Derivation of Draft FlexPLI prototype impactor limits by BASt

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Background

- At the 5th meeting of the IG GTR9-PH, BASt proposed revised FlexPLI threshold values, considering the lower output values of the serial production legforms in comparison to the FlexPLI prototypes (Doc GTR9-5-20).
- As a first response, a document was handed in by members of OICA, opposing those revised threshold values (Doc GTR9-5-23)
- BASt replied during the meeting, pointing out that apparently FlexPLI threshold values and the underlying risk of pedestrian lower extremity injuries were confused in Doc GTR9-5-23.
- It is not the intention of BASt to propose new injury criteria, but introducing revised threshold values due to the change in performance of the different legforms (prototype and serial build level).
- This document briefly summarizes how the injury criteria and impactor limits were derived by BASt as contribution to the Flex-TEG.

Flex-TEG Agreement (TEG-127)

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7 December 2009

Technical Background Information Document for the UN-ECE GRSP explaining the Derivation of Threshold Values and Impactor Certification methods for the FlexPLI version GTR agreed by the FlexPLI-TEG at their 9th Meeting

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1) Tibia Threshold Value: 340 Nm

At the 8th GRSP Flex-TEG meeting on May 19th, 2009, two proposals for the tibia threshold value of the FlexPLI version GTR (also called Flex-GTR) were made by JAMA and BASt, coming to different conclusions.

a) 380 Nm (JAMA)

JAMA derived the Flex-GTR tibia bending moment threshold using a linear transition equation between human and Flex-GTR Finite Element (FE) models derived from computer simulation results. The average human tibia bending moment threshold value was taken from an injury risk curve of the 50th percentile male for tibia fracture, taking into account scaled male and female PMHS data from Nyquist et al. (1985) and Kerrigan et al. (2004) under modification of the standard tibia length and standard tibia plateau height, making the assumption that the height scale factor and length scale factor should correlate to each other. The Weibull Survival Model was used to develop the injury probability function. The proposed final threshold value resulted in 380 Nm.

b) 302 Nm (BASt)

BASt derived the Flex-GTR tibia bending moment threshold also using the corresponding transition equation between human and Flex-GTR FE models. The average human tibia bending moment threshold value was taken from an injury risk curve of the 50th percentile male for tibia fracture, taking into account scaled male PMHS data from Nyquist et al. (1985) using the standard tibia plateau height provided by DIN 33402-2 German anthropometrical database. The cumulative Gaussian distribution was used to develop the injury probability function. The calculated threshold value under consideration of possible scatter of test results and of a reproducibility corridor derived from inverse certification test results was 302 Nm.

A comparison of both approaches revealed that the calculated threshold values mainly depend on

- the underlying set of PMHS data
- the consideration of female and / or male data
- the use of scaled or unscaled data
- the particular anthropometrical database based on which human data are scaled
- the injury risk to be covered
- the statistical procedure to develop an injury probability function

As consensus for both approaches BASt proposed a rounded average value of 340 Nm for maximum tibia bending moment threshold.

In parallel to BASt proposing a rounded average value, JAMA conducted a correlation study on the EEVC WG 17 PLI tibia acceleration and FlexPLI tibia bending moment. As a result, they found that the 170 g EEVC WG 17 PLI tibia acceleration in gtr 9 was correlated to 343 Nm Flex-GTR tibia bending moment

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As this was almost the value proposed by BASt as average value between the BASt and former JAMA proposals, the group agreed at the 9th TEG meeting on September 3rd – 4th, 2009, on a consensus of the rounded value of 340 Nm.

2) MCL Elongation Threshold Value: 22 mm

a) 22 mm (JAMA)

JAMA developed an MCL injury risk function as average function between the risk functions from Ivarsson et al. (2004) and Konosu et al. (2001), latter one revised using the Weibull Survival Model. In this function, a 50% risk of knee injury in terms of MCL rupture corresponded to a human knee bending angle of 19 degrees. This value was converted to 19.1 mm MCL elongation, using a corresponding transition equation from computer simulation. After incorporating the effect of muscle tone the threshold value was calculated at 21 mm. As this value was converted to 16.9 degrees of EEVC WG 17 PLI knee bending angle by using a corresponding transition equation which would be by 11 % more conservative than the currently defined GTR threshold value of 19 deg, a 5% more conservative approach, equal to 18 deg EEVC WG 17 PLI knee bending angle was proposed and transformed to 22 mm MCL elongation, using the same transition equation as before.

b) 22 mm (BASt)

As BASt is not in the position to validate or double-check those results, they investigated a direct correlation between the EEVC WG 17 PLI knee bending angle and the FlexPLI MCL elongation as verification of the JAMA results. A transition equation was developed, based on hardware test results of different vehicle categories and idealized tests. Thus, a knee bending angle of 19 degrees would correspond to 22.7 mm MCL elongation. In order to provide at least the same level of protection as the current GTR, a threshold value of 22 mm was proposed which was in line with the JAMA proposal

At the 9th GRSP Flex-TEG meeting on September 3rd - 4th, 2009, the group agreed on a Flex-GTR threshold value for MCL elongation of 22 mm.

