Development of Injury Probability Functions for the Flexible Pedestrian Legform Impactor

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SAE International™

Paper # 2012-01-0277

Outline

- Background
- Objective
- Development of Human Injury Probability Functions
- Development of FlexPLI Injury Probability Functions
- Validation of Proposed Injury Thresholds for FlexPLI
- Discussion
- Conclusions

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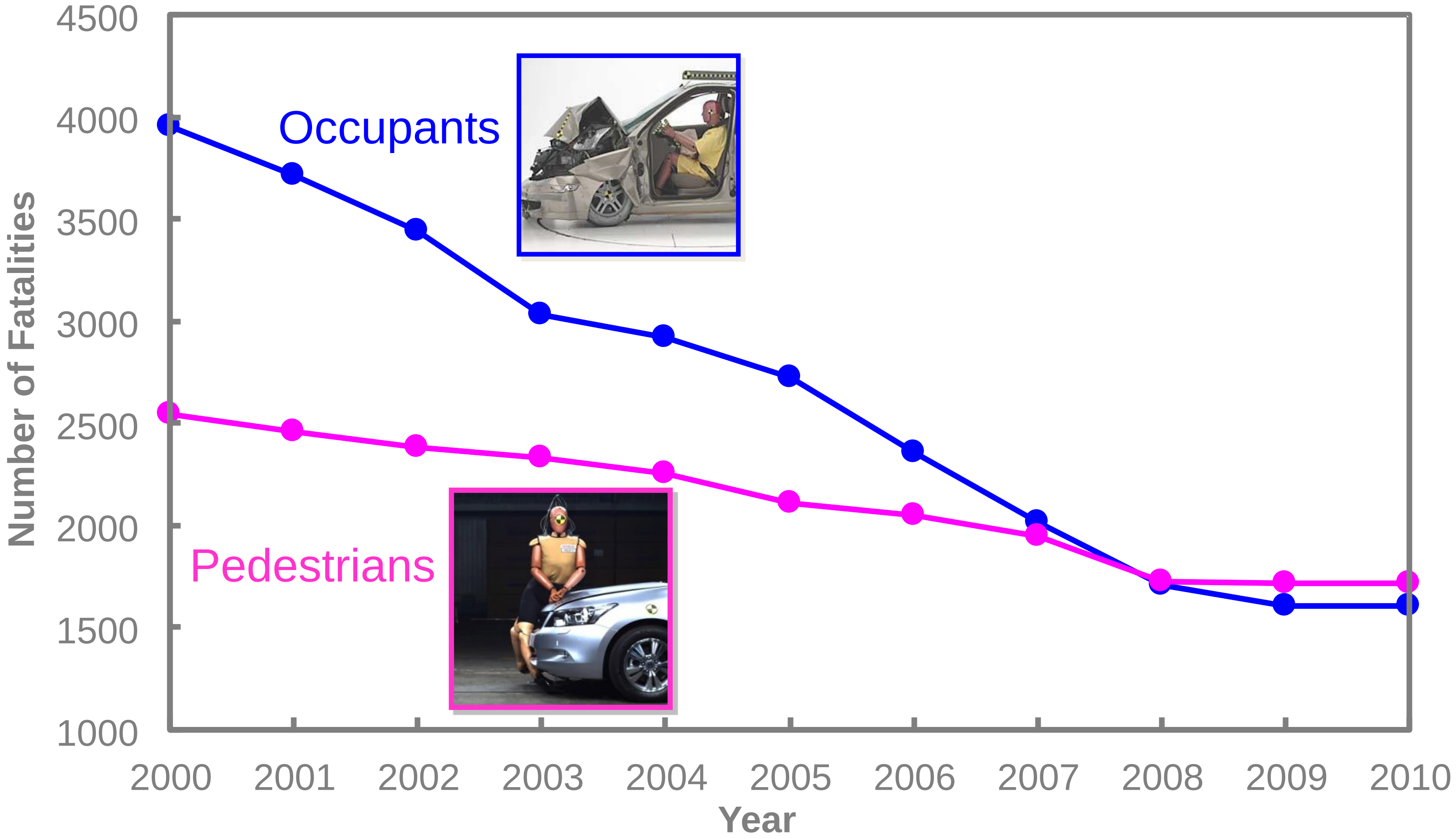
Accident Statistics

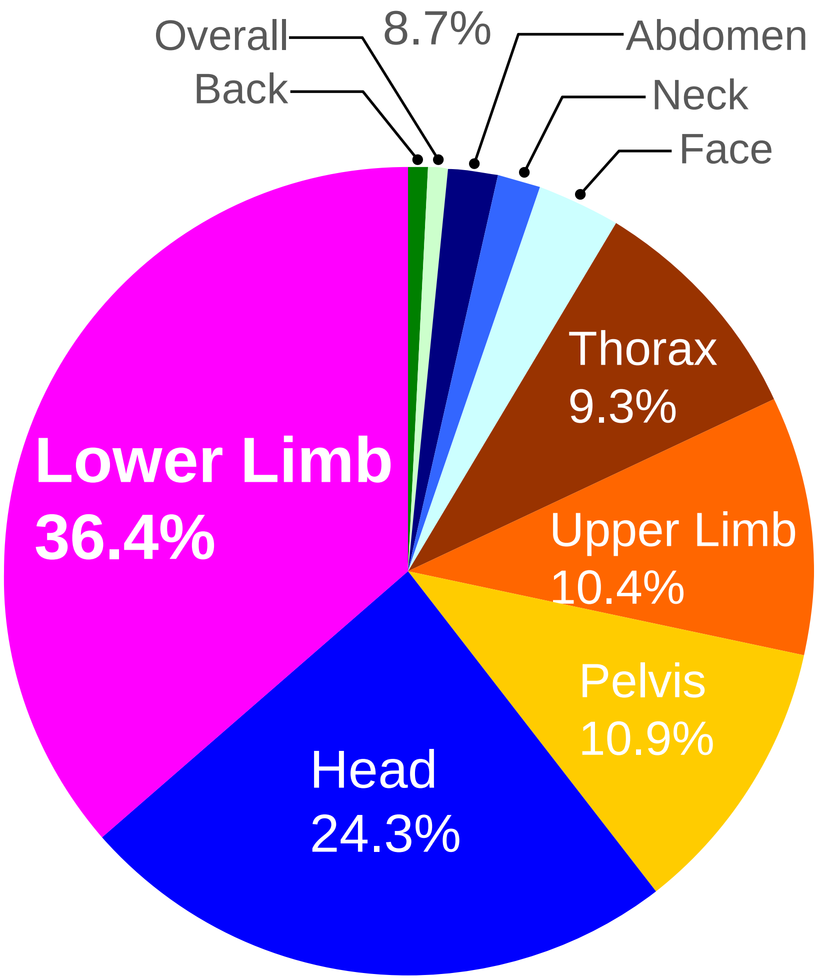
Trend of Traffic Fatalities in Japan



Source : ITARDA – Statistics of Road Accidents

Accident Statistics

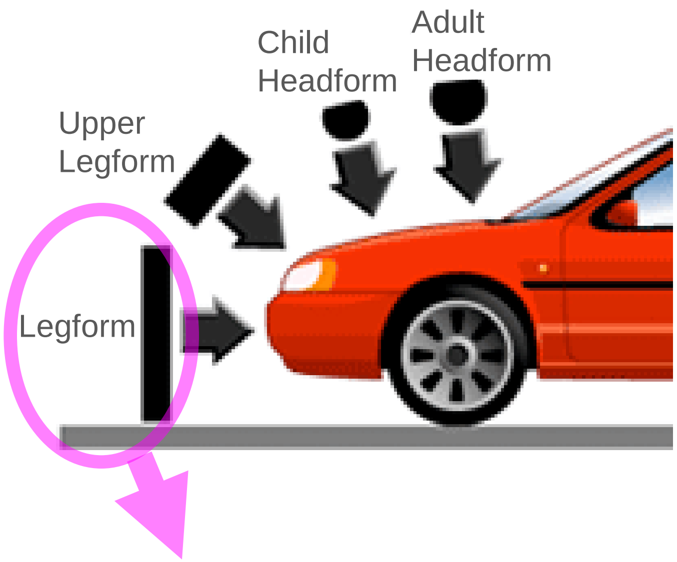
Distribution of Fatal and Severe Injuries by Most Severely Injured Body Region



