Derivation of
Draft FlexPLI prototype impactor limits
by BASSt

6th Meeting of Informal Group GTR9 Phase 2
Washington DC, March 19th - 20th, 2012
Background

- At the 5th meeting of the IG GTR9-PH, BASit 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).
- BASit 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 BASit 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 BASit as contribution to the Flex-TEG.
Flex-TEG Agreement (TEG-127)

TEG-127
7 December 2009

Technical Background Information Document for the UN-ECE GRSP explaining the Derivation of Threshold Values and Impactor Certification methods for the FlexPU version GTR agreed by the FlexPU-TEG at their 5th Meeting

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1) Tibia Threshold Value: 340 Nm

At the 5th GRSP Flex-TEG meeting on May 19th, 2009, two proposals for the tibia threshold value of the FlexPU version GTR (also called Flex-PU) were made by JAMA and BAST, coming to different conclusions.

a) 380 Nm (JAMA)

JAMA derived the Flex-PU tibia bending moment threshold using a linear transition equation between human and Flex-PU 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 95th percentile male for tibia fracture, taking into account scaled male and female PHAMS data from Nyquist et al. (1985) and Kremser 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 Wedell Survival Model was used to develop the injury probability function. The proposed final threshold value resulted in 380 Nm.

b) 322 Nm (BAST)

BAST derived the Flex-PU tibia bending moment threshold also using the corresponding transition equation between human and Flex-PU FE models. The average human tibia bending moment threshold value was taken from an injury risk curve of the 95th percentile male for tibia fracture, taking into account scaled male PHAMS data from Nyquist et al. (1985) using the standard tibia plate height provided by DIN 2402-2 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 322 Nm.

A comparison of both approaches revealed that the calculated threshold values mainly depend on:
- the underlying set of PHAMS 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 WF 17 FL tibia acceleration and FlexPU tibia bending moment. As a result, they found that the 270 g EEVC WF 17 FL tibia acceleration in gtr 9 was correlated to 343 Nm FlexPU tibia bending moment.

At this was almost the value proposed by BAST as average value between the BAST and former JAMA proposals, the group agreed at the 5th TEG meeting on September 3rd – 4th, 2009, on a consensus of the rounded value of 340 Nm.

2) MCL, Elongation Threshold Values: 22 mm

a) 22 mm (JAMA)

JAMA developed an MCL injury risk function as average function between the risk functions from Ivansson et al. (2004) and Kosonosu et al. (2001), latter one revised using the Wedell Survival Model. In this function, a 5% risk of knee injury in terms of MCL rupture corresponded to a human knee bending angle of 10 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 23 mm. As this value was converted to 18.9 degrees of EEVC WF 17 FL knee bending angle by using a corresponding transition equation which would be by 12% more conservative than the currently defined GTR threshold value of 10 deg, a 12% more conservative approach, equalling to 18.8 deg EEVC WF 17 FL 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 these results, they investigated a direct correlation between the EEVC WF 17 FL knee bending angle and the FlexPU MCL elongation as validation of the EEVC WF 17 FL simulation model with the help of different vehicle categories and idealized tests. Thus, a knee bending angle of 18 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 4th GRSP Flex-TEG meeting on September 9th – 10th, 2009, the group agreed on a Flex-PU threshold value for MCL elongation of 22 mm.

3) ACL/PCL Elongation Threshold Value

a) Mandatory with a threshold of 6.5 mm (BAST)

Currently, no injury risk curve for cruciate ligament injuries is available. BAST proposed to therefore use the results of PHAMS tests described by Khwaja et al. (2006), 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 FlexPU should provide at least the same level of protection as the EEVC WF 17 FL, BAST proposed a mandatory threshold value of 55 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 1%) and the biomechanical data is limited. Only 2 data are available from Khwaja et al. (2006), 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.

As no consideration (AC/PCL)

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BASt threshold determination process

Tibia Bending Moment:

1. Biomechanical data scaled to size of legform
2. Gauss distribution
3. Human injury probability functions
4. Correlations & Transfer functions:
   - Human → Human model
   - Human model → FlexPLI model
   - FlexPLI model → FlexPLI

5. Consideration of 1st JAMA approach
6. Consideration of FlexPLI reproducibility
7. FlexPLI Tibia BM threshold (BASt)

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**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 \(M_{\text{Max}}\) [Nm] | Anatomical Measurement (Heel to Tibial Plateau) \(L_{\text{ref}}\) [mm] | Standardized tibia height (DIN 33402-2) \(L_{\text{ref}}\) [mm] | Scaled Fracture Moment \(M_{\text{scaled}}\) [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:**

\[
M_{\text{scaled}} = [(L_{\text{ref}}/L)^3]M_{\text{max}}
\]

\(L_{\text{ref}}\): standardized tibia height for scaling Nyquist data = 460 mm, 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):
  - \( B_{\text{BM}}_{\text{human tibia}} = B_{\text{BM}}_{\text{human tibia model}} \)
  - \( B_{\text{BM}}_{\text{Flex-GTR model}} = B_{\text{BM}}_{\text{Flex-GTR}} \)
- **Calculation of \( B_{\text{BM}}_{\text{Flex-GTR}} \) according to formula:**
  \[ B_{\text{BM}}_{\text{Flex-GTR}} = 1.259 \times 275.2 \text{ Nm} - 72.798 = 273.7 \text{ Nm} \]
- **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 \([0.9\times MV\times 1.1]\):** 246.3 Nm < MV < 301.1 Nm
- **Proposal for Tibia BM** („lower performance limit“): 302 Nm
BASt threshold determination process

Tibia Bending Moment:

- A comparison of both (JAMA & BASSt) 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, BASSt 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

Consideration of JAMA approach

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

FlexPLI MCL EL threshold (BASt)
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.
EEVC WG 17 PLI Knee BA versus FlexPLI MCL EL:

\[ y = 0.91x + 5.37 \]
Conclusions / Proposal:

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

- Calculation of $\text{MCL-EL}_{\text{Flex-GTR}}$ according to transition equation:
  
  \[ \text{MCL-EL}_{\text{Flex-GTR}} = 0.91 \times KBA_{\text{EEVC WG 17 PLI}} + 5.37 = 22.7 \text{ mm} \]

- 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
MCL Elongation:

- JAMA approach and BASSt 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

- Tests on different vehicles
- Inverse tests

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

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

FlexPLI ACL/PCL threshold

Comparison of:
FlexPLI MCL & FlexPLI ACL

Transfer function:
FlexPLI MCL EL ➔ FlexPLI ACL EL

FlexPLI ACL/PCL threshold

Comparison of:
FlexPLI SD & FlexPLI ACL

Consideration of geometry

FlexPLI ACL/PCL threshold

BASt proposal ACL/PCL EL

Oliver Zander
March 19th-20th, 2013
Slide No. 14
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 talar tibial and femoral condyles.

[Source: Teresinski et al. 2001]
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
• The best correlation was found between SD and ACL (which is the ligament being subjected to tension due to application of shear force):

![Graph showing correlation between Shearing Displacement and ACL Elongation](image)

\[ y = 0,8047x + 3,2668 \]

\[ R^2 = 0,2985 \]

• 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.
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.
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
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

- Correlation: FlexPLI model TBM → FlexPLI TBM
- Transfer function: EEVC WG 17 PLI KBA → FlexPLI MCL EL

Affected by different impactor output

- Transfer function: EEVC WG 17 PLI SD → FlexPLI ACL/PCL EL
- Transfer function: FlexPLI MCL EL → FlexPLI ACL EL
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!