EVALUATION OF A FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR (FLEX-PLI) FOR THE IMPLEMENTATION WITHIN LEGISLATION ON PEDESTRIAN PROTECTION

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ABSTRACT

A flexible pedestrian legform impactor (FlexPLI) with biofidelic characteristics is aimed to be implemented within global legislation on pedestrian protection. Therefore, it is being evaluated by a technical evaluation group (Flex-TEG) of GRSP with respect to its biofidelity, robustness, durability, usability and protection level (Zander, 2008). Previous studies at the Federal Highway Research Institute (BASt) and other laboratories already showed good progress concerning the general development, but also the need for further improvement and further research in various areas (Zander et al., 2007). This paper gives an overview of the different levels of development and all kinds of evaluation activities of the Flex-TEG, starting with the Polar II full scale pedestrian dummy as its origin and ending up with the latest legform impactor built level GTR that is expected to be finalized by the end of the year 2009. Using the latest built levels as a basis, the paper reveals gaps that are recommended to be closed by future developments, like the usage of an upper body mass (UBM), the validation of the femur loads, injury risk functions for the cruciate knee ligaments and an appropriate certification method. A recent study on an additional upper body mass being applied for the first time to the Flex-GT is used as means of validation of the lately proposed modified impact conditions by Konosu et al. (2007-2). Therefore, two test series on a modern vehicle front using an impactor with and without upper body mass are being compared. A test series with the Flex-GTR will be used to study both the comparability of the impact behavior of the GT and GTR built level as well as the consistency of test results. Recommendations for the implementation within legislation on pedestrian protection are made.

INTRODUCTION

After being adopted by the World Forum for Harmonisation of Vehicle Regulations (WP.29) and the Executive Committee of the Agreement on Global Technical Regulations from 1998 (AC.3), the Global Technical Regulation on Pedestrian Safety (GTR No. 9) has been published in January 2009 (UNECE, 2009). Its preamble considers the flexible pedestrian legform impactor (FlexPLI), which is deemed to have high biofidelic characteristics along with an excellent leg injury assessment ability to replace the currently used rigid EEVC WG 17 pedestrian legform impactor (EEVC, 2002) in the future. Therefore, the Working Party on Passive Safety (GRSP) of UNECE has tasked the Flexible Pedestrian Legform Impactor Technical Evaluation Group (Flex-TEG) with the technical evaluation of the FlexPLI and a recommendation on the date on which the FlexPLI could replace the EEVC impactor within legislation. Subsequent to a summary of the history of the FlexPLI, the present study gives an overview of the activities carried out by the FlexTEG. The injury criteria and currently proposed, tentative threshold values are briefly discussed. The recently introdcued inverse certification method will be used to assess the repeatability and reproducibility of test results of the final impactor built level. In a test series with the Flex-GTR the protection potential of two modern car frontends are assessed and a comparison between the built levels GT and GTR is made afterwards. An additional series of tests evaluates the effect of a missing upper body mass on the assessment of two modern vehicle front shapes representing the categories SUV and Sedan. Finally, still existing gaps of the final built level GTR are revealed and recommendations for implementation within legislation and future improvements are given.

FLEX-PLI HISTORY

Subsequent to the development of the POLAR-II Pedestrian dummy, the Japanese Automobile Research Institute (JARI) developed the "New JARI legform impactor" in the year 2000. This antecessor of the FlexPLI with a knee joint derived from the POLAR-II leg and rigid aluminium tubes representing the femur and tibia sections of the human leg already showed a higher biofidelity within PMHS tests (Wittek et al, 2001). The next built level called "JAMA-JARI legform impactor ver. 2002" with flexible femur and tibia bones had a more compact design and further improved biofidelic properties on component as well as on assembly level (Konosu et al., 2003). In the years 2003 and 2004 the first two built levels of the FlexPLI were released. Main changes were a further improved biofidelity on component level in version 2003 and improvements w.r.t. the impactor robustness, usability and biofidelity on assembly level in version 2004. Besides, a biofidelity rating system was introduced (Konosu et al., 2005). The subsequent impactor built level Flex-G showed a good repeatability and reproducibility of test results under idealized test conditions, but a comparatively low robustness (Zander et al., 2006). This impactor level was followed in the year 2006 by the Flex-GTα with modified specifications, a higher knee stiffness and knee bending angle limitation. Besides, an increased impact height was meant to improve the injury assessment ability of the impactor (Konosu et al., 2007). Built level GT then revealed moderate changes only, having a continuous outer neoprene skin and symmetrical bones with a smaller diameter (Konosu et al., 2007), which were found to have no significant influence on the impactor output (Zander, 2007).

FLEX-GTR

The final built level Flex-GTR (Figure 1) that has been released as prototype version at the end of 2008 and that is currently assessed by the Flex-TEG shows further improvements like the avoidance of dissymmetric sensitivities and twist in the knee area, an optional on-board data acquisition system and internal wiring. Furthermore, a tibia accelerometer as well as a potentiometer for the acquisition of the lateral collateral ligament elongation are added with the purpose of obtaining additional information during the pendulum function test (Been, 2008). All design changes are intended not to have any influence on the test results. However, the very first validation tests at BASt experienced an inconsistent tibia acceleration signal caused by high vibration during the impact. Due to that reason, the acceleration output will not be examined further within this study.

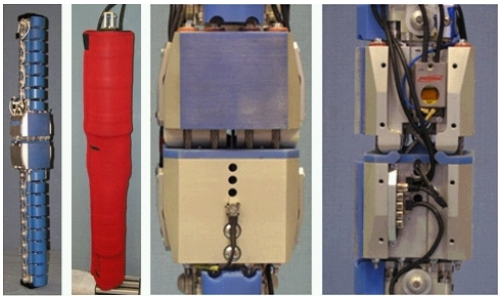

Figure 1. **Flex-GTR impactor and knee detail.**

INJURY CRITERIA AND TENTATIVE THRESHOLD VALUES

The Flex-GTR is aimed by the Flex-TEG to assess pedestrian leg injuries by the maximum bending of the tibia section measured by four strain gauges and the maximum elongations of the medial collateral ligament and the anterior and posterior cruciate ligaments acquired by three string potentiometers.

The current tentative threshold values for the maximum tibia bending moments of the Flex-GTR have been derived from previous studies on the 50% injury risk of the 50th AM (Nyquist et al., 1985 and Kerrigan et al., 2003). Those injury risk levels have been transformed by Konosu (2007) into the upper and lower performance limits for the tibia bending moment of the human model, the Flex-GT model and the Flex-GT impactor. The Japan Automobile Manufacturers Association (JAMA, 2008) lately proposed an average value between the lowmost and upmost limit as injury threshold for the Flex-GTR tibia bending moment.

The tentative threshold values for the medial collateral ligament have been derived by Konosu (2007) transforming the 50% injury risk levels for the 50th AM found by Ivarsson et al. (2004) into the lowmost and upmost limits for the human model knee bending angle and the elongation of the medial collateral ligament (MCL), the Flex GT model MCL elongation and finally into the Flex-GT impactor MCL elongation. JAMA lately proposed a more relaxed threshold value taking into account high bumper vehicles and the effect of muscle tension (2008). On the other hand, BASt proposed new tentative threshold values based on the dynamic response corridor found out by Ivarsson et al. (2004) and the injury risk curve of Konosu et al. (2001), pointing out that high bumper vehicles still have to be taken into account (Zander, 2008-2).

