# Informal Group on GTR9 Phase2 (IG GTR9-PH2) 1st Meeting

## Technical Discussion – Injury Criteria

December 1-2, 2011

Japan Automobile Internationalization Center (JASIC)

# Outline

1. Flex-TEG Discussion on Flex-PLI Injury Thresholds
2. Validation – Tibia Fracture Threshold
3. Validation – MCL Failure Threshold
4. Validation – ACL Failure Threshold
5. Summary

# 1. Flex-TEG Discussion on Flex-PLI Injury Thresholds

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 FlexPLI version GTR agreed by the FlexPLI-TEG at their 9th Meeting**

Drafted by: Atsuhiro Konosu (JARI/J-MLIT) and Oliver Zander (BASt) on behalf of the GRSP FlexPLI Technical Evaluation Group (TEG)

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.

## Injury threshold discussion at Flex-TEG based on various studies by Flex-TEG members

# 1. Flex-TEG Discussion on Flex-PLI Injury Thresholds

## - Proposed Thresholds -

TEG-127

| Injury | Measure | Threshold | Note |
|---|---|---|---|
| Tibia Fracture | Max. Tibia Bending Moment | 340 Nm<br>380 Nm | <br>Relaxation Zone |
| MCL Failure | Max. MCL Elongation | 22 mm | |
| ACL/PCL Failure | Max. ACL/PCL Elongation | 13 mm | |

**Common threshold values were reached and proposed by Flex-TEG**

# 2. Validation – Tibia Fracture Threshold

## - EEVC WG17 Report -


Tibia Fracture Probability
As a Function of Tibia Acceleration

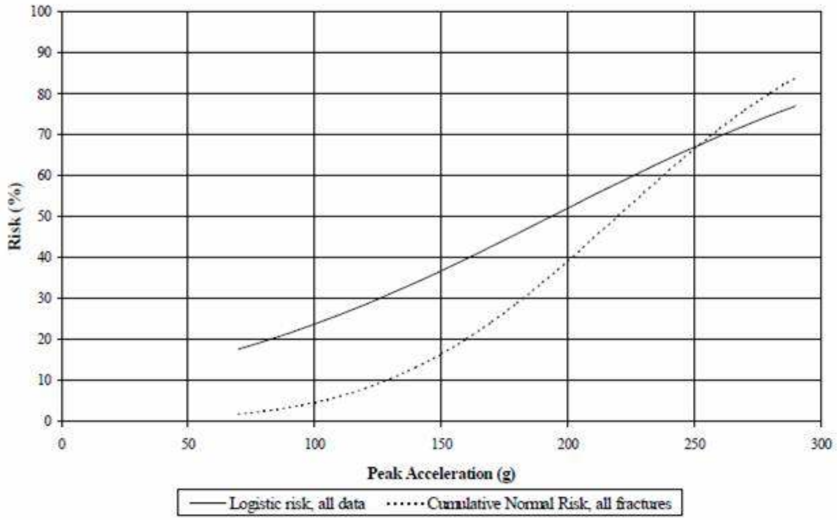


*Figure 3. Comparison of AIS 2+ lower leg injury risk functions based on a logistic method and based on a cumulative normal method using 20 cadaver leg tests[32], obtained from [31].*

**Re-analyze tibia fracture probability function for tibia acceleration**

Reference: European Enhanced Vehicle-safety Committee, EEVC Working Group 17 Report, IMPROVED TEST METHODS TO EVALUATE PEDESTRIAN PROTECTION AFFORDED BY PASSENGER CARS (1998)

# 2. Validation – Tibia Fracture Threshold

## - EEVC WG17 Report -


28. Ishikawa, H. et al.:
*A Study on Injury Criteria of EEVC Pedestrian Legform Test.*
JARI/JAMA, June 1998, EEVC WG17 document 85.

29. JAMA:
*JAMA proposal regarding the Criteria of Pedestrian Protection Test Procedure.*
June 1998, EEVC WG17 document 83.

30. Cesari, D.:
*Pedestrian Protection - synthesis of experimental and simulation researches performed in France.*
INRETS, August 1998, EEVC WG17 document 92.

31. Bunketorp, O. et al.:
*Experimental Study of a Compliant Bumper System.*
SAE paperno. 831623, 1983.


← Data Source


32. Rodmell, C. and G.J.L. Lawrence:
*Comparison between dose-response and cumulative methods of injury risk analysis and implications on the JARI injury risk analysis.*
TRL, November 1998, EEVC WG17 document 111.

33. Schreiber, P. et al.:
*Static and dynamic bending strength of the leg.*
Proceedings IRCOBI Conference, September 1997, EEVC WG17 document 61.


**Human data from Bunketorp et al. (1983)**

Reference: European Enhanced Vehicle-safety Committee, EEVC Working Group 17 Report, IMPROVED TEST METHODS TO EVALUATE PEDESTRIAN PROTECTION AFFORDED BY PASSENGER CARS (1998)

# 2. Validation – Tibia Fracture Threshold

- Bunketorp et al., 1983 -

831623

## Experimental Study of a Compliant Bumper System

Olle Bunketorp, Bertil Romanus, and Tommy Hansson
Dept. of Orthopaedic Surgery
University of Göteborg

Bertil Aldman and Lennart Thorngren
Dept. of Traffic Safety
Chalmers University of Technology
Göteborg

Rolf H. Eppinger
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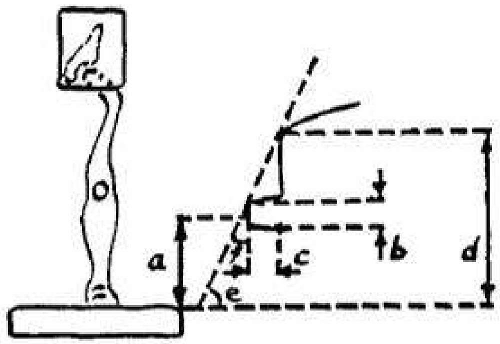
Washington, DC

ABSTRACT

An ordinary rigid bumper system and a ...ian protection

During the last years the annual number of pedestrian casualties constituted approximately 20% of the total number of injured road users /3/.




a=bumper level
b=bumper width
c=bumper lead distance
d=bonnet edge height
e=bumper lead angle
f=front inclination angle (= 90-e)

Figure 1 The experimental set up.

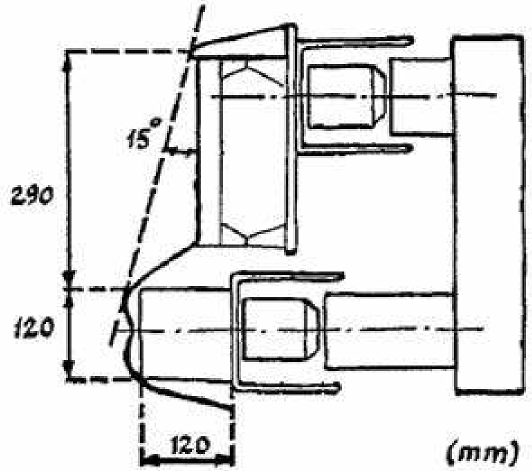



Figure 2 Section of the impact zone

**Isolated lower limbs impacted by high/low and rigid/compliant bumpers**

Reference: Bunketorp O., Romanus B., Hansson T., Aldman B., Thorngren L. Eppinger R., Experimental Study of a Compliant Bumper System, 27th Stapp Car Crash Conference Proceedings, SAE Paper Number 831623 (1983)