Source : ITARDA – Statistics of Road Accidents, 2009

Pedestrian Test Procedure

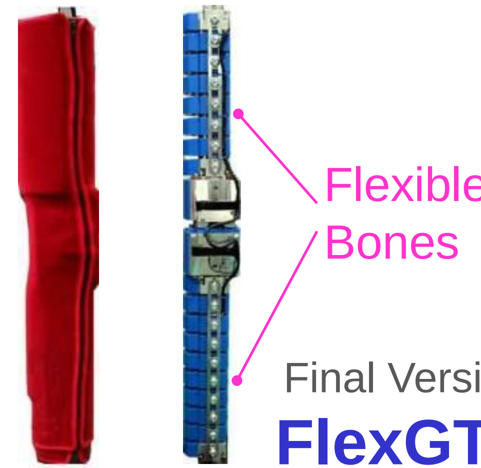
EEVC
Subsystem Impactors



EEVC Legform

FlexPLI

Flexible Pedestrian Legform Impactor



Final Version
FlexGTR

Jointly developed by JARI and JAMA

- UN/ECE/WP29
  - GRSP
    - Inf-PS
      - Flex-TEG
    - IG GTR9-PH2

Incorporation into UN GTR and UN Regulation has been actively discussed

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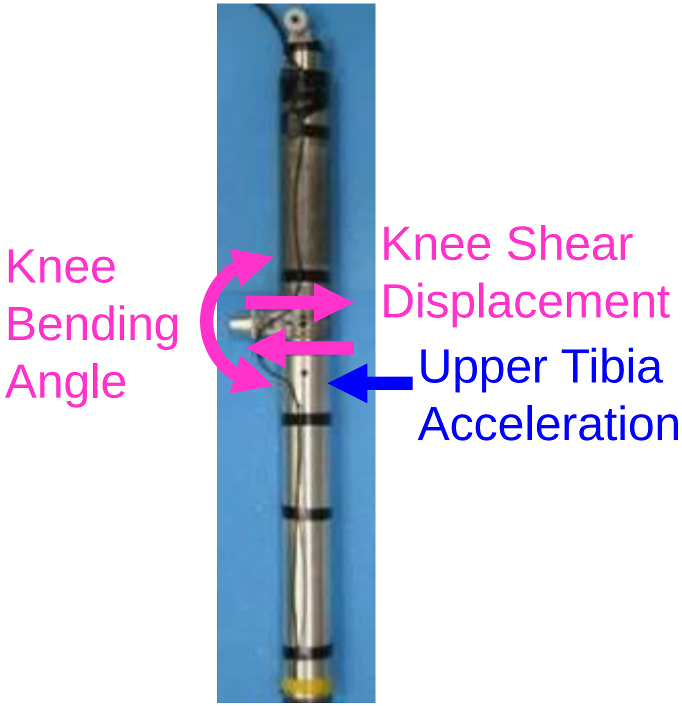
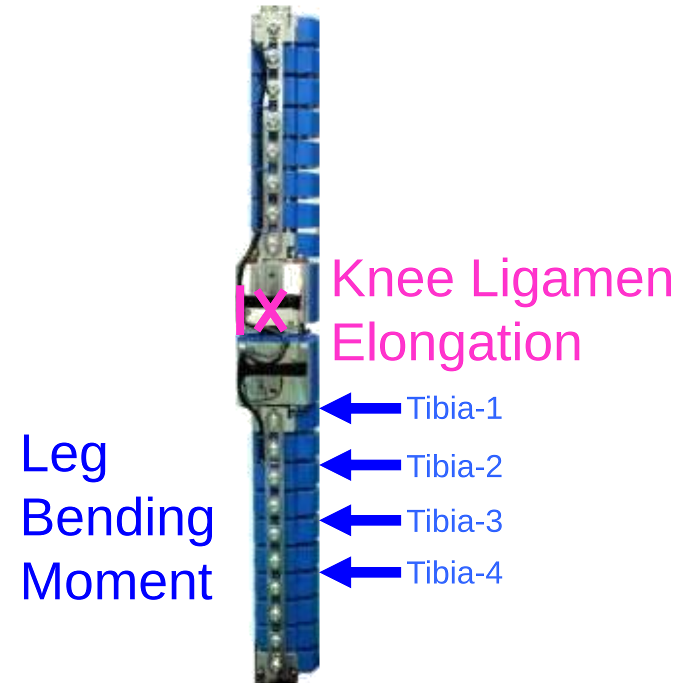
Injury Measures for Legforms

EEVC Legform



FlexPLI

Flexible Pedestrian Legform Impactor



Injury thresholds for the new injury measures need to be determined

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Objective

Develop injury probability functions for leg fracture and knee ligament failure to be used with the FlexPLI to provide a basis for determining biomechanically appropriate injury thresholds

Development of Human Injury Probability Functions

- Scaling/screening of human response data from the literature
- Selection of statistical procedure and development of functions

Development of FlexPLI Injury Probability Functions

- Transformation of the human functions using a transfer function
- Consideration of the effect of muscle tone (knee ligament)

Validation of Proposed FlexPLI Injury Thresholds

- Re-examination of acceleration-based function (leg fracture)
- Examination of equivalence of injury probability against EEVC legform

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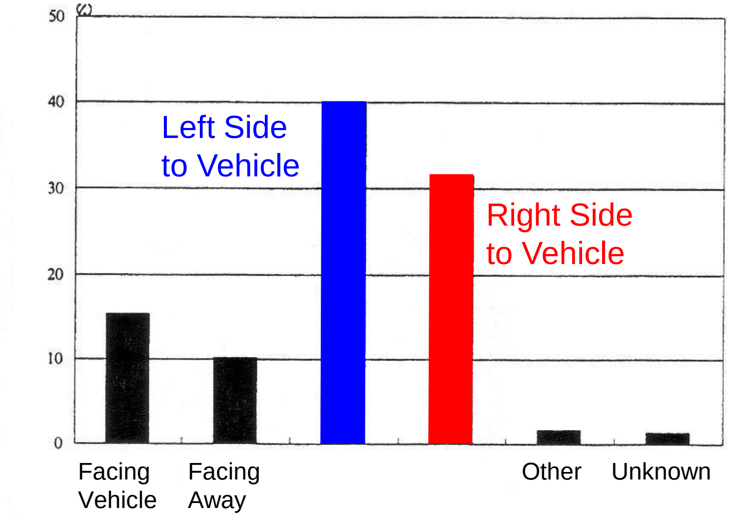
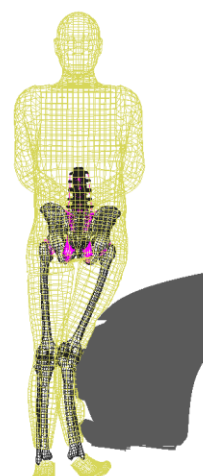
Human Data – Leg

Distribution of Chest Orientation



Source : Okamoto et al., *Pedestrian Head Impact Conditions Depending on the Vehicle Front Shape and its Construction – Full Model Simulation*, IRCOBI (2000)



Pedestrian test procedure presumes lateral impact to a pedestrian

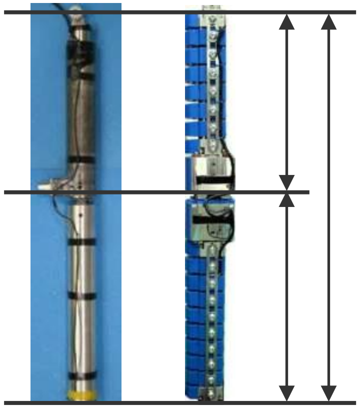
Human Data for Leg in Dynamic 3-point Lateral Bending

Data Source A: Nyquist et al., 1985
B: Kerrigan et al., 2003(a)
C: Kerrigan et al., 2003(b)
D: Kerrigan et al., 2004

Anatomical Measurement Type TH: Tibia Height
TL: Tibia Length

Test No.	Data Sour -ce	Age	Gen -der	Stature (mm)	Weight (kg)	Anatomical Measurement		Fracture Moment (Nm)
						Type	(mm)	
N-126	A	58	M	1740	73	TH	480	224
N-129	A	57	M	1780	99	TH	500	349
N-147	A	57	M	1780	84	TH	405	431
N-127	A	56	M	1760	79	TH	465	237
N-124	A	64	M	1770	82	TH	490	287
N-118	A	54	M	1820	68	TH	520	395
N-132	A	57	M	1870	45	TH	445	264
N-148	A	57	F	1630	75	TH	420	254
N-152	A	51	F	1630	68	TH	430	274
K(a)-134L	B	44	M	1702	73	TL	420	416
K(b)-D1	C	54	M	1905	88	TL	445	463
K(b)-D2	C	54	M	1905	88	TL	450	485
K(b)-D3	C	68	M	1651	51	TL	385	290
K(b)-D4	C	68	M	1651	51	TL	385	309
K(b)-D5	C	65	F	1727	60	TL	378	416
K(b)-D6	C	75	M	1778	65	TL	395	306
9.1	D	66	M	1829	79.8	TL	397	277
9.2	D	69	M	1702	81.6	TL	418	433
9.3	D	62	M	1829	60.8	TL	416	259
9.4	D	54	M	1880	117.9	TL	479	482

