TEG-084

Injury Criteria for Tibia
- JAMA Proposal -

The Japan Automobile Manufacturers Association Inc.
Pedestrian Safety WG

Original Proposal (TEG-035)

Flex-GT Tentative Threshold Values

TEG-035

Human value

Body regions	50% Injury risk level of AM50 (tentative)	References
	Human value	
Leg (Tibia)	BM (312 - 350 Nm)	BM (312 Nm): Kerrigan et al., 2004 BM (350 Nm): INF GR/PS/82
Knee (MCL)	BA (18 - 20 deg)	BA (18 deg).: Ivarsson et al., 2004 BA (20 deg).: INF GR/PS/82

AM50: 50 percentile of american male
BM: Bending moment, BA: Bending angle, EL: Elongation, SD: Shearing displacement.

Based on Nyquist et al. (1985)

Originally proposed threshold for human tibia (TEG-035)

- 312 Nm based on Kerrigan et al. (2004)
- 350 Nm based on Nyquist et al. (1985)
- No single value proposal

JAMA Proposal at 7th Flex-TEG

(TEG-077)

Injury threshold for Flex-PLI Tibia bending moment (JAMA proposal): **318Nm**

Average value of the two threshold values shown in this presentation

- Simply take the average of the proposed two numbers
- JAMA proposal for the Flex-PLI tibia bending moment corresponds to 331 Nm of human tibia bending moment
- No questions have been raised so far

Issues with Previous JAMA Proposal

Further investigation performed by the JAMA Pedestrian Safety Working Group identified three issues with the previous JAMA proposal presented at the 7th session of the Flex-TEG

- Duplication of source data when two originally proposed numbers are averaged
- Scaling factors used by Kerrigan et al. (2004) require modifications for more reasonable data scaling
- Wrong number was used by Kerrigan et al. (2004) for one case taken from Nyquist et al. (1985)

Issues with Previous JAMA Proposal

1. Duplication of source data

- Kerrigan et al. (2004) developed injury risk curves for human tibiae based on data from 4 different data sources
- The data sources included Nyquist et al. (1985)
- Averaging the originally proposed two thresholds takes into account data from Nyquist et al. (1985) TWICE
- Since Kerrigan et al. (2004) used data from Nyquist et al. (1985), only the threshold from Kerrigan et al. (2004) should be used rather than taking the average of the originally proposed two thresholds

Issues with Previous JAMA Proposal

2. Scaling Factor used in Kerrigan et al. (2004)

- Tibia bending moment was scaled based on standard tibia length of 378.7 mm
- The standard tibia length too short
  - Other data sources suggest longer tibia length for average sized male
  - Tibia length scale factors smaller than height scale factors for most subjects

3. Erroneous Data used in Kerrigan et al. (2004)

- One of fracture moment data taken from Nyquist et al. (1985) turned out to be erroneous through investigation of paper by Nyquist et al. (1985)

1. Duplication of Source Data

Table 6. Summary structural and scaling data for specimens tested in this study. Moment arm ratio is the proximal moment arm divided by the distal moment arm. Fracture times are given for the tibia and femur only. "Displacement" measurements are for ram displacement.

	Test ID	Anatomical Bone Length (mm)	λ_L	Moment Arm Ratio	Fracture Time (ms)	Fracture Energy (J)	Actuator Displacement at Fracture (mm)	Fracture Force (N)	Fracture Moment (Nm)	Scaled Displacement at Fracture (mm)	Scaled Fracture Force (N)	Scaled Fracture Moment (Nm)	α* (m)
Thigh, Mid	8.1	465	0.9645	1.00	36.6	76.5	56.3	5064	548	54.3	4767	491	0.10402
	8.2	490	0.9153	0.94	37.4	74.3	58.2	5091	568	53.3	4325	436	0.10223
	8.3	457	0.9814	1.08	34.3	90.1	51.2	6005	640	50.2	5839	605	0.10415
	8.4	525	0.8543	1.00	34.1	67.6	53.1	3545	424	45.3	2636	265	0.10185
	8.5	488	0.9191	0.93	24.4	48.6	37.2	4308	488	34.2	3686	379	0.10389
	8.6	525	0.8543	1.00	37.3	101.9	53.5	5591	685	45.7	4117	427	0.10438
	Average	492.0	0.9148	0.99	34.0	76.5	51.6	4934	559	47.2	4228	434	0.10342
	COV	0.059	0.058	0.054	0.145	0.240	0.145	0.180	0.171	0.156	0.253	0.262	0.011
Thigh, Distal	8.7	466	0.9624	2.17	21.1	53.9	31.3	4439	394	30.1	4148	351	0.08459
	8.8	454	0.9879	2.03	28.1	61.4	42.4	4432	411	41.9	4403	396	0.08992
	8.9	514	0.8726	2.03	30.6	81.9	44.3	5646	599	38.7	4321	398	0.09267
	8.10	525	0.8543	1.95	21.0	49.5	31.8	4616	465	27.2	3391	290	0.08935
	8.11	426	1.0528	2.03	21.5	51.4	32.2	4435	380	33.9	4960	444	0.08999
	8.12	493	0.9097	2.10	24.9	41.5	38.7	4718	466	35.2	3934	351	0.08385
	Average	480.0	0.9400	2.05	24.5	56.6	36.8	4714	453	34.5	4196	372	0.08839
	COV	0.079	0.080	0.036	0.166	0.246	0.158	0.100	0.177	0.157	0.126	0.142	0.039
Leg, Mid	9.1	397	0.9539	0.98	32.2	48.2	51.3	3085	277	48.9	2807	241	0.08590
	9.2	418	0.9060	1.05	22.4	54.2	34.1	4623	433	30.9	3795	322	0.08518
	9.3	416	0.9103	1.01	23.1	34.9	36.7	2759	259	33.4	2287	195	0.08593
	9.4	479	0.7906	0.97	33.3	82.1	50.0	4365	482	39.6	2728	238	0.08777
	Average	427.5	0.8902	1.00	27.8	54.8	43.0	3708	363	38.2	2904	249	0.08620
	COV	0.083	0.078	0.035	0.209	0.363	0.207	0.249	0.307	0.210	0.219	0.212	0.013

from Kerrigan et al. (2004)