# 2. Validation – Tibia Fracture Threshold

## - Bunketorp et al., 1983 -

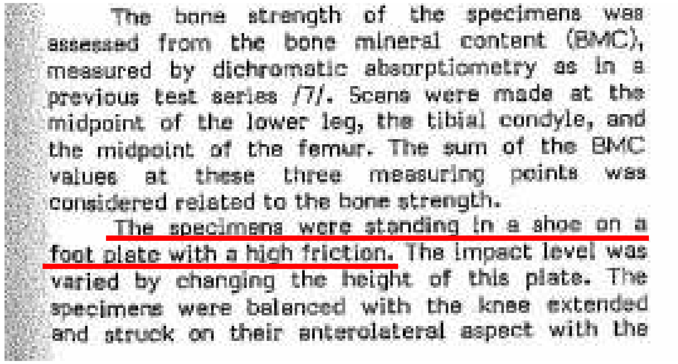
| Front Configuration | Test No. | Age | Gender | Tibia Length (mm) | Peak Accel. (G) | Fem. Condyle Fx | Tib. Condyle Fx. | MCL Failure | ACL Failure | PCL Failure | Tib. Fx | Fib. Fx | Ankle Fx | Ankle Lig. Failure |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| High/Rigid | 1 | 61 | M | 400 | 230 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 2 | 80 | M | 350 | 260 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 3 | 77 | M | 350 | 285 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| | 4 | 81 | F | 360 | 295 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| | 5 | 77 | M | 380 | 245 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| High/Compliant | 6 | 71 | M | 390 | 95 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| | 7 | 76 | F | 350 | 85 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 8 | 65 | M | 370 | 70 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| | 9 | 72 | M | 380 | 85 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| | 10 | 54 | M | 420 | 100 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Low/Rigid | 11 | 73 | F | 380 | 225 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| | 12 | 73 | F | 370 | 275 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| | 13 | 75 | M | 350 | 200 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | 14 | 86 | M | 390 | 270 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| | 15 | - | - | 370 | 280 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Low/Compliant | 16 | 74 | F | 350 | 70 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 17 | 75 | F | 340 | 80 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 18 | 83 | F | 350 | 115 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |
| | 19 | 76 | M | 380 | 120 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 20 | 69 | M | 400 | 80 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

Injury Data 0: No Injury, 1: Injury

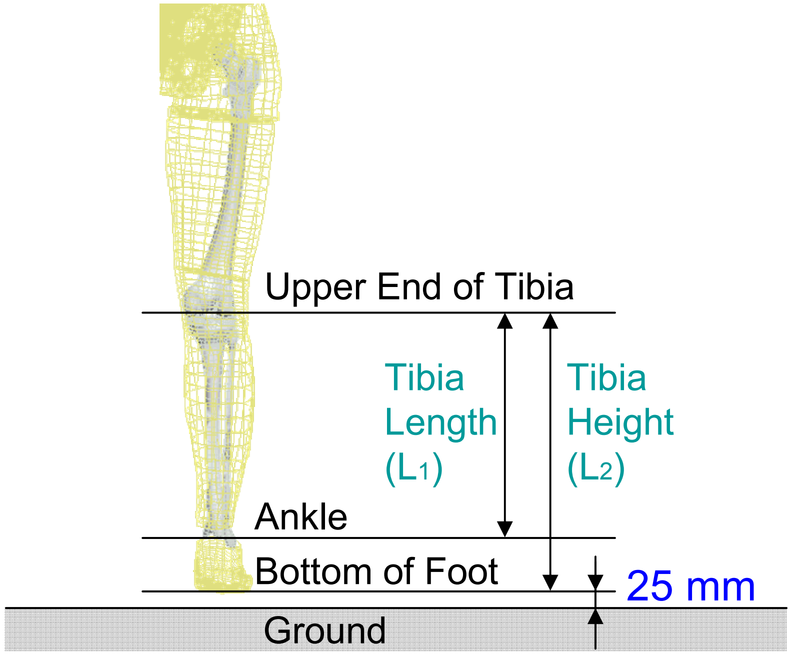
- **EEVC probability functions used all the tibia/fibula fracture data regardless of the impact location relative to the fracture location**
- **Fracture data due to direct impact should be used to develop fracture probability function for upper tibia acceleration**

# 2. Validation – Tibia Fracture Threshold

## - Assumption -


The bone strength of the specimens was assessed from the bone mineral content (BMC), measured by dichromatic absorptiometry as in a previous test series /7/. Scans were made at the midpoint of the lower leg, the tibial condyle, and the midpoint of the femur. The sum of the BMC values at these three measuring points was considered related to the bone strength.

The specimens were standing in a shoe on a foot plate with a high friction. The impact level was varied by changing the height of this plate. The specimens were balanced with the knee extended and struck on their anterolateral aspect with the




- Bunketorp et al. provides Tibia Length
- Estimate Knee Height from the ground

Leg specimens were wearing a shoe

**Assume 25mm between the ground and the bottom of the foot**

UMTRI Anthropometric Study :
$L_1$ = 402 mm
$L_2$ = 483 mm

**Assume $L_2 / L_1$ = 1.2015 (Ratio from UMTRI data) for all specimens**

# 2. Validation – Tibia Fracture Threshold

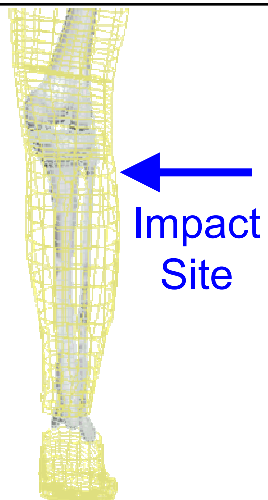
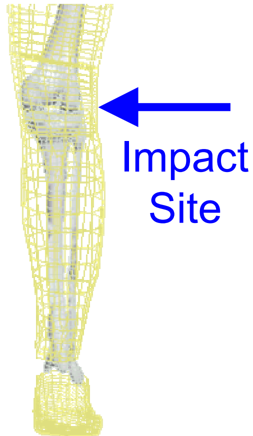
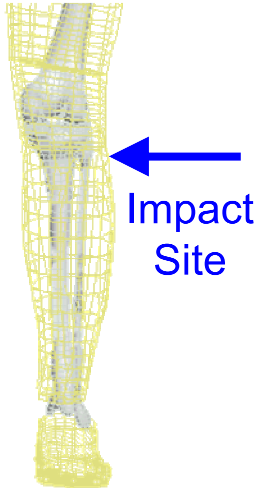
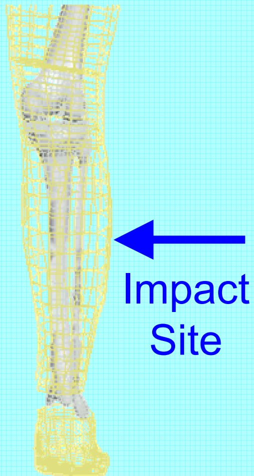
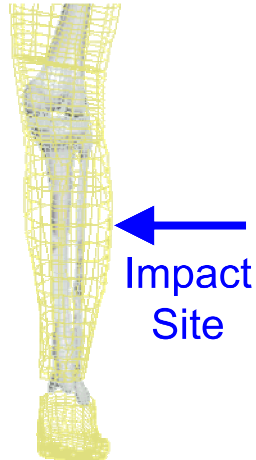
| Front Configuration | Test No. | Age | Gender | Tibia Length (mm) | Peak Accel. (G) | Tib. Condyle Fx. | Tib. Fx | Fib. Fx | Estimated Tibia Height (mm) | Estimated Ground-Knee (mm) | Bumper Height (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High/Rigid | 1 | 61 | M | 400 | 230 | 1 | 0 | 0 | 480.6 | 505.6 | 450 |
| | 2 | 80 | M | 350 | 260 | 0 | 0 | 0 | 420.5 | 445.5 | 450 |
| | 3 | 77 | M | 350 | 285 | 1 | 0 | 1 | 420.5 | 445.5 | 450 |
| | 4 | 81 | F | 360 | 295 | 0 | 0 | 0 | 432.5 | 457.5 | 450 |
| | 5 | 77 | M | 380 | 245 | 0 | 0 | 0 | 456.6 | 481.6 | 450 |
| High/Compliant | 6 | 71 | M | 390 | 95 | 1 | 1 | 1 | 468.6 | 493.6 | 450 |
| | 7 | 76 | F | 350 | 85 | 0 | 0 | 0 | 420.5 | 445.5 | 450 |
| | 8 | 65 | M | 370 | 70 | 0 | 0 | 0 | 444.6 | 469.6 | 450 |
| | 9 | 72 | M | 380 | 85 | 0 | 0 | 0 | 456.6 | 481.6 | 450 |
| | 10 | 54 | M | 420 | 100 | 0 | 0 | 0 | 504.6 | 529.6 | 450 |
| Low/Rigid | 11 | 73 | F | 380 | 225 | 1 | 0 | 1 | 456.6 | 481.6 | 325 |
| | 12 | 73 | F | 370 | 275 | 0 | 1 | 1 | 444.6 | 469.6 | 325 |
| | 13 | 75 | M | 350 | 200 | 1 | 0 | 1 | 420.5 | 445.5 | 325 |
| | 14 | 86 | M | 390 | 270 | 0 | 1 | 1 | 468.6 | 493.6 | 325 |
| | 15 | - | - | 370 | 280 | 0 | 0 | 1 | 444.6 | 469.6 | 325 |
| Low/Compliant | 16 | 74 | F | 350 | 70 | 0 | 0 | 0 | 420.5 | 445.5 | 325 |
| | 17 | 75 | F | 340 | 80 | 0 | 0 | 0 | 408.5 | 433.5 | 325 |
| | 18 | 83 | F | 350 | 115 | 0 | 0 | 1 | 420.5 | 445.5 | 325 |
| | 19 | 76 | M | 380 | 120 | 0 | 0 | 0 | 456.6 | 481.6 | 325 |
| | 20 | 69 | M | 400 | 80 | 0 | 0 | 0 | 480.6 | 505.6 | 325 |