3) ACL/PCL Elongation Threshold Value

a) Mandatory with a threshold of 13 mm (BASt)

Currently, no injury risk curve for cruciate ligament injuries is available. BASt proposed to therefore use the results of PMHS tests described by Bhalla et al. (2003), stating that below a shear displacement of 12.7 mm sufficient protection is provided to the cruciate ligaments. Thus, and in the absence of more data but having in mind that the FlexPLI should provide at least the same level of protection as the EEVC WG 17 PLI, BASt proposed a mandatory threshold value of 13 mm for ACL/PCL.

b) Monitoring against a threshold of 13 mm (JAMA)

In contrast, JAMA stated that the percentage of isolated ACL/PCL injuries in real world data is low (less than 3%) and the biomechanical data is limited (only 2 data are available from Bhalla et al. (2003), which does not allow development of an injury probability function. Therefore, the tentative threshold value should be set for monitoring, subject to future modification to the tentative threshold based on additional biomechanical data.

c) No consideration (ACEA)

BASt threshold determination process

Tibia Bending Moment:

Biomechanical data scaled to size of legform

↓

Gauss distribution

↓

Human injury probability functions

↓

Correlations & Transfer functions:
Human ➔ Human model
Human model ➔ FlexPLI model
FlexPLI model ➔ FlexPLI

↓

Consideration of FlexPLI reproducibility

↓

FlexPLI Tibia BM threshold (BASt)

Consideration of 1st JAMA approach

←

BASt proposal Tibia BM

BASt threshold determination process

Tibia Bending Moment:

- **PMHS (only male) tests from Nyquist (1985):**

Test	Source	Gender	Age	Stature (cm)	Body Mass (kg)	Impact Speed (m/s)	Loading Direction	Peak BM at Midspan (CFC 60) [Nm]	Peak BM at Midspan M_{Max} [Nm]	Anatomical Measurement (Heel to Tibial Plateau) L [mm]	Standardized tibia height (DIN 33402-2) L_{ref} [mm]	Scaled Fracture Moment M_{scaled} [Nm]
118	Nyquist et. al.	M	54	182	68	3,5	LM*	395	434,5	520	460	300,8
124	Nyquist et. al.	M	64	177	82	4,2	LM*	287	315,7	490	460	261,2
126	Nyquist et. al.	M	58	174	73	4,2	LM*	224	246,4	480	460	216,9
127	Nyquist et. al.	M	56	176	79	3,7	LM*	237	260,7	465	460	252,4
129	Nyquist et. al.	M	57	178	99	3,7	LM*	349	383,9	500	460	298,9
132	Nyquist et. al.	M	57	187	45	3,8	LM*	264	290,4	445	460	320,8

*: Lateral to Medial

Source: Zander O.(TEG-098r1, 2010)

Calculation of scaled fracture moments: $M_{scaled}=[(L_{ref}/L)^3]*M_{max}$

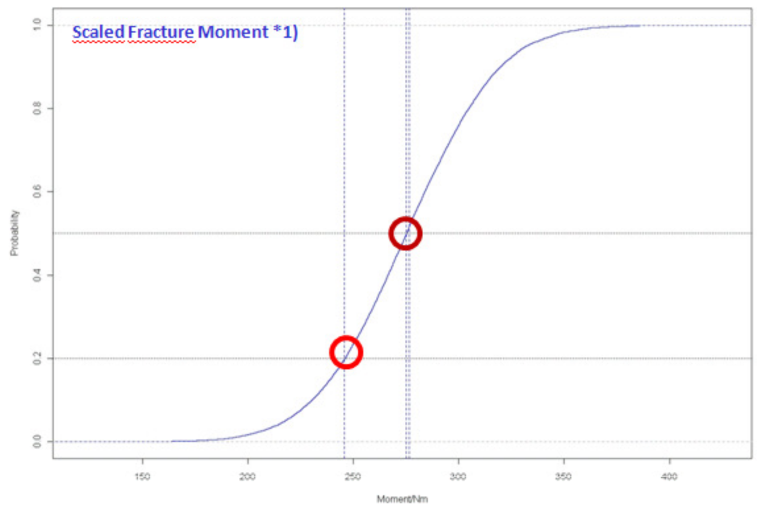
L_{ref}: standardized tibia height for scaling Nyquist data = 460 cm, taken from DIN 33402-2 for 18-65 yrs old male

BASt threshold determination process

Tibia Bending Moment:

- Development of injury risk function using Gaussian distribution
- Proposed bending moment threshold for 50% risk of human tibia bone fracture: 275,2 Nm (20% injury risk: 245,6 Nm)
- Assumptions (TEG-048):
  $BM_{human\ tibia} = BM_{human\ tibia\ model}$
  $BM_{Flex\text{-}GTR\ model} = BM_{Flex\text{-}GTR}$
- Calculation of $BM_{Flex\text{-}GTR}$ according to formula:
  $BM_{Flex\text{-}GTR} = 1{,}259 * 275{,}2\ Nm - 72{,}798 = 273{,}7\ Nm$
- Calculation of mean value of nine inverse tests (SN01, SN02, SN03) with reproducible test results acc. to ISO/TC22/SC12/WG5Doc N751 (CV's < 5%) and consideration of reproducibility corridor [0,9*MV*1,1]: 246,3 Nm < MV < 301,1 Nm