In terms of the threshold values for the cruciate ligaments, no injury risk curve has been developed so far. Therefore, and as the cruciate ligaments are estimated being sufficiently protected by the MCL thresholds, the International Harmonised Research

Activities Pedestrian Safety Working Group (IHRA-PS) suggested 10 mm maximum elongation of the anterior cruciate ligament (ACL) / posterior cruciate ligament (PCL) taking the risk of cruciate ligament rupture sufficiently into account (IHRA, 2004). Meanwhile, BASt tried to derive an injury threshold from impact tests with the Flex-PLI and the EEVC WG 17 PLI on identical impact locations of different vehicles representing a modern vehicle fleet (1box, Sedan, SUV). By linear regression it was found that the assessment of cruciate ligament protection provided by car front shapes using the FlexPLI ACL/PCL elongation readings is not comparable to the assessment using the WG 17 PLI shearing displacement results and vice versa. Therefore, BASt proposed to stick with PMHS knee shearing results evaluated by Bhalla et al. (2003) for knee shear displacement of the 50th AM as the tentative threshold value, even though the timing of injury could not be clearly identified and the common injury mechanisms still have to be better understood. (Zander, 2008-2).

Due to the missing effect of an upper body mass on the impactor kinematics and test results, the loadings of the femur sections are currently not considered as injury criteria for the assessment of pedestrian leg injuries. However, the knee and tibia injury assessment ability were found within a computer simulation study to be improved by lifting up the impactor by 75 mm above ground level when impacting the vehicle bumper (Konosu et al., 2007-2). The actual effects of an upper body mass on the femur, tibia and knee loadings are discussed later within this study.

An overview of the currently proposed Flex-GTR injury threshold values based on the 50% injury risk for the 50th AM is given in Table 1.

Table 1.
Proposed Flex-GTR injury threshold values based on the 50% injury risk of the 50th AM (Zander et al., 2009)

Leg region	50% injury risk level for 50th AM	Flex-GTR thresholds (tentative)
Tibia	312 - 350 Nm	318 Nm
MCL	16 - 20°	16 - 23 mm
ACL	12,7 mm	12,7 mm
PCL	12,7 mm	12,7 mm

FLEX-TEG EVALUATION ACTIVITIES

The Flex-TEG of GRSP that had been tasked with the technical evaluation of the FlexPLI started its work in 2005. Previous activities included the technical evaluation of built levels G and GT by means of a technical review of the impactor and its calibration methods, an analysis of the so far applied certification methods by carrying out inverse and pendulum tests, and an analysis of the injury assessment ability by performing simplified vehicle tests and real car tests. In this context, the repeatability and reproducibility of test results were found as good in most cases respect to the tibia and MCL values, while a partly high scatter was found in the cruciate ligament test results. From the simplified vehicle tests no direct correlation between the impact height and the test results could be derived. Furthermore, only the loadings on the medial collateral ligament were found critical when modern shaped vehicle frontends were tested with the Flex-GT, while good test results obtained with the rigid legform impactor according to EEVC WG 17 were in line with good results with the Flex-GT/GTα (Zander, 2008). Besides, first studies related to the application of an upper body mass to the FlexPLI were performed, showing already to some extent comparable results of a Flex-GT legform model and a MADYMO full pedestrian dummy (Mallory et al., 2008). Moreover, the injury risk functions were reviewed and the tentative threshold values modified as discussed before. Finally, a first evaluation of the pedestrian protection level provided by the FlexPLI was done, estimating 2797 lower extremity injuries being prevented by the introduction of the FlexPLI, which is equal to 40% addressed by the GTR (JAMA/JARI, 2007).

Currently ongoing Flex-TEG activities related to the final built level GTR as the finalization of the inverse certification test procedure, repeatability and reproducibility (r&R) assessment, real car tests and a comparison of the impactor output to the GT version will be discussed in the following chapters as well as the introduction of an upper body mass for future improvement of the injury assessment ability and impact kinematics.

INVERSE CERTIFICATION TEST

An inverse test setup, having its origin in the assessment of the repeatability and reproducibility of tests results with the EEVC WG 17 legform impactor (Zander et al., 2005) is proposed to be introduced as the certification procedure for the FlexPLI. In this test, the stationary FlexPLI is impacted by a linearly guided aluminium honeycomb impactor having its upper edge in line with the impactor knee joint, causing bending of the bones and shearing and bending of the knee in a soft impact (Figure 2).

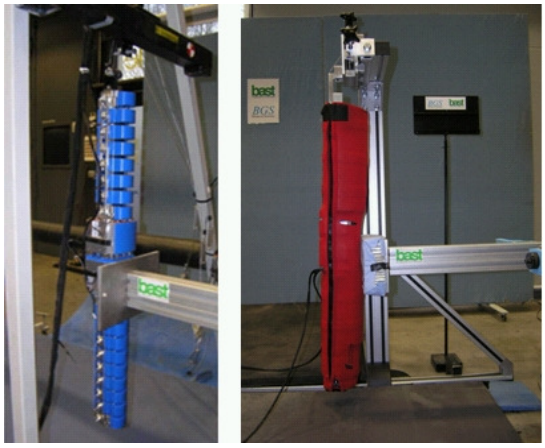

Figure 2. Flex-GTR inverse certification test.

Pass/fail parameters of the inverse certification test are the outputs of the four tibia strain gauges and the ACL, PCL and MCL potentiometer. As exemplarily shown by means of the traces for ligaments and tibia bending moments (Figure 3), this procedure is found to mirror the loadings of the FlexPLI during a real car impact in a realistic way with respect to the timing, the kinematics and the maxima. Besides, the impactor rotation as well as the high influence of the impactor mass and the location of its center of gravity on real car test results are appropriately taken into account.

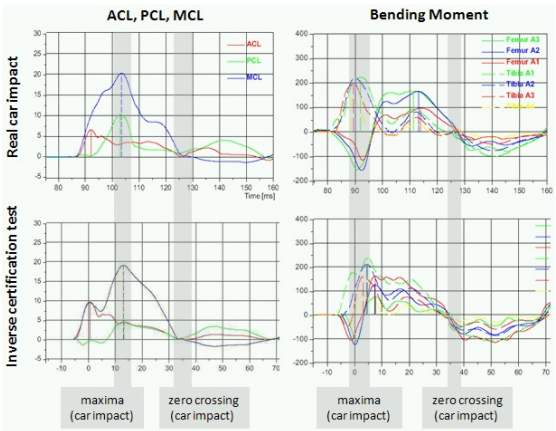

Figure 3. Comparison of the traces in real car and inverse certification test (Zander et al., 2008).

Currently, the FlexTEG is discussing the type of honeycomb material used for the inverse test w.r.t. properties and dimensions. The material so far used was of 5052 alloy type with a crush strength of 75 PSI, a density of 3.1 lb/ft³ and a cell size of 3/16 inches. The honeycomb dimensions were 250*160*60 mm.

ASSESSMENT OF REPEATABILITY AND REPRODUCIBILITY OF TEST RESULTS

In a joint project with the European Automobile Manufacturers' Association (ACEA) BASt has carried out a series of inverse certification tests with the first prototypes of the Flex-GTR in order to assess the repeatability and reproducibility of test results. By using the inverse test setup idealized impact conditions with identical test parameters kept the focus on the impactor output itself.

Test results under idealized impact conditions

Three GTR impactors, one of these equipped with the conventional external Data Acquisition System (DAS) (SN01) and two with different on-board DAS, the MESSRING M-BUS (SN02) and the DTS Slice system (SN03) were each tested three times at an impact speed of 40 km/h. The results for the tibia bending moments and knee elongations (ACL, PCL and MCL) being the currently by the Flex-TEG proposed pass/fail parameters are given in Figures 4 and 5.

