REVIEW OF THE EURO NCAP UPPER LEG TEST

Nils Lubbe
Toyota Motor Europe, Belgium
Hiromi Hikichi
Hiroyuki Takahashi
Toyota Motor Corporation, Japan
Johan Davidsson
Chalmers University of Technology, Sweden
Paper Number 11-0137

ABSTRACT

The EEVC WG17 upper leg test as used in Euro NCAP was reviewed. Previous work revealed shortcomings of the EEVC WG17 test set-up. Recent published accident data show that injuries to the lower extremities by the bonnet leading edge, not including ground impacts, only accounted for 5% of all AIS2+ injuries and 4% of all AIS3+ injuries. Previous work and this data indicate a discrepancy in importance of the upper leg test between Euro NCAP and real-life injury frequencies.

Suggested legform impactor threshold values have so far not been based on human injury risk transferred to impactor values. The implications of the proposed improvements to the test set-up from Snedeker et al. (2005) for Euro NCAP test results have not been assessed. Both the above issues are aimed at in this study. They are important as only with the right targets and evaluation methods, traffic related injuries can be minimized.

Human injury threshold values for femur and pelvis impact were derived from applicable and original PMHS data. Data was scaled to a mid-sized male, survival analysis with Weibull fit was performed with exact femur 3-point bending data, logistic regression with doubly censored pelvis impact data. Legform thresholds were derived using a linear regression between impactor and THUMS values derived form tests conducted by Snedeker et al. (2005). It is assumed that THUMS and upper leg surrogates have a similar response. The implications of the new set-up and thresholds for Euro NCAP test results were assessed for results published 2009 and 2010 using empirical relationships between impact energy, measured force and moment.

Using this approach, the resulting thresholds to be used with the legform were determined to be 7.9-9.0 kN for the pelvis test and 300-365 Nm for the femur test. These values correspond to 5 and 20% fracture risk, respectively.

With the currently used set-up and limits, the average score for the upper leg test is 22% of the maximum score. With the proposed method and limits, the average score calculated is 70%. With only 30% missing, the score matches better with the accident frequency of bonnet leading edge induced injuries to lower extremities.

INTRODUCTION

Aim

Euro NCAP uses a test developed by EEVC WG17 to rate a vehicle's ability to protect pedestrians from femur and pelvis fractures when impacted. Previous work and recently published accident data indicated a discrepancy between test results in Euro NCAP and real-life injury risk. Based on these findings Snedeker et al. (2005) suggested test set-up changes. However, suggested legform impactor threshold values have so far not been based on human injury risk that have been transferred to impactor values which might be required due to the limited biofidelity of the legform.

This work aimed at deriving legform impactor threshold values from applicable and original PMHS data to be used with the proposed test set-up from Snedeker et al. (2005). Finally, the implications for Euro NCAP test results and the match with real-life injury risk were assessed.

The Euro NCAP Upper Leg Test

The Euro NCAP upper legform test was developed by the European Experimental Vehicles Committee (EEVC) in the working groups (WG) 7, 10 and 17 since the 80s (Lawrence 2005). The final version was published in 2002 (EEVC 2002).

In Euro NCAP, the upper legform test is one part of the pedestrian protection assessment, and aims at measuring the level of protection for the femur and pelvis area. Car manufacturers can be awarded full score for the upper leg test when not exceeding impactor threshold force and moment values which are 5 kN and 300 Nm, respectively (upper performance limit) for any of the tested impact points. These values were adopted from EEVC WG17. When exceeding the lower performance limit, set by Euro NCAP, which is 6kN and 380 Nm, no score is awarded. Between the upper and lower performance limits proportional score is awarded. The upper leg tests can provide up to 17% (6 points) of the total maximum achievable score in Euro NCAP (36 points, Euro NCAP 2009) and is therefore important.

The test uses a guided legform which is made to impact the bonnet leading edge (BLE) while force and bending moment are measured. Impact velocity, angle and energy are depending function of the vehicle geometry, namely BLE height and bumper lead, defined as the horizontal distance between upper bumper reference line (UBRL) and BLE, as depicted in figure 1. (EEVC 2002).

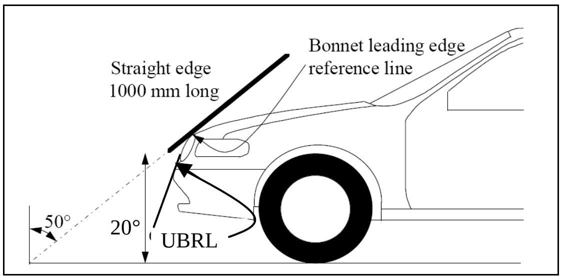


Figure 1. Geometric definition of BLE. Adopted from Euro NCAP (2009).

The used relations between impact velocity and angle and car geometries were established by full scale dummy tests (EEVC 2002, Lawrence 1998). The impact energy dependency on the vehicle geometry was developed by use of computer simulations by TRL. In their simulations a 50th percentile dummy model was used and deformation energy was estimated for several car shapes (EEVC 2002).

Acceptance levels or impactor thresholds were identified by accident reconstruction. For 39 accidents the dent depth on the forward bonnet area, close to the BLE was reproduced with the upper leg impactor (Rodmell and Lawrence 1998, Matsui 1998). Recording impactor bending moment and force as well as occurrence of femur or pelvis fracture allowed the construction of injury risk curves. Impactor thresholds are 5 kN and 300 Nm, defined from the 20% risk of fracture determined as the average values from logistic regression and cumulative normal distribution (EEVC 2002, Rodmell and Lawrence 1998).

Accident Data

Liers (2010) and Liers and Hannawald (2009) analyzed GIDAS pedestrian accidents occurring between 1999 and 2008 with the vehicle front of passenger cars at impact velocities up to 40 km/h. There was no restriction to model years, the average was 1991. Table 1 shows the classification of 517 AIS2+ injuries according to injury-causing vehicle part and injured body region.

Fredriksson et al. (2010) used GIDAS data from 1999 to 2008 to analyze pedestrians being hit by a vehicle front of passenger cars, resulting in a sample of 1030 cases. There was no restriction to model years. 161 pedestrians sustained at least one AIS 3+ injury, pedestrians sustaining at least one injury in the given body region are listed together with the injury causing vehicle part in table 2. Differently from Liers and Hannawald (2009), SUVs were not included but all impact velocities were considered.