Injury Data 0: No Injury, 1: Injury

**Investigate impact locations relative to the leg for each specimen with leg fractures using estimated knee height**

# 2. Validation – Tibia Fracture Threshold

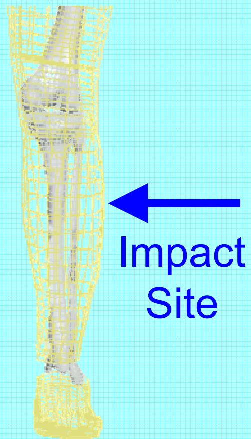
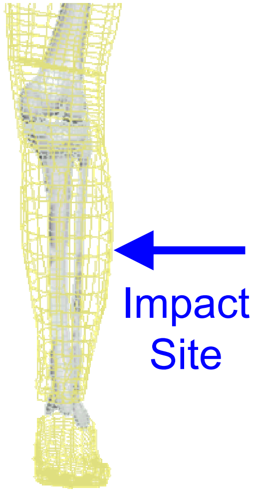
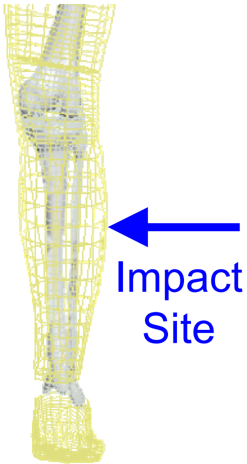
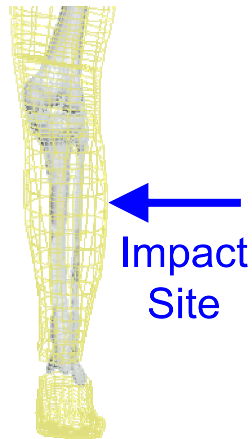
## - Specimens with Leg Fractures -

| Test # | 1 | 3 | 6 | 11 | 12 |
|---|---|---|---|---|---|
| Schematics (Impact locations) |  |  |  |  |  |
| Documented Leg Fractures | • Tibial Condyle | • Tibial Condyle<br>• Fibula | • Tibial Condyle<br>• Tibia (shaft)<br>• Fibula | • Tibial Condyle<br>• Fibula | • Tibia (shaft)<br>• Fibula |
| Direct / Indirect Estimation | Direct (Tibia) | Direct (Tibia and Fibula) | Direct (Tibia and Fibula)<br>Indirect (Tibia) | Indirect (Tibia)<br>Direct (Fibula) | Direct (Tibia and Fibula) |

*fracture locations possibly due to direct loading: in blue

# 2. Validation – Tibia Fracture Threshold

## - Specimens with Leg Fractures -

| Test # | 13 | 14 | 15 | 18 |
|---|---|---|---|---|
| Schematics (Impact locations) |  Impact Site |  Impact Site |  Impact Site |  Impact Site |
| Documented Leg Fractures | • Tibial Condyle<br>• Fibula | • Tibia (shaft)<br>• Fibula | • Fibula | • Fibula |
| Direct / Indirect Estimation | Indirect (Tibia)<br>Direct (Fibula) | Direct (Tibia and Fibula) | Direct (Fibula) | Direct (Fibula) |

*fracture locations possibly due to direct loading: in blue

# 2. Validation – Tibia Fracture Threshold

- Development of Fracture Probability Function from Bunketorp et al. (1983) -

- Develop fracture probability function under the following conditions
  - Weibull Survival Model
  - Fracture data analyzed as "left censored" (no data provided as to the correlation between fracture and peak acceleration)
  - No fracture data analyzed as "right censored"
  - Acceleration data scaled to standard anthropometry (UMTRI data) using the standard tibia length (402 mm) : Scale factor for acceleration is $1/\lambda_L$ (where $\lambda_L$ is length scaling factor)
- Data classification (Injury / No injury)
  - Injury data : Test 1, 3, 6, 12, 14
  - No injury data : Test 2, 4, 5, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20
  - Eliminate tests 11 and 13 (fracture due to indirect loading)