1st data source for tibia bending (4 cases)

Kerrigan et al., ***Tolerance of the Human Leg and Thigh in Dynamic Latero-Medial Bending***, ICRASH (2004)

(Paper referred to by TEG-035, basis for proposal of 312 Nm)

1. Duplication of Source Data

Table 8. Structural failure data for the leg specimens from the previous studies. “N” corresponds to specimens from [16], “K(a)” corresponds to specimens from [11], and “K(b)” corresponds to specimens from [12].

の使用手順を表示

Test	Actuator Displacement at Fracture (mm)	Fracture Force (N)	Fracture Moment (Nm)	Length Scale Factor	Scaled Displacement at Fracture (mm)	Scaled Fracture Force (N)	Scaled Fracture Moment (Nm)	Data Type
N-126	-	3520	224	0.960	-	3243	198	Censored
N-129	-	5500	349	0.921	-	4669	273	Censored
~~N-147~~	~~-~~	~~6780~~	~~431~~	~~1.138~~	~~-~~	~~8773~~	~~634~~	~~Censored~~
N-127	-	3730	237	0.991	-	3661	230	Censored
N-124	-	4250	270	0.940	-	3757	224	Censored
N-118	-	5180	395	0.886	-	4066	275	Censored
N-132	-	4150	264	1.035	-	4448	292	Censored
N-148	-	4000	254	1.097	-	4813	335	Censored
N-152	-	4310	274	1.071	-	4948	337	Censored
K(a)-134L	46.2	4452	416	0.9017	41.6	3620	305	Exact
K(b)-D1	49.7	4373	463	0.8510	42.3	3167	285	Exact
K(b)-D2	44.4	4706	485	0.8416	37.4	3333	289	Exact
K(b)-D3	49.7	3290	290	0.9836	48.9	3183	276	Exact
K(b)-D4	50.3	3523	309	0.9836	49.4	3409	294	Exact
K(b)-D5	45.5	4450	416	1.0019	45.6	4467	418	Exact
K(b)-D6	38.8	3382	306	0.9587	37.2	3108	269	Exact
Average	46.4	4350	336	0.9726	43.2	4167	308	
COV	0.088	0.206	0.255	0.087	0.116	0.331	0.326	

2nd data source (8 cases)

3rd data source (1 case)

4th data source (6 cases)

← Not used (outlier)

from Kerrigan et al. (2004)

2nd : Nyquist et al., ***Tibia Bending: Strength and Response***, SAE Paper #851728 (1985)

3rd : Kerrigan et al., ***Experiments for establishing pedestrian-impact lower limb injury criteria***, SAE Paper #2003-01-0895 (2003)

4th : Kerrigan et al., ***Response Corridors for the Human Leg in 3-Point Lateral Bending***, 7th US National Congress on Computational Mechanics (2003)

Kerrigan et al. (2004) used data from Nyquist et al. (1985)

2. Scaling Factor used in Kerrigan et al. (2004)

Data Scaling Procedure used by Kerrigan et al.

Data Scaling

Equation 1 shows that the stress arising in a bone (modeled as a linearly elastic beam) is proportional to the moment applied and the cross sectional geometry of the bone. To provide a basis for comparing specimen responses, it is common to assume that specimens are geometrically similar and thus can be scaled to a reference geometry. Thus the bones in this study are scaled to a reference geometry using a scale factor ($\lambda_L = L_{ref}/L$) based on the length of the bone specimen.

from Kerrigan et al. (2004)

- Assume geometric similarity between the leg specimens
- Tibia bending moment was scaled using the following equations

$$\lambda_L = L_{ref} / L$$

$$M_{scaled} = \lambda_L^{\ 3} M$$

where

L_{ref} : Reference tibia length

L : Tibia length of specimen

M : Measured tibia bending moment

M_{scaled} : Scaled tibia bending moment

2. Scaling Factor used in Kerrigan et al. (2004)

Data Scaling Procedure used by Kerrigan et al.

- Data from the experiments performed by Kerrigan et al. (1st, 3rd and 4th data sources) were scaled using a reference tibia length because tibia length was provided for each specimen in the papers
- Data from Nyquist et al. (1985) were scaled using a reference tibial plateau height from the base of the foot since only this dimension was provided in the paper

The anatomical bone lengths were measured for all specimens in the current study as well as in three of the previous studies [10-12]. However Nyquist [16] only provided tibial plateau height (from the base of the foot) for their specimens. Diffrient [26] cites the ratio of tibial plateau height (500 mm) to anatomical tibial length (411 mm) for a 50th percentile male (174.8 cm 78 kg) as .9214. Since the reference geometry used in this paper is not exactly AM50 (it is taken from a single PMHS whose stature is near AM50), the specimens tested by Nyquist [16] will be scaled by tibial plateau height to a reference height of 460.7 mm (determined by applying the .9214 ratio to the 378.7 mm SMT anatomical length).

from Kerrigan et al. (2004)

2. Scaling Factor used in Kerrigan et al. (2004)

Reference Tibia Length used by Kerrigan et al.