Table 1.
Injury causing vehicle part and injured body region for car to pedestrian accidents. Adopted from Liers (2010)

	Head /Face	Neck	Thorax	Abdomen	Spine	Upper Extr.	Lower Extr.	Total
Windscreen frame	31	0	6	0	3	5	0	45
Windscreen	74	0	1	0	3	5	0	83
Bonnet	15	1	7	4	5	8	5	45
BLE	1	0	0	6	0	1	17	25
Bumper	0	0	0	1	1	0	134	136
Other	3	0	5	2	3	3	12	28
Ground	92	0	18	0	7	27	11	155
Total	216	1	37	13	22	49	179	517

Table 2.
Injury causing vehicle part and injured body region for car to pedestrian accidents. Adopted from Fredriksson et al. (2010)

	Head /Face	Neck	Chest(1)	Upper extremities	Lower extremities	Total
Windscreen incl. frame	40	0	20	1	3	64
Bonnet	8	1	23	5	10	47
BLE	1	0	1	0	8	10
Bumper	2	0	5	2	68	77
Other	5	1	5	0	3	14
Ground	19	0	15	7	6	47
Total	75	2	69	15	98	259

(1) Chest includes: Thorax, abdomen and spine

Comparison with Euro NCAP Test Results

It is important to note that the exact test zones in Euro NCAP might differ from injury-causing vehicle part in real life accidents. For example, depending on the vehicle geometry, only a part of the hood might be tested for head injuries in Euro NCAP while injury frequencies are given for the complete hood. Despite this limitation, accident frequencies for the corresponding Euro NCAP pedestrian protection subtests can be taken from the accident data in table 1 and table 2.

For the type of accident targeted by the upper leg test, the relative injury frequency is calculated as the proportion of BLE induced injuries to lower extremities compared to all injuries without ground impact and others. This frequency was 5% for AIS2+ (table 1) and was 4% for AIS3+ injuries (table 2).

In contrast, the relative injury frequencies of adult and child head injuries from impacts to the windscreen and bonnet were 36% (AIS2+, table 1) and 24% (AIS3+, table 2).

Also injuries to the lower extremities (knee and tibia) when subjected to impacts by vehicle bumpers are much higher than the BLE related injuries. Lower leg injuries account for 40% (table 1) and 34% (table 2), of all injuries without ground impacts and others, respectively, and are thereby the most common type of injuries.

In Euro-NCAP, injuries form ground impacts are not considered even though they account for 30% of all AIS2+ injuries (table 1) and 18% of all AIS3+ injures (table 2).

These relative injury frequencies can be compared to the score awarded to recent vehicles in Euro NCAP pedestrian protection testing. The comparison shown in figure 2 includes two different measures for indicated hazard. The real-life hazard is expressed by the relative injury frequencies at AIS3+ level presented above. The Euro NCAP indicated hazard is the fraction of the total pedestrian score not achieved in Euro NCAP. These statistics are given for a few combinations of vehicle parts and body regions.

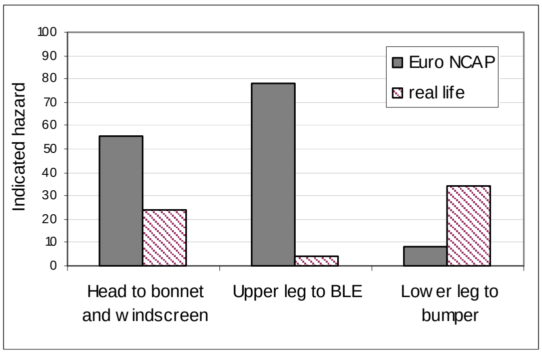


Figure 2. Euro NCAP and real-life indicated hazard for several body region – vehicle part combinations.

The fraction not achieved in Euro NCAP score can be expected to be particularly low for the tests corresponding to low injury frequency, as the level of protection could be judged high from the accident data and thus the level of protection indicated by the Euro NCAP score should be high.

A low relative injury frequency can be demonstrated for BLE induced injuries, which means that the BLE is not a hazardous vehicle area in real-life. Despite this fact, the score awarded in upper leg test is low: the average score for this test is 1.44 points out of 6 points, which means that Euro NCAP is highlighting the BLE area as particularly hazardous. This is an apparent mismatch. Discrepancies between real-life relevance and test severity have been reported before. The majority of vehicles tested give legform test values that exceed the used thresholds while BLE to upper leg or pelvis injuries are scarce (EEVC 2002, Hardy et al. 2006, JARI 2004, Snedeker et al. 2003).

Review of the Test Set-Up

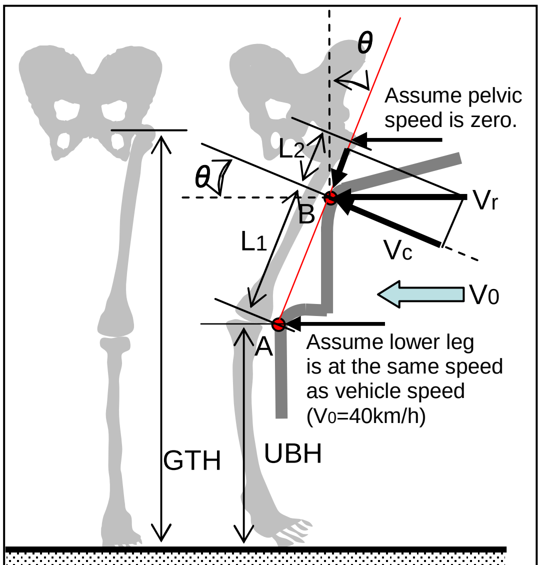
It has been argued that the bumper lead is not a significant parameter determining upper leg injuries, thus should be excluded from determining the impact energy (Matsui et al. 1998). The suggested impact energies are generally too high (Konosu et al. 1998, Honda 2001). The impactor test speed was shown to be inaccurate as bonnet roundness is not sufficiently reflected (Snedeker et al. 2003). Furthermore, a separation in femur and pelvis tests was suggested as the injury mechanisms differ (Honda 2001, Snedeker et al. 2005).

Snedeker et al. (2005) proposed a modified test set-up, addressing several of the highlighted issues. A wrap around contact definition is used, which was based on PMHS testing and computer simulation with THUMS, and which is summarized in figure 3. A small change in the geometric definition of the BLE is proposed. The impactor mass is fixed to represent human properties, the impactor velocity is defined from car geometry and the impact energy results accordingly. In the current set-up, impact energy and velocity are defined by the car geometry and the impactor mass results accordingly.

Legform Impactor Thresholds

Several legform impactor threshold values have been proposed and are summarized in table 3. In this table "the peak bending moment relates to the risk of femur fracture while the risk of pelvis fracture is more related to the peak force." (Matsui et al. 1998).

Rodmell and Lawrence (1998) included 12 cases reported of Matsui et al. (1998) for the construction of their injury risk curve. However, it seems that information from 2 cases (#5 and #7) was wrongly reported by Rodmell and Lawrence (1998) and should be corrected.



A: Upper bumper reference line defined by EEVC
B: First point of contact between the hood and a 1,000mm long string rotated from A
GTH: Height of AM50 greater trochanter (=900mm)
UBH: Height of upper bumper reference line
UBH+L1= Modified leading edge height: MLEH
Vr: Vehicle closing speed (=L1/(L1+L2) x V0)
Vc: Contact speed (=legform impact speed) (=Vr x cosθ= L1/(L1+L2) x V0 x cosθ)
If MLEH > 900mm, then Vc=V0 (=40km/h) & θ =0

Figure 3. Proposed test set-up from Snedeker et al. (2005).

