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Development of New Injury Risk Curves for the Knee/Distal Femur and the Hip for Use in Frontal Impact Testing

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16. Abstract

This report describes how new injury risk curves for the knee/distal femur and the hip were developed through reanalyses of existing peak knee impact force data. New hip injury risk curves were developed using survival analysis with a lognormal distribution. This distribution was parameterized to account for the effect of stature, which was the only subject characteristic that had a statistically significant effect on the relationship between peak force applied to the hip and the risk of hip fracture. The empirically defined effects of hip flexion and abduction from a standardized seated driving posture on mean hip fracture force were also incorporated into the lognormal distribution as mean shifts. Injury risk curves for the midsize male crash test dummy were defined by applying the stature associated with this dummy and posture of 30° flexion and 15° abduction from a standard reference posture and the standard reference posture (0°flexion, 0° adduction) to the lognormal distribution.

A new risk curve describing the relationship between peak force applied at the knee and the likelihood of knee/distal femur fracture was developed by applying survival analysis to an existing dataset in which there was uncensored, left censored, and right censored peak knee impact force data. This risk curve is similar to that currently used by the NHTSA to assess the risk of AIS 2+ KTH injury. Because the fracture forces in the dataset used to develop the new knee/distal femur risk curve were primarily from tests where rigid surfaces loaded the knees of elderly midsize male cadavers, the new risk curve only applies to rigid knee impacts and this segment of the occupant population. Future work should focus on developing knee/distal femur risk curves that apply to other segments of the driving population by characterizing and accounting for the effects of subject factors and impact surface rigidity on KTH fracture forces.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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4. Introduction

The process used to develop injury risk curves usually involves loading unembalmed cadavers in a manner that simulates the loading conditions that a human occupant experiences in a particular mode and severity of crash and measuring the applied loading and the resulting response and injury to the cadaver. These data are then statistically analyzed to identify an injury criterion and to develop a relationship between this criterion and the occurrence of a particular severity and type of injury.

Statistical methods that are commonly used to develop injury risk curves include logistic regression and survival analysis. Logistic regression is used when injury criteria are associated with a binary outcome. Survival analysis is used when the outcome is censored, i.e., the calculated injury criterion is either greater than or less than the value of the injury criterion that is associated with the occurrence of injury. For example, peak chest compression can be a censored injury criterion for rib fracture because rib fractures can occur prior to peak chest compression. Note that if a sensor, like a crack detection gage, is used to identify the time at which rib fractures occurs in a test, the chest compression associated with rib fracture can be determined and the association between chest compression and rib fracture is uncensored.

This report describes how injury risk curves for the hip and for the knee and distal femur were developed by reanalyzing existing datasets of forces associated with hip fracture and/or dislocation (Rupp et al. 2003 and Rupp 2006) and peak knee impact forces associated with knee and distal femur fractures (Kuppa et al. 2001). In development of both of these risk curves, survival analysis was used since the occurrence and type of censoring in the experimental datasets could be identified. Because the amount of uncensored data on hip fracture forces was large, experimental data were used to define how the risk of hip fracture varies with subject characteristics. Since the amount of uncensored data on knee and distal femur fracture was limited, it was not possible to account for the effects of subject characteristics on knee/distal femur injury risk.

5. Methods

5.1 Development of Hip Injury Risk Curves

The peak force data and the associated subject characteristics used to develop hip injury risk curves were obtained from studies by Rupp et al. (2003) and Rupp (2006). In these studies, the knees of cadaver pelvis and lower-extremity specimens were sequentially loaded in tests where the pelvis was fixed in a controlled posture by gripping the iliac wings. Fixing the iliac wings allowed the effects of hip flexion and abduction from a standard driving posture on hip fracture force to be quantified. It also eliminated the inertially induced drop in force between the knee and the hip. Since all fixed-pelvis tests produced hip fractures or dislocations, and since there were no indications of macroscopic fracture prior to the time of peak applied force, the peak forces reported in these studies constitute an uncensored dataset of forces associated with hip injury.