Large Femur
487.6mm

Large
411.6mm

Medium Femur
448.5mm

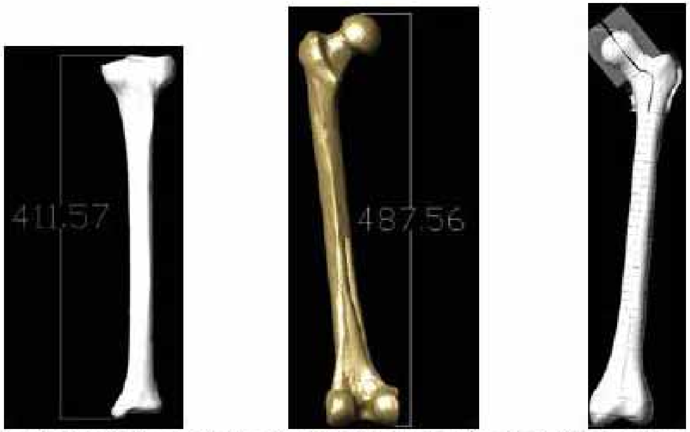


Figure 2. Orientation of length measurements used to scale the data for the leg and thigh specimens. The femur and tibia shown here in the center and on the left, are AUTOCAD representations of the large sized tibia and femur digital geometries available through the International Society of Biomechanics Mesh Repository (ISB MR, 2004). These geometries correspond to the Sawbones Large Sized Third Generation Left Composite Femur and Tibia. The picture on the right is of an AUTOCAD representation of the Standardized Femur (The Standardized Femur Homepage). The dimensions included in the left and center pictures (411.6 mm and 487.6 mm) are the anatomical lengths of the tibia and femur.

Currently (January, 2004) there are geometric models of the SLF and the SLT available from the International Society of Biomechanics Mesh Repository website ([25], Figure 2). The anatomical length of the SLF and the Sawbones Large Tibia (SLT) (as measured by importing the IGES data into AUTOCAD) are 487.6 mm and 411.6 mm respectively. The anatomical length of the SMF (as measured by importing the IGES data from the Standardized Femur Homepage into AUTOCAD) is 448.5 mm. Since there is no digital model of the Sawbones Medium Tibia (SMT) available, the assumption of geometric similarity was used to determine a scale factor for the length of the SMF and the SLF. The length of the SMT (378.7 mm) was then calculated as the length of the SLT multiplied by the scale factor (0.92). Thus the anatomical lengths used to scale all leg and thigh specimens (in this and all previous studies discussed here) were 378.7 mm and 448.5 mm respectively.

from Kerrigan et al. (2004)

2. Scaling Factor used in Kerrigan et al. (2004)

Reference Tibia Length used by Kerrigan et al.

- Sawbones: Commercially available biomechanical test product (Pacific Research Labs, Vashon Island, WA, USA)
- Products from Pacific Research Labs
  - Sawbones Medium Sized Composite Femur: SMF (Model 3303)
  - Sawbones Medium Sized Composite Tibia: SMT (Model 3301)
  - Sawbones Large Sized Composite Femur: SLF (Model 3306)
  - Sawbones Large Sized Composite Tibia: SLT (Model 3302)
- From above listed models, 3D geometric models are available on the web for the following 3 models
  - International Society of Biomechanics Mesh Repository website
    - SLF = 487.6 mm
    - SLT = 411.6 mm
  - The Standardized Femur Homepage
    - SMF = 448.5 mm
- Since the length of SMT is unknown, it was estimated using the following equation

  SMT = SLT * SMF / SLF = 378.7 mm

Reference tibia length used by Kerrigan et al. (2004) determined as 378.7 mm

2. Scaling Factor used in Kerrigan et al. (2004)

Reference Tibial Plateau Height used by Kerrigan et al.

The anatomical bone lengths were measured for all specimens in the current study as well as in three of the previous studies [10-12]. However Nyquist [16] only provided tibial plateau height (from the base of the foot) for their specimens. Diffrient [26] cites the ratio of tibial plateau height (500 mm) to anatomical tibial length (411 mm) for a 50th percentile male (174.8 cm 78 kg) as .9214. Since the reference geometry used in this paper is not exactly AM50 (it is taken from a single PMHS whose stature is near AM50), the specimens tested by Nyquist [16] will be scaled by tibial plateau height to a reference height of 460.7 mm (determined by applying the .9214 ratio to the 378.7 mm SMT anatomical length).

from Kerrigan et al. (2004)

- Diffrient et al. (1993) : For 50th percentile male (174.8 cm, 78 kg)
  - Heel to tibial plateau height = 500 mm
  - Tibia length = 411 mm
- Rather than using the data from Diffrient et al., the reference tibia length was multiplied by the ratio of the tibial pleteau height to tibia length to estimate reference tibial plateau height of 460.7 mm

Reference tibial plateau height used by Kerrigan et al. (2004) determined as 460.7 mm

2. Scaling Factor used in Kerrigan et al. (2004)

Validity of Reference Length used by Kerrigan et al.

- Reference tibia length used by Kerrigan et al. (2004) = 378.7 mm

- Diffrient et al. (1993) : Tibia length for 50th percentile male = 411 mm
- UMTRI data : Length between lateral malleolus and tibiale (x, z resultant) = 404.36 mm
- A human tibia model shows tibia length is larger than UMTRI dimension

UMTRI Data

Technical Report Documentation Page

1. Report No.
2. Government Accession No.
3. Recipient's Catalog No.
4. Title and Subtitle: DEVELOPMENT OF ANTHROPOMETRICALLY BASED DESIGN SPECIFICATIONS FOR AN ADVANCED ADULT ANTHROPOMORPHIC DUMMY FAMILY, Volume 1
5. Report Date: December 1983
6. Performing Organization Code
7. Author(s): L.W. Schneider, D.H. Robbins, M.A. Pflüg, R.G. Snyder
8. Performing Organization Report No.: UMTRI-83-53-1
9. Performing Organization Name and Address: The University of Michigan, Transportation Research Institute, 2901 Baxter Road, Ann Arbor, Michigan 48109
10. Work Unit No. (TRAIS)
11. Contract or Grant No.: DTNH22-80-C-07502
12. Sponsoring Agency Name and Address: U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington, D.C. 20590
13. Type of Report and Period Covered: FINAL REPORT, Oct. 1980 - Dec. 1983
14. Sponsoring Agency Code
15. Supplementary Notes: Volume 2: Anthropometric Specifications for Mid-Sized Male Dummy

