhalla K., Bose D., Crandall J., Kent R. 2004. „Dynamic response corridors and injury thresholds of the pedestrian lower extremities.“ IRCOBI conference proceedings 2004.

Kajzer J., Matsui Y., Ishikawa H., Schroeder G., Bosch U. 1997. „Shearing and bending effects at the knee joint at high speed lateral loading.“ Proceedings of the 41st Stapp Car Crash Conference, SAE paper no. 973326.

Kerrigan J., Bhalla K., Madeley N., Funk J., Bose D., Crandall J. 2003. „Experiments for establishing pedestrian-impact lower limb injury criteria.“ SAE World Congress, SAE paper no. 2003-01-0895

Konosu A., Ishikawa H., Tanahashi M. 2001. „Reconsideration of injury criteria for pedestrian

subsystem legform test - problems of rigid legform impactor -." Paper no. 01-S8-O-263 of ESV conference proceedings 2003.

Konosu A., Issiki T., Tanahashi M. 2005. „Development of a pedestrian lower extremity protection car using a biofidelic flexible pedestrian legform impactor." Paper no. 05-0106 of ESV conference proceedings 2005.

Konosu A. 2006. „Information on the flexible pedestrian legform impactor GT alpha (Flex-GTα)." 3rd Meeting of GRSP technical evaluation group. Bergisch Gladbach, Germany, 2006.

Konosu A. 2006. „Evaluation activities on injury assessment ability of the flexible pedestrian legform impactor GT alpha (Flex-GTα)." 3rd Meeting of GRSP technical evaluation group. Bergisch Gladbach, Germany, 2006.

Mertz, H. 2004.: "Calculation methods & acceptance levels for assessing repeatability and reproducibility (R & R)." ISO/TC22/SC12/WG5 Document N751.

Nakahira Y., Furukawa K., Niimi H., Ishihara T., Miki K., Matsuoka F. 2000. "A combined evaluation method and a modified maximum likelihood method for injury risk curves." IRCOBI conference proceedings 2000.

Nyquist G., Cheng R., El-Bohy A., King A. 1985. "Tibia bending: strength and response." Proceedings of the 29th Stapp Car Crash Conference, SAE paper no. 851728.

United Nations Economic Comission for Europe. 2006. "Proposal for a global technical regulation on uniform provisions concerning the approval of vehicles with regard to their construction in order to improve the protection and mitigate the severity of injuries to pedestrians and other vulnerable road users in the event of a collision." ECE/TRANS/WP.29/GRSP/2006/2. 3 March 2006.

Zander O., Lorenz B., Leßmann P., Gehring D. 2005. "The pedestrian legform impactor according to EEVC WG 17 - results of an actual research and possibilities for the implementation within regulations on pedestrian protection." IRCOBI conference proceedings 2005.

Zander O., Lorenz B. 2006. " Assessment of the flexible pedestrian legform impactor (FlexPLI-G) as a test tool for legislation on pedestrian protection." IRCOBI conference proceedings 2006.