CHEST INJURY CRITERION: AN UPDATE OF THE EQUIVALENT DEFLECTION (DEQ)

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ABSTRACT

The rodpot chest deflection measured on the HIII dummy does not discriminate the contributions of the belt and the airbag in crashes. The risks associated to the deflection being different for these two kinds of devices, the assessment of the risk with the rodpot deflection is erroneous for combined restraining systems. Combined restraints known to be efficient in protecting the thorax are consequently penalized. In 2003, the equivalent deflection (Deq) criterion based on the HIII rodpot deflection and the shoulder belt force and applicable to belt, airbag as well as combined restraints was proposed. It has since been evaluated and reviewed by users providing some requests for improvements such as the sensitivity to changes in the pelvic restraint. The objective of this study was to update the Deq criterion to address as much as possible the feedbacks from the users and better predict chest injuries.
New data from HIII 50th percentile tests performed under conditions more representative of the loading encountered with current restraints were collected from the literature. It allowed to better define the relationship between the shoulder load and the deflection caused by the belt. The Deq formulation was updated in order to increase its sensitivity, particularly to airbag loading. Additional paired dummy and PMHS (Post-Mortem Human Subject) tests allowed increasing the size of the sample used to validate the principle of the Deq criterion. The validation of the new formulation was also conducted through simulations with human and HIII models. Then, the biomechanical data were re-processed with currently recommended statistical methods (based on survival analysis) to build a thoracic injury risk curve for the HIII 50th dummy. Finally, a thoracic injury risk curve was provided for the HIII 5th female.
This paper provides the set of data (dummy, PMHS and numerical simulations) used to define and validate the criterion, as well as the equations of the thoracic injury risk curves as a function of the Deq resulting from their processing. The feedbacks from the users as well as the related improvements of the criterion are presented. The effect of the rodpot deflection and the upper shoulder belt force on the Deq is described.
The aim of the Deq criterion is to improve the thoracic protection in frontal crash in the short term, therefore using the currently used HIII dummy. As such, this criterion enhances the prediction of the risk associated with combined restraints compared to the HIII rodpot deflection. However, it does not fully compensate the error introduced by the use of the rodpot deflection.

INTRODUCTION

For several years now, car manufacturers have made significant efforts in the field of thoracic protection. After first limiting the forces in the shoulder belt to 6 kN, these forces are now usually limited to 4 kN, with airbags intentionally designed to absorb the surplus of energy. If this technology is rewarded by a considerable improvement in safety on the road, it remains penalized by the usual biomechanical criteria, when calculated on the Hybrid III and if applied to all restraint systems.
To remedy this problem, a new criterion, valid in all the current restraint configurations (belt, airbag only or airbag and belt) was proposed by Petitjean et al. (2003).

The principle of the thoracic criterion proposed is the following:

The risks associated to a belt and to an airbag are different in terms of deflection. Therefore, the deflections due to a belt or due to an airbag must be evaluated separately.
The risk due to a belt loading can be calculated using the maximal deflection caused by the belt. This localized deflection is evaluated from the shoulder belt force, resolving the differential Equation 1. The stiffness used to calculate this deflection comes from belt-only tests.

$$Fbelt(t)=k1.dl(t)+c1.vl(t) \quad \textbf{Eq.1}$$

Where k1 and c1 are the linear stiffness and the damping and dl(t) and vl(t) are the deflection and the rate of deflection respectively.

The risk due to an airbag can be calculated using the maximal deflection caused by the airbag. This distributed deflection is calculated subtracting the localized deflection from the total deflection, as the deflections are supposed to be added.

The localized and distributed deflections are then combined in order to take into account the different risks associated to each restraint and the interaction between them.

However, before, they have to be normalized so that the same value of each deflection produces the same risk. For this reason, the distributed deflection is scaled by the factor Fn.
Finally, the localized deflection and the scaled distributed deflection can be combined to form the Deq (Equivalent Deflection).

This criterion, developed in 2003, was updated in order to take into account more recent restraint systems, PMHS testing performed since 2003 as well as other statistical methods to build the injury risk curves.

METHODS

The principle of the Deq is described in the original paper (Petitjean et al., 2003) and remains the same. The following items were reviewed and updated:

- relationship between the shoulder belt force and the deflection
- Deq formulation
- Validation sample
- Injury Risk Curves (IRCs)

The Deq was evaluated against the validation sample and HIII/HBM simulations.
Test results were analyzed to scale the Deq to the HIII 5th and provide IRCs.