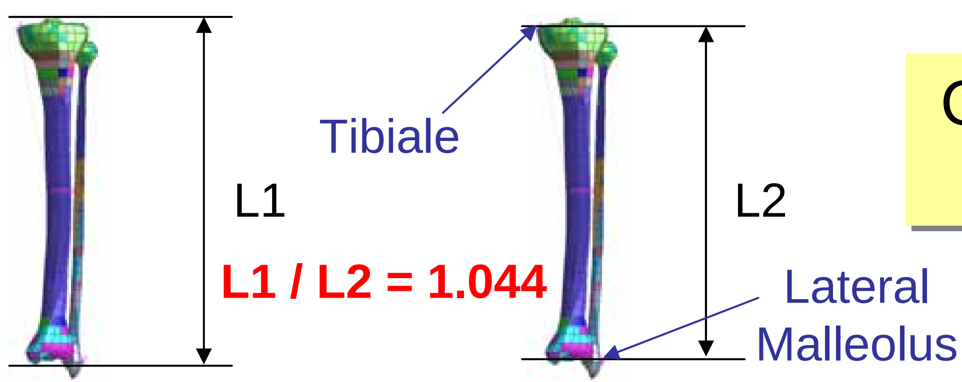
TABLE 5.4
SURFACE LANDMARKS RELATIVE TO H-POINT (Continued)

Body Segment	Surface Landmark	SMALL FEMALE			MID-SIZED MALE			LARGE MALE		
		X_H	Y_H	Z_H	X_H	Y_H	Z_H	X_H	Y_H	Z_H
Shoulder	Clavicale	-146	± 17	397	-145	± 23	443	-171	± 25	473
	Acromio-Clavicular Artic.	-198	±152	356	-215	±182	443	-247	±192	480
	Greater Tubercle Humerus	-153	±178	380	-173	±218	421	-185	±223	469
	Acromion	-206	±171	376	-224	±200	419	-256	±217	454
	Anterior Scye	-106	±130	337	- 87	±154	380	-115	±167	421
	Posterior Scye	-191	±164	286	-214	±197	306	-245	±221	328
	Superior Margin Scapula	-363	± 66	379	-396	±79	403	-331	±83	446
	Inferior Margin Scapula	-250	±109	292	-276	±126	267	-304	±147	271
Arm	Lateral Humeral Epicondyle	12	±211	206	33	±243	334	34	±266	270
	Radiale	28	±207	193	46	±243	309	52	±261	252
	Medial Humeral Epicondyle	15	±150	190	32	±173	159	37	±189	236
	Olecranon	34	±183	177	53	±210	186	48	±234	225
	Ulnar Styloid	130	±182	383	336	±191	387	363	±197	398
	Stylion	121	±136	387	211	±135	399	245	±138	414
Leg and Foot	Lateral Femoral Epicondyle	360	±119	72	404	±189	129	411	±207	157
	Medial Femoral Epicondyle	365	± 32	69	407	± 87	142	414	± 98	175
	Tibiale	378	± 35	58	424	± 88	128	433	± 97	163
	Patella	404	± 81	91	449	±150	172	460	±168	202
	Sphyrion	599	± 57	-172	684	± 61	-149	721	±63	-131
	Metatarsal-Phalangeal I	698	± 76	-120	756	± 84	- 86	845	± 85	- 70
	Digit II	729	±126	- 74	839	±147	- 37	889	±150	- 14
	Metatarsal-Phalangeal V	693	±157	-147	785	±174	-124	832	±187	-105
	Lateral Malleolus	584	±115	-194	680	±126	-185	711	±135	-169
	Posterior Calcaneus**	618	± 90	-254	705	± 94	-250	741	± 97	-238

*Left side of body (+).

**Landmark location determined by construction.

Human Model



Other data sources suggest longer tibia length

2. Scaling Factor used in Kerrigan et al. (2004)

Summary of Data used by Kerrigan et al.