# 2. Validation – Tibia Fracture Threshold

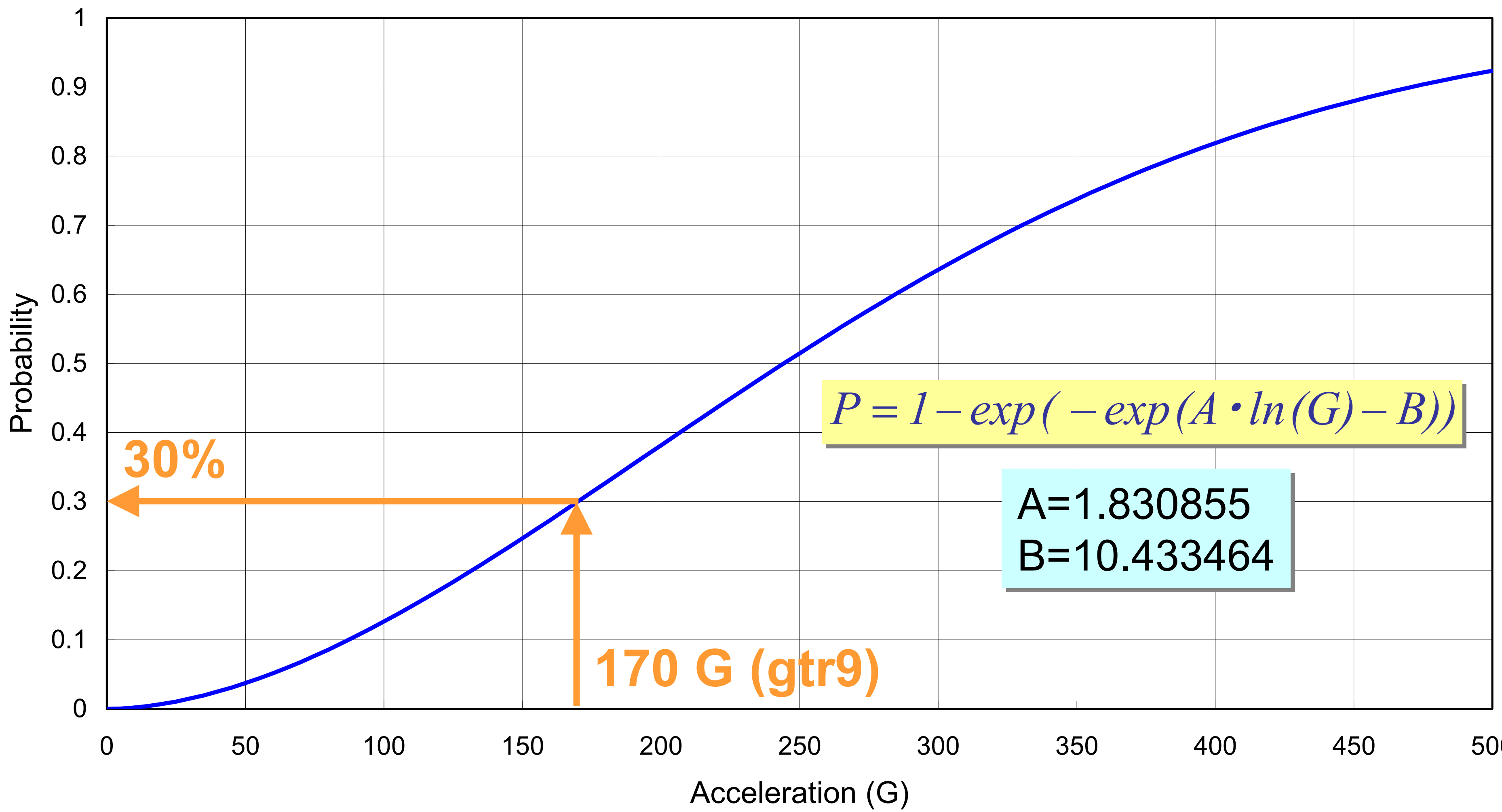
## - Development of Fracture Probability Function from Bunketorp et al. (1983) -

| Front Configuration | Test No. | Age | Gender | Tibia Length (mm) | Peak Accel. (G) | Tib. Condyle Fx. | Tib. Fx | Fib. Fx | Peak Accel. (G) | UMTRI Tibia Length | UMTRI Length Scale Factor | UMTRI Scaled Accel. (G) | Classification |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| High/Rigid | 1 | 61 | M | 400 | 230 | 1 | 0 | 0 | 230 | 402 | 1.0050 | 228.9 | Injury |
| | 2 | 80 | M | 350 | 260 | 0 | 0 | 0 | 260 | 402 | 1.1486 | 226.4 | No Injury |
| | 3 | 77 | M | 350 | 285 | 1 | 0 | 1 | 285 | 402 | 1.1486 | 248.1 | Injury |
| | 4 | 81 | F | 360 | 295 | 0 | 0 | 0 | 295 | 402 | 1.1167 | 264.2 | No Injury |
| | 5 | 77 | M | 380 | 245 | 0 | 0 | 0 | 245 | 402 | 1.0579 | 231.6 | No Injury |
| High/Compliant | 6 | 71 | M | 390 | 95 | 1 | 1 | 1 | 95 | 402 | 1.0308 | 92.2 | Injury |
| | 7 | 76 | F | 350 | 85 | 0 | 0 | 0 | 85 | 402 | 1.1486 | 74.0 | No Injury |
| | 8 | 65 | M | 370 | 70 | 0 | 0 | 0 | 70 | 402 | 1.0865 | 64.4 | No Injury |
| | 9 | 72 | M | 380 | 85 | 0 | 0 | 0 | 85 | 402 | 1.0579 | 80.3 | No Injury |
| | 10 | 54 | M | 420 | 100 | 0 | 0 | 0 | 100 | 402 | 0.9571 | 104.5 | No Injury |
| Low/Rigid | 11 | 73 | F | 380 | 225 | 1 | 0 | 1 | 225 | 402 | 1.0579 | 212.7 | Not Used |
| | 12 | 73 | F | 370 | 275 | 0 | 1 | 1 | 275 | 402 | 1.0865 | 253.1 | Injury |
| | 13 | 75 | M | 350 | 200 | 1 | 0 | 1 | 200 | 402 | 1.1486 | 174.1 | Not Used |
| | 14 | 86 | M | 390 | 270 | 0 | 1 | 1 | 270 | 402 | 1.0308 | 261.9 | Injury |
| | 15 | - | - | 370 | 280 | 0 | 0 | 1 | 280 | 402 | 1.0865 | 257.7 | No Injury |
| Low/Compliant | 16 | 74 | F | 350 | 70 | 0 | 0 | 0 | 70 | 402 | 1.1486 | 60.9 | No Injury |
| | 17 | 75 | F | 340 | 80 | 0 | 0 | 0 | 80 | 402 | 1.1824 | 67.7 | No Injury |
| | 18 | 83 | F | 350 | 115 | 0 | 0 | 1 | 115 | 402 | 1.1486 | 100.1 | No Injury |
| | 19 | 76 | M | 380 | 120 | 0 | 0 | 0 | 120 | 402 | 1.0579 | 113.4 | No Injury |
| | 20 | 69 | M | 400 | 80 | 0 | 0 | 0 | 80 | 402 | 1.0050 | 79.6 | No Injury |

**Probability function for tibia fracture due to direct impact was developed using scaled peak acceleration data**

# 2. Validation – Tibia Fracture Threshold

- Development of Fracture Probability Function from Bunketorp et al. (1983) -




**Probability of tibia fracture due to direct loading at 170G is estimated as 30%**

# 2. Validation – Tibia Fracture Threshold

## - Standard Anthropometry (UMTRI Study) -

TABLE 1.4

MID-SIZED MALE STANDARD ANTHROPOMETRY
(Descriptive Statistics, cm or as noted)