- Proposal for Tibia BM („lower performance limit"): 302 Nm



*1): according to formula $M_{scaled}=[(L_{ref}/L)^3]*M_{max}$ under consideration of DIN standardized tibia heights

Source: Pastor C. (2009)

BASt threshold determination process

Tibia Bending Moment:

- A comparison of both (JAMA & BASt) approaches revealed that the calculated threshold values mainly depend on
  - the underlying set of PMHS data
  - the consideration of female and / or male data
  - the use of scaled or unscaled data
  - the particular anthropometrical database for human data scaling
  - the injury risk to be covered
  - the statistical procedure to develop an injury probability function
- For GTR threshold value, BASt proposed to average both approaches at 340 Nm

BASt threshold determination process

MCL Elongation :

Correlation study

EEVC WG 17 PLI vs. FlexPLI

Tests on:
- Three different vehicles
- Inverse tests

Comparison of:
EEVC WG 17 PLI KBA
&
FlexPLI MCL EL

Transfer function:
EEVC WG 17 PLI KBA ➔ FlexPLI MCL EL

FlexPLI Tibia BM threshold (BASt)

Consideration of JAMA approach

BASt proposal MCL EL

BASt threshold determination process

MCL Elongation :

- Too many unknown factors within JAMA proposal that cannot be easily validated, also due to missing access to the different models

- Therefore, a direct correlation between knee BA and MCL output is meant as kind of verification of the JAMA results.

- For this purpose, a dataset 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) as well as inverse test results has been used

BASt threshold determination process

MCL Elongation :

- The used dataset comprised:

    - Two impact locations on 1Box front
    - Two impact locations on Sedan #1 front (assessed with both EEVC WG 17 PLI and FlexPLI, whereas the FlexPLI values have been calculated from the average of four tests)
    - Three impact locations on Sedan #2 front
    - Two impact locations on SUV front
    - Three inverse tests at +10 / 0 / -10 mm impact height

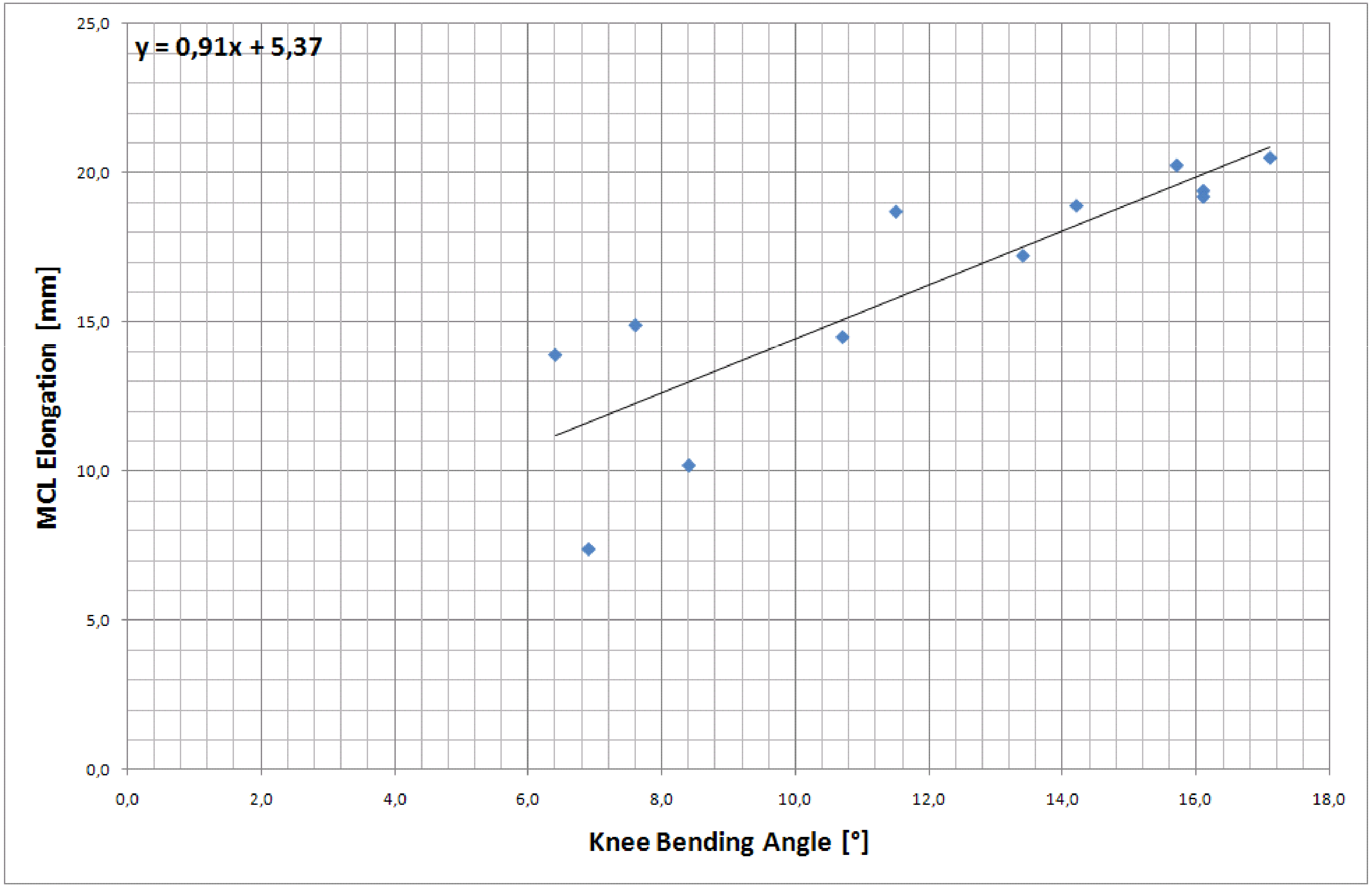
- All impact locations have been tested with both legform impactors.