RESULTS

Relationship between the shoulder belt force and the deflection

Localized Deflection Calculation
The upper shoulder belt load was used to determine the deflection caused by the localized loading. Belt only tests with HIII were collected in order to determine the relationship between the upper shoulder belt load and the deflection caused by the localized loading.

The limitations of the belt only tests used in 2003 are that the belt restraints used did not correspond to up-to-date restraint (dual stage load limiter for example) and present shoulder belt force much higher than the load limitation used nowadays (up to 12.7 kN). Additional belt only tests were therefore collected to investigate the relationship between the upper shoulder belt load and the stiffness for belt restraints closer to those currently used in the vehicles. Belt only tests are not easy to collect as most of the restraints include the combination of a belt and of an airbag. A lot of tests were collected in the NHTSA Biomechanics Test Database. The number of belt only tests used was 49 compared to 21 in the 2003 version. The range of maximum upper shoulder belt load was from 2.7 to 12.7 kN with a median equal to 6.2 kN (the median for the belt only sample used in the 2003 version was 8.6 kN).

The stiffness to be used to calculate the maximum localized deflection was chosen to be the one representing the mean **minus** one standard deviation using all the tests included which are shown in Figure 1. The stiffness calculated is described in Equation 2.

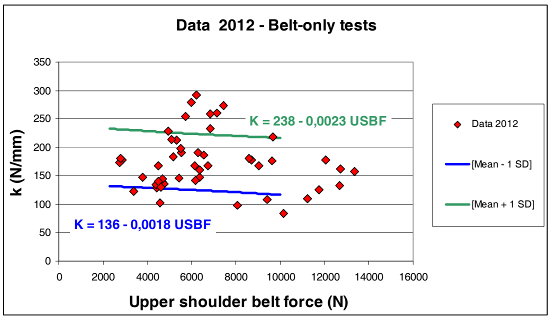

Figure 1. Relationship between the upper shoulder belt load and the stiffness.

$k_l = -0.0018*F_{belt\,max} + 136$ with k_l in N/mm and Fbelt in N	**Eq. 2**

The belt only tests were also used to determine the relationship between the linear stiffness and the linear damping, provided in Equation 3 and represented in Figure 2.

$c1= 0.0185*kl -0.2357$ with k_l in N/mm and c in N.s/mm, R^2=0.31	**Eq. 3**

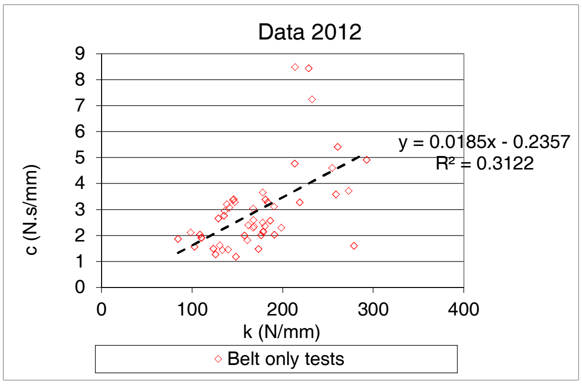

Figure 2. Relationship between the damping and the stiffness to be used for the calculation of the deflection due to localized loading and due to the distributed loading.

The localized deflection was calculated from the upper shoulder belt load using Equation 1, Equation 2 and Equation 3.

Distributed Deflection Calculation
The deflection caused by the distributed loading such as an airbag is calculated subtracting the localized deflection from the total deflection, as described in Equation 4.

$d_{dist}(t) = d_{rodpot}(t)-d_{lr}(t)$	**Eq. 4**
$d_{dist}(t)$: deflection caused by the distributed loading	
$d_{rodpot}(t)$: rodpot deflection	
$d_{lr}(t)$: localized deflection at the rodpot location	

However, the total deflection is only known at the rodpot location. Therefore, this is the localized deflection at the rodpot location that must be removed from the total deflection measured at the rodpot location. The maximum localized deflection as defined in the previous section cannot be used because it does not correspond to the localized deflection at the rodpot location.

To account for this drawback, the stiffness to be used in the calculation of the distributed deflection was chosen to be the one representing the mean **plus** one standard deviation using all the tests included in Figure 1. The stiffness calculated is described in Equation 5.