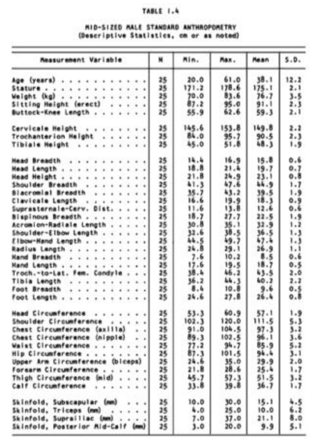
Data Scaling – Leg

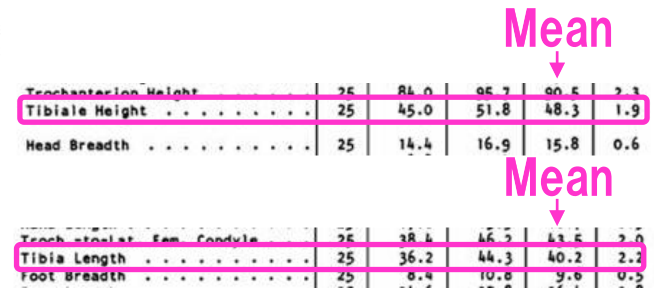


Legform dimensions were determined based on UMTRI anthropometric study

(EEVC, 1994 : Cesari et al., 1994)

UMTRI Data for 50th %ile Male





Tibia Height : 483 mm
Tibia Length : 402 mm

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

Geometric Data Scaling

$$M_{scaled} = \lambda_L^3 M = (Lref/L)^3 M$$

M : Measured bending moment

M_{scaled} : Scaled bending moment

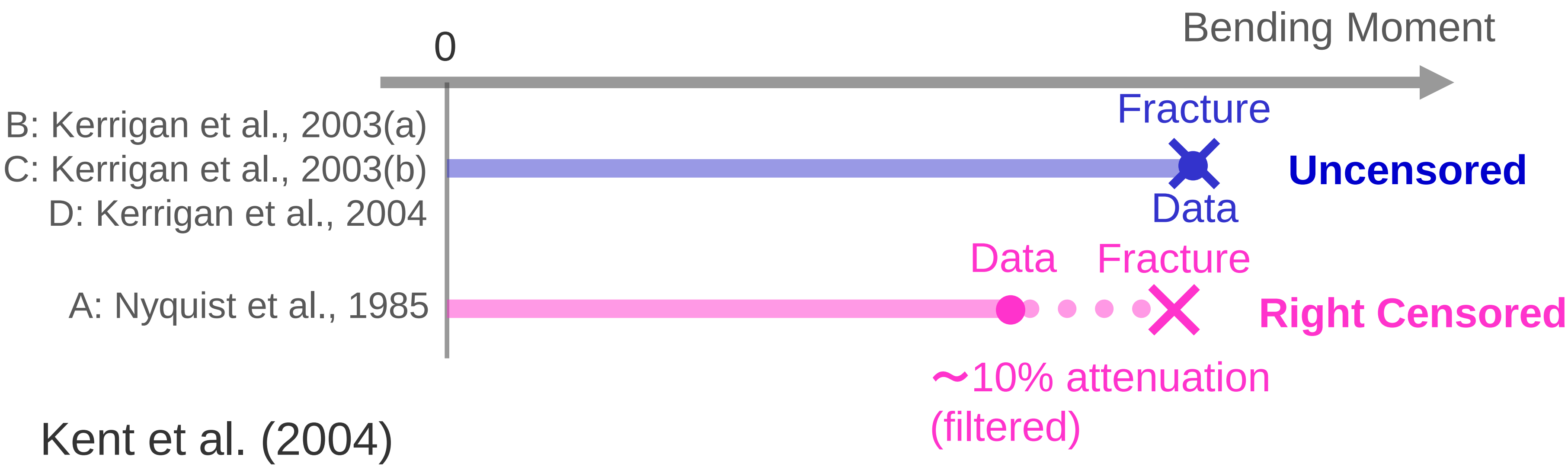
M : Length scale factor

M_{scaled} : Measured dimension (Tibia Length / Height)

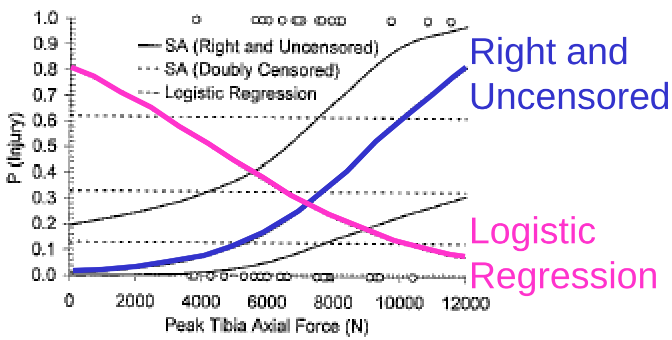
λ_L : Standard dimension (Tibia Length / Height)

- Statistically insignificant difference in material parameters between male and female data
- All data included regardless of gender
- One data (N-147) omitted as an outlier based on Grubbs' test

Statistical Procedure



Kent et al. (2004)



- Logistic regression assumes doubly censored data
- Unrealistic probability functions may be obtained when uncensored data are included

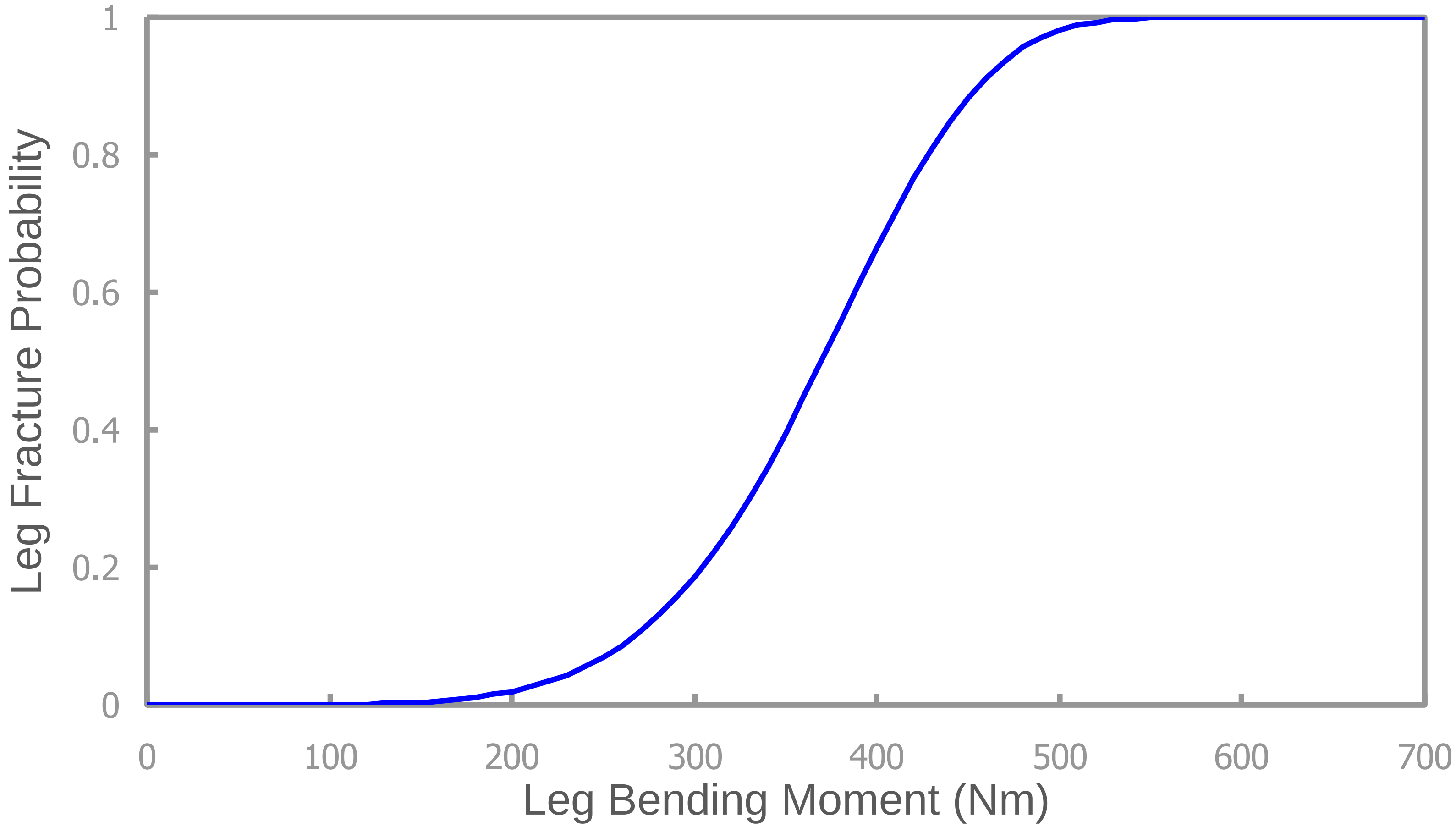
- **Use Weibull Survival Model**
  - ✓ **Combined right censored and uncensored dataset**
  - ✓ **Zero probability for zero input**