- 30 tests in total (12 tests with the EEVC WG 17 PLI and 18 tests with the FlexPLI) were taken into account.

BASt threshold determination process

MCL Elongation :

EEVC WG 17 PLI Knee BA versus FlexPLI MCL EL:



BASt threshold determination process

MCL Elongation :

Conclusions / Proposal:

- In the relevant range, an acceptable correlation between knee bending angle and medial collateral ligament elongation within analysed tests.

- Calculation of $MCL\text{-}EL_{Flex\text{-}GTR}$ according to transition equation:
  $MCL\text{-}EL_{Flex\text{-}GTR} = 0{,}91 * KBA_{EEVC\ WG\ 17\ PLI} + 5{,}37 = 22{,}7\ mm$

- A maximum permitted Knee BA of 19 deg according to the GTR corresponds to 22,7 mm MCL elongation.

- As the FlexPLI should provide at least the same level of protection when being compared to the EEVC WG 17 PLI, the limit of 22 mm proposed by JAMA seems appropriate.

- Proposal for MCL EL: 22 mm

BASt threshold determination process

MCL Elongation :

- JAMA approach and BASt correlation study almost in line in terms of the outcome
- Consensus at 9th meeting of Flex-TEG:

Maximum MCL elongation: 22 mm

BASt threshold determination process

ACL / PCL Elongation: Correlation study

EEVC WG 17 PLI vs. FlexPLI

FlexPLI

FlexPLI

- Tests on different vehicles
- Inverse tests

Comparison of:
EEVC WG 17 PLI SD
&
FlexPLI ACL/PCL EL

Comparison of:
FlexPLI MCL
&
FlexPLI ACL

Comparison of:
FlexPLI SD
&
FlexPLI ACL

Transfer function:
EEVC WG 17 PLI SD
➔ FlexPLI ACL/PCL EL

Transfer function:
FlexPLI MCL EL
➔ FlexPLI ACL EL

Consideration of geometry

FlexPLI ACL/PCL threshold

FlexPLI ACL/PCL threshold

FlexPLI ACL/PCL threshold

BASt proposal ACL/PCL EL

BASt threshold determination process

- **For cruciate ligament injuries, so far no injury risk curve has been developed**
- **The IHRA/PS-WG just described an example of 10 mm from a computer simulation analysis carried out by IHRA (2004)**
- **The EEVC WG 17 PLI uses the knee shear displacement (relative displacement between tibia and femur at the knee joint level in lateral direction) to evaluate cruciate ligament (ACL, PCL) injuries (EEVC, 2002)**
- **ACL the more critical ligament because under the defined impact conditions less protected:**

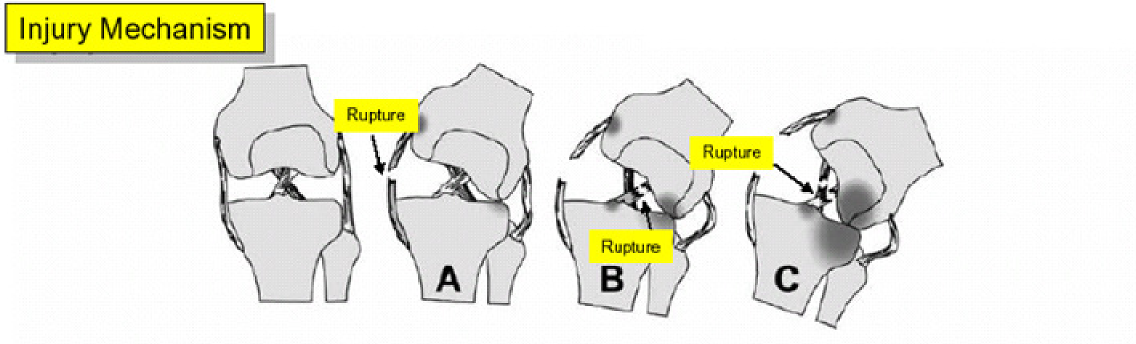


Fig. 8. Stages of the left knee injury (frontal view) in the mechanism of valgus flexion. (A) Avulsion of the medial collateral ligament; (B) avulsion of the anterior cruciate ligament; (C) avulsion of the posterior cruciate ligament. A → C increasing compression of the lateral tibial and femoral condyles.

Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents, Forensic Science International 124 (2001) 74-82
[Source: Teresinski et al, 2001]

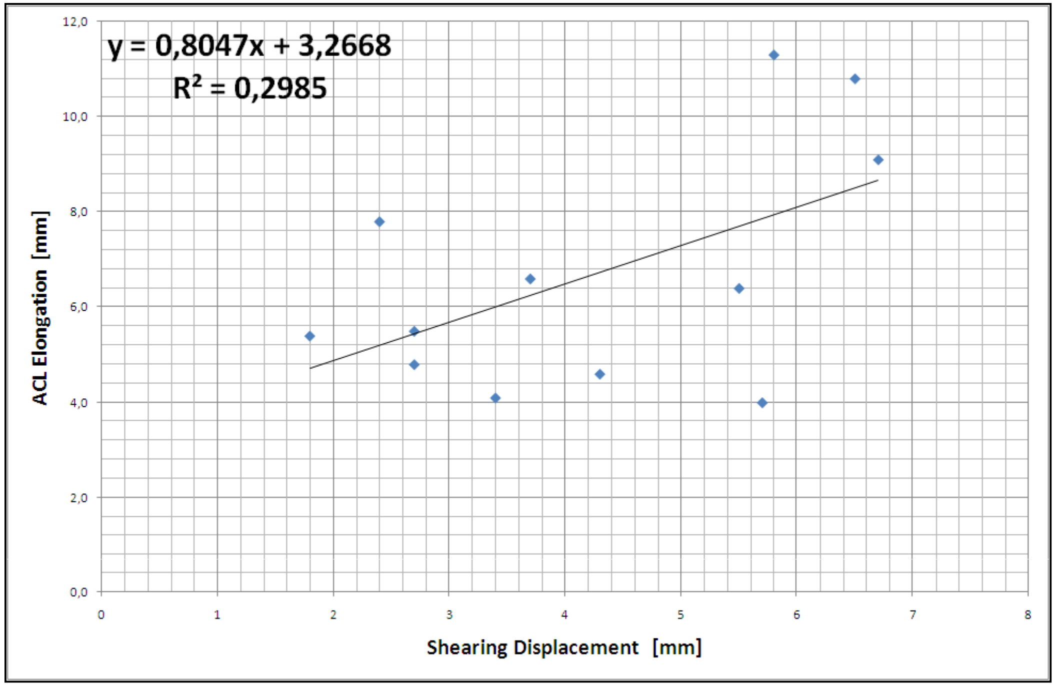
BASt threshold determination process

1) EEVC WG 17 PLI SD & FlexPLI ACL/PCL correlation study

- Derivation of FlexPLI threshold from a dataset of 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) as well as inverse test results
- The used dataset comprised:
  - ➢ Two impact locations on 1Box front
  - ➢ Two impact locations on Sedan #1 front (assessed with both EEVC WG 17 PLI and FlexPLI, whereas the FlexPLI values have been calculated from average of four tests)
  - ➢ Three impact locations on Sedan #2 front
  - ➢ Two impact locations on SUV front
  - ➢ Three inverse tests at +10 / 0 / -10 mm impact height
- All impact locations have been tested with both legform impactors.
- In total, 12 tests with the EEVC WG 17 PLI and 18 tests with FlexPLI

BASt threshold determination process

- The best correlation was found between SD and ACL (which is the ligament being subjected to tension due to application of shear force):



- According to the transition equation y = 0,8x + 3,27 a maximum permitted shearing displacement of 6 mm according to the GTR would correspond to 8 mm ACL elongation.

BASt threshold determination process

2) FlexPLI MCL & FlexPLI ACL correlation study

- In a second step, a correlation study between FlexPLI MCL and ACL output was carried out

- Reason: the described knee injury mechanism in the defined lateral car-to-pedestrian accidents leads to the assumption that ACL rupture occurs before PCL rupture (Teresinski et al, 2001)

- The 50% risk of MCL rupture has been determined and agreed by the Flex-TEG at 22 mm elongation

- Dataset for correlation study consisted of test results of:

– Two impact locations on 1Box front
– Two impact locations on Sedan #1 front
– Two impact locations on Sedan #2 front
– Inverse tests