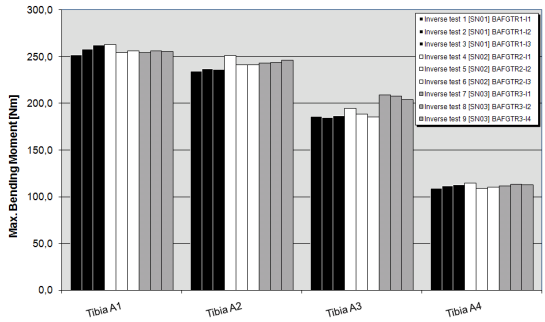

Figure 4. Tibia bending moment results of Flex-GTR inverse certification tests.

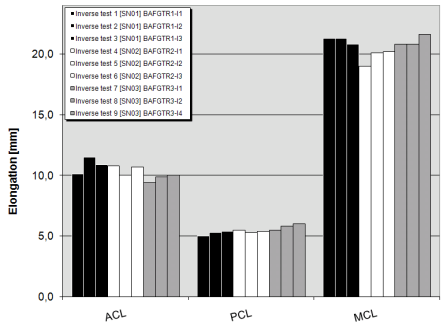

Figure 5. Knee ligament elongation results of Flex-GTR inverse certification tests.

The impactor output of all three prototypes showed very comparable results with the maximum values in a range being expected for real car test results as well.

Repeatability

The repeatability (r) of test results was studied using the best practice guidelines for crash test dummies. Here, the coefficients of variation (CV) of the three impactors are assessed according to Table 2.

Table 2.
Assessment of repeatability of test results

Ranking	Criterion
Good	$0\% \leq CV \leq 3\%$
Acceptable	$3\% < CV \leq 7\%$
Marginal	$7\% < CV \leq 10\%$
Not acceptable	$10\% < CV$

Figure 6 gives an overview of the coefficients of variation of all tibia bending moment and knee ligament elongation results of the three impactors. Thus, the repeatability of all tibia bending moments is assessed good, while the repeatability of the ligament elongations is between good and acceptable. Even though the repeatability was, most likely by the symmetrical knee design, significantly improved being compared to impactor built level GT, the cruciate ligament elongations still produce the highest coefficients of variation. However, all results are in an at least acceptable range.

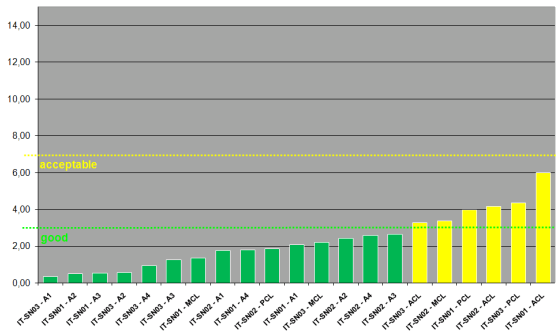

Figure 6. Repeatability of GTR impactor test results under idealized impact conditions.

Reproducibility

The reproducibility (R) of test results is assessed by drafting a reproducibility corridor which is based on the pooled means (MV) of all segments with a coefficient of variation lower than 5% according to Mertz (2004):

Table 3.
Assessment of reproducibility of test results

Ranking	Criterion
Not acceptable	$x < 0{,}9*MV$
Acceptable	$0{,}9*MV \leq x \leq 1{,}1*MV$
Not acceptable	$x > 1{,}1*MV$

According to this assessment method, all tibia segments and knee ligaments gave reproducible test results with their pooled means within the reproducibility corridor. Only the ACL results of the impactor with external DAS (SN01) were outside the reproducibility corridor (CV = 6%).

REAL CAR TESTS

Aim of performing impact tests with the Flex-GTR on modern vehicle fronts was to obtain information on the feasibility of the current requirements as well as a verification of the impactor output of built level GTR that was required to stay in line with the previous results.

Flex-GTR tests on Sedan #1

A modern vehicle with Sedan front shape and a borderline to green bumper area according to the Euro NCAP requirements (Euro NCAP, 2009) was tested three times on two different impact locations with the same impactor (SN02) at 40 km/h and the currently proposed impact height of 75 mm above ground level. The test results are given in Figures 7 and 8.

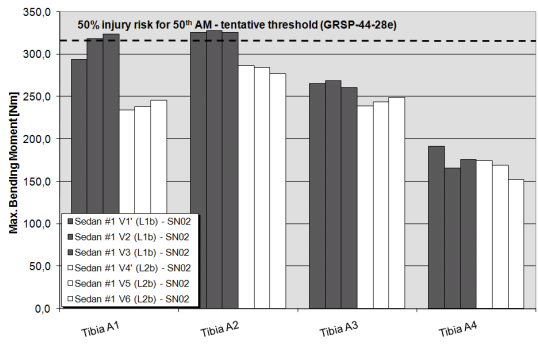

Figure 7. Tibia bending moment results of Sedan #1 tests.

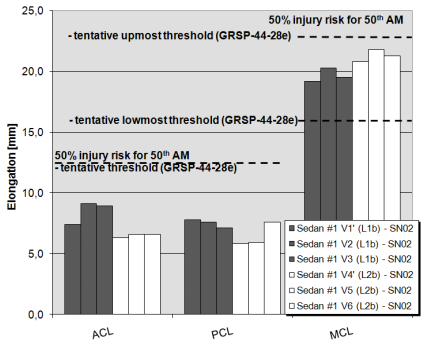

Figure 8. Knee ligament elongation results of Sedan #1 tests.

Both impact locations fulfilled the tentative requirements for most of the tibia segments except impact location #1 for the two tibia segments that

were at height of the vehicle cross beam. The tentative thresholds for the cruciate ligaments were clearly met by both impact locations. In terms of the medial collateral ligament, all results were found in between the lowmost and upmost tentative threshold. Thus, the marginal Euro NCAP knee bending angle results were confirmed by the MCL test results with the Flex-GTR.

The tests showed a high repeatability of the MCL and most tibia segments while the coefficient of variation of the cruciate ligaments was partly not acceptable (Figure 9). This was, to some extent, according to the results of the previous built level GT.

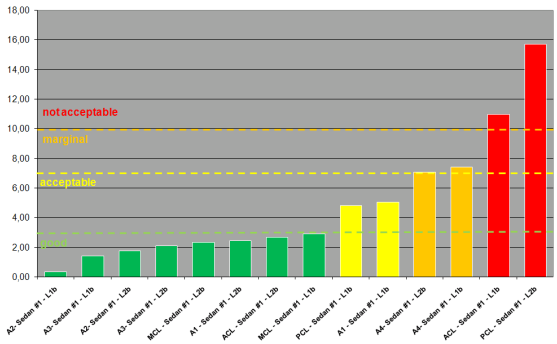

Figure 9. Repeatability of impactor test results with Sedan #1.

Flex-GTR tests on Sedan #2

In a tests series on a second Sedan shaped vehicle front within this joint project between ACEA and BASt two impact locations were tested, the first one with all three impactors three times each, the second one three times with Flex-GTR SN02.

Figure 10 gives an overview of the tibia peak results. At the first impact location impactor SN03 obviously gave a significantly higher output at segment A3 in all three tests.