The peak forces associated with hip fracture/dislocation and the characteristics of the 27 cadavers from which specimens were obtained for fixed-pelvis tests are listed in Table 5.1. All of the fracture forces in Table 5.1 are associated with the standard driving posture for a midsize male defined by Schneider et al. (1983) because hip flexion and adduction/abduction from this posture have been shown to significantly alter hip fracture force (Rupp et al. 2003).

The data in Table 5.1 were analyzed using parametric survival analysis in SAS version 9.2 (SAS Institute Inc., Cary, N.C) with a lognormal distribution. All forces were treated as uncensored. Chi-squared tests were used to determine whether subject characteristics, including age, gender, stature, and mass, are significant predictors of the force required to produce hip fracture in the standard driving posture.

The effects of hip flexion and abduction on the force associated with hip injury were incorporated into the lognormal distribution produced by applying survival analysis to the data in Table 5.1 as mean shifts of 1% per degree of hip abduction and -1% per degree of hip flexion. These values are the effects of hip flexion and abduction from the standard automotive-seated posture on mean hip fracture/dislocation force that resulted from the fixed-pelvis tests described above.

An injury risk curve for the midsize male crash-test dummy hip was developed by applying the subject characteristics associated with this crash test dummy and a posture of 30° flexion and 15° abduction to the parametric hip injury risk curve developed from analysis of the data in Table 5.1. This posture was used because previous studies suggested that it was the approximate posture at the time of peak knee impact force in front-impact sled tests with airbag deployment (Rupp 2006, Rupp et al. 2008).

Table 5.1: Hip Fracture/Dislocation Force Data from Tests Using Hip Postures That Corresponded to a Standard Male Driving Posture

Test ID	Fracture Force (kN)	Gender	Age	Stature (cm)	Mass (kg)
NB0105L&R	5.48	F	55	163	113
NB0106L	4.85	M	86	173	91
NB0108L&R	7.70	M	79	180	82
NB0110L	6.60	M	60	178	125
NB0112R	6.67	M	72	173	81
NB0114R	4.65	F	68	165	71
NB0216R	5.59	F	71	178	82
NB0217L	4.79	M	75	175	72
NB0218L	5.57	M	72	178	82
NB0222L	8.85	M	41	176	91
NB0224R	3.92	M	60	178	82
NB0225L&R	5.77	F	86	168	68
NB0226L	6.60	M	62	183	91
NB0228R	4.05	F	65	163	82
NB0230R	6.09	M	45	185	75
NB0231R	5.63	F	79	165	91
NB0234L	8.17	M	74	175	100
NB0337R	5.09	M	58	175	62
NB0338RH	4.59	M	86	173	59
NB0340RH	7.54	M	63	183	66
NB0341RH	6.89	M	79	165	68
NB0342RH	6.26	M	83	189	93
NB0343RH	9.79	M	79	191	109
NB0345RH	5.11	M	82	173	75
NB0447RH	6.14	F	49	157	59
NB0448RH	6.13	M	76	178	80
NB0450LH	6.03	M	73	178	86

[†] Average of hip fracture forces produced in tests where the left and right sides of the KTH complex from the same subject were loading in the standard male driving posture.

5.2 Development of Knee/Distal Femur Injury Risk Curve

An injury risk curve for the knee and distal femur was developed using a meta-analysis of peak knee impact force data from six studies in the biomechanical literature in which the knees of whole seated cadavers were impacted (Kroell et al. 1976, Melvin and Nusholtz 1980, Cheng et al. 1982, Leung et al. 1983, Cheng et al. 1984, Donnelly and Roberts 1987). Data from these studies were obtained from Kuppa et al. (2001) who reprocessed the knee impact force histories from these six studies using consistent filtering and zeroing techniques and then applied logistic regression to the resulting dataset to establish KTH risk curves for AIS 2+ and AIS 3+ injuries.