Leg Fracture Probability Function

$$P = 1 - exp[-exp\{5.77458 \cdot ln(M) - 34.51175\}]$$

P : Leg fracture probability

M : Leg bending moment (Nm)



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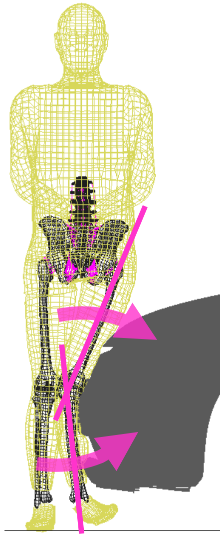
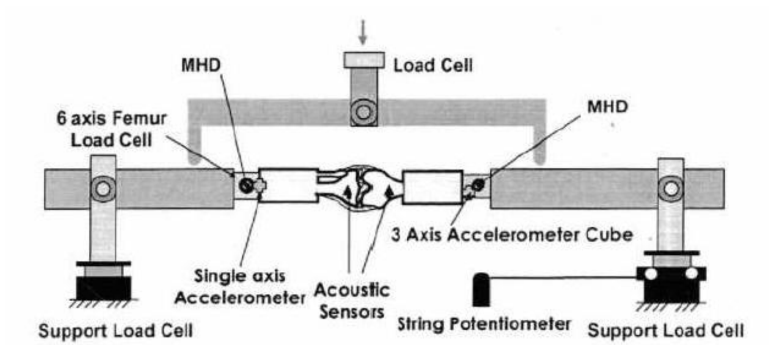
Human Data – Knee Ligament



Valgus bending of the knee joint due to lateral impact from a vehicle

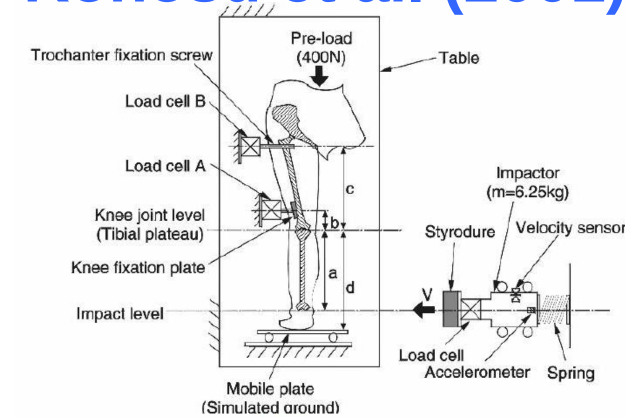
Develop injury probability function for Medial Collateral Ligament (MCL) based on published experiments in knee valgus bending

Ivarsson et al. (2004)



- Data source : Bose et al. (2004)
- Dynamic 4-point valgus bending of isolated human knees

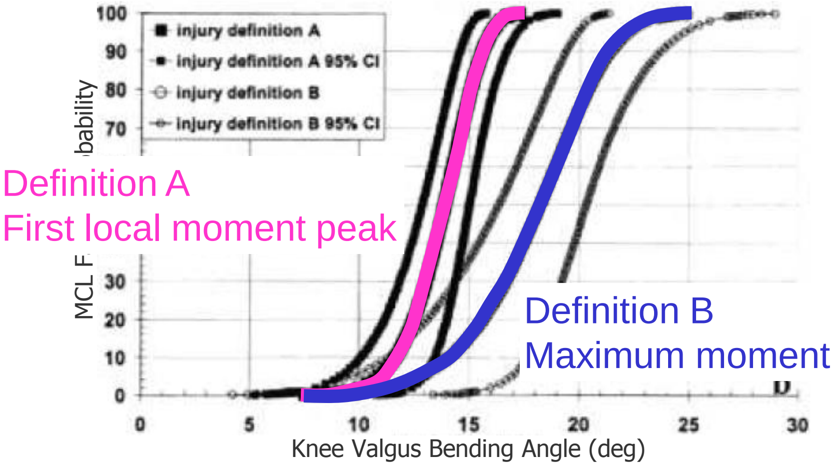
Konosu et al. (2001)



- Data source : Kajzer et al. (1997)
- Lateral impact to the ankle with the thigh fixed

MCL Failure Probability Function

Ivarsson et al. (2004)



- MCL failure probability function as a function of knee valgus bending angle
- Based on data from Bose et al. (2004) and Weibull Survival Model

Bose et al. (2004)

Table 3: Injuries observed in each tested specimen

Test #	Specimen #	Aspect	Test	ACL	PCL	MCL	LCL
Bend 1	51000944-004	Right	4 pt	v	v	P	v
Bend 2	2002-FRM-159	Right	4 pt	v	v	P	v
Bend 3	2001-FRM-141	Left	4 pt	v	v	P	v
Bend 4	2002-FRM-179	Right	4 pt	v	v	P	v
Bend 5	2002-FRM-179	Left	4 pt	v	v	C	v
Bend 6	2001-FRM-141	Right	4 pt	v	v	P	v
Bend 7	2003-FRM-187	Left	4 pt	v	v	v	v
Bend 8	2001-FRM-152	Left	4 pt	v	v	P	v
Comb 1	2002-FRM-178	Right	3 pt	v	v	v	v

- 8 4-point bending tests
  - MCL partial failure : 6 cases
  - MCL complete failure : 1 case
  - No injury : 1 case

Use the function for Definition B from Ivarsson et al.

MCL Failure Probability Function

Konosu et al. (2001)

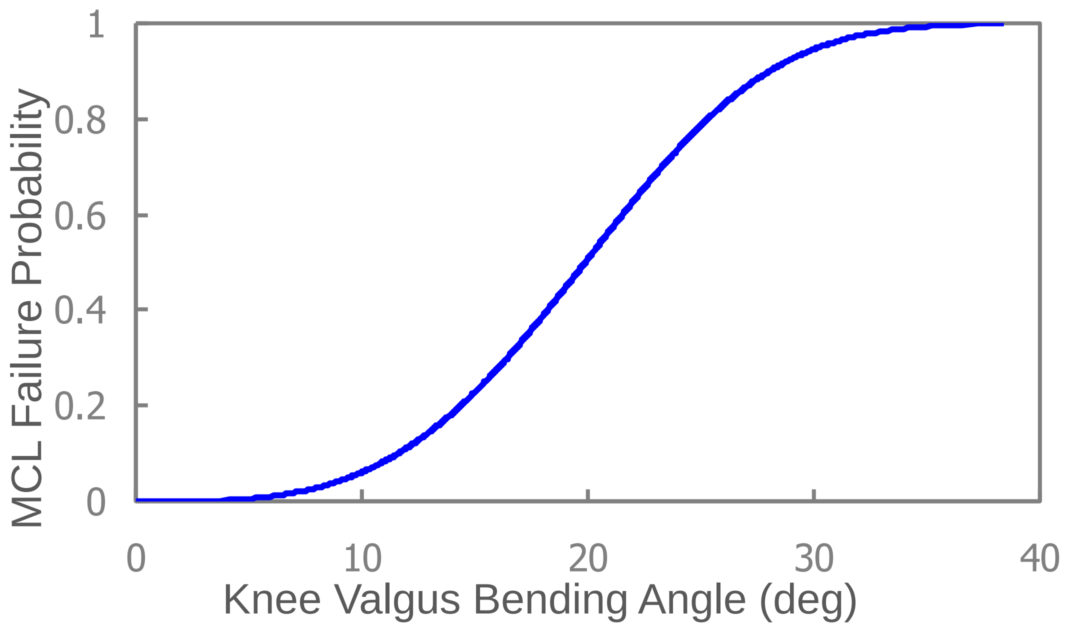
Dynamic bending test

Test No.	Bending angle, Ligament: No injury	Bending angle, Ligament: Injury	Data Censoring
2B	19.5		Right Censored
3B		14.4	Uncensored
6B		14.7	Uncensored
7B	21.9		Right Censored
10B	15.5		Right Censored
11B	14.8		Right Censored
14B	10.0		Right Censored
15B	12.6		Right Censored
18B	20.4		Right Censored
22B	12.3		Right Censored
27B		10.2	Uncensored
30B		14.3	Uncensored

unit (deg.)