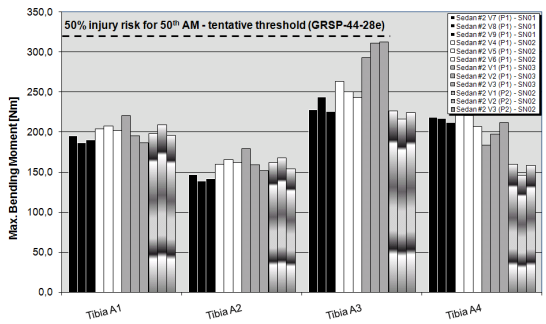

Figure 10. Tibia BM results of Sedan #2 tests.

The peak knee ligament elongation results are summarized in Figure 11. The output of all three impactors at impact location #1 is comparable except in the first test of SN03. The test results at impact location #2 were similar as well.

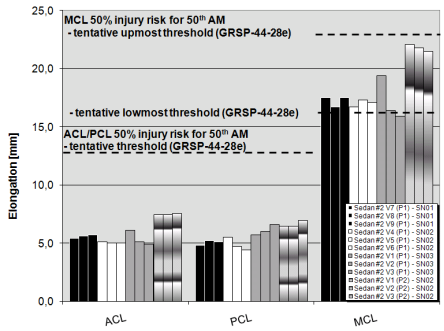

Figure 11. Knee EL results of Sedan #2 tests.

In terms of repeatability of test results, the cruciate ligament output was still partly not acceptable (Figure 12). The high coefficient of variation of SN03 MCL was found due to the detachment of a fixation in the first test. Altogether, Flex-GTR SN03 showed the lowest repeatability of test results. However, the majority of results was good or acceptable.

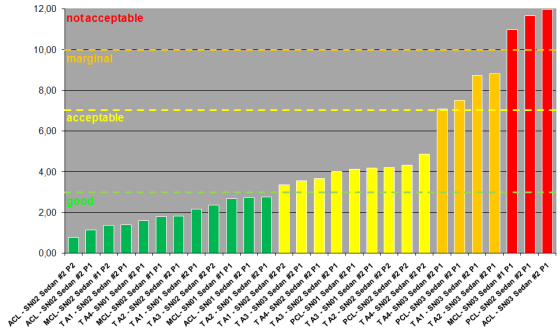

Figure 12. Repeatability of impactor test results with Sedan #2.

COMPARISON OF THE OUTPUT OF BUILT LEVELS GT AND GTR

A comparison of the impactor output of the final built level GTR with the previous one (Zander, 2007-2) was meant by the FlexTEG to ensure a consistent level of biofidelity. As the tests under idealized conditions focusing on the impactor only were generally found to have a higher repeatability than tests on real cars they were examined more in detail.

Most tibia segments of impactor level GTR gave an output that was about 10 to 15 percent higher than that of built level GT. Only segment A1 showed comparable results with both built levels. This trend was confirmed by real car tests on Sedan #1 that had been conducted within a previous study with the Flex-GTα. Also the Sedan #2 tests confirmed the higher results obtained with the

Flex-GTR at both impact locations. On the other hand, in latter case it has to be taken into account that only one test on each impact location had been carried out with the Flex-GTα (Zander, 2007).

A comparison of the ligament elongation results of the two impactor built levels showed a higher output of the medial collateral ligament potentiometer of the latest built level GTR. This trend was in line with the real car tests of Sedan #1 with Flex-GTR and Flex-GTα w.r.t. the second impact location. Here, the Flex-GTR gave an output that was 10 to 20 percent higher for all ligament elongations. At the first impact location, the real car tests did not show any clear tendency.

In a comparison of the coefficients of variation it was found out that built level GT still had segments with a repeatability in a marginal or even not acceptable range only, especially with respect to the cruciate ligaments, while at GTR level, the repeatability of test results was generally further improved. This improvement most likely had been addressed by the new symmetrical knee design.

On the other hand, the repeatability improvement of the cruciate ligament elongation results was only partly mirrored by the real car tests on both Sedans. However, the MCL and most of the tibia car test results showed a significantly improved repeatability.

EFFECTS OF AN UPPER BODY MASS

The Flex-TEG had been tasked by GRSP to evaluate the FlexPLI with the aim of its introduction into global legislation on pedestrian protection and, after a certain transition time, replacing the rigid legform impactor according to EEVC WG 17. However, as the FlexPLI in its final built level is missing an upper body mass (UBM), the output of the femur strain gauges is currently not considered for the assessment of femur injuries and therefore is used for monitoring purposes only. On the other hand, computer simulation studies carried out by JARI found that vertically lifting the impactor by 75 mm in relation to ground level would compensate best the missing effect of an upper body mass with respect to impact kinematics and impactor tibia and knee loadings (Konosu et al., 2007-2).

Based on simulation results with the Pedestrian Total Human Model for Safety (THUMS) on a generic SUV front, a pedestrian upper body mass was developed and applied to the flexible legform impactor built level GT within the European FP6 research project on Advanced Protection Systems (APROSYS). In tests against a real SUV front shape the effects of this upper body mass on the impact kinematics and test results were studied in detail. SUV front shapes were found to have a greater influence on the impact kinematics of a pedestrian in a collision. The isolated legform impacted above its center of gravity in most cases results in overrunning the legform. This impact behaviour is not according to a real pedestrian impact because its torso mass causes the pedestrians' body to wrap around the vehicle even when being impacted above the center of gravity of the leg (Bovenkerk et al., 2009).

Besides, the effect of the pedestrian upper body mass was also studied by BASt within additional tests on a Sedan shaped vehicle in order to verify the proposed impact conditions for lower bumper vehicles as well.

Upper body mass development

THUMS simulations of a collision between a pedestrian and a large SUV carried out by Compigne et al. (2009) found optimum parameters for an upper body mass to be applied to the FlexPLI in a total mass of 6 kg, an adjustable location of the center of gravity w.r.t. height and offset and an inclination of the leg by 6° taking into account the orientation of the human leg. According to these recommendations an upper body mass of 6.8 kg with four adjustable positions was developed and manufactured (Figure 13).

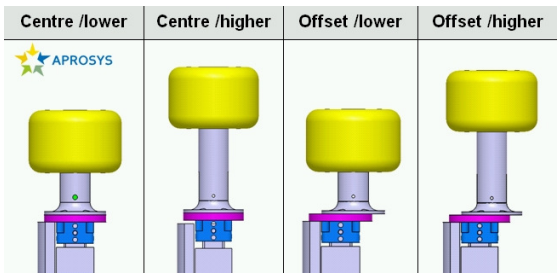

Figure 13. Development of an upper body mass for the Flex-GT (Bovenkerk et al., 2009).

For feasibility and comparability purposes it was decided to carry out the real car tests at the center lower position of the UBM (CoG at 110 mm, no offset) without leg inclination angle.

SUV test matrix and impact kinematics

In a first series of tests an SUV with a soft nose design and a consistently green rated bumper area according to Euro NCAP was tested at two different impact locations three times with the Flex-GT with and without UBM (Table 4).

Table 4.
SUV Test matrix for Flex-GT and Flex-GT UBM

Impact location	Lateral vehicle position [mm]	Impactor setup	Impact height [mm]	No. of tests
1	-350	GT Standard	75	3
		GT UBM	25	3
2	128	GT Standard	75	3
		GT UBM	25	3

As test positions the most likely worst impact locations according to the European New Car Assessment Programme (Euro NCAP, 2009) pedestrian testing protocol were selected (Figure 14).

Figure 14. Test setup Flex-GT UBM against SUV and impact locations.