Because the Kuppa et al. analysis used logistic regression, it did not explicitly account for censoring in peak knee impact force data, which occurred for several reasons. Right censoring occurred because some peak forces were not associated with KTH fractures, whereas left censoring occurred because some tests produced only patellar fractures, (which could occur prior to the time of peak force because the KTH can continue to resist loading after a patellar fracture).

In the current analysis, censoring in peak force data was accounted for by applying survival analysis with a Weibull distribution to peak-force data. All peak forces associated with tests that did not produce injury were treated as right censored, while tests that resulted in only patellar fractures were treated as left censored. Tests that only produced knee ligament injuries were treated as right censored, because these injuries have been shown to occur from posterior motion of the tibia relative to the femoral condyles rather than from peak force applied to the knee.

6. Results

6.1 Hip Injury Risk Curves

Table 6.1 lists the results of survival analysis and shows the parameters that describe the lognormal distribution that best fit the experimental data. Stature was the only subject characteristic that was a significant predictor of hip fracture force ($X^2(1)=6.03, p=0.014$). Equation 6.1 describes the lognormal distribution defined in Table 6.1 with the effects of flexion and abduction on hip fracture/dislocation force included. Figure 6.1 shows the lognormal distribution predicted using Equation 6.1 and the mean stature of the dataset (174 cm). Figure 6.1 also shows the 95% confidence intervals on fracture force for 0.1 increments in hip fracture risk.

Table 6.1. Fit of Lognormal Distribution to Hip Fracture/Dislocation Force Data

Term	Estimate	Std Error	Lower CL	Upper CL	ChiSq	Pr>ChiSq
Intercept	-0.214	0.840	-1.925	1.486	0.00	0.998
Stature (cm)	0.011	0.005	0.002	0.021	6.03	0.014
σ	0.199	0.027	0.156	0.267		

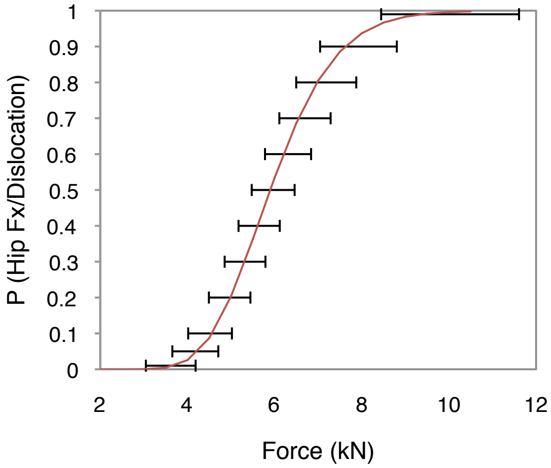

Figure 6.1. Fitted lognormal distribution and 95% confidence intervals on predicted hip fracture/dislocation force.

$$P(HipFX) = \Phi\left[\frac{Ln[F] - Ln[Exp[(0.2141 - 0.0114s)] * (1 - f + a)/100]}{0.1991}\right] \quad [6.1]$$

where, Φ is the cumulative distribution function of the standard normal distribution,
F is peak force transmitted to the hip in kN,
s is the target stature,
f is the hip flexion angle in degrees, and
a is the hip abduction angle in degrees.

Figure 6.2 compares the midsize male hip injury risk curve in the standard automotive posture to the midsize male risk curve for a 30° flexed and 15° abducted posture.

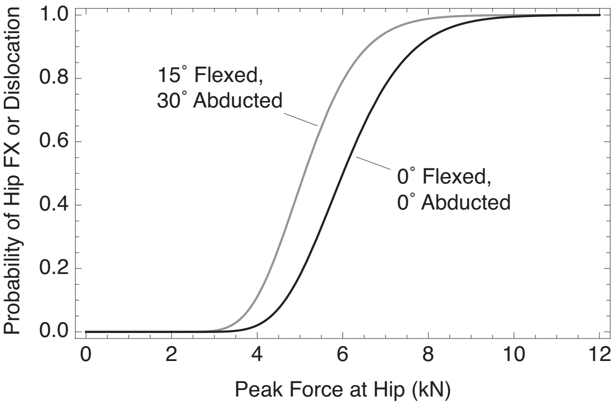

Figure 6.2. Hip injury risk curves for the midsize male in the standard automotive posture and for a 30° flexed, 15° abducted posture.