Test	Source	Age	Gender	Stature (mm)	Weight (kg)	Anatomical Measurement (mm)	Anatomical Measurement Description	STD Anatomical Measurement (mm)	Length Scale Factor	Fracture Moment (Nm)	Scaled Fracture Moment (Nm)	STD Stature (mm)	Height Scale Factor
9.1	Kerrigan et al. ICRASH 2004	66	M	1829	79.8	397	Bone Length	378.7	0.9539	277	240	1750	0.9568
9.2	Kerrigan et al. ICRASH 2004	69	M	1702	81.6	418	Bone Length	378.7	0.9060	433	322	1750	1.0282
9.3	Kerrigan et al. ICRASH 2004	62	M	1829	60.8	416	Bone Length	378.7	0.9103	259	195	1750	0.9568
9.4	Kerrigan et al. ICRASH 2004	54	M	1880	117.9	479	Bone Length	378.7	0.7906	482	238	1750	0.9309
N-126	Nyquist et al. SAE 1985	58	M	1740	73	480	Heel to Tibial Plateau	460.7	0.9598	224	198	1750	1.0057
N-129	Nyquist et al. SAE 1985	57	M	1780	99	500	Heel to Tibial Plateau	460.7	0.9214	349	273	1750	0.9831
N-127	Nyquist et al. SAE 1985	56	M	1760	79	465	Heel to Tibial Plateau	460.7	0.9908	237	230	1750	0.9943
N-124	Nyquist et al. SAE 1985	64	M	1770	82	490	Heel to Tibial Plateau	460.7	0.9402	287	224	1750	0.9887
N-118	Nyquist et al. SAE 1985	54	M	1820	68	520	Heel to Tibial Plateau	460.7	0.8860	395	275	1750	0.9615
N-132	Nyquist et al. SAE 1985	57	M	1870	45	445	Heel to Tibial Plateau	460.7	1.0353	264	293	1750	0.9358
N-148	Nyquist et al. SAE 1985	57	F	1630	75	420	Heel to Tibial Plateau	460.7	1.0969	254	335	1750	1.0736
N-152	Nyquist et al. SAE 1985	51	F	1630	68	430	Heel to Tibial Plateau	460.7	1.0714	274	337	1750	1.0736
K(a)-134L	Kerrigan et al. SAE 2003	44	M	1702	73	420	Bone Length	378.7	0.9017	416	305	1750	1.0282
K(b)-D1	Kerrigan et al. US NCCM 2003	54	M	1905	88	445	Bone Length	378.7	0.8510	463	285	1750	0.9186
K(b)-D2	Kerrigan et al. US NCCM 2003	54	M	1905	88	450	Bone Length	378.7	0.8416	485	289	1750	0.9186
K(b)-D3	Kerrigan et al. US NCCM 2003	68	M	1651	51	385	Bone Length	378.7	0.9836	290	276	1750	1.0600
K(b)-D4	Kerrigan et al. US NCCM 2003	68	M	1651	51	385	Bone Length	378.7	0.9836	309	294	1750	1.0600
K(b)-D5	Kerrigan et al. US NCCM 2003	65	F	1727	60	378	Bone Length	378.7	1.0019	416	418	1750	1.0133
K(b)-D6	Kerrigan et al. US NCCM 2003	75	M	1778	65	395	Bone Length	378.7	0.9587	306	270	1750	0.9843

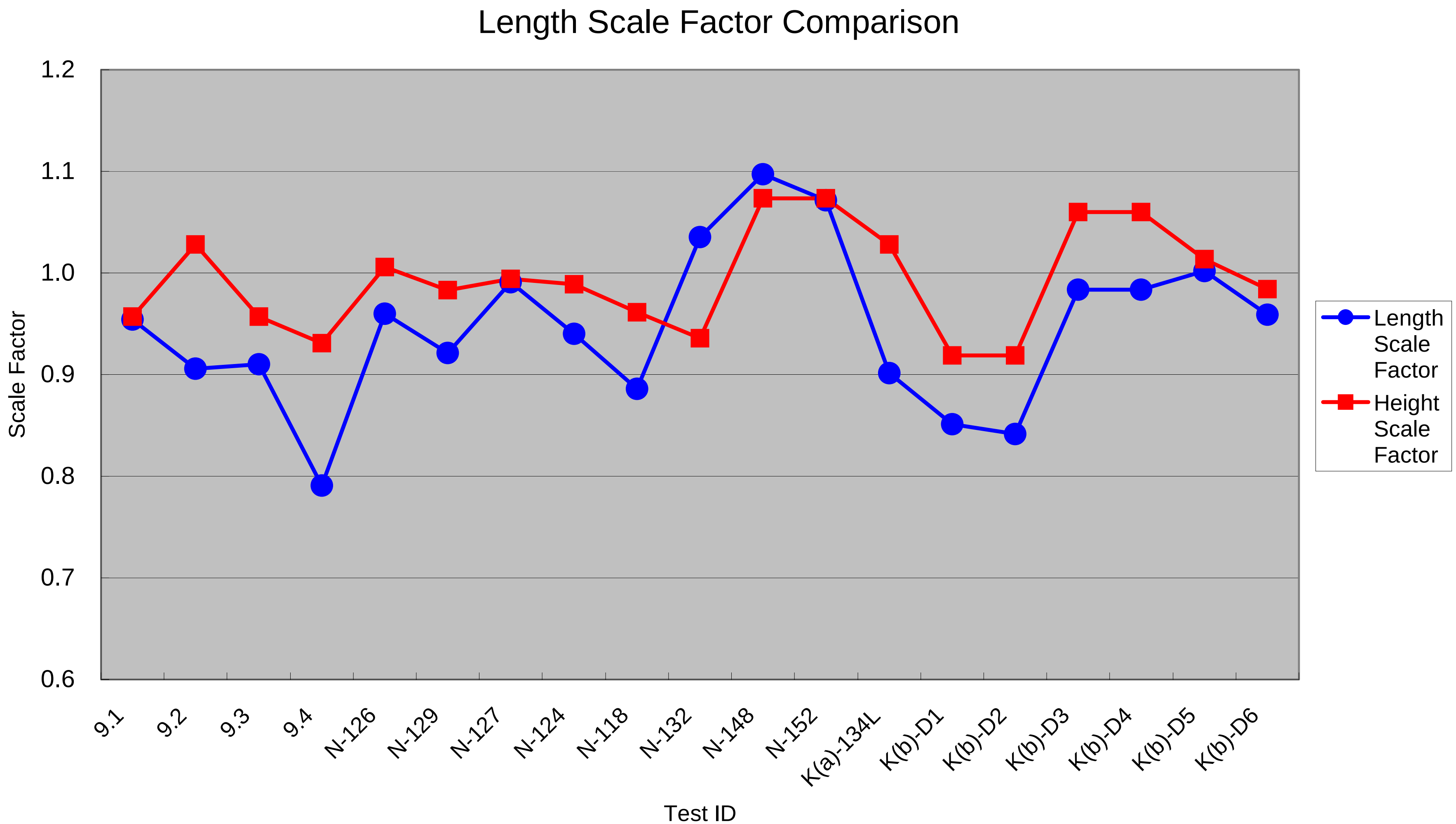
Length scale factor used by Kerrigan et al. (2004)