An exemplary evaluation of the high speed film sequences of impact location #2 already revealed the significant differences of the impact kinematics of the Flex-GT Standard and the UBM version (Figure 15).

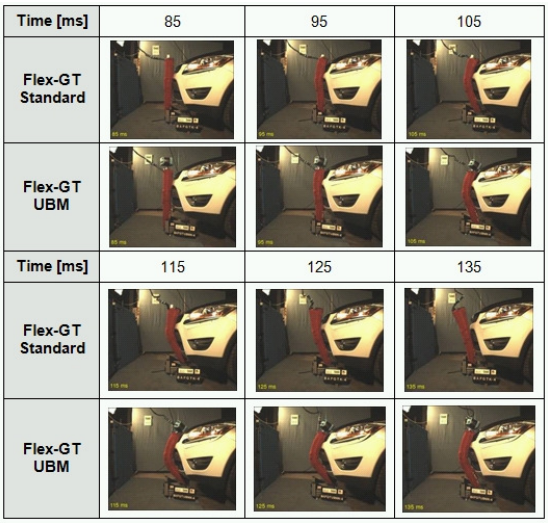

Figure 15. Effects of the upper body mass on the SUV impact kinematics (t_0 = impactor release).

In the first flight phase up to 100 ms from impactor release the kinematics of the standard impactor and the one with applied upper body mass were quite similar. Having reached its maximum knee bending the Flex-GT Standard passed over into the rebound phase while the UBM version reached its highest bending level at a significantly later time at around 125 ms, likely due to the forces induced by the additional mass.

A comparison of the time of maximum loads of the femur segments of the Flex-GT Standard and the Flex-GT UBM showed the standard impactor being loaded with the maximum femur bending moments at an earlier stage than the UBM version. In the latter one, the peak value of segment A1 being the closest one to the vehicle cross beam occurred at a later time, i.e. that the additional mass was suspected to have the highest influence on the impact kinematics of this segment.

Like for the femur bending moments, the maximum loads of the tibia section of the standard impactor version occurred earlier than those of the UBM version. The maximum values for segment tibia A1 of the UBM impactor were reached at a later time than those for the other segments. This effect could have been caused by the decreased impact height in relation to the standard impactor version along with a possibly different influence of the lower stiffener on that area of the legform.

A comparison of the ligament elongations confirmed the different impact kinematics of both impactors w.r.t. the time and maximum loading. The maximum ligament elongations of the UBM version all occurred at a later time. Despite the modified impact height for the UBM version the additional mass showed its highest influence on the medial collateral ligament and the cruciate ligaments.

Analysis of SUV traces

In Figures 16 and 17 the traces for the femur and tibia segments of both impactor versions are exemplarily given for the respectively first test of impact location #2.

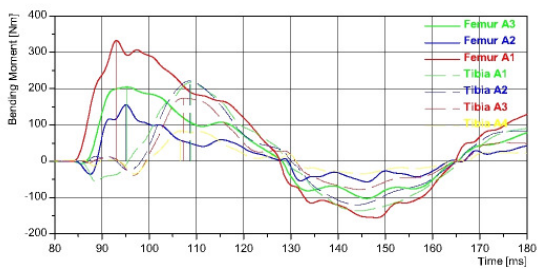

Figure 16. Femur and tibia test results of Flex-GT Standard at impact location #2 (Test V4).

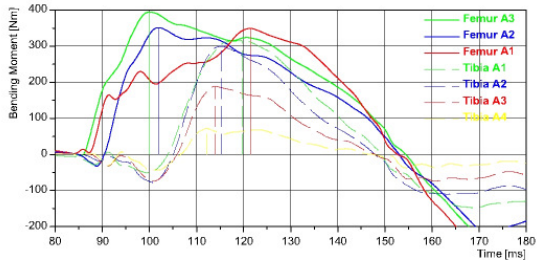

Figure 17. Femur and tibia test results of Flex-GT with UBM at impact location #2 (Test V4).

The traces show the femur and tibia segments of the UBM version being longer loaded than those of the standard impactor.

All three femur segments of the standard GT impactor reached their maximum values at almost identical times in all three tests of impact location #2. Femur segment A1 showed the highest bending. The time interval for the maximum femur bending moments of the Flex-GT with UBM was within 22 ms. In the UBM version of the impactor segment A3 showed the highest results. Besides the application of the upper body mass, the changed impact height (25 mm with UBM vs. 75 mm w/o UBM) was expected to have an influence on the femur test results as well. In addition, the UBM version of the impactor showed a significantly higher negative bending of the femur segments after the zero-crossing.

In terms of the tibia section, all segments of the standard GT impactor reached their highest loads in a time interval of 5 ms in all three tests, again in each test at almost identical times. Tibia segment A2 showed the highest bending moments, closely followed by segment A1. The maximum tibia bending moments of the UBM equipped legform at impact location #2 occurred in a time interval of 9 ms, and to some extent at a later time than with the standard impactor. Tibia segment A1 showed in all three tests the highest bending moments, closely followed by segment A2. An explanation for this reciprocal order was assumed by the changed impact height along with a modified distance of the segments to the vehicle main cross beam and the body mass having an effect on the peak results.

A comparison of the femur and tibia traces of the impactor with and without upper body mass gave clear evidence that especially the loads on the femur parts and the upper tibia segments (A1 and A2) increase significantly with a additional mass induction. In other words, the higher load transmission due to the upper body mass is not proven to be sufficiently compensated by an increase of the impact height by 50 mm compared to GTR level when related to SUV fronts.

Finally, the tibia A1 load measured by the Flex-GT with applied UBM was comparable to its bending moment simulated by the weighted impactor model w.r.t. to time and curve progression. On the other hand, the result was not comparable to that produced by the THUMS model.

The ligament traces for both impactors are exemplarily given as well for the respectively first test of impact location #2 (Figures 18 and 19).

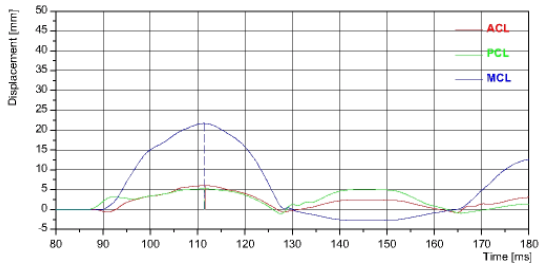

Figure 18. Ligament test results of Flex-GT Standard at impact location #2 (Test V4).

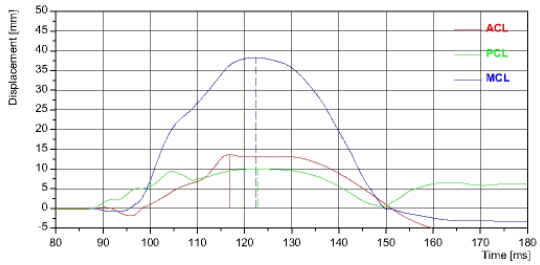

Figure 19. Ligament test results of Flex-GT UBM at impact location #2 (Test V4).

The peak values for the ACL, PCL and MCL elongation of the standard impactor occurred at almost identical times with very similar ACL and PCL maxima. Only the maximum PCL value in the last test was observed at a later time. The cruciate ligament characteristics are very similar to each other before the zero-crossing of the MCL elongation. After 130 ms measured from impactor release, the ACL output was significantly lower than that of the posterior cruciate ligament.