| Measurement Variable | N | Min. | Max. | Mean | S.D. |
|---|---|---|---|---|---|
| Age (years) | 25 | 20.0 | 61.0 | 38.1 | 12.2 |
| Stature | 25 | 171.2 | 178.4 | 175.1 | 2.1 |
| Weight (kg) | 25 | 70.0 | 83.4 | 76.7 | 3.5 |
| Sitting Height (erect) | 25 | 87.2 | 95.0 | 91.1 | 2.3 |
| Buttock-Knee Length | 25 | 55.9 | 62.6 | 59.3 | 2.1 |
| Cervicale Height | 25 | 145.6 | 153.8 | 149.8 | 2.2 |
| Trochanterion Height | 25 | 84.0 | 95.7 | 90.5 | 2.3 |
| Tibiale Height | 25 | 45.0 | 51.8 | 48.3 | 1.9 |
| Head Breadth | 25 | 14.4 | 16.9 | 15.8 | 0.6 |
| Head Length | 25 | 18.8 | 21.4 | 19.7 | 0.7 |
| Head Height | 25 | 21.8 | 24.3 | 23.1 | 0.8 |
| Shoulder Breadth | 25 | 41.3 | 47.6 | 44.9 | 1.7 |
| Biacromial Breadth | 25 | 35.7 | 43.2 | 39.5 | 1.9 |
| Clavicale Length | 25 | 16.6 | 19.3 | 18.3 | 0.9 |
| Suprasternale-Cerv. Dist. | 25 | 11.6 | 13.8 | 12.6 | 0.6 |
| Bispinous Breadth | 25 | 18.7 | 27.7 | 22.5 | 1.9 |
| Acromion-Radiale Length | 25 | 30.8 | 35.1 | 32.9 | 1.2 |
| Shoulder-Elbow Length | 25 | 32.6 | 38.5 | 36.5 | 1.3 |
| Elbow-Hand Length | 25 | 44.5 | 49.7 | 47.6 | 1.3 |
| Radius Length | 25 | 24.8 | 29.1 | 26.9 | 1.1 |
| Hand Breadth | 25 | 7.6 | 10.3 | 8.5 | 0.6 |
| Hand Length | 25 | 17.6 | 19.5 | 18.7 | 0.5 |
| Troch.-to-Lat. Fem. Condyle | 25 | 38.4 | 46.2 | 43.5 | 2.0 |
| Tibia Length | 25 | 36.2 | 44.3 | 40.2 | 2.2 |
| Foot Breadth | 25 | 8.4 | 10.8 | 9.6 | 0.5 |
| Foot Length | 25 | 24.6 | 27.8 | 26.4 | 0.8 |
| Head Circumference | 25 | 53.3 | 60.9 | 57.1 | 1.9 |
| Shoulder Circumference | 25 | 102.3 | 120.0 | 111.5 | 5.3 |
| Chest Circumference (axilla) | 25 | 91.0 | 104.5 | 97.3 | 3.2 |
| Chest Circumference (nipple) | 25 | 89.3 | 102.5 | 96.1 | 3.6 |
| Waist Circumference | 25 | 77.2 | 94.7 | 85.9 | 5.2 |
| Hip Circumference | 25 | 87.3 | 101.5 | 94.4 | 3.1 |
| Upper Arm Circumference (biceps) | 25 | 24.6 | 35.0 | 29.9 | 2.0 |
| Forearm Circumference | 25 | 21.8 | 28.6 | 25.4 | 1.7 |
| Thigh Circumference (mid) | 25 | 45.7 | 57.3 | 51.5 | 3.2 |
| Calf Circumference | 25 | 33.8 | 39.8 | 34.7 | 1.7 |
| Skinfold, Subscapular (mm) | 25 | 10.0 | 30.0 | 15.1 | 4.5 |
| Skinfold, Triceps (mm) | 25 | 4.0 | 25.0 | 10.0 | 6.3 |
| Skinfold, Suprailiac (mm) | 25 | 7.0 | 37.0 | 21.1 | 8.0 |
| Skinfold, Posterior Mid-Calf (mm) | 25 | 3.0 | 20.0 | 9.9 | 5.1 |

Mean ↓

| | | | | | |
|---|---|---|---|---|---|
| Trochanterion Height | 25 | 84.0 | 95.7 | 90.5 | 2.3 |
| Tibiale Height | 25 | 45.0 | 51.8 | 48.3 | 1.9 |
| Head Breadth | 25 | 14.4 | 16.9 | 15.8 | 0.6 |

Mean ↓

| | | | | | |
|---|---|---|---|---|---|
| Troch.-to-Lat. Fem. Condyle | 25 | 38.4 | 46.2 | 43.5 | 2.0 |
| Tibia Length | 25 | 36.2 | 44.3 | 40.2 | 2.2 |
| Foot Breadth | 25 | 8.4 | 10.8 | 9.6 | 0.5 |

**To develop probability function for tibia fracture due to bending, bending moment data were scaled using UMTRI study, based on which impactor dimensions were determined**

Reference: Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Volume 1, UMTRI Report UMTRI-83-53-1, 1983