6.2 Knee/Distal Femur Injury Risk Curve

Figure 6.3 compares the risk curve developed by applying survival analysis with a Weibull distribution to peak force data reported by Kuppa et al. (2001) to the Kuppa et al. risk curve developed using logistic regression on the same dataset. Equation 6.2 defines the Weibull distribution based risk curve. The two curves are almost identical, except of for small differences in the upper and lower quantiles of risk. In fact, both risk curves associate 10 kN with a 35% risk of AIS 2+ knee/distal femur injury.

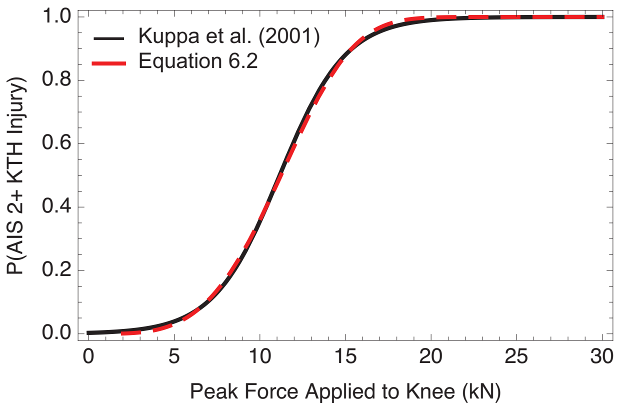

Figure 6.3 Comparison of knee/distal femur risk curves reported by Kuppa et al. and described by Equation 6.2.

$$P(AIS2+) = 1 - Exp[-Exp[(Ln[F] - 2.514)/0.2611]] \qquad [6.2]$$

where F is peak axial compressive force applied to the knee in kN.

7. Discussion

7.1 Hip Injury Risk Curves

Analyses of hip fracture/dislocation force data indicated that age, gender, or mass, were not significant predictors of hip fracture/dislocation force. The lack of an age effect is not surprising, since the presence of osteoporosis, which is one of the primary factors that would result in a decrease in fracture force with age, was used as an exclusion criterion in subject selection in the studies from which hip fracture force data were obtained. The lack of gender and mass effects is thought to be from an insufficient sample size to quantify these effects and is somewhat surprising since heavier people tend to have larger bones (Chumlea et al. 2001). Also, women tend to have acetabular surfaces that cover a greater portion of the surface area of the femoral head than similar sized men and should therefore experience lower acetabular stresses than men in a given posture and at a given level of acetabular loading (Wang et al. 2004).

There are several issues with the most commonly used adult frontal crash-test dummies, the Hybrid III midsize male and small female, which limit their ability to assess hip fracture risk using Equation 6.1. These include that Equation 6.1 expresses injury risk in terms of peak force at the hip while current crash test dummies only measure force in the shaft of the femur, which will always be greater than peak force at the hip because of inertial effects. Further, using Equation 6.1 to assess hip injury risk requires that crash test dummies and similar sized humans produce the similar acetabular forces under knee similar loading conditions. However, results of several studies suggest that this is not the case (Rupp et al. 2005, Rupp et al. 2009). Recent efforts are addressing these issues through the development of new adult crash-test dummies that measure acetabular force and have a more biofidelic knee impact response (e.g., Shams et al. 1999, Shams et al. 2002) as well as by developing methods that allow Hybrid III femur force histories to be used to assess hip injury risk (Rupp et al. 2009, Kuppa and Kirk 2009).