In the tests with Flex-GT UBM, the MCL and PCL maxima occurred almost simultaneously. The cruciate ligament traces diverged to a higher extent than in the standard tests which was more related to the structure of the impact location than to the effect of the upper body mass because at impact location #1 this divergence could not be observed. On the other hand, after the zero-crossing of MCL, the ACL output stayed always lower than that of PCL.

A comparison of the ligament elongation traces of the Flex-GT standard and Flex-GT UBM again

revealed the significant influence of the upper body mass on the test results. The potentiometer output of all ligaments was increased by nearly 100 percent in all tests at impact location #2. The difference in ACL/PCL results at impact location #1 showed similar tendencies. As already with the femur and tibia loads, the increase of impact height by 50 mm doesn't seem to compensate the mass effect when testing an SUV shaped vehicle front.

Finally, a comparison of the Flex-GT UBM traces with the output of the THUMS and 6 kg UBM impactor model confirmed the produced MCL values around or beyond 40 mm elongation. Anyway, it has to be stated that those loads were far beyond the biomechanical limits of the human knee.

SUV test results

Tentative threshold values for the maximum tibia bending moments of the Flex-GTR had been derived from a previous study on the 50% injury risk of the 50th AM (Kerrigan et al., 2003). As the femur bending moments of the FlexPLI had not been taken into account by the Flex-TEG for the assessment of leg injuries, for the time being those limits were withdrawn. For the introduction of an upper body mass and the corresponding assessment of femur injuries, those thresholds were tentatively introduced again. Thus, the 50 % risk of femur fracture for the 50th AM was estimated at a bending moment between 372 and 447 Nm.

Figure 20 shows the peak femur bending moment results on impact location #1 when tested with the Flex-GT with and without upper body mass.

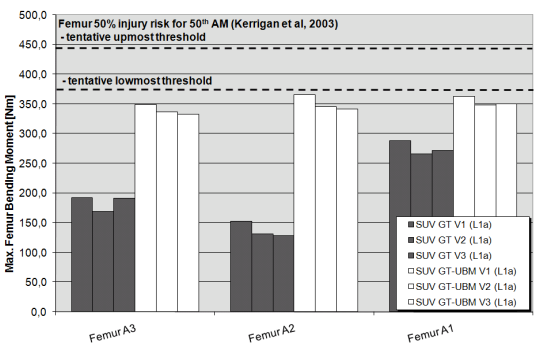

Figure 20. Femur bending moment results of impact location #1 (SUV).

It can be easily seen that the peak values for the femur loads increased significantly when the impact location was loaded with the UBM-equipped legform. The vertical distance between the vehicle cross beam and the particular femur strain gauge seemed to have an influence on the effect of the upper body mass. However, test results obtained with UBM were more homogeneous over the whole femur length. Altogether, all test results obtained with this configuration still fulfilled the tentative upper performance limits.

The results of the tibia bending moments for impact location #1 are shown in Figure 21.

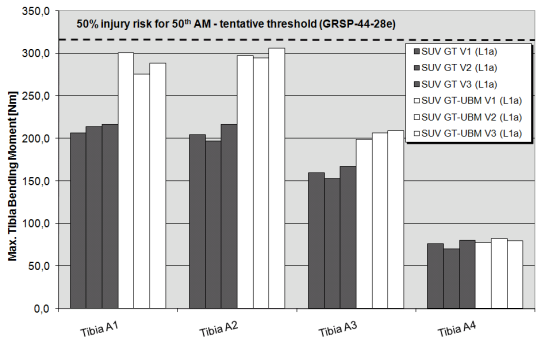

Figure 21. Tibia bending moment results of impact location #1 (SUV).

The tibia results for segments A1-A3 were significantly higher when the impact location was tested with the Flex-GT with UBM. In this context it also had to be taken into consideration that the height of the segments A1 and A2 was close to that of the vehicle main cross beam; therefore these loads were by trend higher than those of the two lower tibia segments. For segment A4, no difference in test results between standard and UBM legform could be observed.

Figure 22 shows the ligament elongation results of impact location #1.

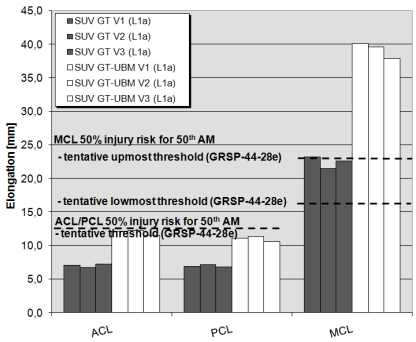

Figure 22. Knee ligament elongation results of impact location #1 (SUV).

As already seen with most of the bending moment results, the upper body mass also had a significant influence on the test results of the cruciate and medial collateral ligaments. While the cruciate ligament elongation requirements could just be fulfilled by impact location #1 when being impacted with the Flex-GT with UBM, the currently discussed MCL threshold values were

exceeded by almost 100 percent, i.e. as well that the MCL results obtained with the Flex-GT with UBM clearly exceeded the biomechanical limits of the human knee.

No evidence was given that the Flex-GT Standard being lifted up by 50 mm in relation to the UBM version could compensate the missing mass effect on the tibia and knee loads when testing an SUV shaped vehicle front.

The peak femur bending moment results of impact location #2 are given in Figure 23.

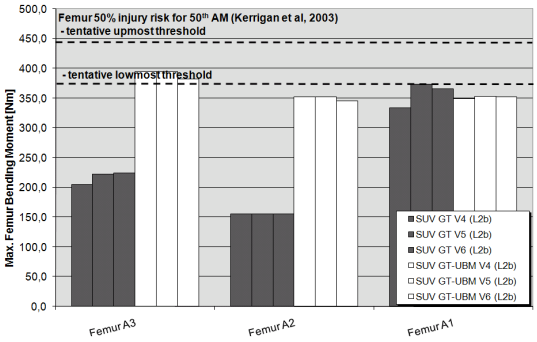

Figure 23. Femur bending moment results of impact location #2(SUV).

For the femur segments A3 and A2 the same tendencies as for impact location #1 could be observed: the test results obtained with Flex-GT and UBM were significantly higher than those without UBM. Again, latter ones were more homogeneous over the whole femur length. Besides, this impact location did not meet the upper performance limit at femur A3 when tested with UBM. At femur segment A1, the UBM did not have any influence on the peak values.

The tibia test results at impact location #2 showed the same tendencies as at impact location #1 (Figure 24).

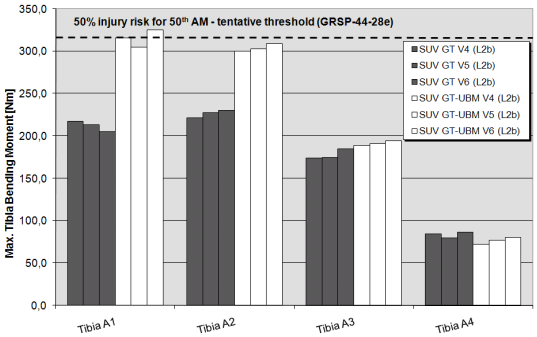

Figure 24. Tibia bending moment results of impact location #2 (SUV).

On the tibia segments A1 and A2 the applied UBM had a significant influence on the test results. For segment A3 the difference was marginal, while for segment A4 no influence of the UBM could be observed.

The test results of the crucial and medial collateral ligaments of impact location #2 are given in Figure 25.