# 2. Validation – Tibia Fracture Threshold

## - Development of Tibia Fracture Probability Function due to Bending -

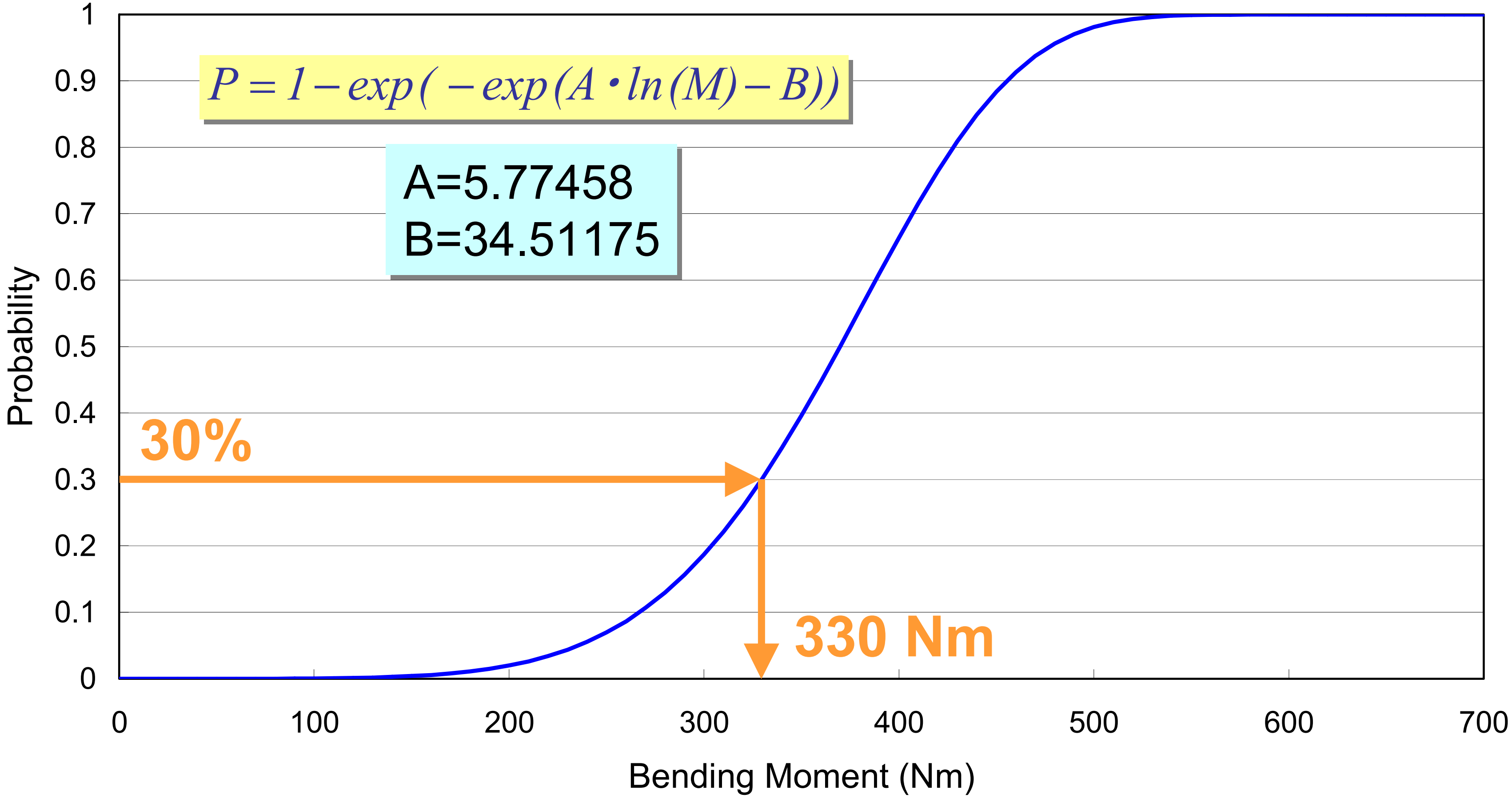
| Test | Source | Age | Gender | Stature (mm) | Weight (kg) | Anatomical Measurement (mm) | Anatomical Measurement Description | Fracture Moment (Nm) | **UMTRI** STD Anatomical Measurement (mm) | **UMTRI** Length Scale Factor | **UMTRI** Scaled Fracture Moment (Nm) | Data Censoring |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.1 | Kerrigan 2004 | 66 | M | 1829 | 79.8 | 397 | Tibia Length | 277 | 402 | 1.0126 | 287.6 | Uncensored |
| 9.2 | Kerrigan 2004 | 69 | M | 1702 | 81.6 | 418 | Tibia Length | 433 | 402 | 0.9617 | 385.2 | Uncensored |
| 9.3 | Kerrigan 2004 | 62 | M | 1829 | 60.8 | 416 | Tibia Length | 259 | 402 | 0.9663 | 233.7 | Uncensored |
| 9.4 | Kerrigan 2004 | 54 | M | 1880 | 117.9 | 479 | Tibia Length | 482 | 402 | 0.8392 | 284.9 | Uncensored |
| N-126 | Nyquist 1985 | 58 | M | 1740 | 73 | 480 | Tibia Height | 224 | 483 | 1.006 | 228.2 | Right Censored |
| N-129 | Nyquist 1985 | 57 | M | 1780 | 99 | 500 | Tibia Height | 349 | 483 | 0.966 | 314.6 | Right Censored |
| N-147 | Nyquist 1985 | 57 | M | 1780 | 84 | 405 | Tibia Height | 431 | 483 | 1.193 | 731.1 | Right Censored |
| N-127 | Nyquist 1985 | 56 | M | 1760 | 79 | 465 | Tibia Height | 237 | 483 | 1.039 | 265.6 | Right Censored |
| N-124 | Nyquist 1985 | 64 | M | 1770 | 82 | 490 | Tibia Height | 287 | 483 | 0.986 | 274.9 | Right Censored |
| N-118 | Nyquist 1985 | 54 | M | 1820 | 68 | 520 | Tibia Height | 395 | 483 | 0.929 | 316.5 | Right Censored |
| N-132 | Nyquist 1985 | 57 | M | 1870 | 45 | 445 | Tibia Height | 264 | 483 | 1.085 | 337.6 | Right Censored |
| N-148 | Nyquist 1985 | 57 | F | 1630 | 75 | 420 | Tibia Height | 254 | 483 | 1.150 | 386.3 | Right Censored |
| N-152 | Nyquist 1985 | 51 | F | 1630 | 68 | 430 | Tibia Height | 274 | 483 | 1.123 | 388.3 | Right Censored |
| K(a)-134L | Kerrigan SAE 2003 | 44 | M | 1702 | 73 | 420 | Tibia Length | 416 | 402 | 0.9571 | 364.8 | Uncensored |
| K(b)-D1 | Kerrigan NCCM 2003 | 54 | M | 1905 | 88 | 445 | Tibia Length | 463 | 402 | 0.9034 | 341.3 | Uncensored |
| K(b)-D2 | Kerrigan NCCM 2003 | 54 | M | 1905 | 88 | 450 | Tibia Length | 485 | 402 | 0.8933 | 345.8 | Uncensored |
| K(b)-D3 | Kerrigan NCCM 2003 | 68 | M | 1651 | 51 | 385 | Tibia Length | 290 | 402 | 1.0442 | 330.1 | Uncensored |
| K(b)-D4 | Kerrigan NCCM 2003 | 68 | M | 1651 | 51 | 385 | Tibia Length | 309 | 402 | 1.0442 | 351.8 | Uncensored |
| K(b)-D5 | Kerrigan NCCM 2003 | 65 | F | 1727 | 60 | 378 | Tibia Length | 416 | 402 | 1.0635 | 500.4 | Uncensored |
| K(b)-D6 | Kerrigan NCCM 2003 | 75 | M | 1778 | 65 | 395 | Tibia Length | 306 | 402 | 1.0177 | 322.6 | Uncensored |