Table 3.
Proposed legform impactor thresholds

Source	Pelvis	Femur	Basis
EEVC WG10	4 kN	220 Nm	50% risk from accident reconstruction
EEVC WG17	5 kN	300 Nm	20% risk from accident reconstruction
Matsui et al. 1998	7.5 kN	510 Nm	50% risk from accident reconstruction
TRL 2006	6.25 kN	375 Nm	Feasibility
EC/78/2009	(5 kN)	(300 Nm)	Monitoring only
Matsui et al. 2006	6.3 kN	417 Nm	20% risk from accident reconstruction
Snedeker et al. 2005	10 kN(2)	320 Nm(1)	Human tolerance data: (1)(2)

(1)base: Yamada (1971); Powell et al. (1975); Kress et al. (2001) (2)base: Cesari (1982)

More fundamentally, one might question the quality of the proposed thresholds by EEVC WG17 when these were developed from matching dent depths caused by impacts with a human leg and the upper legform. As outlined above, biofidelity and kinematic representation have been questioned.

More commonly, impactor thresholds are developed by transferring human injury risk to impactor risk, using either proven biofidelity or some kind of transfer function. For the upper legform, Bovenkerk et al. (2008) recommend the use of a transfer function. None of the proposed thresholds listed in table 3 were developed from human injury risk subsequently modified by a transfer function.

METHODS AND MATERIALS

Legform Impactor Thresholds

Literature concerning human pelvis and femur fracture risk was selected when the following criteria were met:

- Measurement of bending moments for femur fracture or impact force for pelvis fracture;
- Identification of this measurement to be a suitable predictor for fractures;
- Dynamic testing;
- Listing of relevant specimen geometries to allow normalization;
- Only 3-point bending considered for femur fracture risk;
- Addressing pedestrian impact conditions for pelvis fracture risk.

Having identified applicable data as shown in table 4 and 5, pelvis and femur injury risk curves were constructed.

Femur Fracture risk was assessed using data published by Kerrigan et al. (2004) and Kennedy et al. (2004). All 70 data points were normalized to the size of an average male as proposed in these publications. The reference in Kerrigan et al. (2004) is a femur length of 448.5 mm taken from an implant measure and a cross sectional area of 467.26 mm^2 taken from the male average value in the sample in Kennedy et al. (2004). The bending moment was scaled to the third power of the length scale factor, i.e. fraction of femur length and fraction of the square root of the sectional area, as proposed in Kleinberger et al. (1998). As fracture was a force limiting event, thus data was exact, survival analysis was performed in line with the latest proposed recommendations from ISO WG6.

From the survival analysis, the hazard function was obtained. Confidence intervals were obtained adopting p-bootstrap methods proposed by Efron and Tibshirani (1993). The basic idea is that having a sample but no information on the underlying distribution, the sample itself is the best approximation. Thus, randomly taking equally sized samples of the original dataset (drawing with replacement), one obtains the possible variation of samples taken from the underlying distribution.

This resampling was executed 1000 times and 2.5 and 97.5 percentile values for each step in the hazard function were taken to give the 95% confidence intervals for each probability value.

The hazard function is a step function as given in equation (1) and as such not very convenient to use. To smoothen the curves, a Weibull function as given in equation (2) was fitted by least square optimization as given in Cullen and Frey (1999) for lower and upper confidence data as well as for the hazard function itself.

$$F(x_i) = P(X < x_i) = \frac{i-0.5}{n}$$

where: $F(x_i)$: Fracture risk (CDF); x_i: bending moment of data point i; n: sample size; i= 1,2,..n; and $x_1 < x_2 < \ldots < x_n$ (1).

$$F(x) = 1 - e^{\left(-\frac{x}{\alpha}\right)^{\beta}}$$

where: F(x): Fracture risk (CDF); x: bending moment; α, β: shape parameter (2).

The resulting data and functions were checked for several potentially influential variables, i.e. whether these variables have an influence on the obtained risk curves and therefore would require the use of an appropriate sub-set. These variables were:

- origin of the dataset;
- bending direction ;
- specimen age;
- specimen gender.

These were identified as the most influential factors in this study as well as in Carrol and Hynd (2007). The check was done by two means.

Firstly, a Kolmogorov-Smirnov (K-S) test, as recommended for goodness-of-fit testing by Diamond (2001), was conducted from the survival data without Weibull fit to see if the cumulative distribution function (CDF) of subset A might origin from the data of subset B and vice versa at a significance level of 0.05.

Secondly, graphical evaluation was conducted. This means the injury risk curve and its confidence intervals of the subsamples were compared. Overlap of the confidence intervals indicated that there is no difference in injury risk due to the variable defining the sub samples.

Pelvis fracture risk was reviewed as listed in table 5. Only Matsui et al. (2003) aimed at reproducing pedestrian impact conditions and thus is used. Peak impact forces were scaled as proposed in Kleinberger et al. (1998), given in equation (3), thus the scaling methodology of the original publication was not followed. The average normalized peak force remained at 9.1 kN, individual loads were up to 0.33 kN lower and 0.69 kN higher than originally proposed.

$$F_{scaled} = \left(\frac{75kg}{PMHSmass}\right)^{\frac{2}{3}} F_{peak}$$

where: F_{scaled}: normalized maximum force; F_{peak}: recorded maximum force for a mass of PMHSmass (3).

Impact energy was pre-set and equipment to indicate initial damage was not used, thus fracture was not necessarily a force limiting event. The data should be treated as doubly censored, i.e. it is only known that non-fracture cases withstand at least the maximum recorded force and fracture cases fail before maximum recorded force. For this type of data, logistic regression is suitable and was used.

Parameters for the logistic function in equation (4) were determined by maximizing log-likelihood based on all 4 fracture and 8 non-fracture cases, thus including one case of femur shaft and 3 of anterior pelvic ring fracture.

$$F(x) = \frac{e^{\beta_0 + \beta_1 x}}{1 + e^{\beta_0 + \beta_1 x}}$$

where: F(X): Fracture risk (CDF); x: impact force; β_0, β_1: shape parameter (4).

One might note that Matsui et al. (2003) performed statistical analysis with the Certainty Method. Implications for different statistical analysis and a comparison of the injury risk curves developed from Cesari et al. (1982) can be found in the discussion section.

Human injury thresholds for fracture risk were calculated at 20% level as done by EEVC WG17. For femur fracture risk, the Weibull-survival function was used. For pelvis fracture risk, the average of normal CDF and logistic regression was taken, as done in EEVC (2002). As Euro NCAP does not use a pass/fail threshold but an upper and lower performance limit, these limits also needed to be defined. Even though the current EEVC recommendation is taken as the lower performance limit, it is thought to be more in line with the general philosophy to take this value as an upper performance limit. Thereby the test requires higher protection levels by the BLE in order to provide points to the overall assessment. The lower performance limit was set to 20% risk, the upper one to 5% risk. The current Euro NCAP lower limit corresponds 34% for moment and 37% for force while the upper limit is set to 20% for both.