Re-analysis of data using Weibull Survival Model

- No Injury : Right Censored
- Injury : Uncensored



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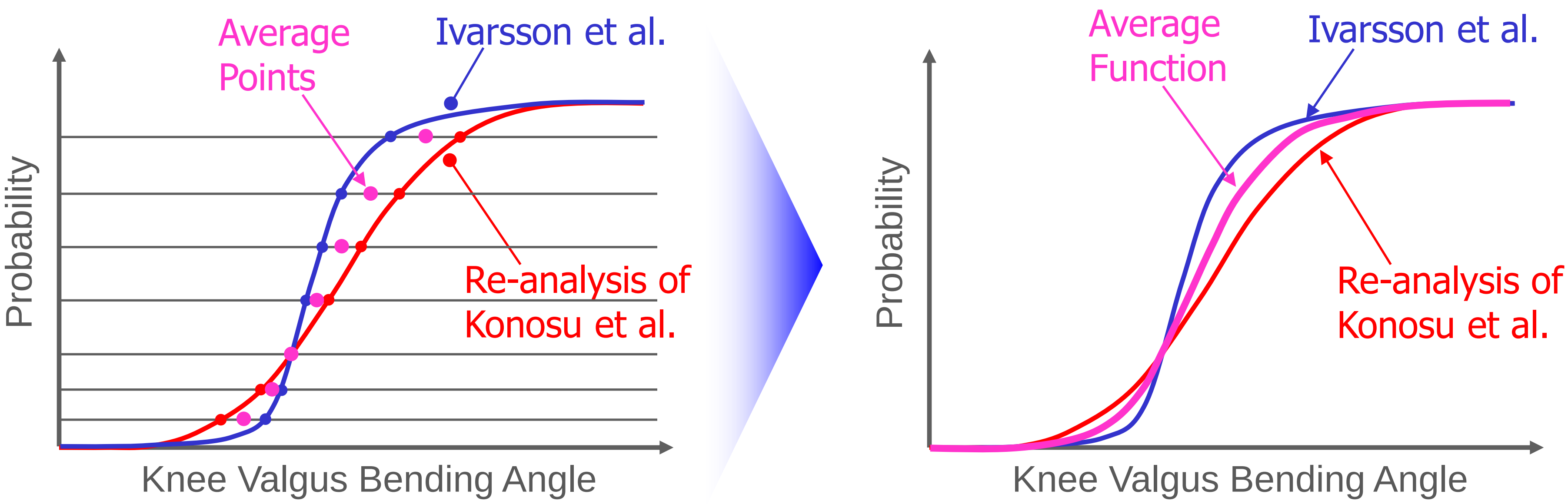
MCL Failure Probability Function

Averaged Injury Probability Function

- Impossible to combine two datasets due to the lack of tabulated data from Ivarsson et al.
- Average knee valgus bending angle rather than statistically obtained injury probability



MCL Failure Probability Function

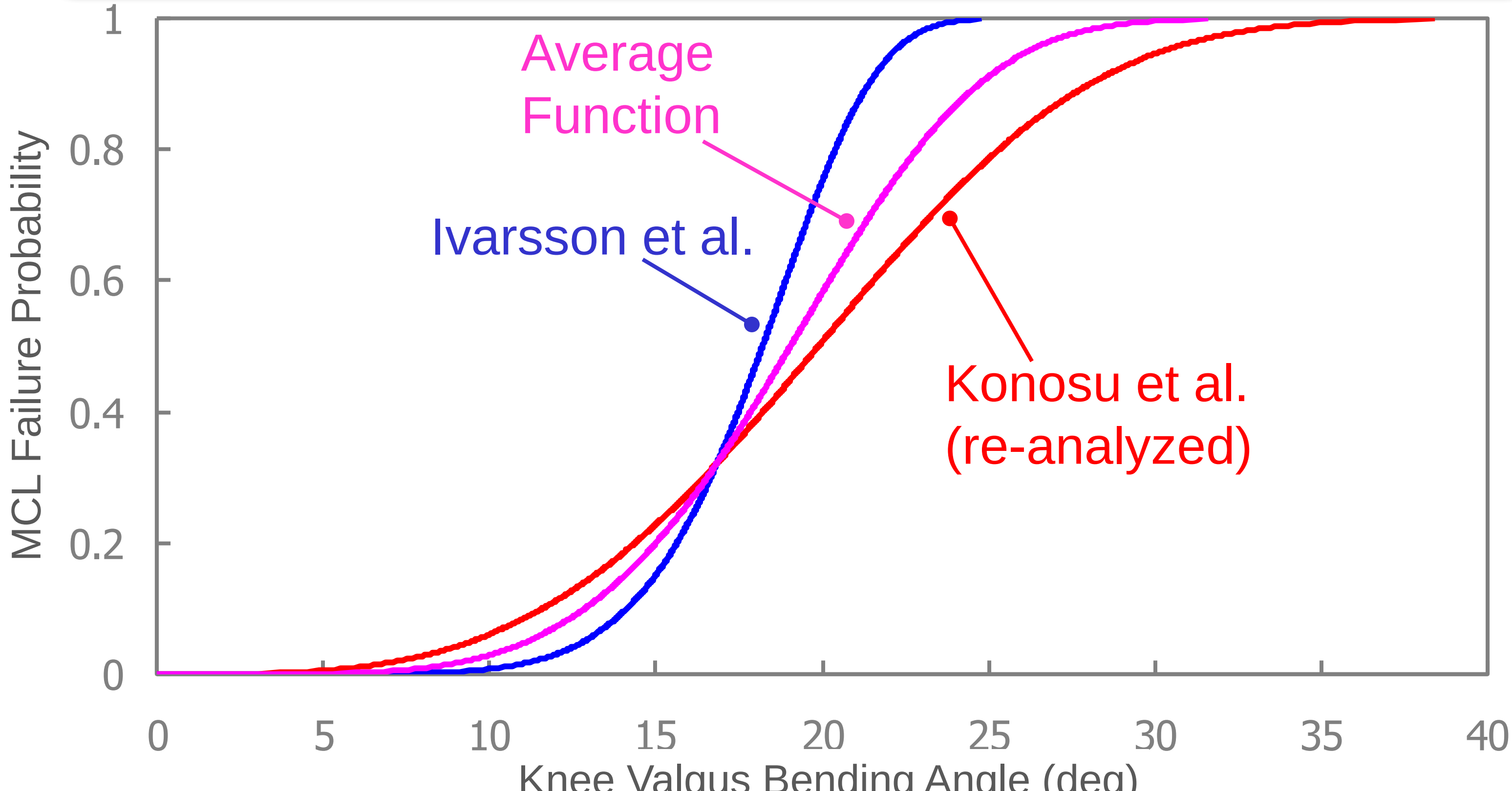
$$\beta = [exp(B_1/A_1)[-ln(1-P)\}^{1/A1} + exp(B_2/A_2)[-ln(1-P)\}^{1/A2}]/2$$

P : MCL failure probability

β : Knee valgus bending angle (deg)

$A_1 = 7.43354$, $A_2 = 3.49323$

$B_1 = 21.937127$, $B_2 = 10.810883$



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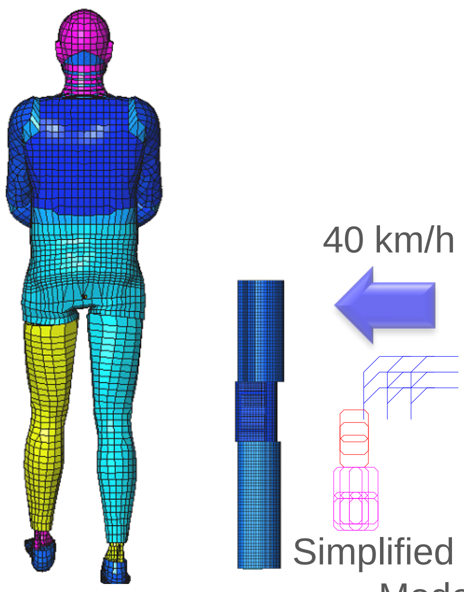
Human-FlexPLI Correlation

JAMA-JARI Correlation Analysis (TEG-096 (2009))

Impact Simulations

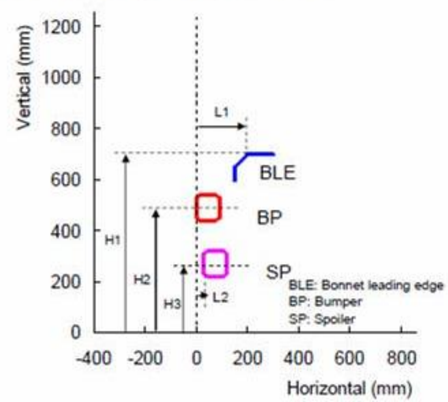


Simplified Vehicle Model Parameters

Simplified Car Model Parameters

Parameter	Unit	Level 1	Level 2	Level 3
K1 (BLE stiffness*)	mm	0.4	0.6	
K2 (BP stiffness**)	JC***	0.7	0.8	1.0
K3 (SP stiffness**)	JC***	0.6	0.8	1.0
H1 (BLE height)	mm	650	700	750
H2 (BP height)	mm	450	490	530
H3 (SP height)	mm	250	270	350
L1 (BLE lead)	mm	125	200	275
L2 (SP lead)	mm	-20	0	30