7.2 Knee/Distal Femur Injury Risk Curve

A new risk curve for the knee and distal femur was developed by using survival analysis to reanalyze peak knee impact force data and the associated KTH injuries from multiple studies in the literature that were originally reported by Kuppa et al (2001). Because the injuries produced in these studies were almost exclusively knee and distal femur fractures, this new risk curve applies to the knee and distal femur and not the more proximal parts of the knee-thigh-hip complex. This is in contrast to the risk curve that Kuppa et al. generated by analyzing the same dataset, which was assumed to apply to the entire KTH complex.

The new knee/distal femur injury risk curve was developed using a Weibull distribution because other choices of distribution produced risk curves that were not substantially different from that produced by the use of a Weibull distribution. Further, the use of the

Weibull distribution resulted in a risk curve that associated a peak force of 10 kN with a 35% risk of injury, similar to the current FMVSS 208 maximum femur force criterion.

Although subject characteristics such as age, gender, stature, and mass are likely to affect the relationship between peak force applied to the knee and the probability of knee/distal femur fracture, these effects were not explored in any analyses because the variability of these parameters in the Kuppa et al. dataset (and particularly the subset of the data that contained uncensored fracture forces) was small. Assuming that subject characteristics affect injury outcome, then the knee and distal femur risk curve shown in Figure 6.3 only applies to subjects who are male and have the average stature, age, and mass of the Kuppa et al. dataset (i.e., 68 kg, 61 yrs., and ~173 cm).

The effects of knee impact surface stiffness, which has been shown to affect the fracture tolerance of the knee (Atkinson et al. 1997, Meyer et al., 2003), were not explored in this study because of a lack of uncensored fracture force data from tests in which the knees were loaded with surfaces that were not rigid. Future work should focus on assembling a larger dataset of peak knee impact forces associated with KTH fracture that encompasses a greater range of subject characteristics and levels of impactor padding.

7.3 Future Research Needs

The risk curves developed in this study relate forces in the KTH complex to the probabilities of hip and knee/distal femur injuries. However, hip, knee, and distal femur injuries account for only about two-thirds of all AIS 2+ KTH injuries in frontal crashes (Kirk and Kuppa 2009). The remaining third of KTH injuries are to the shaft of the femur. This suggests that further research is needed to develop a comprehensive injury criterion for the entire KTH complex that includes the femoral shaft as well as the hip and knee/distal femur. Because the femoral shaft most commonly fails in bending, such a criterion will likely need to consider peak bending moment in the femur. The effects of muscle tension on KTH injury will also need to be considered in any new comprehensive KTH injury criterion because results of computational modeling of knee impacts suggest that muscle tension increases the probability of femoral shaft fracture (Chang et al. 2008). The development of a comprehensive KTH injury criterion also requires additional research to characterize how subject characteristics and knee impact surface rigidity affect knee/distal femur fracture forces.

Additional work is also needed to improve crash test dummy knee impact response biofidelity if the risk curves developed in this study are to be used to directly assess KTH injury risk in frontal crashes. In particular, for hip and knee/distal injury risk curves to be used with crash test dummies, the relationships between femur and acetabular forces measured by crash test dummies and forces produced at the human knee and hip needed to be determined. This is because hip injury risk curves are expressed in terms of peak force at the human hip and the knee/distal femur injury risk curve is based on peak force applied to the human knee. However, determining relationships between forces measured by crash test dummy KTH load cells and forces at the cadaver knee and hip is complicated by the fact that the relationship between forces measured by crash test dummies and forces sustained by humans under similar knee loading conditions depends on the force-deflection characteristics of the surface loading the knee (Rupp 2006).

8. Conclusions

Hip fracture/dislocation forces and the associated subject characteristics were analyzed using survival analysis to define a lognormal distribution that describes the relationship between peak force at the hip and the probability of hip fracture or dislocation. This distribution was parameterized to account for the effect subject stature, which was the only subject characteristic that significantly affected the relationship between peak force applied to the hip and the probability of hip fracture. This distribution was also parameterized to account for the effects of hip posture on the probability of hip fracture using data from the literature on the effects of posture on mean hip fracture force. Injury risk curves for midsize males in a standard automotive posture and posture in which the hip was 30˚ flexed and 15˚ abducted were defined by applying these postures to the parametric lognormal distribution.