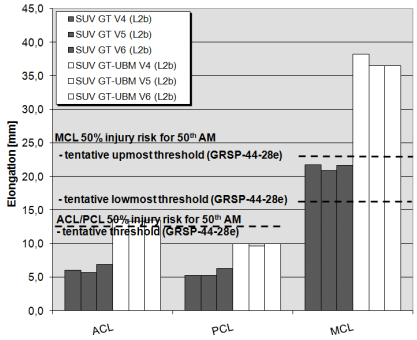

Figure 25. Knee ligament elongation results of impact location #2(SUV).

Again, the application of the upper body mass was of significant influence on all ligament test results. In case of the ACL results, the UBM signed responsible for the exceedence of the currently proposed threshold values. In case of the MCL results, latter ones clearly missed the tentative upmost threshold and were almost twice the results obtained without UBM. Once again, the elongations of the medial collateral ligament measured by the Flex-GT equipped with UBM clearly exceeded the biomechanical limits of the human knee which is expected to suffer from ligament rupture at an earlier stage of the accident already.

Influence of upper body mass on repeatability of test results (SUV)

As for the Flex-GTR inverse and Sedan tests, in order to gain additional information on the repeatability of test results, the influence of the upper body mass on the coefficient of variation for each of the segments was examined.

Figure 26 summarizes the repeatability of all ligament elongation results as well as all tibia and femur bending moment results for both impact points when impacted with the Flex-GT standard version.

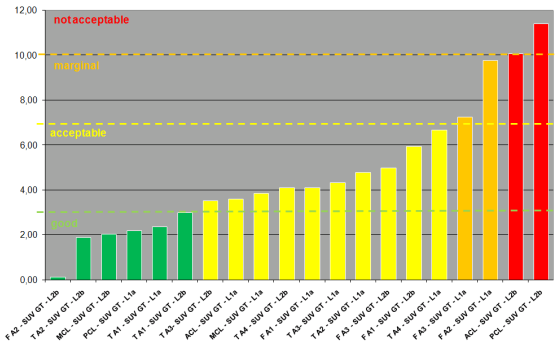

Figure 26. Repeatability of Flex-GT standard test results on SUV front.

As it can be seen, the repeatability of test results was at least in an acceptable range for most of the segments. Only the femur loads of segments A3 and A2 were in a marginal range when testing impact location #1. Besides, the repeatability of the cruciate ligament elongation results when testing impact location #2 was not acceptable. This was, to some extent, a confirmation of previously made observations w.r.t. the repeatability of the ACL/PCL results of impactor built level GT. The partly high scatter was found due to the play in the knee area and the dissymmetrical design of the knee in combination with impactor rotation caused by the design of particular impact areas (Zander et al., 2007 and 2008).

The repeatability of test results obtained with the Flex-GT with applied upper body mass is shown in Figure 27.

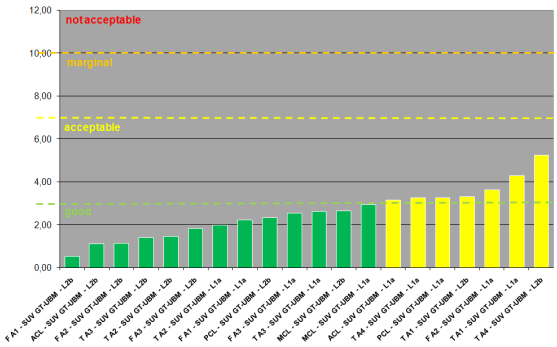

Figure 27. Repeatability of Flex-GT UBM test results on SUV front.

All test results were in a good or at least acceptable range (CV < 5.5%). The influence of the applied upper body mass seemed to some extent the cause for this improved repeatability such that the knee dissymmetries and possible knee twist at the point of impact appeared to be negligible.

Study of UBM effects on Sedan test results

An additional test series carried out by BASt was meant to study the effect of an applied upper body mass on test results of a Sedan shaped vehicle. The influence was expected to be lower in comparison to that on SUV fronts due to the center of gravity of the isolated legform at or above bumper height in most of the cases.

Therefore, three tests with the Flex-GT with UBM were performed at the proposed impact height of 25 mm on a Sedan shaped car at an impact location formerly being tested with the rigid EEVC WG 17 legform impactor and assessed borderline to green according to Euro NCAP (Figure 28). The results were compared to tests with the Flex-GTα Standard at 25 as well as 75 mm impact height carried out by Zander et al. (2007).

Figure 28. Test setup Flex-GT UBM against Sedan and impact location.

The high speed sequence for the respectively first test of the Flex-GTα at 75 mm and the Flex-GT UBM is given in Figure 29.

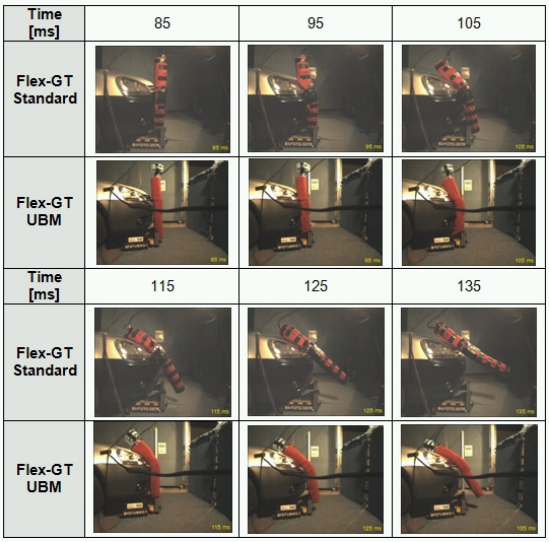

Figure 29. Effects of the upper body mass on the Sedan impact kinematics (t_0 = impactor release).

As for the SUV, the first flight phase up to 100 ms from impactor release the kinematics of both impactors were comparable. Having reached its maximum knee bending the Flex-GTα standard impactor turned over into its rebound phase while the UBM version was loaded with a high bending moment during a significantly longer time interval. Thus, the second flight phase in its entirety was different due to the induced upper body mass.

Figures 30 shows the curve progressions of the respectively first test carried out with each test setup.

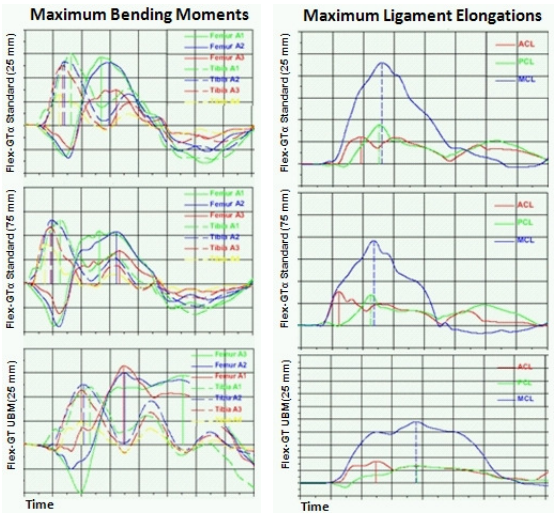

Figure 30. Femur, tibia and knee test results of Flex-GTα Standard at 25 and 75 mm and Flex-GT with UBM (Test V1).

While the traces of the Flex-GTα at 25 and 75 mm impact height showed to some extent a comparable behavior for the tibia segments and ligament elongations, the Flex-GTα femur output in the tests at an impact height of 75 mm w.r.t. its shape went more in line with the UBM version. The Flex-GT UBM showed an entirely different behavior of the knee ligaments w.r.t. shape and time interval. Altogether, the loadings measured by the UBM version were significantly higher for the femur part and occurred during a longer time interval. The traces for the tibia section were in line with those acquired by the standard impactor regardless its impact height.