Table 4.
Literature considered for human femur fracture risk. Applicable data is given on white background, omitted data on grey background

Author	Year	Impact condition	Data Scaling	N	Tabulated moment data	Proposed threshold
Yamada	1971	Static				182 Nm
Kress and Porta	2001	Dynamic, simply suspended leg	No	604	No	100-500 Nm
Matsui et al.	2004	Dynamic, simulated standing posture	Yes	13	No	8.8 kN
Kerrigan et al.	2003	Dynamic 3 point bending, L-M with surrounding flesh		7	Yes	412 Nm
Funk et al.	2004	Dynamic 3 point bending, L-M and A-P, isolated femur	No	15	Yes	458 Nm
Kerrigan et al.	2004	Dynamic 3 point bending, L-M , with surrounding flesh	Yes, femur length	12	Yes	372–447 Nm
Kennedy et al.	2004	Dynamic 3 point bending, L-M and A-P, isolated femur	Yes, cross sectional area	45	Yes	395 Nm

Note: Kerrigan et al. (2004) includes raw data from Kerrigan et al. (2003) and Funk et al. (2004)

Table 5.
Literature considered for human pelvis fracture risk. Applicable data is given on white background, omitted data on grey background

Author	Year	Threshold for	Impact condition	Data Scaling	N	Tabulated force data	Proposed threshold
Mertz et al.	2003	Vehicle occupant	Not specified	Yes, not specified	-	No	6 kN peak force
Matsui et al.	2003	Pedestrian	Full PMHS, restrained pelvis, dynamic ram	Yes, PMHS mass	12	Yes	8.9 kN peak force
Guillemot et al.	1997	Vehicle occupant	Isolated restrained pelvis, static	No	10	No	-
Zhu et al.	1993	Vehicle occupant	Load plate	Yes, PMHS mass	17	Yes	5 kN average force
Cavanaugh et al.	1990	Vehicle occupant	Load plate	Yes, PMHS mass	12	Yes	8 kN
Viano	1989	Vehicle occupant	Pendulum impact, suspended full PMHS	Yes	14	Yes	27% compression[(2)]
Marcus et al.	1983	Vehicle occupant	Load plate	Yes, PMHS mass	11	No	-
Maltese et al.	2002	Vehicle occupant	Load plate	Yes, PMHS mass	36	No	-
Cesari et al.	1980	Vehicle occupant	Dynamic ram	No	36	Yes	5 kN
Cesari et al.	1982	Vehicle occupant	Dynamic ram	Yes (PMHS height &mass)	60 [(1)]	Yes	10 kN

Note: Cesari et al. (1982) includes raw data from Cesari et al. (1980)
[(1)]out of those, 52 complete, unpadded cases were used [(2)]Force was identified to not predict injuries

Transfer functions from human thresholds to legform thresholds were calculated using unpublished data from 20 tests with the physical impactor and THUMS simulations of the same impact conducted in the Snedeker et al. (2005) study as given in table 6.

The data can be used to establish a correlation between the physically measured values (tests with the leg form) and the corresponding human values. These are represented by the values measured with THUMS.

Table 6.
Test data for physical impact and THUMS simulation from Snedeker et al. (2005).

No	Bonnet edge radius	Femur moment [Nm]		Pelvis force [kN]		
		Test	THUMS	Test	THUMS	MLEH
1	0	397	177			778
2	50	385	189			763
3	100	397	180			746
4	250	206	174			670
5	500	165	171			627
6	0	725	275			904
7	50	520	300			885
8	100	325	305			868
9	250	295	255			799
10	500	210	235			735
11	0			30	13.8	1040
12	50			12.7	14.3	1014
13	100			14	20	984
14	250			11	17.5	895
15	500			8	14	852
16	0			9.1	8.9	904
17	50			9.2	11.8	885
18	100			10.3	14.4	868
19	250			7.1	11.1	799
20	500			5.5	7.5	735

The impactor limits were then used together with the test set-up from Snedeker et al. (2005) to assess the implications for Euro NCAP test results and the match with real-life injury risk.

Implications for Euro NCAP Test Results

It was estimated how the results in Euro NCAP scoring would change when applying the proposed method and thresholds from all vehicle ratings published in 2009 and 2010 as used in the initial comparison between Euro NCAP score and real-life injury risk. Vans and SUV were assessed with the pelvis test, other vehicles with the femur test from Snedeker et al. (2005).

First, the changes of impact energy, resulting from the proposed new set-up, were calculated for six modern cars, ranging from compact to van, and 3 impact points each from CAE geometry data as measured forces and moments are dependent on the impact energy.

For 32 vehicles, tested in Euro NCAP between 2004 and 2010, both the impact energy and the recorded force and moment were known for the impact point in the vehicle center. All these vehicles obtained some score in the upper leg area; therefore it can be presumed they were designed to comply with the test. Vehicles not designed to achieve score were excluded as this would give high response values no matter which impact energy was used and therefore misleading results. From these data a relationship between impact energy and recorded force and moment was calculated. Using the average of the previous calculated change in impact energy, the estimated average change in impactor measurements was determined.

The legform impactor measurements were reduced by this expected change as described above and Euro NCAP score was calculated with the proposed upper and lower performance limit. For comparison, the expected Euro NCAP score when using the performance limits from Snedeker et al. (2005) was calculated as well.

RESULTS

Human Femur Fracture Risk

Human femur fracture injury-risk curves were constructed by Weibull fit to survival analysis together with p-bootstrap confidence intervals. The evaluation of the origin of the dataset Kerrigan et al. (2004) or Kennedy et al. (2004), bending direction (anterior-posterior or lateral-medial), age and gender influence are depicted in figure 4 to 7. The best estimate is given as a solid line, the upper and lower confidence limit are given as dotted lines in the same color.

Figure 4 reveals overlap of pooled data with both individual data sets for all femur fracture risk levels. The K-S test indicated no significant difference between the curves. Therefore, origin of the dataset is not considered a major influence. Figure 5 shows that loading direction has almost no influence on the injury risk curve. The individual curves lie well within the confidence bounds of each other. The K-S test also shows no significant influence. Figure 6 depicts a lower fracture risk for females compared to males. The gender has a significant influence on the bending moment according to the K-S test. Figure 7 illustrates the fact that age had only negligible influence on the bending strength in this data set. It is important to note that the age span was limited to subjects of 40 years and older while Yamada (1971) found age to be influential based on a wider span of subject ages. Further discussion can be found in Carrol and Hynd (2007).

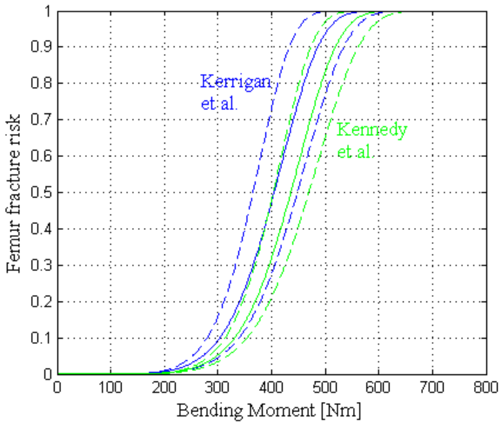


Figure 4. Influence of data source on the injury risk curve.