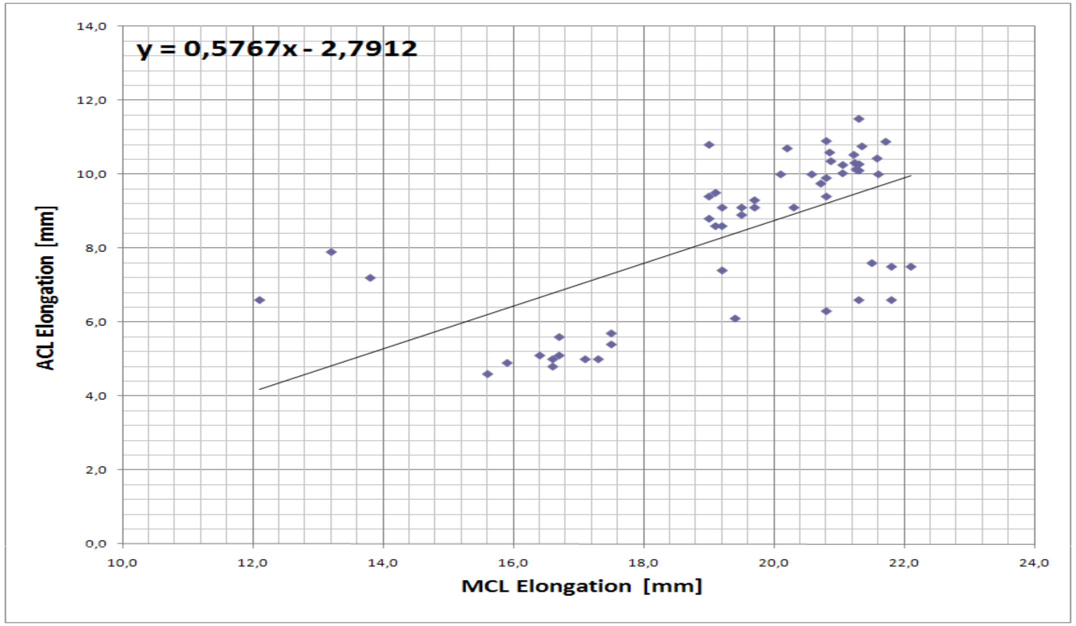
- In total 55 tests with the FlexPLI-GTR were taken into account

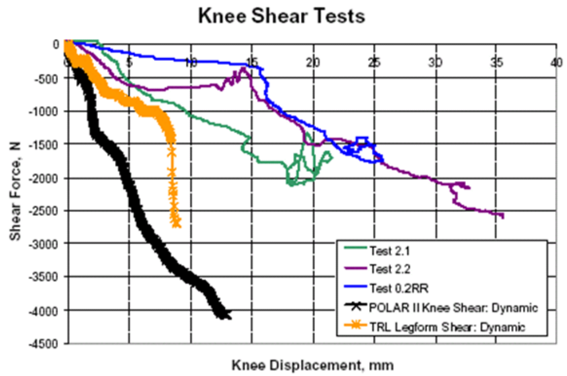
BASt threshold determination process

- According to the developed transition equation
  y = 0,5767x -2,7912
  a 22 mm Flex-GTR MCL elongation corresponds to 9,9 mm ACL elongation

- Therefore, if the previously made assumptions are correct, it can be assumed that ACL rupture occurs beyond 10 mm elongation output of the Flex-GTR

- On the other hand, Bhalla et al (2003) stated a tolerance of at least 12,7 mm for human knee shear displacement of the 50th male, see next slide.



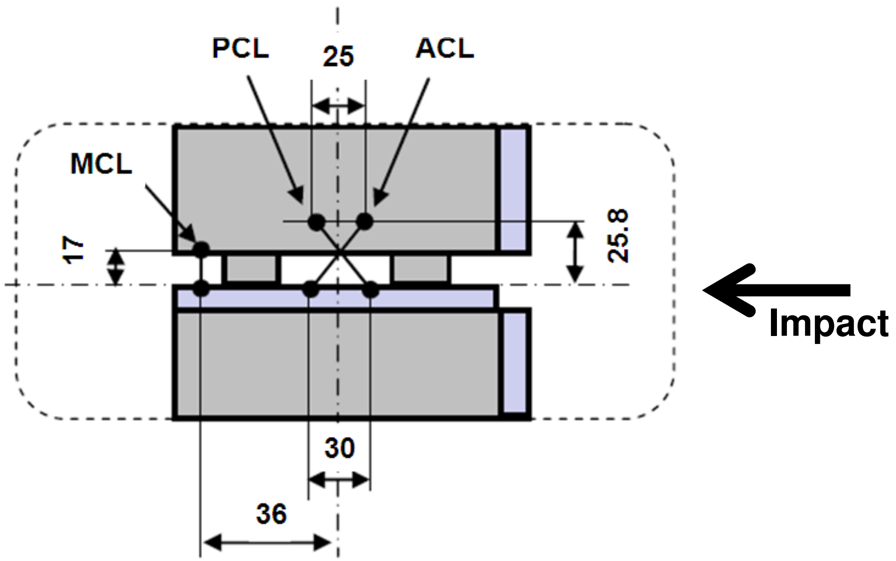


Dynamic shear tests on the TRL legform and POLAR-II knee joint plotted along with two PMHS shear tests performed by UVA)
[Source: Bhalla et al, 2003]