A comparison of the peak femur results acquired with all three test setups is given in Figure 31.

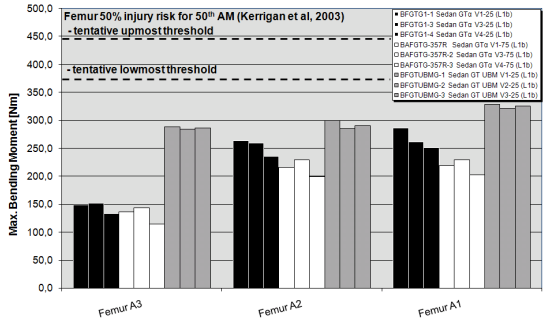

Figure 31. Femur bending moment results of Flex-GTα Standard (25 and 75 mm) and Flex-GT with UBM.

The results give evidence of the modified impact height not having any effect on the maximum femur loads compensating a missing upper body mass. Far from it, the peak results acquired by the UBM version went more in line with the results when using the original test setup. However, the tentative upper performance limit was met in tests with all three test setups.

In Figure 32, the maximum tibia bending moments are given.

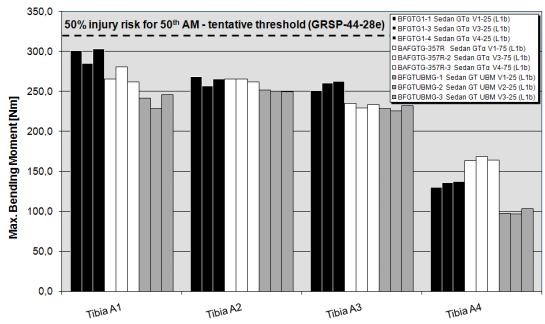

Figure 32. Tibia bending moment results of Flex-GTα Standard (25 and 75 mm) and Flex-GT with UBM.

Only in terms of tibia segments A1 and A3 the upper body mass effect was meant to be compensated by an increased impact height of the standard impactor. For segment A2, no effect could be observed, the peak results of segment A4 using the UBM impactor version were closer to the standard test setup at 25 mm impact height. Again, the tentative threshold was met in all three cases.

The knee elongation peak results are summarized in Figure 33.

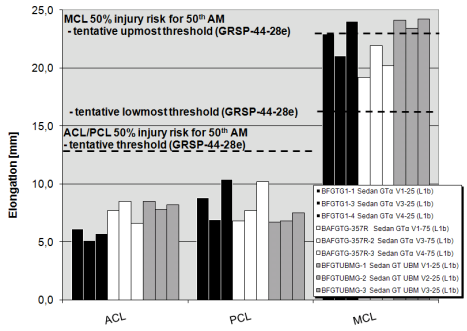

Figure 33. Knee elongation results of Flex-GTα Standard (25 and 75 mm) and Flex-GT with UBM.

Again, no justification for the increased impact height of the standard impactor could be found in the maximum output of the ligaments during the Sedan testing.

Figure 34 shows the coefficients of variation for the assessment of the repeatability of test results.

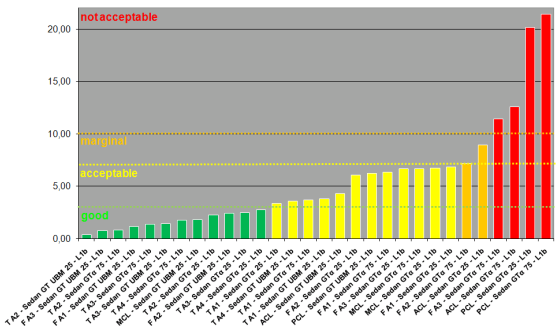

Figure 34. Repeatability of Flex-GT test results on Sedan front.

As during the SUV tests, the repeatability of the Sedan test results was significantly improved using the UBM impactor. All results were in a good or acceptable range. Concerning the standard impactor version, the cruciate ligament results gave as expected the highest scatter regardless the selected impact height.

DISCUSSION

In the present study, tests with the final built level of the FlexPLI were carried out on two Sedan shaped vehicles with pedestrian-friendly bumpers according to Euro NCAP. Once again it could be confirmed that pedestrian protection packages that pass the Euro NCAP criteria are as well in line with the Flex-GTR requirements. On the other hand, in the current tests the impactor output of built level GTR was observed in most cases to be 10 to 20 percent higher than that of the Flex-GT while showing an improved repeatability especially for the cruciate ligament elongation results.

The developed inverse certification method gives an output that is in the range of real car tests w.r.t. traces and maxima and is therefore proposed as the Flex-GTR certification method.

New threshold values for the ligament elongations and the tibia bending moments were proposed. However, no injury risk curves for the cruciate ligaments are available due to the fact that ACL / PCL rupture is expected to be prevented as well by the protection of MCL. On the other hand, high bumper vehicles as well as the effect of muscle tension still need to be included when transforming the human knee bending angles into impactor model elongation results.

A comparative test series with built level GT and upper body mass against an SUV shaped car front revealed the effects of an applied upper body mass on the impact kinematics and test results of the FlexPLI. This effect cannot be compensated by just an increase of the impact height of the standard impactor by 75 mm in relation to ground level as recommended by Konsou et al. (2007). In the tests against a modern SUV with green rated bumper according to Euro NCAP, the loads on the medial collateral ligament increased by almost 100 percent. Furthermore, the femur loads showed significantly different characteristics w.r.t their traces and maximum values. Despite of the different impact heights, a comparison of the kinematics between the Flex-GT UBM version and the Flex-GT UBM model gave quite similar results until maximum loading. Therefore, the influence of impact height compared to the mass effect is concluded to be marginal. All in all it has to be stated that the pedestrian protection packages of modern SUV frontends that fulfill regulatory as well as the biomechanical requirements assessed by the FlexPLI do not necessarily take sufficiently into account the influence of the upper body mass during a pedestrian vehicle collision. It is therefore recommended to aim for the introduction of an upper body mass for the assessment of leg injuries caused by SUV frontends.

Testing a Sedan front shape also revealed the very limited effect of an increased impact height in comparison to the application of an upper body mass. Therefore, the UBM effect on Sedan shaped car fronts needs to be investigated further.

CONCLUSIONS

In the present study the final built level of the FlexPLI foreseen for the implementation within global legislation on pedestrian protection was evaluated. The robust impactor shows an output that is mostly 10 to 20 percent higher than that of the previous built level. An extension of the test

series to vehicles with different front shapes is recommended. The repeatability and reproducibility of test results has been improved especially by eliminating the previously dissymetrical knee design along with possible knee twist. Due to an inconsistent tibia acceleration signal caused by high vibration during the impact it is recommended to remove the tibia accelerometer because the output value is not found to give any usable additional information.

A new impactor certification method is recommended to be introduced for the Flex-GTR and new tentative injury threshold values are derived.

For an improved assessment ability of cruciate ligament injuries and a development of ACL/PCL injury risk functions, further research on the knee injury mechanisms is needed.

Gaps regarding the assessment of the risk of femur fracture are proposed to be closed by the introduction of an upper body mass developed in the FP 6 project APROSYS rather than by an increased impact height because latter one does not compensate the effects of a missing upper body mass of the FlexPLI. However, further research in this field is needed. It is therefore recommended to extend the study on the influence of the upper body mass to more vehicle frontend shapes in order to generate a classification of vehicles to be tested with the FlexPLI with upper body mass.

ACKNOWLEDGEMENT

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