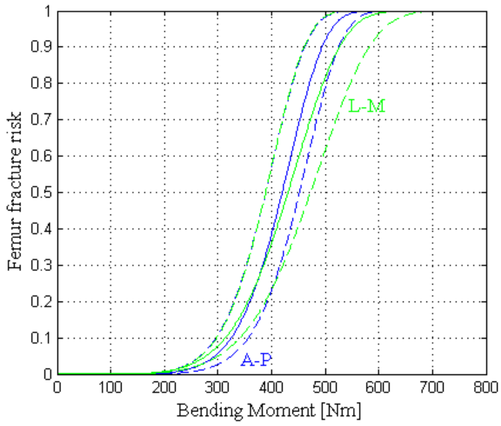


Figure 5. Influence of loading direction (A-P: Anterior-Posterior, L-M: Lateral-Medial) on the injury risk curve.

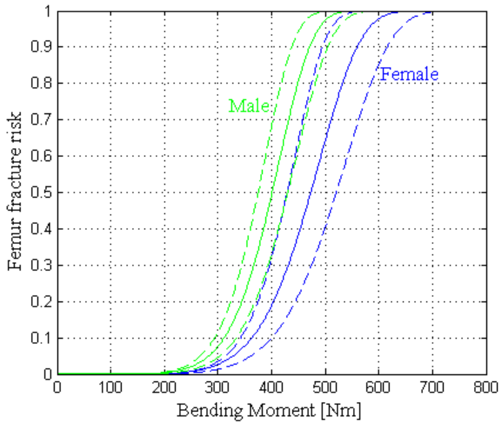


Figure 6. Influence of gender on the injury risk curve.

The evaluation led to the conclusion that only gender has a major influence and the data should therefore be restricted to male data. In conclusion, the injury risk curve was based on male PHMS data from Kerrigan et al. (2004) and Kennedy et al. (2004), omitting not applicable female data as depicted in figure 8. The injury-risk curve is based on a Weibull fit. The parameters for the risk function as given in equation (2) are given in table 7. A fracture risk of 20% corresponds to 344 Nm and 5% to 283 Nm.

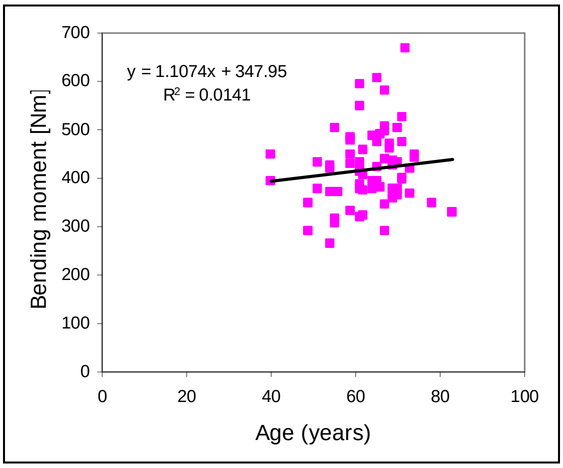


Figure 7. Influence of age on peak bending moment.

Table 7.
Parameter for the femur fracture risk function

	Best estimate	Lower limit	Upper limit
α	420.9	393.5	450.4
β	7.48	7.67	7.50

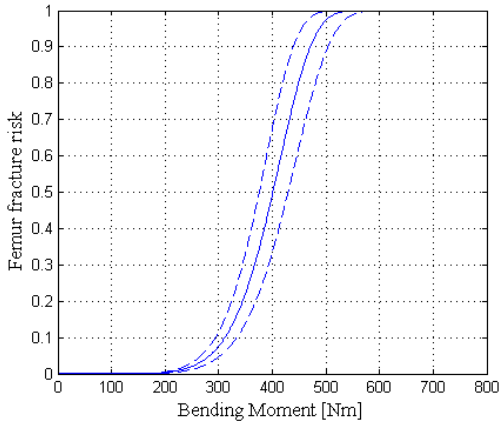


Figure 8. Injury risk curve for human femur fracture with 95% confidence limits.

Human Pelvis Fracture Risk

The pelvis fracture risk curve is shown in figure 9. The parameters for the logistic regression in the form of equation (4) are calculated to be β_0= -5.3378 and β_1= 0.5065. A fracture risk of 20% corresponds to 7.8 kN, 5% fracture risk corresponds to 4.7 kN.

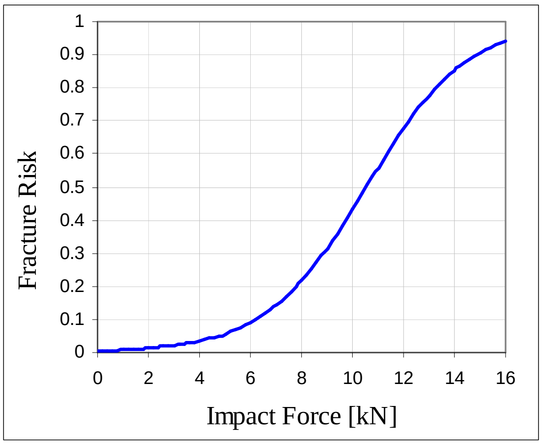


Figure 9. Injury risk curve for human pelvis impact.

Transfer Function

Not all values from the Snedeker et al. (2005) study as given in table 6 can be used for a regression. The proposed test method measures the force when the Modified Leading Edge Height (MLEH) is below 900 mm and the bending moment when above 900 mm. Thus the values from test 6, 15, and 17-20 are not applicable. Although test 14 lies slightly outside the corridor, it is used to increase the number of cases. Test 11 is identified as outlier. There seem to be two different linear trends for the tests 1-10. Figure 10 shows a linear relation for each group of small BLE radii (test 1, 2, 3, and 7) and large radii (test 4, 5, 8, 9, and 10).

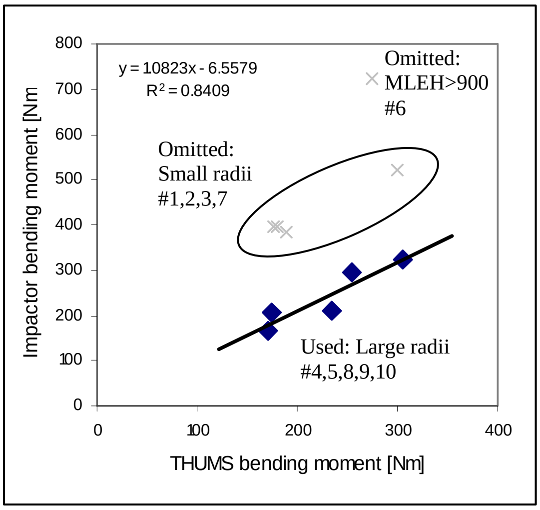


Figure 10. Transfer function human to impactor for femur bending moment.

This is not surprising as Snedeker e al. (2003) already found small radii leading to higher legform impactor measurements compared to full body simulations for sedan and van type vehicles. As most modern cars have large bonnet edge radii (Snedeker et al. 2003), this group was taken to establish a transformation function. For the pelvis force no such split exists and all applicable values were used to calculate a transfer function as given in figure 11.