A new knee/distal femur injury risk curve that accounts for the effects of censoring on the relationship between peak force applied at the knee and the probability of knee/distal femur fracture was developed by applying survival analysis with a Weibull distribution to peak knee impact force data from the literature that were associated with either AIS 2+ KTH injury or no KTH injury. This risk curve is similar to that reported by Kuppa et al. (2001).

9. Appendix A – Knee Impact Forces Used in Development of new Knee/Distal Femur Risk Curve

NHTSA Test #	Subj. Mass (kg)	Subj age (yr.)	Sex	Peak Force (kN)	MAIS	Censored	Censor Interval Lower	Censor Interval Upper	Reference
45	72.7	66	M	7.94	0	Yes	7.94		Cheng et al. (1982)
45	72.7	66	M	8.68	0	Yes	8.68		Cheng et al. (1982)
46	50	54	F	5.45	0	Yes	5.45		Cheng et al. (1982)
46	50	54	F	4.25	0	Yes	4.25		Cheng et al. (1982)
47	96.3	56	M	10.22	0	Yes	10.22		Cheng et al. (1982)
47	96.3	56	M	10.4	0	Yes	10.4		Cheng et al. (1982)
48	74	63	M	12.28	0	Yes	12.28		Cheng et al. (1982)
48	74	63	M	11.67	0	Yes	11.67		Cheng et al. (1982)
109	83.1	68	M	11	0	Yes	11		Cheng et al. (1982)
109	83.1	68	M	10.37	0	Yes	10.37		Cheng et al. (1982)
110	60	67	M	9.18	0	Yes	9.18		Cheng et al. (1982)
110	60	67	M	8.18	0	Yes	8.18		Cheng et al. (1982)
251	87.7	61	M	7.08	0	Yes	7.08		Cheng et al. (1982)
251	87.7	61	M	6.86	0	Yes	6.86		Cheng et al. (1982)
252	60.9	66	M	8.85	0	Yes	8.85		Cheng et al. (1982)
252	60.9	66	M	7.63	0	Yes	7.63		Cheng et al. (1982)
453	80.4	58	F	10.08	3	No	10.08	10.08	Cheng et al. (1984)
453	80.4	58	F	9.27	3	No	9.27	9.27	Cheng et al. (1984)
249	60	21	M	9.35	0	Yes	9.35		Cheng et al. (1984)
249	60	21	M	9.16	0	Yes	9.16		Cheng et al. (1984)
250	56.3	65	M	6.31	0	Yes	6.31		Cheng et al. (1984)
253	95.9	29	M	9.75	0	Yes	9.75		Cheng et al. (1984)
253	95.9	29	M	10.97	0	Yes	10.97		Cheng et al. (1984)
450	51.3	56	F	10.42	0	Yes	10.42		Cheng et al. (1984)
450	51.3	56	F	5.94	0	Yes	5.94		Cheng et al. (1984)
452	70.4	63	M	10.6	0	Yes	10.6		Cheng et al. (1984)
452	70.4	63	M	7.86	0	Yes	7.86		Cheng et al. (1984)
454	74.5	58	M	10.09	0	Yes	10.09		Cheng et al. (1984)
454	74.5	58	M	12.25	0	Yes	12.25		Cheng et al. (1984)
798	67.2	46	F	6.94	0	Yes	6.94		Cheng et al. (1984)
799	80.9	60	M	9.08	0	Yes	9.08		Cheng et al. (1984)
799	80.9	60	M	8.23	0	Yes	8.23		Cheng et al. (1984)
800	52.2	63	M	8.21	0	Yes	8.21		Cheng et al. (1984)
800	52.2	63	M	10.33	0	Yes	10.33		Cheng et al. (1984)
1052	73.1	61	M	14.02	0	Yes	14.02		Cheng et al. (1984)
1052	73.1	61	M	11.26	0	Yes	11.26		Cheng et al. (1984)
875	57.2	60	F	8.55	3	No	8.55	8.55	Donnelly and Roberts (1987)
876	57.2	60	F	7.73	2	Yes		7.73	Donnelly and Roberts (1987)
879	59.5	70	F	9.4	3	No	9.4	9.4	Donnelly and Roberts (1987)
880	59.5	70	F	7.91	2	Yes		7.91	Donnelly and Roberts (1987)
883	68.1	69	M	11.39	3	Yes	11.39		Donnelly and Roberts (1987)