* Stiffness is changed by steel plate thickness.
** Stiffness is changed by joint characteristics.
*** JC: Joint characteristics
# BLE: Bonnet leading edge, BP: Bumper, SP: Spoiler



Combinations of Parameters (18 Cases)

Simplified Car model specifications

Simplified Car Model ID	K1 (BLE stiffness*) mm	K2 (BP stiffness**) JC***	K3 (SP stiffness**) JC***	H1 (BLE height) mm	H2 (BP height) mm	H3 (SP height) mm	L1 (BLE lead) mm	L2 (SP lead) mm
S1	0.4	0.7	0.6	650	450	250	125	-20
S2	0.4	0.7	0.8	700	490	270	200	0
S3	0.4	0.7	1.0	750	530	350	275	30
S4	0.4	0.8	0.6	650	490	270	275	30
S5	0.4	0.8	0.8	700	530	350	125	-20
S6	0.4	0.8	1.0	750	450	250	200	0
S7	0.4	1.0	0.6	700	450	350	200	30
S8	0.4	1.0	0.8	750	490	250	275	-20
S9	0.4	1.0	1.0	650	530	270	125	0
S10	0.6	0.7	0.6	750	530	270	200	-20
S11	0.6	0.7	0.8	650	450	350	275	0
S12	0.6	0.7	1.0	700	490	250	125	30
S13	0.6	0.8	0.6	700	530	250	275	0
S14	0.6	0.8	0.8	750	450	270	125	30
S15	0.6	0.8	1.0	650	490	350	200	-20
S16	0.6	1.0	0.6	750	490	350	125	0
S17	0.6	1.0	0.8	650	530	250	200	30
S18	0.6	1.0	1.0	700	450	270	275	-20

* Stiffness is changed by steel plate thickness.
** Stiffness is changed by joint characteristics.
*** JC: Joint characteristics
# BLE: Bonnet leading edge, BP: Bumper, SP: Spoiler

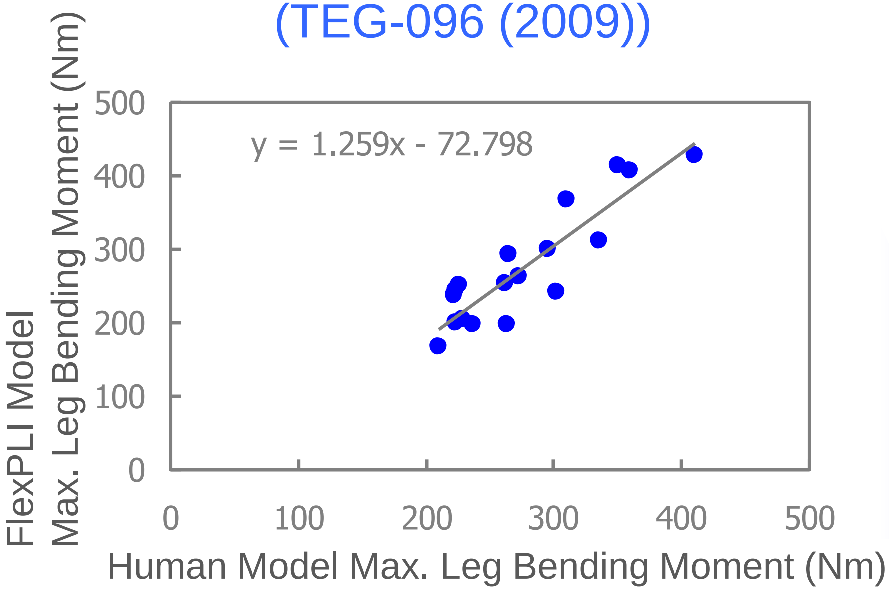
Based on L18 orthogonal table

Convert human injury probability functions to FlexPLI functions using the results of the correlation analysis

Leg Fracture Probability Function

Results of Correlation Analysis

(TEG-096 (2009))

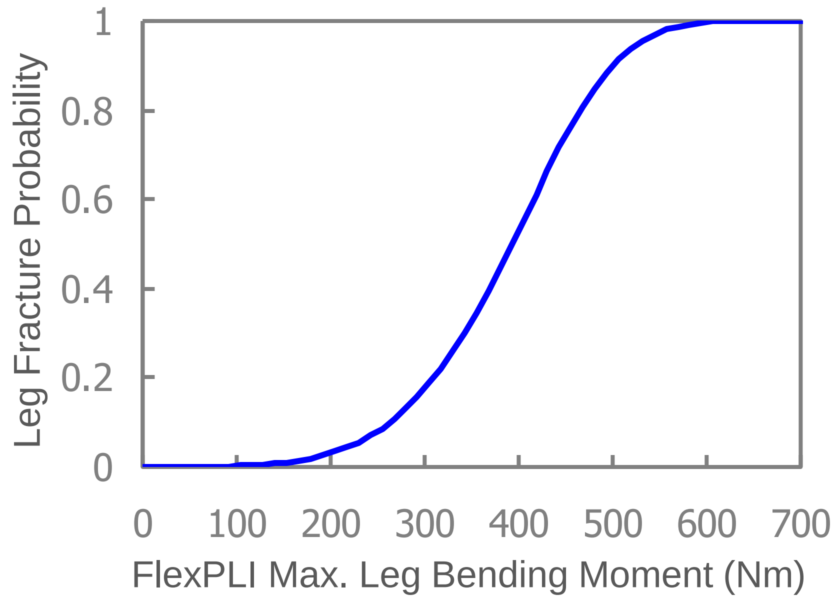


$$M_{FlexPLI} = 1.259 \cdot M_{Human} - 72.798$$

M_{Human}: Human model max leg bending moment Nm)

$M_{Flex-GTR}$: FlexPLI model max leg bending moment Nm)

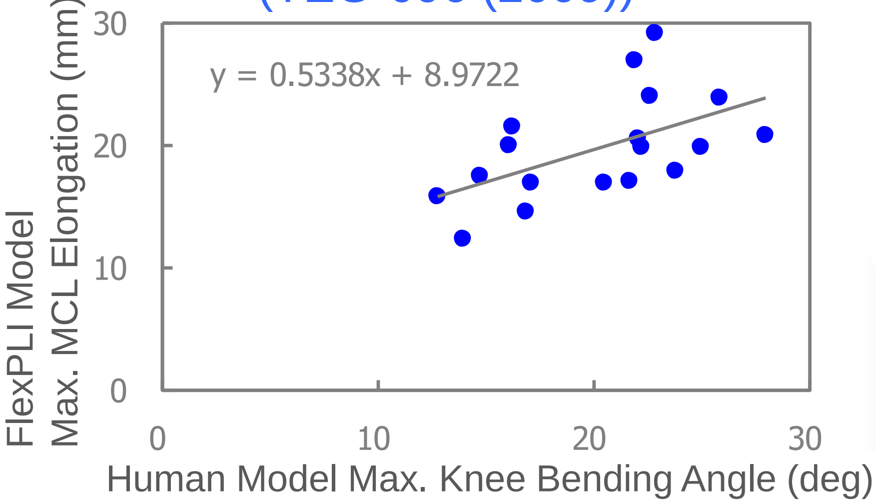
Injury Probability Function



MCL Failure Probability Function

Results of Correlation Analysis

(TEG-096 (2009))

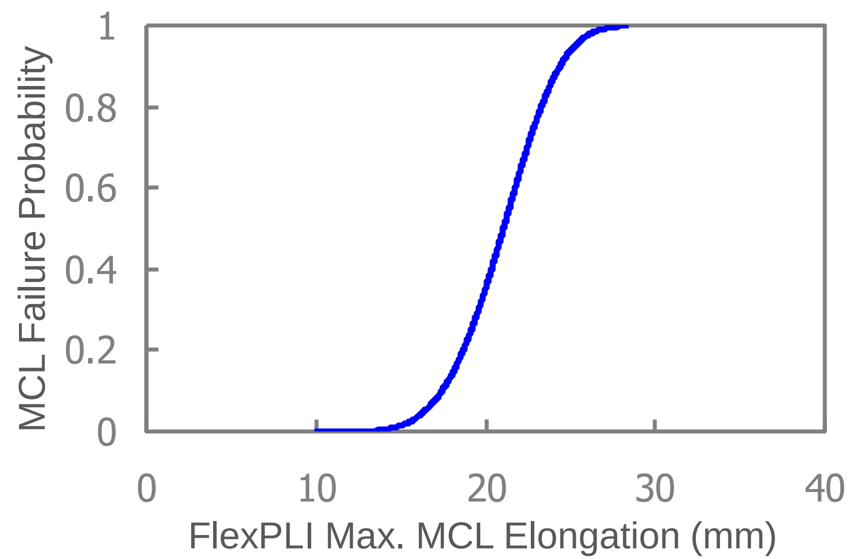


Effect of Muscle Tone

Lloyd et al. (2001)