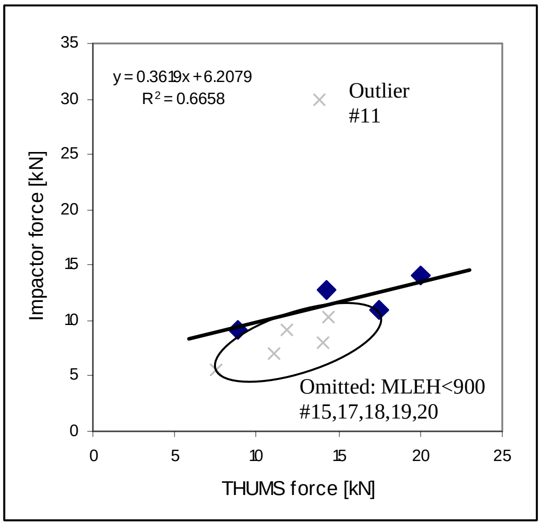


Figure 11. Transfer function human to impactor for pelvis force.

Legform impactor thresholds are listed in table 8. They are derived from human values using the transfer functions as given in figure 10 and 11.

Table 8.
Human and legform impactor values for 20% and 5% fracture risk

Fracture risk	Human values		Impactor values	
20%	344 Nm	7.8 kN	365 Nm	9.0 kN
5%	283 Nm	4.7 kN	300 Nm	7.9 kN

Implications for Euro NCAP Test Results

For several vehicles currently on sale, the change of impact energy was calculated as given in table 9. On average, the impact energy was reduced by 431 J for the proposed femur test and by 60 J for the proposed pelvis test. The relationship between impact energy and vehicle response was derived from empirical relations for 32 vehicles, tested in Euro NCAP between 2004 and 2010, as shown in figure 12 and 13. From the calculated average reduction in impact energy and the linear regression equations for energy and legform impactor response, the average reduction for the pelvis test was calculated to be 0.26 N and the average reduction for the femur test is 60 Nm.

The expected influence on the Euro NCAP score was calculated by reducing the published legform impactor measurements for the 2009-2010 vehicles with the above values (0.26 kN and 60 Nm) and applying the proposed lower and upper performance limit (7.9-9.0 kN, 300-365 Nm). For comparison, the expected results when using the limits 10 kN and 320 Nm from Snedeker et al. (2005) were calculated as well.

Table 9.
Impact energies using the EEVC WG17 method and the proposed changes for modern vehicles

Car	Point	EEVC energy [J]	MLEH [mm]	New energy [J] Femur	Pelvis
Car 1	PPU-1	700	895	327	
Sedan	PPU-2	700	863	321	
	PPU-3	700	915		686
Car 2	PPU-1	700	1005		686
SUV	PPU-2	700	868	261	
	PPU-3	671	983		686
Car 3	PPU-1	700	881	294	
Van	PPU-2	700	895	345	
	PPU-3	700	900	292	431
Car 4	PPU-1	668	808	160	
Sedan	PPU-2	700	824	233	
	PPU-3	672	838	187	
Car 5	PPU-1	564	783	104	
Sedan	PPU-2	508	813	185	
	PPU-3	700	980		686
Car 6	PPU-1	700	839	195	
Sedan	PPU-2	700	807	194	
	PPU-3	651	868	230	
Average reduction [J]				431	60
Average reduction [%]				64	9

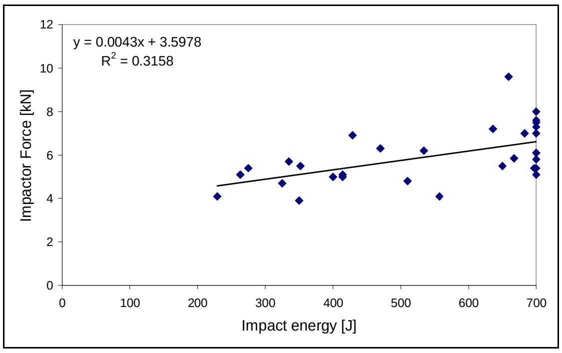


Figure 12. Impactor force dependency on impact energy.

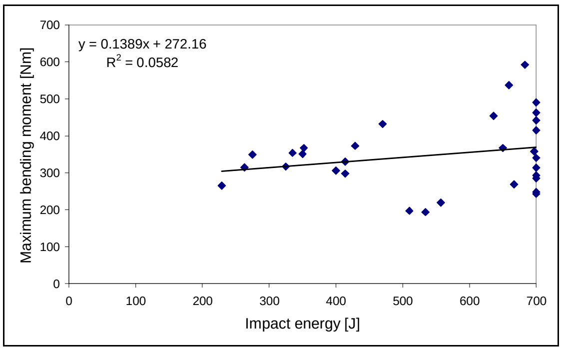


Figure 13. Impactor bending moment dependency on impact energy.

With the proposed method and limits, the average score calculated is 4.19 points, corresponding to 70% of the maximum score. By applying the limits from Snedeker et al. (2005), the average score is 4.47 points, corresponding to 75% of the maximum score. This is a significant increase compared to the score with the current method (1.31 points or 22% of the maximum score). Thus, the indicated hazard of this injury type, expressed as % gap to maximum score, is reduced to 30% for the proposed method and limits and to 25% when using the limits from Snedeker et al. (2005) as depicted in figure 14. It can be seen that the proposed changes for the upper leg test better reflect the real-life indicated hazard of this injury type. Still, the test might highlight the bonnet leading edge as more dangerous than it is.

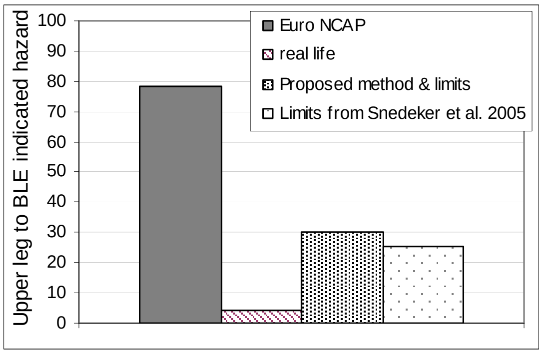


Figure 14. The proposed changes lead to a better match between Euro NCAP and real-life indicated hazard.

DISCUSSION

Construction of Injury-Risk Curves

For the construction of the injury-risk curves, survival analysis was applied for the exact data of femur fracture. For pelvis fracture logistic regression was used to construct injury-risk curves from the doubly censored data. Which methods are most appropriate for this purpose are still being discussed, e.g. in the ISO working group (TC 22/SC12/WG 6). Thus it can be argued that other methods should be applied.

In general, survival analysis, logistic regression and normal CDF are most commonly used, a variety of other methods exist (e.g. Certainty Method, Consistent Threshold Estimate, Median Rank method, Mertz/Weber method). Survival analysis has beneficial attributes such as zero risk at zero stimulus and monotonic increase of risk with increased stimulus, which logistic regression does not have (Kent and Funk, 2004). Figure 16 illustrated these properties. Furthermore, survival analysis is originally non-parametric, thus no assumption has to be made on the underlying distribution. The hazard function of a survival analysis reduces to an empirical cumulative distribution function at Hazen plotting position when all data is exact as given in equation (1) in the notation of Cullen and Frey (1999), thus can be seen as unbiased. Fitting a Weibull function in a second step to smooth the curve and allow easy calculation still gives more freedom for the shape of the curve as the fit of a normal distribution does.