Height scale factor using reference height of 175 cm

- Tibia length should be highly correlated with height
- Compare tibia length scale factor with height scale factor

2. Scaling Factor used in Kerrigan et al. (2004)

Comparison between tibia length scale factor and height scale factor



Tibia length scale factors biased towards smaller numbers relative to height scale factors

2. Scaling Factor used in Kerrigan et al. (2004)

Options for More Reasonable Length Scale Factor

Option 1

- Determine reference length such that the average length scale factor coincides with the average height scale factor
  - Assumption: overall tibia length distribution should correlate well with overall height distribution
  - Assume the same ratio of tibial plateau height to tibia length as that used by Kerrigan et al. (1.22)
  - Reference tibia length (for scaling Kerrigan data) : 397.4 cm
  - Reference tibial plateau height (for scaling Nyquist data) : 483.5 cm

Option 2

- Use unscaled data
  - Average height of the specimens (176.6 cm) is close to 50^{th} percentile

Reanalyze injury risk curves using the same statistical procedures as those used by Kerrigan et al. under these two options

2. Scaling Factor used in Kerrigan et al. (2004)

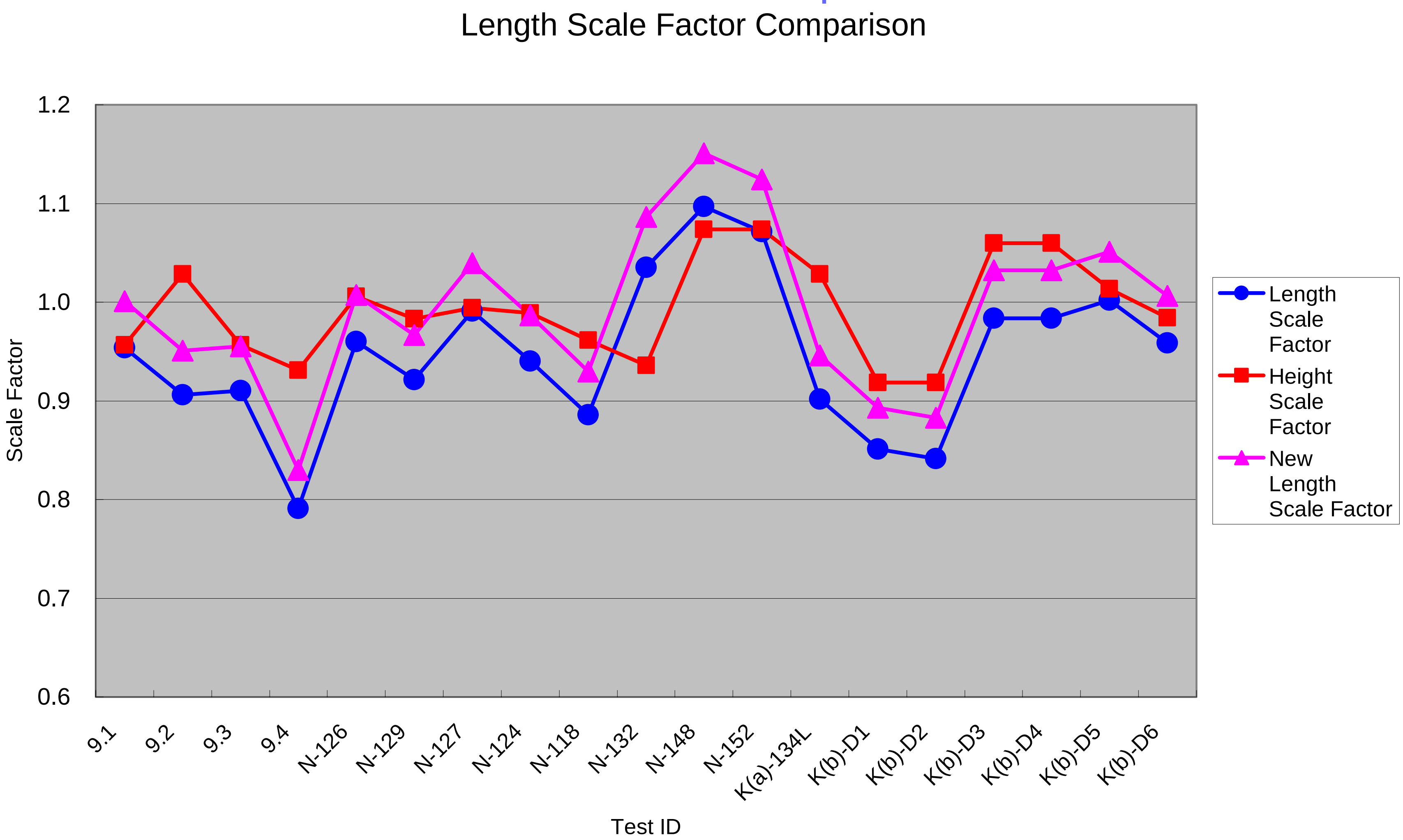
Summary of Data with Modified Length Scale Factors