- **Tibia bending moment data sources : Kerrigan et al. (2003, 2003, 2004), Nyquist et al. (4 papers)**
- **One data from Nyquist et al. was omitted as an outlier**

References:
- Kerrigan et al., Tolerance of the Human Leg and Thigh in Dynamic Latero-Medial Bending, ICRASH (2004)
- Kerrigan et al., Experiments for establishing pedestrian-impact lower limb injury criteria, SAE Paper #2003-01-0895 (2003)
- Kerrigan et al., Response Corridors for the Human Leg in 3-Point Lateral Bending, 7th US National Congress on Computational Mechanics (2003)
- Nyquist et al., Tibia Bending: Strength and Response, SAE Paper #851728 (1985)

# 2. Validation – Tibia Fracture Threshold

## - Tibia Fracture Probability Function due to Bending -

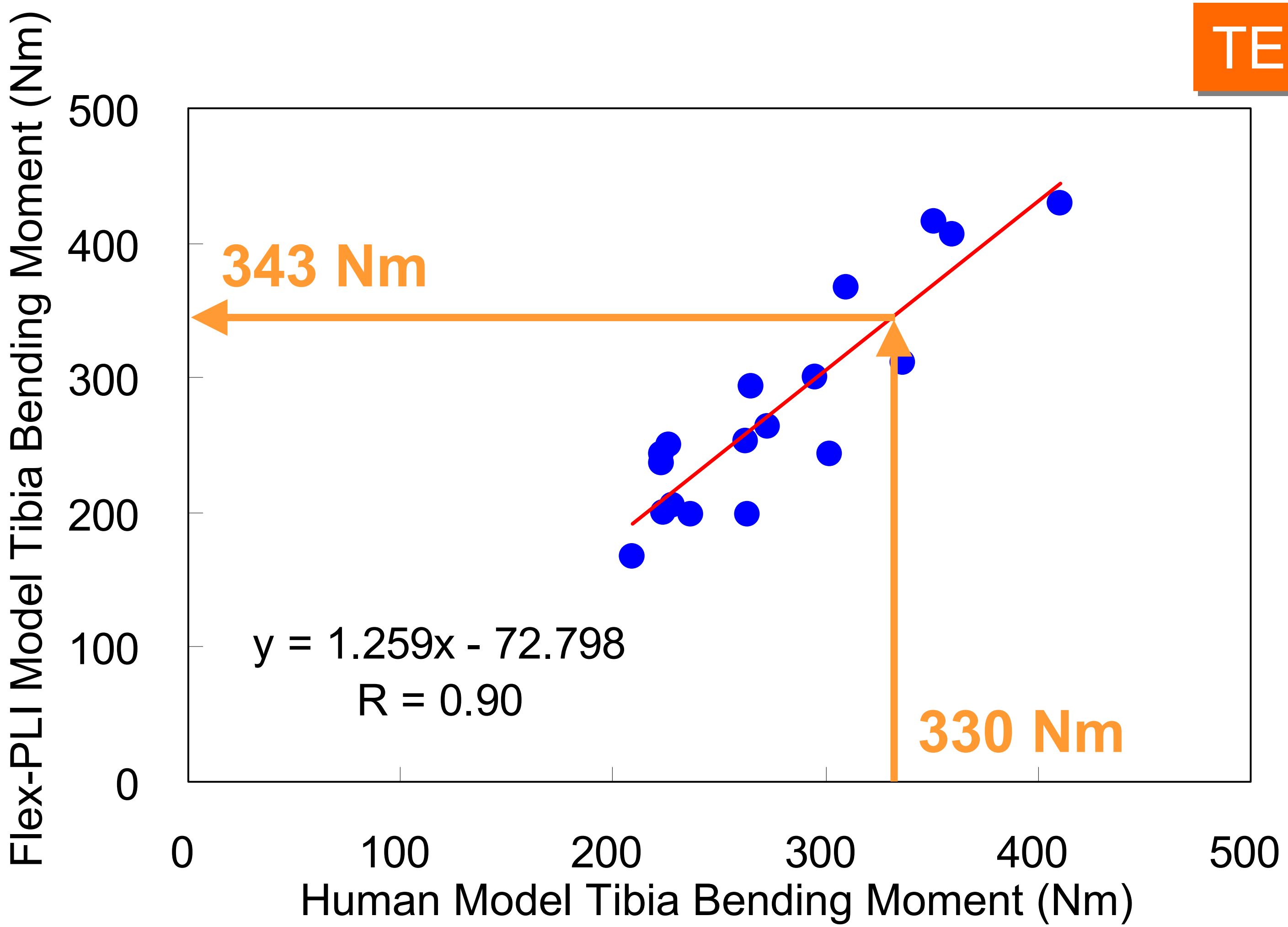



**Human tibia bending moment @ 30% probability of fracture is estimated as 330 Nm**

# 2. Validation – Tibia Fracture Threshold

- Human – Flex-PLI Correlation for Tibia Bending Moment -

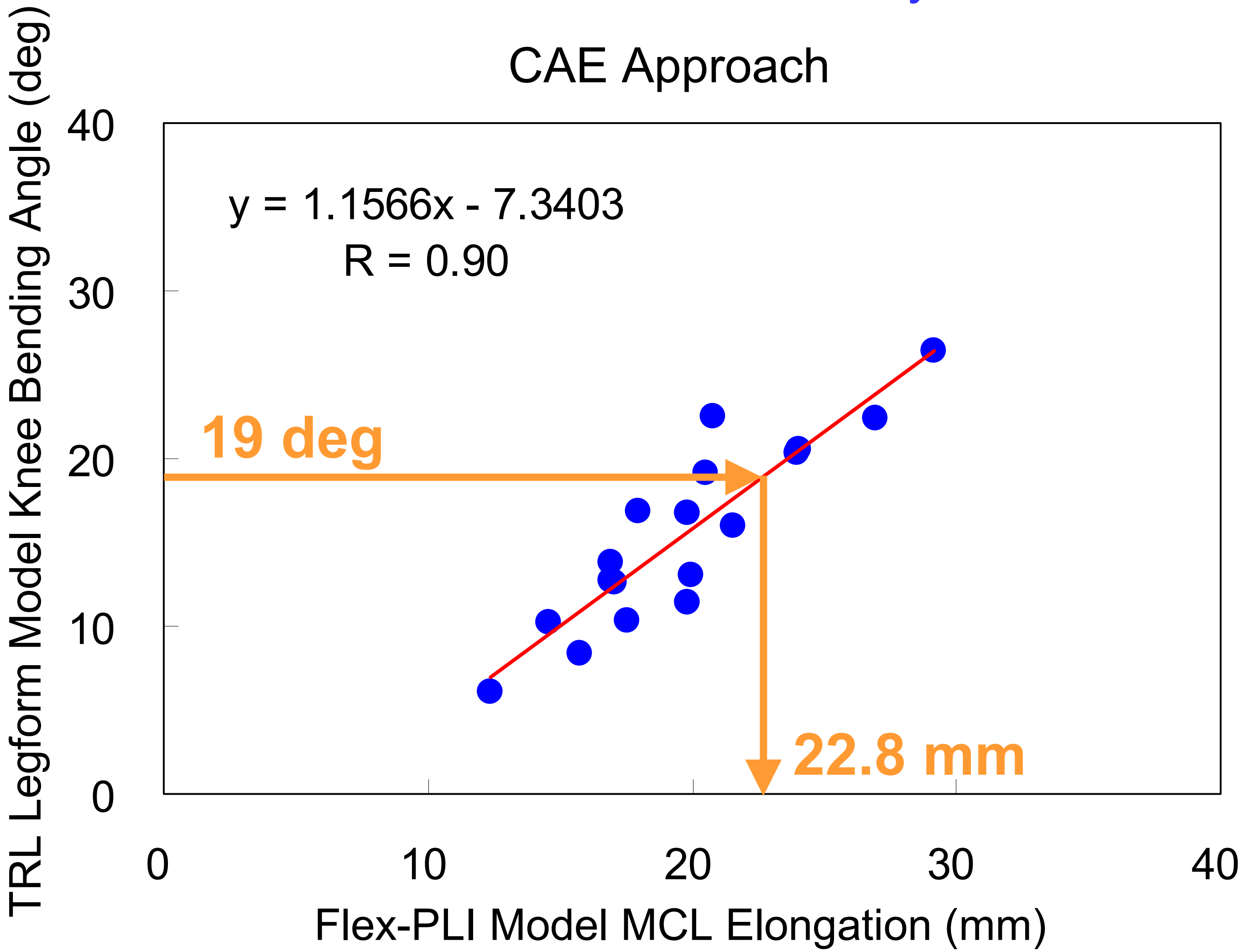
TEG-096




**Flex-PLI tibia bending moment corresponding to 330 Nm of human tibia bending moment is estimated as 343 Nm**

# 3. Validation – MCL Failure Threshold

- CAE Correlation Study -

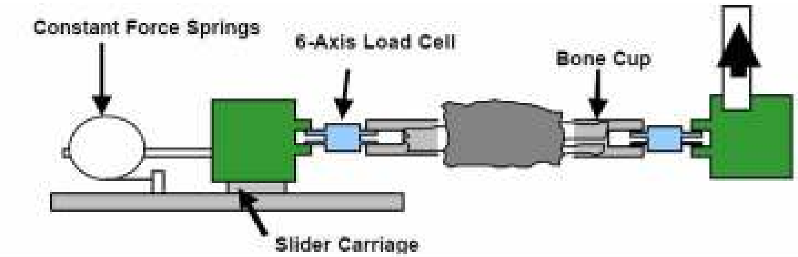



**Flex-PLI threshold is more conservative than TRL legform threshold by 3.5 %**

# 3. Validation – ACL Failure Threshold

- Bhalla et al. (2003) -

Dynamic Shear Tests
of Isolated Knee Joints




Knee Shear Stiffness

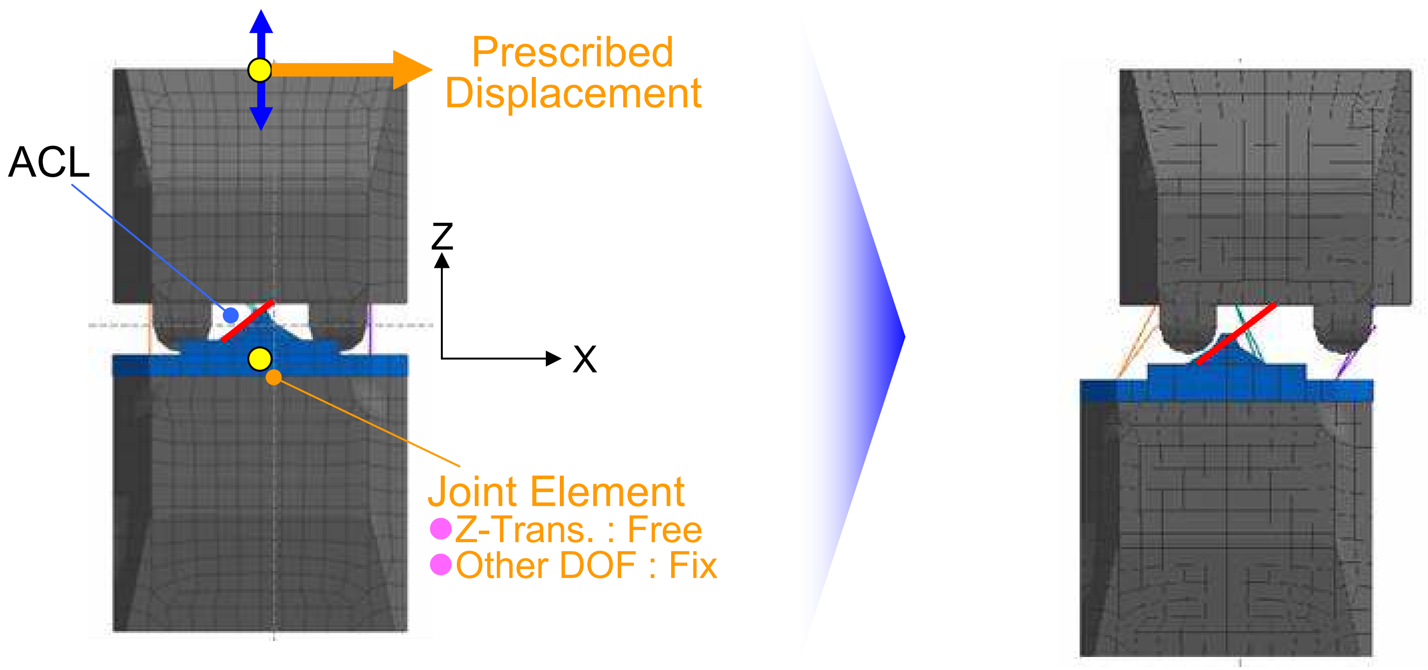

*Since tibial-spine gouging/plowing is likely an ongoing process, a drop in forces is likely due to ACL damage. Thus, it is hypothesized that the early peak in shear forces (at* ***12.7 mm*** *of shear displacement, 693N shear force) in Test 2.2 is due to ACL failure. Similarly, ACL failure in Test 2.1 occurs at a shear force of 1839N and a shear displacement of* ***17.8 mm****.*

**13 mm knee shear displacement would be a conservative failure threshold for ACL**

Reference: Bhalla et al., Evaluation of the Response of Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading, 18th ESV Conference, Paper Number 429 (2003)

# 3. Validation – ACL Failure Threshold

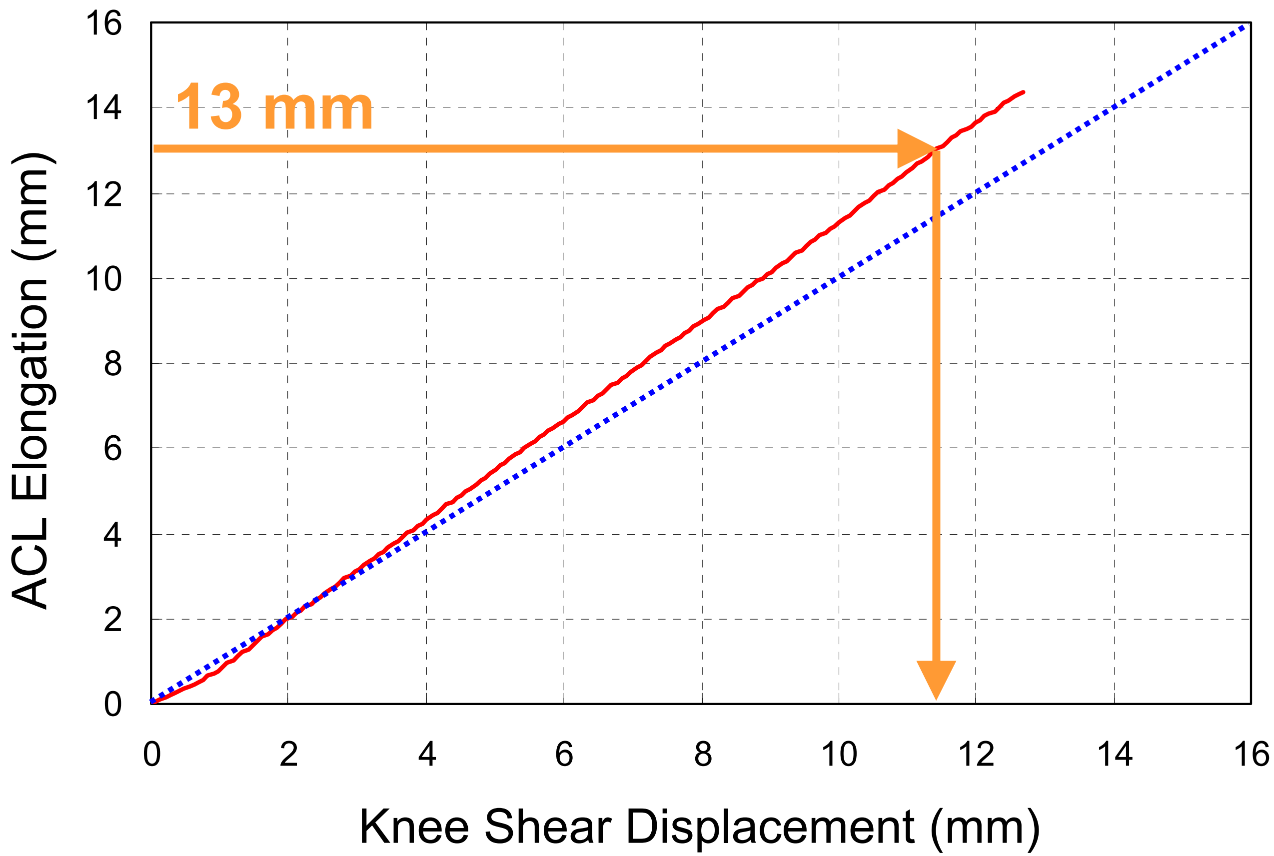
- Flex-PLI Knee Joint Model -