Survival analysis was used on the data for femur fracture risk curve in this study, due to its beneficial attributes as outlined above. Confidence intervals given for the resulting curve depict the inherent uncertainty. For the pelvis fracture risk curve, the data was assumed to be doubly censored. However, one might assume that pelvis fracture is a force limiting event, thus survival analysis or normal CDF could be applied. Figure 15 depicts injury-risk curves obtained from these statistical methods. 20% and 5% risk values from logistic regression are the most conservative estimate. Thus, the fracture risk is more likely to be overestimated than underestimated. Logistic regression appears to be the safe choice for the data at hand.

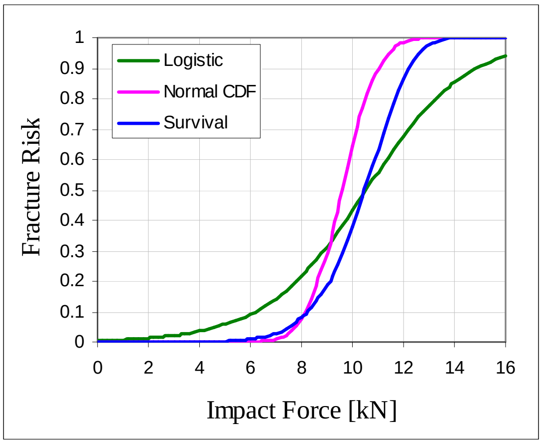


Figure 15. Injury-risk curves for pelvis impact obtained with different statistical methods.

Cesari et al. (1982) repeatedly tested the same pelvis until failure to be close to the exact failure load, thus recorded peak force levels, normalized according to equation (3), are not independent. This is a violation against pre-requisites for logistic regression which is shown in figure 16 to indicate substantial risk at zero stimulus. Normal CDF and survival analysis can be performed assuming failure load to be exact. The resulting failure loads for 5% and 20% fracture risk using the Cesari et al data of 5-6.2 kN and 7.2-9.2 kN are of the same order as the ones derived from Matsui et al. (2003) of 4.7 kN and 7.8 kN, thus not contradicting the findings.

Confidence intervals were not given as they only express the uncertainty related to fitting the data points to the selected distribution. It might be misleading to give these confidence intervals as there is additional uncertainty on which distribution to select.

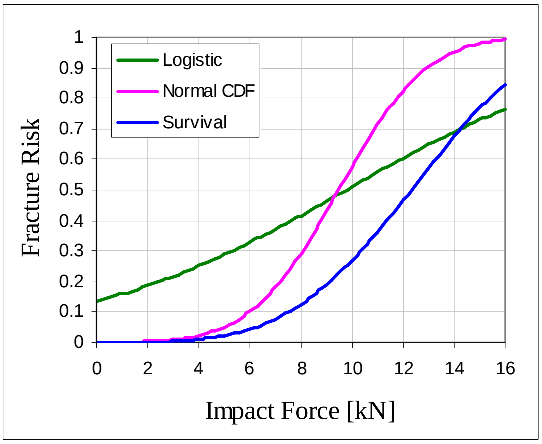


Figure 16. Injury-risk curves for pelvis impact developed from raw data of Cesari et al. (1982).

Data Scaling

Throughout this study, data was scaled to a mid-sized male as proposed in Kleinberger et al. (1998). Kerrigan et al. (2004) used this methodology, other sources had to be re-calculated. Kennedy et al. (2004) originally used multivariate regression, Cesari et al. (1982) adjusted for overweight and underweight, and Matsui et al. (2004) raised the mass fraction to the power of 1/2 instead of 2/3. While consistency has been achieved, consideration could be given whether this factor is too heavy. The rather surprising, but not necessarily invalid finding, that females have lower fracture risk could be explained: The unscaled data reveals the expected higher fracture risk for females, thus the scaling might have shifted the data too much. However, structural differences could explain the lower fracture risk as well.

Transfer Functions

The transfer from human thresholds to impactor thresholds was based on limited data and on the assumption that THUMS and human surrogate measurements are equal. Additional data could strengthen the relationships.

Snedeker et al. (2005) Test Set-Up

The proposed test set-up by Snedeker et al. (2005) addressed several of the highlighted issues with the current EEVC WG17 method as summarized earlier. In a more recent simulation study with THUMS, Compigne et al. (2008) have again highlighted differences in human and impactor kinematics as well as higher contact forces and vehicle damage using the EEVC WG17 upper leg test.

It has been shown that the set-up is expected to contribute to a better match between real-life injury data and Euro NCAP results. The authors advocate the use of this set-up as an improvement over the current one. It requires only small modifications to the test tool as a weight reduction of the legform for the femur test from 9.5 kg to 7.5 kg, thus below the current minimum weight, was suggested to be better aligned with the mass of a human thigh, and could be implemented with short lead time. New test tools might bring even further improvements but are not expected to be available in the near future.

Real-Life Relevance and Other NCAPs

Aside from Euro NCAP, the EEVC WG17 upper leg test is currently used in ANCAP and EU regulation.

In the EU directives 78/2009 and 631/2009, the upper leg test is prescribed for monitoring purposes with thresholds of 5 kN and 300 Nm. Monitoring means, that compliance with the thresholds is not required. The upper leg test is not included in JNCAP, US-NCAP and the global technical regulation on pedestrian safety (gtr No 9, ECE/TRANS/180/Add.9). The relevant section mentions that “some delegates had concerns about the biofidelity of the upper legform impactor and the limitations of the test tool in assessing injury”. Euro NCAP appears to give upper leg protection a higher weight and the EEVC WG17 test a higher relevance than other before mentioned parties do.

CONCLUSIONS

Previous studies have indicated a discrepancy between the EEVC WG17 upper leg test results in Euro NCAP and real-life injury risk as well as shortcomings in the test set-up. The test set-up proposed by Snedeker et al. (2005) was identified to address several of the highlighted issues and has the potential to be an improvement over the current test method. Legform impactor thresholds developed by EEVC WG17 and Snedeker et al. (2005) could be further improved constructing injury risk curves from applicable raw data. For the first time, these thresholds were based on human risk as defined in PMHS testing. These thresholds were then transferred to be used with the upper legform, thus potentially more favorable than the ones originally developed using accident reconstructions. Using the test method proposed by Snedeker et al. (2005) together with new performance criteria as proposed in this paper (7.9-9.0 kN for the pelvis test and 300-365 Nm for the femur test), the Euro NCAP test results could be better aligned with real-life injury risks. Setting the right targets and evaluation methods is crucial to minimize the traffic related injuries as manufacturers might develop cars based on these tests.

REFERENCES

Bovenkerk, J., Hardy, R.N., Neal-Sturgess, C.E., Hardy, B.J., van Schijndel - de Nooij, M., Willinger, R., Guerra, L.J., and Martinez, L. (2008), Biomechanics of real world injuries and their associated injury criteria, APROSYS, report number AP-SP33-001R.

Carroll, J.A. and Hynd,D. (2007), Material Property Scaling for Human Body Modelling, APROSYS, report number AP-SP51-0048.