Test	Source	Age	Gender	Stature (mm)	Weight (kg)	Anatomical Measurement (mm)	Anatomical Measurement Description	Fracture Moment (Nm)	Original STD Anatomical Measurement	Original Length Scale Factor	Original Scaled Fracture Moment (Nm)	Option-1 STD Anatomical Measurement (mm)	Option-1 Length Scale Factor	Option-1 Scaled Moment (Nm)	Option-2 Unscaled Fracture Moment	Data Type
9.1	Kerrigan et al. ICRASH 2004	66	M	1829	79.8	397	Bone Length	277	378.7	0.9539	240	397.4	1.0010	277.8	277	Uncensored
9.2	Kerrigan et al. ICRASH 2004	69	M	1702	81.6	418	Bone Length	433	378.7	0.9060	322	397.4	0.9507	372.1	433	Uncensored
9.3	Kerrigan et al. ICRASH 2004	62	M	1829	60.8	416	Bone Length	259	378.7	0.9103	195	397.4	0.9553	225.8	259	Uncensored
9.4	Kerrigan et al. ICRASH 2004	54	M	1880	117.9	479	Bone Length	482	378.7	0.7906	238	397.4	0.8296	275.2	482	Uncensored
N-126	Nyquist et al. SAE 1985	58	M	1740	73	480	Heel to Tibial Plateau	224	460.7	0.960	198	483.5	1.0072	228.9	224	Right Censored
N-129	Nyquist et al. SAE 1985	57	M	1780	99	500	Heel to Tibial Plateau	349	460.7	0.921	273	483.5	0.9669	315.5	349	Right Censored
N-127	Nyquist et al. SAE 1985	56	M	1760	79	465	Heel to Tibial Plateau	237	460.7	0.991	230	483.5	1.0397	266.4	237	Right Censored
N-124	Nyquist et al. SAE 1985	64	M	1770	82	490	Heel to Tibial Plateau	287	460.7	0.940	239	483.5	0.9866	275.7	287	Right Censored
N-118	Nyquist et al. SAE 1985	54	M	1820	68	520	Heel to Tibial Plateau	395	460.7	0.886	275	483.5	0.9297	317.4	395	Right Censored
N-132	Nyquist et al. SAE 1985	57	M	1870	45	445	Heel to Tibial Plateau	264	460.7	1.035	293	483.5	1.0864	338.5	264	Right Censored
N-148	Nyquist et al. SAE 1985	57	F	1630	75	420	Heel to Tibial Plateau	254	460.7	1.097	335	483.5	1.1511	387.4	254	Right Censored
N-152	Nyquist et al. SAE 1985	51	F	1630	68	430	Heel to Tibial Plateau	274	460.7	1.071	337	483.5	1.1243	389.4	274	Right Censored
K(a)-134L	Kerrigan et al. SAE 2003	44	M	1702	73	420	Bone Length	416	378.7	0.9017	305	397.4	0.9462	352.4	416	Uncensored
K(b)-D1	Kerrigan et al. US NCCM 2003	54	M	1905	88	445	Bone Length	463	378.7	0.8510	285	397.4	0.8930	329.7	463	Uncensored
K(b)-D2	Kerrigan et al. US NCCM 2003	54	M	1905	88	450	Bone Length	485	378.7	0.8416	289	397.4	0.8831	334.0	485	Uncensored
K(b)-D3	Kerrigan et al. US NCCM 2003	68	M	1651	51	385	Bone Length	290	378.7	0.9836	276	397.4	1.0322	318.9	290	Uncensored
K(b)-D4	Kerrigan et al. US NCCM 2003	68	M	1651	51	385	Bone Length	309	378.7	0.9836	294	397.4	1.0322	339.8	309	Uncensored
K(b)-D5	Kerrigan et al. US NCCM 2003	65	F	1727	60	378	Bone Length	416	378.7	1.0019	418	397.4	1.0513	483.4	416	Uncensored
K(b)-D6	Kerrigan et al. US NCCM 2003	75	M	1778	65	395	Bone Length	306	378.7	0.9587	270	397.4	1.0061	311.6	306	Uncensored

- Calculate injury risk curves using Original, Option-1 and Option-2 datasets
- Weibull univariate survival model
- Data from Nyquist et al. (1985) treated as right censored data because of peak moment attenuation due to filtering
- All other data treated as uncensored data because peak moment corresponds to fracture

2. Scaling Factor used in Kerrigan et al. (2004)

Scale Factors for Option-1



Option-1 yields average scale factor identical to average height scale factor while allowing individual variation