$k_{lr} = -0.0023*F\ belt\ max + 238$	**Eq. 5**
with k_{lr} in N/mm and Fbelt in N	

It must be noted that the localized deflection used to calculate the distributed deflection is more likely to be underestimated than the one in the 2003 version. It means that the distributed deflection is more likely to be overestimated. This allows having a conservative limit for the Deq.

Statistical method to calculate Injury Risk Curves

Petitjean and Trosseille (2011) evaluated the different methods to construct injury risk curves using statistical simulations. The parameters evaluated were the theoretical distribution of the tolerance (normal, Weibull), the distribution of the points relative to this theoretical distribution (lower end, upper end, centered loosely, centered tightly), the size of the sample (from 10 to 50) and the proportion of exact data (no exact data, 10%, 25% and 50% of exact data). The conclusion is that the survival analysis is recommended to be used to construct injury risk curves for biomechanical samples over the other methods.

In the 2012 updates, all the injury risk curves were built using the survival analysis with the Weibull distribution. As the survival analysis is a parametric method, the age of the PMHS was included as a co-variable in the analysis.

Calculation of the normalization factor for distributed loading

Once the deflection caused by a localized and a distributed loading are calculated, they are combined in the Deq such that the difference of tolerance due to a localized and a distributed loading is taken into account. A normalization factor allowing to have the same risk for a given value of localized or distributed loading was then determined.

For this purpose, two samples – one with localized loadings and one with distributed loadings – were combined and analyzed together to characterize their difference.

Sample with localized loading only
As the Foret-Bruno sample (Foret-Bruno et al., 1998) was close in terms of upper shoulder belt force to more recent restraints and as the size of this sample was much more important than the one of the APR sample (used in 2003), it was chosen to use it to build the injury risk curve as a function of the localized loading. The maximum upper shoulder belt load is the only measure available from the original Foret-Bruno sample. It was then needed to convert the maximum upper shoulder belt load into maximum localized deflection.

First, the relationship between the maximum upper shoulder belt force and the upper shoulder belt force at the time of the maximum deflection was determined using the tests provided in Figure 1. This relationship is provided in Equation 6 and illustrated in Figure 3.

$F\ belt\ d\ l\ max = 0.8373*\ F\ belt\ max$	**Eq. 6**

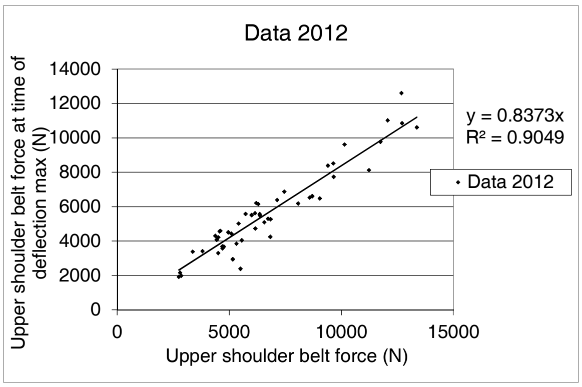

Figure 3. Comparison of the maximal upper shoulder belt load and of the upper shoulder belt load at the time of maximal deflection.

The combination of Equation 1 and Equation 6 then leads to the relationship between the maximum upper shoulder belt force and the maximum localized deflection (Equation 7).

F belt max = (kl/0.8373) dl max **Eq. 7**
With Fbelt max in N, k1 in N/mm and d1 max in mm

The maximal upper shoulder belt loads from Foret-Bruno accident cases were, in this way, converted to dummy maximal localized deflection.

Sample with distributed loading only
Impactor tests performed by Kroell et al. (1971, 1974) were used to characterize the distributed loading. The tests performed with a mass significantly lower than 23 kg were not used for the construction of the injury risk curves. The sample selected to build the injury risk curve is presented in annex (Table A 1).

Definition of the normalization factor
A survival analysis was performed including the sample providing the localized deflection calculated for the Foret-Bruno sample and the sample providing the distributed deflection calculated for the impactor tests. The severity considered was AIS3+ for the Foret-Bruno sample and a number of rib fractures equal or higher than 6 for the Kroell sample. The co-variables were the deflection (localized or distributed), the age of the occupant or PMHS and the type of loading (belt or impactor). This method allowed calculating a single normalization factor, independent from the age and the level of risk.
The results of the survival analysis are presented in Equation 8.

$$Risk_{50th}(AIS3+) = 1 - \exp\left[-\exp\left(\frac{\ln(deflection) - 4.886 - 0.016 \times age + 0.176 \times loading}{0.23}\right)\right]$$

Eq. 8

The normalization factor was found to be 0.84.