Cavanaugh, J., Walilko, T., Malhotra, A., Zhu, Y., and King, A. (1990), “Biomechanical response and injury tolerance of the pelvis in twelve sled side impacts”, STAPP Conference Proceedings, SAE 902305, p. 1–12.

Cesari, D., Ramet, M., and Clair, P.-Y. (1980), “Evaluation of pelvic fracture tolerance in side impact”, STAPP Conference Proceedings, SAE 801306, p. 231–253.

Cesari, D. and Ramet, M. (1982), “Pelvic tolerance and protection criteria in side impact”, STAPP Conference Proceedings, SAE 821159, p. 145–154.

Compigne, S., Guerra, L.J., Martínez, L., and Bovenkerk, J. (2008), Review of the current pedestrian lower and upper leg test procedures. APROSYS, report number AP-SP33-0016R.

Diamond, W.J. (2001), Practical Experiment Designs: for Engineers and Scientists, Wiley.

EEVC WG10 (1994), Proposals for methods to evaluate pedestrian protection for passenger cars. EEVC Working Group 10 Report

EEVC WG17 (2002), Improved test methods to evaluate pedestrian protection afforded by passenger cars. EEVC Working Group 17 Report

Efron , B. and Tibshirani, R.J (1993) An Introduction to the Bootstrap, Chapman & Hall.

Euro NCAP (2009), Assesment Protocol-Pedestrian Protection. Version 5.0.

Fredriksson, R., Rosén, E., and Kullgren, A. (2010), “Priorities of pedestrian protection - A real-life study of severe injuries and car sources” Accident Analysis and Prevention, 42(6), p.1672-81.

Funk, J.R., Kerrigan, J.R., and Crandall, J.R. (2004), “Dynamic bending tolerance and elastic plastic material properties of the human femur”, 48th annual proceedings AAAM.

Guillemot, H., Besnault, B., Robin, S., Got, C., LeCoz, J.Y., Lavaste, F., and Lassau, J.P. (1997) “Pelvic injuries in side impact collisions: A field accident analysis and dynamic tests on isolated pelvic bones”, Stapp Conference Proceedings, SAE 973322, p. 91–100.

Hardy, B.J., Lawrence, G.J.L., Knight, I.M., and Carroll, J.A. (2006), A study on the feasibility of measures relating to the protection of pedestrians and other vulnerable road users, report for the European Commission, Contract FIF.200330937.

JARI, (2004), Technical Feasibility Study on EEVC/WG17 Pedestrian Subsystem Test, report number INF GR/PS/101.

Kennedy, E.A., Hurst, W.J., Stitzel, J.D., Cormier, J.M., Hansen, G.A., Smith, E.P., and Duma, S.M. (2004), “Lateral and posterior dynamic bending of the mid-shaft femur: fracture risk curves for the adult population”, Stapp Car Crash J, p. 27-51.

Kent, R.W. and Funk, J.R. (2004) “Data Censoring and Parametric Distribution Assignment in the Development of Injury Risk Functions from Biomechanical Data”, SAE paper 2004-01-0317.

Kerrigan, J.R., Bhalla,K., Madeley, N.J., Funk, J.R., Bose, J., and Crandall, J.R. (2003), “Experiments for establishing pedestrian-impact lower limb injury criteria” SAE paper 2003-01-0895.

Kerrigan, J.R., Drinkwater, D.C., Kam, C.Y., Murphy, D.B., Ivarsson, B.J., Crandall, J.R., and Patrie, J. (2004), “Tolerance of the human leg and thigh in dynamic latero-medial bending”. IJCrash, 9(6) p.607-623.

Kleinbaum, D. G. and Klein, M. (2005), Survival Analysis. A Self-Learning Text, Springer.

Kleinberger, M., Sun, E., Eppinger, R., Kuppa, S., and Saul, R. Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems, NHTSA report.

Konosu, A., Ishikawa, H., and Sasaki, A. (1998), “A Study on Pedestrian Impact Test Procedures by Computer Simulation - The Upper Legform to Bonnet Leading Edge Test”, ESV conference, report number ESV 98-S 1 O-W- 19.

Lawrence, G.J.L., (2005), “The next steps for pedestrian protection test methods”, ESV conference, report number ESV 05-0379.

Liers, H. (2010), Extension of the Euro NCAP effectiveness study with focus on MAIS3+ injured pedestrians, Report under contract of ACEA.

Liers, H. and Hannawald, L., (2009) Benefit estimation of the EuroNCAP pedestrian rating concerning real-world pedestrian safety, Report under contract of ACEA.

Maltese, M., Eppinger, R., McFadden, J., Saul, R., Pintar, F., Yognandan, N., and Hines, M. (2002) “Response corridors of human surrogates in lateral impacts”, Stapp Car Crash J, p. 321–351.

Marcus, J.H., Morgan, R.M., Eppinger, R.H., Kallieris, D., Mattern, R., and Schmidt, G. (1983), “Human response to injury from lateral impact”, Stapp Conference Proceedings, SAE 831634.

Matsui, Y., Ishikawa, H., and Sasaki, A. (1998), “Validation of Pedestrian Upper Legfrom Impact test – Reconstruction of pedestrian Accidents”, ESV conference, report number ESV 98-S10-O-05.

Matsui, Y., Kajzer, J., Wittek, A., Ishikawa, H., Schroeder, G., and Bosch, U. (2003), “Injury pattern and tolerance of human pelvis under lateral loading simulating car-pedestrian impact”, 2003 SAE World Congress, SAE paper 2003-01-0165.

Matsui, Y., Schroeder, G., and Bosch, U. “Injury pattern and response of human thigh under lateral loading simulating car-pedestrian impact”, 2004 SAE World Congress, SAE paper 2004-01-1603.

Mertz, H.J. and Irwin, A.L. (2003) “Biomechanical and Scaling Bases for Frontal and Side Impact Injury Assessment Reference Values”, STAPP Car Crash Journal, p.155-188.

Rodmell, C. and Lawrence, G.J.L. (1998), Further pedestrian accident reconstructions with the upper legform impactor, EEVC WG17 document 113.

Snedeker, J.G., Muser, M.H., and Walz, F.H. (2003), “Assessment of Pelvis and Upper Leg Injury Risk in Car-Pedestrian Collisions: Comparison of Accident Statistics, Impactor Tests and a Human Body Finite Element Model”, Stapp Car Crash J, p. 437-457.

Snedeker, J.G., Walz, F.H., Muser, M.H., Lanz, C., and Schroeder, G. (2005), “Assessing Femur and Pelvis Injury Risk in Car – Pedestrian Collisions: Comparison of Full Body PMTO Impacts, and a Human Body Finite Element Model”, ESV conference, report number ESV 2005-103.

Viano, D.C. (1989) “Biomechanical response and injuries in blunt lateral impact”, STAPP Conference Proceedings, pp.113–142, SAE 892432.

Zhu, J.Y., Cavanaugh, J.M., and King, A.I. (1993), “Pelvic biomechanical response and padding benefits in side impact based on a cadaveric test series”, Stapp Conference Proceedings, p. 223–233, SAE 933128