2. Scaling Factor used in Kerrigan et al. (2004)

Results of Survival Analysis for Original, Option-1 and Option-2 Datasets

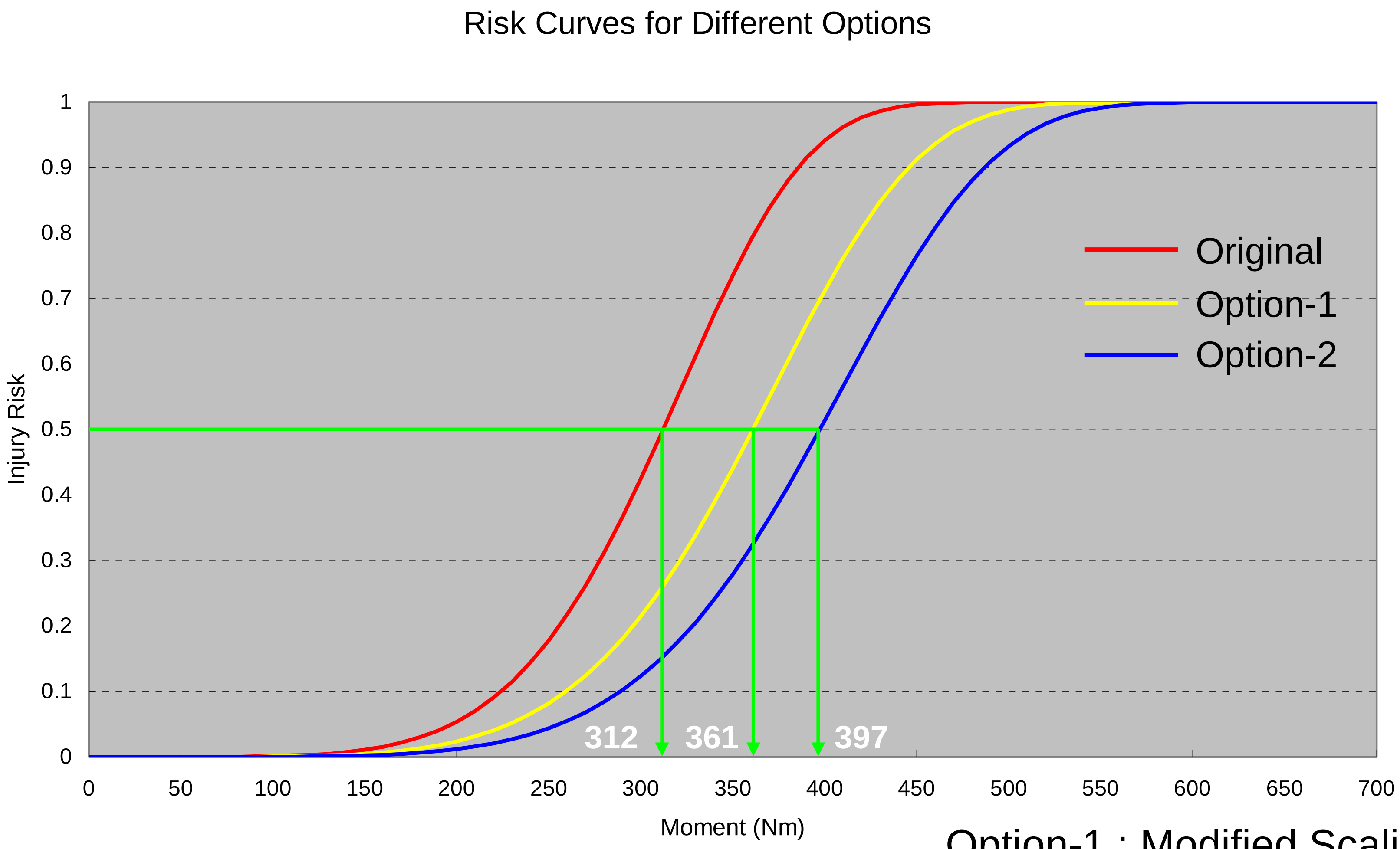
$$Risk = 1 - exp(- exp(A \cdot ln(M) - B))$$

Case	Intercept	Scale	A	B	M50%
ORG	5.80766352	0.17571234	5.69112	33.05211	312
Option-1	5.953058	0.1753883	5.7016346	33.9421615	361
Option-2	6.046711	0.1689358	5.91940844	35.7929521	397

Option-1 : Modified Scaling
Option-2 : No Scaling

2. Scaling Factor used in Kerrigan et al. (2004)

Injury Risk Curves for Original, Option-1 and Option-2 Datasets



Option-1 : Modified Scaling

Option-2 : No Scaling

3. Erroneous Data used by Kerrigan et al. (2004)

Table 8. Structural failure data for the leg specimens from the previous studies. "N" corresponds to specimens from [16]. "K(a)" corresponds to specimens from [11], and "K(b)" corresponds to specimens from [12].

Test	Actuator Displacement at Fracture (mm)	Fracture Force (N)	Fracture Moment (Nm)	Length Scale Factor	Scaled Displacement at Fracture (mm)	Scaled Fracture Force (N)	Scaled Fracture Moment (Nm)	Data Type
N-126	-	3520	224	0.960	-	3243	198	Censored
N-129	-	5500	349	0.921	-	4669	273	Censored
N-147	-	6780	431	1.138	-	8773	634	Censored
N-127	-	3730	237	0.991	-	3661	230	Censored
N-124	-	4250	270	0.940	-	3757	224	Censored
N-118	-	5180	395	0.886	-	4066	275	Censored
N-132	-	4150	264	1.035	-	4448	292	Censored
N-148	-	4000	254	1.097	-	4813	335	Censored
N-152	-	4310	274	1.071	-	4948	337	Censored
K(a)-134L	46.2	4452	416	0.9017	41.6	3620	305	Exact
K(b)-D1	49.7	4373	463	0.8510	42.3	3167	285	Exact
K(b)-D2	44.4	4706	485	0.8416	37.4	3333	289	Exact
K(b)-D3	49.7	3290	290	0.9836	48.9	3183	276	Exact
K(b)-D4	50.3	3523	309	0.9836	49.4	3409	294	Exact
K(b)-D5	45.5	4450	416	1.0019	45.6	4467	418	Exact
K(b)-D6	38.8	3382	306	0.9587	37.2	3108	269	Exact
Average	46.4	4350	336	0.9726	43.2	4167	308	
COV	0.088	0.206	0.255	0.087	0.116	0.331	0.326	

from Kerrigan et al. (2004)

Kerrigan et al. (2004)
Fracture moment for N-124 (from Nyquist et al.) : 270 Nm

TABLE 6

Bending Moment, Section Modulus and Stress

Test Number	Peak Bending Moment At Midspan (N.m)*	Section Modulus (mm^3)	Peak Tensile Stress (MPa)
116	176	960	183
117	326	2510	130
118	395	1500	263
121	302	1340	225
122	-	1210	-
123	453	1450	312
124	287	2310	124
125	182	1370	133
126	224	920	243

from Nyquist et al. (1985)

Nyquist et al. (1985)
Fracture moment for N-124 : 287 Nm

- Analysis in previous section used correct data
- No big impact on the results identified

Proposal for Human Tibia Moment Threshold

- Only data used by Kerrigan et al. (2004) were used in order to avoid duplicated data entry
- Unscaled data resulted in different injury risk curve from that obtained using modified scale factors with the average scale factor identical to the average height scale factor
- Although the average height of the specimens was close to that of 50^{th} percentile male, data scaling should allow more appropriate threshold for the Flex-PLI that represents 50^{th} percentile male anthropometry

- Proposed bending moment threshold for human tibia : **361 Nm**
- Flex-GTR tibia bending moment threshold needs to be investigated based on the response correlation between the Flex-GTR and human lower limb