NHTSA Test #	Subj. Mass (kg)	Subj age (yr.)	Sex	Peak Force (kN)	MAIS	Censored	Censor Interval Lower	Censor Interval Upper	Reference
884	68.1	69	M	15.13	2	Yes		15.13	Donnelly and Roberts (1987)
887	72.7	61	M	17.18	2	Yes	17.18		Donnelly and Roberts (1987)
888	72.7	61	M	10.89	2	Yes		10.89	Donnelly and Roberts (1987)
902	68.6	71	M	9.33	0	No	9.33	9.33	Donnelly and Roberts (1987)
903	68.6	71	M	7.02	3	No	7.02	7.02	Donnelly and Roberts (1987)
906	84	66	M	18.66	2	Yes		18.66	Donnelly and Roberts (1987)
907	84	66	M	18.13	2	Yes		18.13	Donnelly and Roberts (1987)
910	64	55	M	21.06	2	Yes		21.06	Donnelly and Roberts (1987)
911	64	55	M	19.68	3	No	19.68	19.68	Donnelly and Roberts (1987)
918	73.1	57	M	13.29	2	Yes		13.29	Donnelly and Roberts (1987)
919	73.1	57	M	14.06	2	Yes		14.06	Donnelly and Roberts (1987)
922	46.8	57	F	9.34	2	Yes		9.34	Donnelly and Roberts (1987)
923	46.8	57	F	8.99	3	No	8.99	8.99	Donnelly and Roberts (1987)
1055	79.5	62	M	10.01	3	No	10.01	10.01	Donnelly and Roberts (1987)
1056	79.5	62	M	14.19	3	No	14.19	14.19	Donnelly and Roberts (1987)
1099	86.3	66	M	11.6	3	No	11.6	11.6	Donnelly and Roberts (1987)
1100	86.3	66	M	11.88	3	No	11.88	11.88	Donnelly and Roberts (1987)
2284	40	34	M	1.26	0	Yes	1.26	.	Leung et al. 1983
2284	40	34	M	2.97	0	Yes	2.97	.	Leung et al. 1983
2285	60.9	60	M	2.41	0	Yes	2.41	.	Leung et al. 1983
2285	60	60	M	6.09	0	Yes	6.09	.	Leung et al. 1983
2286	49	57	M	3.3	0	Yes	3.3	.	Leung et al. 1983
2286	49	57	M	7.15	0	Yes	7.15	.	Leung et al. 1983
2288	51.8	63	M	6	0	Yes	6	.	Leung et al. 1983
2288	51.8	63	M	6.91	0	Yes	6.91	.	Leung et al. 1983
2289	55.9	68	M	7.28	0	Yes	7.28	.	Leung et al. 1983
2289	55.9	68	M	8.09	0	Yes	8.09	.	Leung et al. 1983
2290	51.8	42	F	2.28	0	Yes	2.28	.	Leung et al. 1983
2290	51.8	42	F	3.16	0	Yes	3.16	.	Leung et al. 1983
2291	64	42	M	5.68	0	Yes	5.68	.	Leung et al. 1983
2291	64	42	M	7.45	0	Yes	7.45	.	Leung et al. 1983
2292	70.9	68	M	5.39	0	Yes	5.39	.	Leung et al. 1983
2292	70.9	68	M	8.12	0	Yes	8.12	.	Leung et al. 1983
2293	65.9	62	M	5.5	0	Yes	5.5	.	Leung et al. 1983
2294	81.8	55	M	5.42	0	Yes	5.42	.	Leung et al. 1983
2294	81.8	55	M	7.8	0	Yes	7.8	.	Leung et al. 1983
2295	50	52	M	2.49	0	Yes	2.49	.	Leung et al. 1983
2295	50	52	M	3.64	0	Yes	3.64	.	Leung et al. 1983
2296	77.7	62	M	10.6	2	Yes		10.6	Leung et al. 1983
2296	77.7	62	M	12.53	3	No	12.53	12.53	Leung et al. 1983
2297	63.1	73	M	7.73	3	No	7.73	7.73	Leung et al. 1983
2297	63.1	73	M	9.1	2	Yes		9.1	Leung et al. 1983
2298	69	71	M	11.26	3	No	11.26	11.26	Leung et al. 1983
2298	69	71	M	11.56	0	Yes		11.56	Leung et al. 1983
2266	77.1	75	M	12.99	3	No	12.99	12.99	Melvin and Nusholtz 1980