**Flex-PLI model was subjected to prescribed shear displacement to clarify relationship between knee shear displacement and ACL elongation**

# 3. Validation – ACL Failure Threshold

- Flex-PLI Knee Joint Model -




- **ACL elongation nearly equals to knee shear displacement**
- **13 mm ACL elongation corresponds to knee shear displacement smaller than 13 mm**

# 4. Summary

- Injury thresholds proposed for Flex-PLI by Flex-TEG were determined based on different studies performed by different participants
- Tibia bending moment threshold proposed for Flex-PLI was estimated to be very similar to upper tibia acceleration threshold for TRL legform in terms of fracture probability
- MCL failure threshold proposed for Flex-PLI was estimated to be more conservative (by 3.5 %) than knee bending angle threshold for TRL legform in terms of fracture probability
- ACL failure threshold proposed for Flex-PLI corresponds to knee shear displacement smaller than 13 mm, which is the smaller value of the two data from Bhalla et al.

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- Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Volume 1, UMTRI Report UMTRI-83-53-1 (1983)
- Bunketorp, O., Romanus, B., Hansson, T., Aldman, B., Thorngren, L., Eppinger, R., *Experimental Study of a Compliant Bumper System*, SAE Paper Number 831623 (1983)
- Kerrigan, J., Bhalla, K., Madeley, N., Funk, J., Bose, D., Crandall, J., Experiments for Establishing Pedestrian-Impact Lower Limb Injury Criteria, SAE Paper Number 2003-01-0895 (2003a)
- Kerrigan, J., Bhalla, K., Madeley, N., Crandall, J., Deng, B., *Response Corridors for the Human Leg in 3-Point Lateral Bending*, 7$^{th}$ US National Congress on Computational Mechanics (2003b)
- Kerrigan,J., Drinkwater, D., Kam, C., Murphy, D., Ivarsson, B., Crandall, J., Patrie, J., *Tolerance of the Human Leg and Thigh in Dynamic Latero-Medial Bending*, ICRASH (2004)

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- Bhalla, K., Bose, D., Madeley, N., Kerrigan, J., Crandall, J., Longhitano, D., Takahashi, Y., *Evaluation of the Response of Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading*, 18th ESV Conference, Paper Number 429 (2003)

***Thank you for your attention***