Knee valgus bending moment increased by **10±6.3%** due to muscle tone

Injury Probability Function



$$\delta_{FlexPLI} = \underline{1.1} \cdot (0.5338 \cdot \beta_{Human} + 8.9722)$$

β_{Human} : Human model knee valgus bending angle (deg)

β_{Human} : FlexPLI model MCL elongation (mm)

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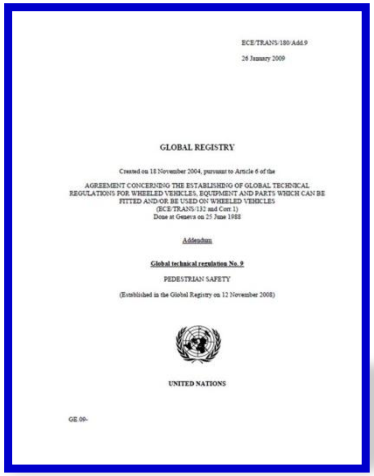
Proposed Injury Thresholds

EEVC Legform



ECE/TRANS/180/Add.9

26 January 2009

GLOBAL REGISTRY

Created on 18 November 2004, pursuant to Article 6 of the

AGREEMENT CONCERNING THE ESTABLISHING OF GLOBAL TECHNICAL REGULATIONS FOR WHEELED VEHICLES, EQUIPMENT AND PARTS WHICH CAN BE FITTED AND/OR BE USED ON WHEELED VEHICLES
(ECE/TRANS/132 and Corr.1)
Done at Geneva on 25 June 1998

Addendum

Global technical regulation No. 9

PEDESTRIAN SAFETY

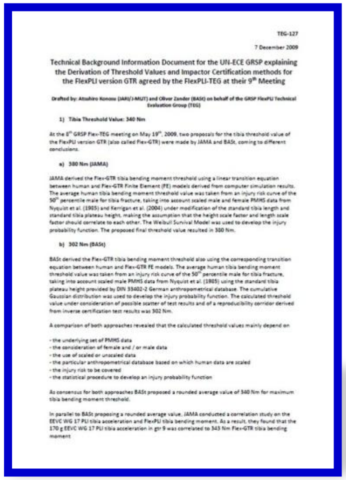
(Established in the Global Registry on 12 November 2008)

UNITED NATIONS

GE.09-

UN GTR No.9

FlexPLI



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. 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.

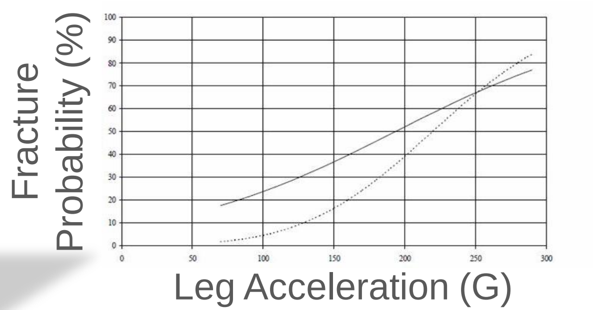
b) 302 Nm (BASt)

Flex-TEG TEG-127

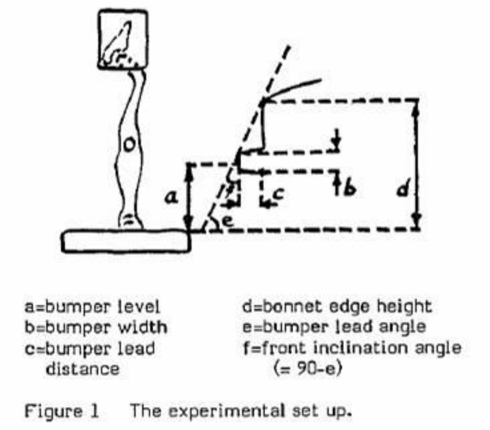
Injury	EEVC Legform		FlexPLI	
	Injury Measure	Threshold	Injury Measure	Threshold
Leg Fracture	Upper Tibia Acceleration	**170 G**	Bending Moment	**340 Nm**
MCL Failure	Knee Bending Angle	**19 deg**	MCL Elongation	**22 mm**

Equivalence of Leg Fracture Thresholds

EEVC Leg Fracture Probability Function



Bunketorp et al. (1998)

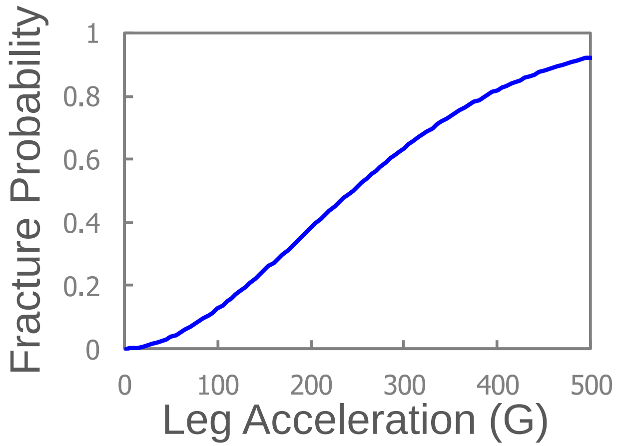


- 20 tests : High/Low bumper height, Rigid/Compliant bumper stiffness
- 2 tests excluded due to fracture caused by indirect loading
- 2 tests with fibula fracture only were treated as no injury data
- Geometrically scaled leg acceleration
- Weibull Survival Model

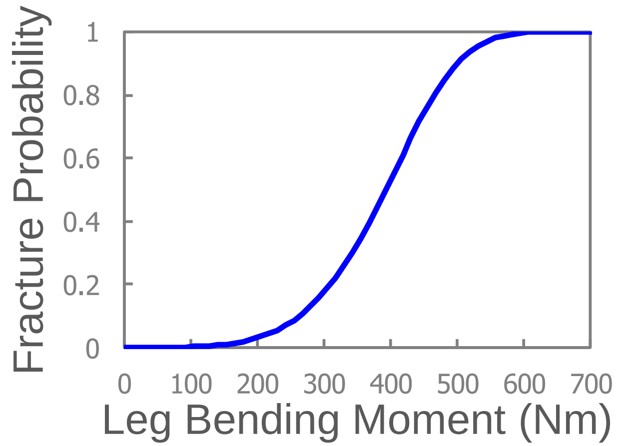
Equivalence of Leg Fracture Thresholds

Leg Fracture Probability Functions

Leg Acceleration (EEVC Legform)



Leg Bending Moment (FlexPLI)