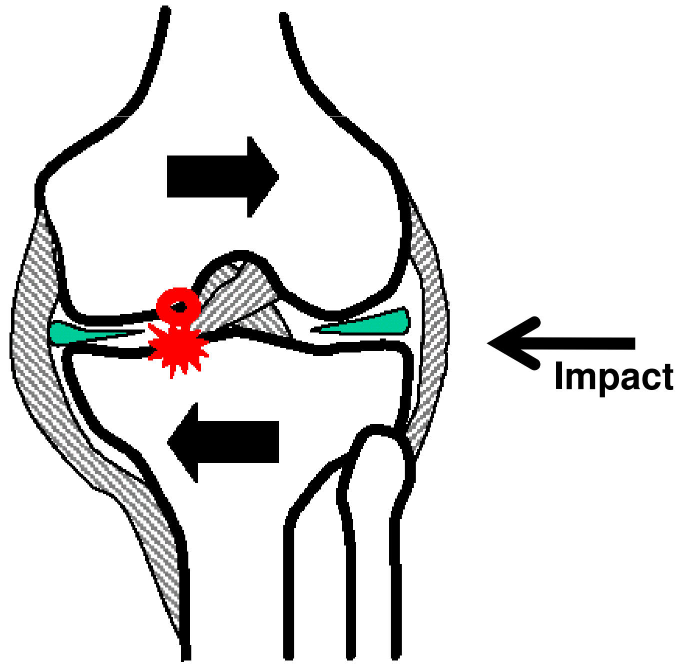
BASt threshold determination process

3) FlexPLI SD & FlexPLI ACL correlation study

- **Bhalla et al (2003) found tolerances of 12,7 mm and 17,8 mm for human knee shear displacement of the 50th male**
- **The knee shear displacement can be transformed to FlexPLI ACL /PCL elongation, taking into account the knee measurement locations**

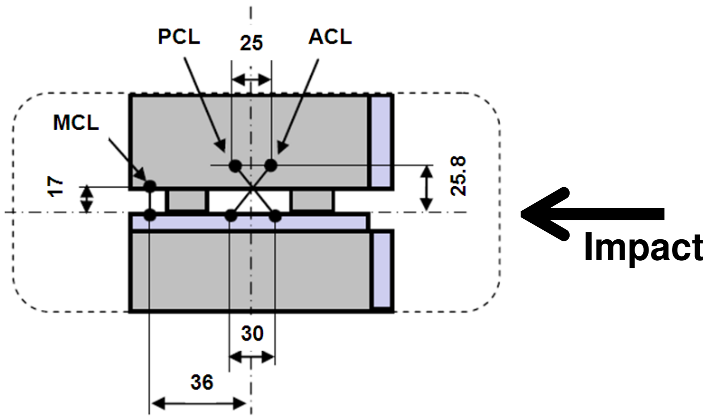


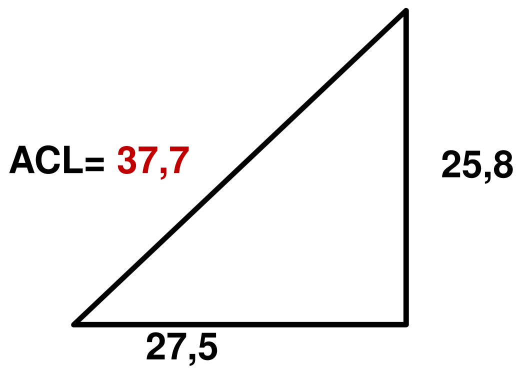
Flex measurement location [Source: JARI, April 2010]



Damage mechanism in knee shear loading
[Source: Bhalla et al, 2003]

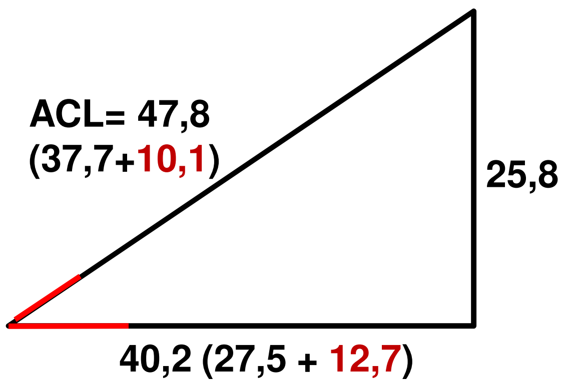
BASt threshold determination process



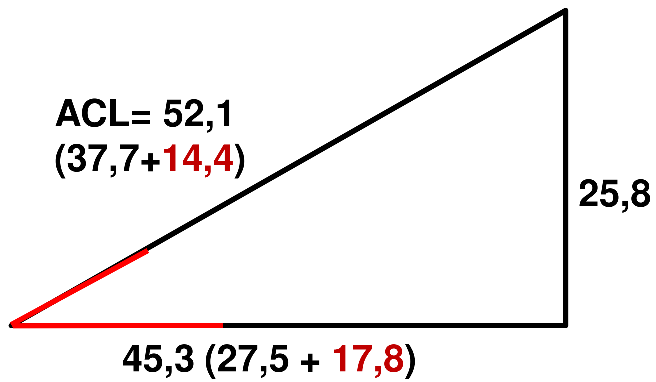


ACL length in unloaded condition @ approx. 37,7 mm

Shearing of 12,7 mm causes ACL EL of approx. 10,1 mm



Shearing of 17,8 mm causes ACL EL of approx. 14,4 mm



BASt threshold determination process

Under the previously made observations, the following transformations were defined:

1. WG 17 PLI SD to FlexPLI ACL EL transition:
   6 mm SD → 8 mm ACL EL

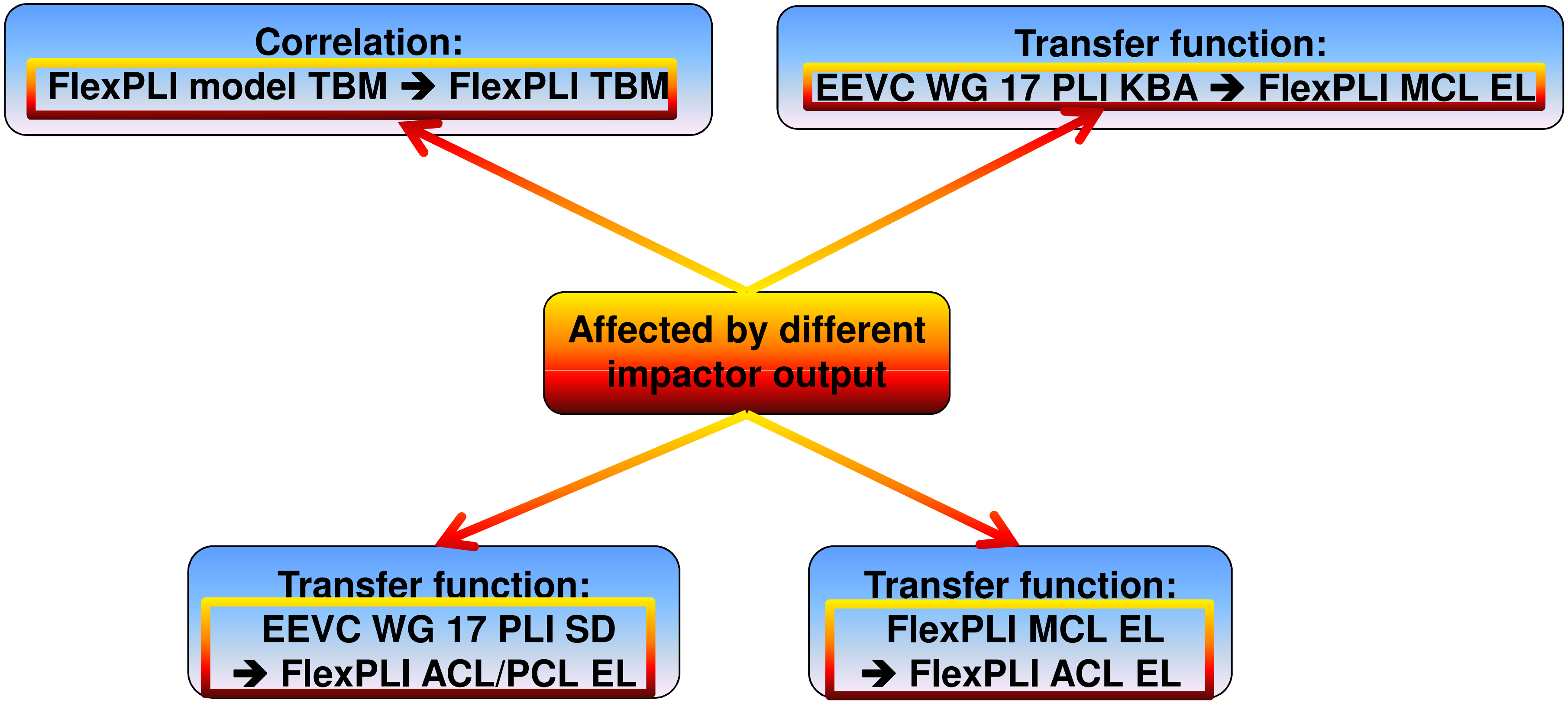
2. FlexPLI MCL to FlexPLI ACL EL transition:
   22 mm MCL EL → 9,9 mm ACL EL

3. Human knee SD to FlexPLI SD to FlexPLI ACL EL transition:
   12,7 mm Human knee SD (Bhalla PMHS SD test result)
   → 12,7 mm FlexPLI SD → 10,1 mm FlexPLI ACL EL
   (Assumption: Human knee SD ↔ FlexPLI SD)

Proposal:

In absence of injury risk functions for the cruciate ligaments and information on actual relation between human knee and FlexPLI ACL/PCL elongation a threshold value of 13 mm ACL/PCL elongation was proposed as performance limit.

Conclusions



Conclusions

- In this document, the process of determining the injury criteria and corresponding impactor threshold values used by BASt is described.
- The procedure used by BASt deriving the FlexPLI threshold values was depending on the actual performance of the FlexPLI prototypes.
- Therefore, due to the different impactor behaviour of the master legforms, having an impact on the developed transfer functions, BASt is proposing to modify the FlexPLI threshold values accordingly.
- However, the change in impactor performance has no influence on the described injury criteria, which are therefore proposed to remain unchanged.

Thank you !