NHTSA Test #	Subj. Mass (kg)	Subj age (yr.)	Sex	Peak Force (kN)	MAIS	Censored	Censor Interval Lower	Censor Interval Upper	Reference
2266	77.1	75	M	21.7	3	No	21.7	21.7	Melvin and Nusholtz 1980
2267	87	49	M	18.21	3	No	18.21	18.21	Melvin and Nusholtz 1980
2267	87	49	M	21.73	3	No	21.73	21.73	Melvin and Nusholtz 1980
2268	83	79	M	20.75	3	No	20.75	20.75	Melvin and Nusholtz 1980
2268	83	79	M	18.84	3	No	18.84	18.84	Melvin and Nusholtz 1980
2269	47.3	58	F	6.35	0	Yes	6.35	.	Melvin and Nusholtz 1980
2269	47.3	58	F	8.6	0	Yes	8.6	.	Melvin and Nusholtz 1980
1160	68.1	62	M	6.39	0	Yes	6.39	.	Morgan et al. (1987)
1160	68.1	62	M	2.26	0	Yes	2.26	.	Morgan et al. (1987)
1265	54.5	79	M	0.93	0	Yes	0.93	.	Morgan et al. (1987)
1265	54.5	79	M	2.13	0	Yes	2.13	.	Morgan et al. (1987)
1444	78.6	74	M	2.51	0	Yes	2.51	.	Morgan et al. (1987)
1444	78.6	74	M	2.7	0	Yes	2.70	.	Morgan et al. (1987)
1445	77.2	68	M	3.25	0	Yes	3.25	.	Morgan et al. (1987)
1445	77.2	68	M	2.69	0	Yes	2.69	.	Morgan et al. (1987)
1789	70.4	75	M	3.22	0	Yes	3.22	.	Morgan et al. (1987)
1789	70.4	75	M	2.37	0	Yes	2.37	.	Morgan et al. (1987)
1790	58.1	74	M	7.24	0	Yes	7.24	.	Morgan et al. (1987)
1790	58.1	74	M	4.11	0	Yes	4.11	.	Morgan et al. (1987)
1817	53.1	60	F	8.63	0	Yes	8.63	.	Morgan et al. (1987)
1877	59	56	M	2.09	0	Yes	2.09	.	Morgan et al. (1987)
1877	59	56	M	6.66	0	Yes	6.66	.	Morgan et al. (1987)
1878	76.3	72	M	4.91	0	Yes	4.91	.	Morgan et al. (1987)
1878	76.3	72	M	4.56	0	Yes	4.56	.	Morgan et al. (1987)
1880	57.2	54	M	6.79	0	Yes	6.79	.	Morgan et al. (1987)
1880	57.2	54	M	4.18	0	Yes	4.18	.	Morgan et al. (1987)

10. Glossary

Injury Risk Curve –A mathematical relationship between an injury criterion and the likelihood of injury to a human body region

Injury Criterion–A parameter determined to be a good prediction of the occurrence of a particular type and severity of injury.

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