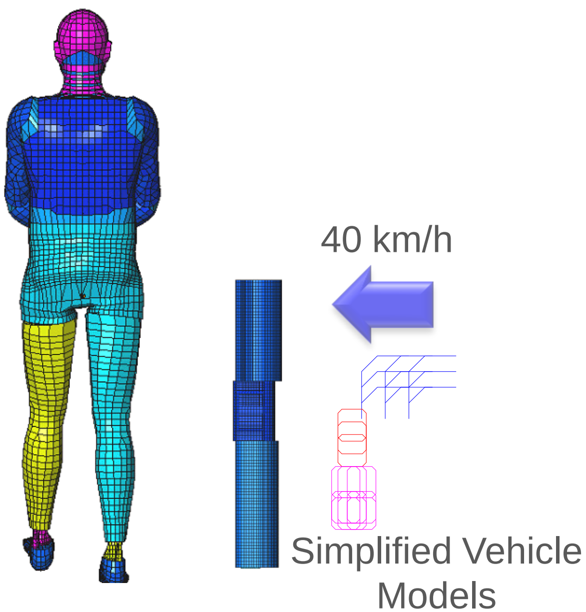


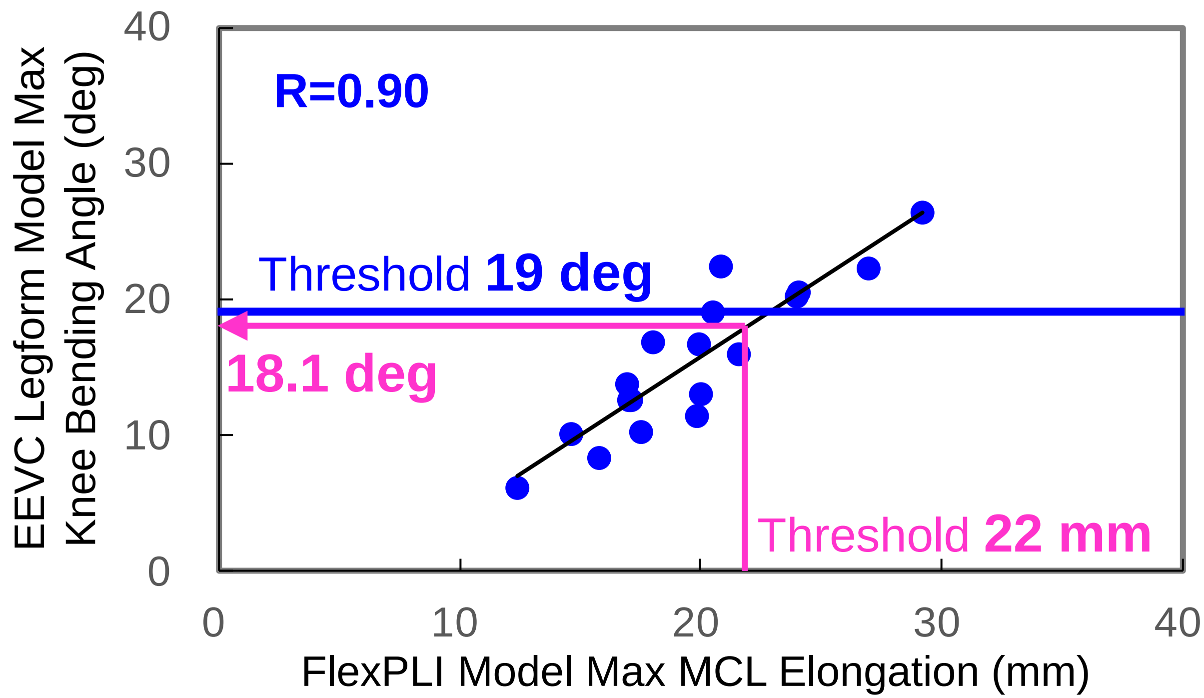
Legform	Injury Measure	Threshold	Injury Probability
EEVC Legform	Leg Acceleration	170 G	**30.0 %**
FlexPLI	Leg Bending Moment	340 Nm	**29.2 %**

Equivalence of MCL Failure Thresholds

MCL Failure Measure Correlation

Impact Simulations





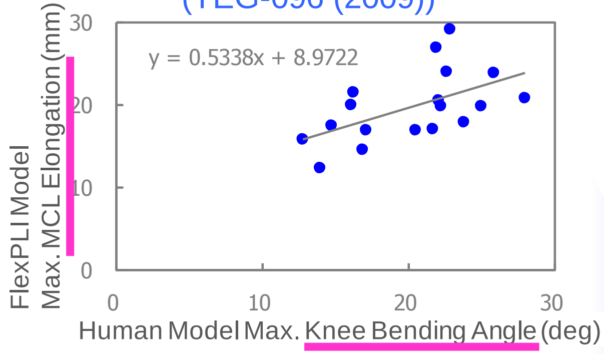
Outline

- Background
- Objective
- Development of Human Injury Probability Functions
- Development of FlexPLI Injury Probability Functions
- Validation of Proposed Injury Thresholds for FlexPLI
- Discussion
- Conclusions

Conversion of MCL Failure Function

Results of Correlation Analysis

(TEG-096 (2009))

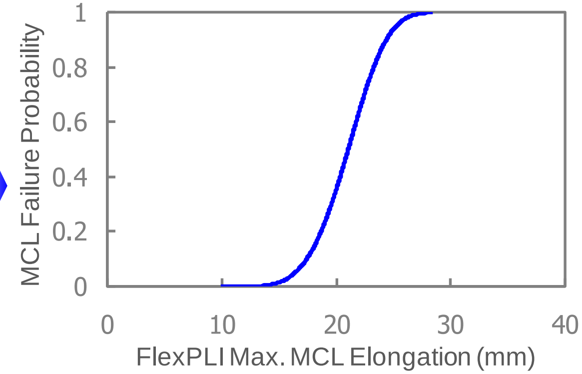


Effect of Muscle Tone

Lloyd et al. (2001)

Knee valgus bending moment increased by 10±6.3% due to muscle tone

Injury Probability Function



$$\delta_{FlexPLI} = 1.1 \cdot (0.5338 \cdot \beta_{Human} + 8.9722$$

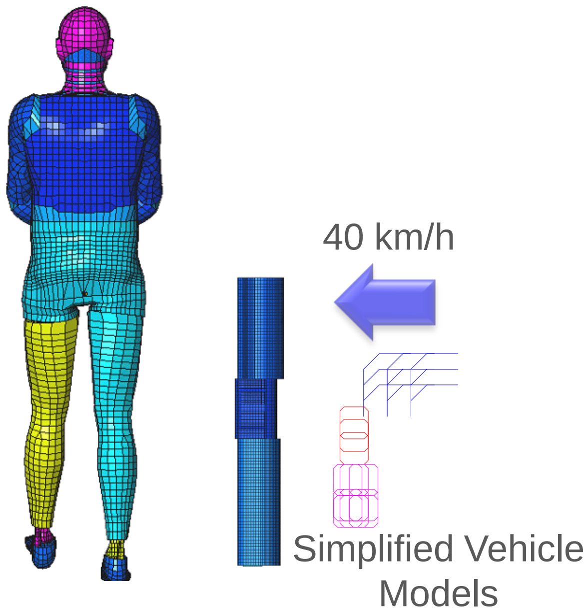
β_{Human} : Human model knee valgus bending angle (deg)

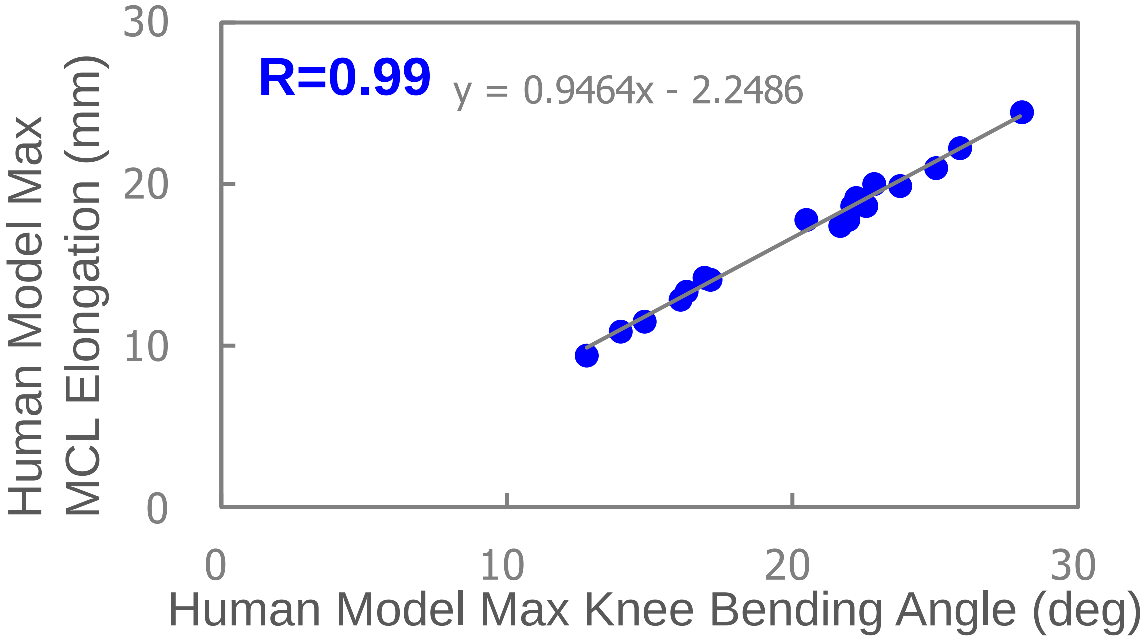
$\delta_{Flex-GTR}$: FlexPLI model MCL elongation (mm)

- Human model knee bending angle converted to FlexPLI model MCL elongation
- This conversion is valid only when human model knee bending angle correlates with MCL elongation

Bending Angle vs. MCL Elongation

Impact Simulations





- **Very good correlation between human model knee bending angle and MCL elongation**
- **Conversion from human model knee bending angle to FlexPLI model MCL elongation does not significantly affect the results**

Paper # 2012-01-0277

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Conclusions

- **Human injury probability functions were developed**
  - Leg fracture and MCL failure
  - Weibull Survival Model

- **Human injury probability functions were converted to FlexPLI functions**
  - Human-FlexPLI correlation functions from a previous study
  - Consider effect of muscle tone in converting MCL function

- **Injury thresholds proposed for FlexPLI were validated**
  - Equivalence of injury probability to EEVC legform thresholds
  - FlexPLI leg bending moment threshold corresponds to almost the same injury probability as that for EEVC legform leg acceleration
  - FlexPLI MCL elongation threshold is slightly more conservative than knee bending angle threshold for EEVC legform

CITATION:

Takahashi, Y., Matsuoka, F., Okuyama, H. and Imaizumi, I., "Development of Injury Probability Functions for the Flexible Pedestrian Legform Impactor," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(1):2012, doi:10.4271/2012-01-0277.