Deq formulation

The original Deq was the resultant of the belt deflection and the airbag deflection (Deq quadratic, Equation 9). However, it was not demonstrated that this form was the best one. For this reason, a linear combination of the belt deflection and the airbag deflection (Equation10) was investigated.

Deq quad = max (SQRT{dbelt (t)² + (Fn * dairbag (t))²}) **Eq. 9**

Deq Lin = max (dbelt (t) + Fn * dairbag (t)) **Eq. 10**

In addition, a Deq calculated from the lower shoulder belt force was evaluated. The use of this belt force was suggested because it is less influenced by the belt force limitation and is more likely to show the effects of the pelvis restraint.

Validation sample

The Deq was validated against tests including different types of restraints such as belt, combined belt and airbag and airbag only tests.
The PMHS sample used in 2003 was reviewed and some tests were excluded. As the effect of the liquid injected into the PMHS remains uncertain, the PMHS included in the sample were fresh or frozen. The list of PMHS tests used in the 2012 update is included in annex (Table A 2). Tests with more up-to-date restraints were included compared to the 2003 version, such as dual stage pretensioner or low load limiter. These tests are a selection from Forman et al. (2006 and 2009), Humos (2000), Petitjean et al. (2002), Kent at al. (2001) and Lebarbé et al. (2005).

To assess the performance of the different criteria, IRCs were constructed with this validation sample, using a survival analysis. The quality of the curves was compared by means of statistical index.

The Akaike Information Criterion (AIC) assesses the likelihood of a model and takes into account the number of variables used in the model (AIC= -2*log likelihood+2*number of variables). The lowest AIC indicated the best fit of the model with the test data.

For the validation sample, the AIC is the highest for the injury risk curve built as a function of the rodpot deflection (Table 1). This means that the fit of the injury risk curves as a function of the Deq whatever the option considered is always better than the one for the rodpot deflection.
Among the different options, the lowest AIC values are found for the Deq based on the lower shoulder belt load compared to the Deq based on the upper shoulder belt load. This measurement is sometimes measured during crash tests. However, depending on the seat geometry and belt anchorages, it is not always easy to measure. The Deq based on the upper shoulder belt load would be easier to measure and would still show a better performance than the rodpot deflection.
There is no significant difference between the quadratic and the linear combination of the localized and distributed deflection regarding the fit of the data for the whole validation sample for Deq based on upper shoulder belt load. The AIC

based on the quadratic combination of the localized and distributed deflection is lower than the one based on the linear combination, when based on the lower shoulder belt load.

Table 1.
AIC values and c index for the injury risk curves built using the validation sample

	Rodpot defl. (mm)	Deq			
		Lower shoulder belt		Upper shoulder belt	
		Quad	Linear	Quad	Linear
AIC values	49.6	31.3	35.4	37.2	39.2
C index	0.747	0.92	0.885	0.874	0.864

The appropriateness of a criterion to predict a risk can be assessed by constructing a risk curve as a function of this criterion and calculating the percentage of concordance and discordance and the c statistic index.
A c statistic value equal to 0.5 indicates an inappropriate criterion to predict the risk while a c value equal to 1 indicates a perfect appropriateness. The higher the c value is, the better the criterion predicts the risk.
The injury risk curve as a function of the Deq based on the lower shoulder belt load and the quadratic combination offered the best prediction (Table 1). The other options of Deq have similar c index values. The injury risk curves as a function of the Deq present a better c index value than the rodpot deflection.

Finally, based on the same validation sample, the quality index, as defined by Petitjean and Trosseille (2011) were found to be better for the Deq than for the Rodpot deflection (Table 2).

Table 2.
Quality index based on the size of the 95% confidence interval for Rodpot and Deq

Risk	5%	25%	50%
Deq	Unaccept.	Fair	Fair
Rodpot	Unaccept.	Unaccept.	Unaccept.

HIII/HBM simulations

Simulations were run with Humos2Lab (Song et al. 2011) and Hybrid III models in the same conditions. The restraints were based on lap and shoulder belt and airbag. The contribution of the belt and of the airbag varied, lowering the belt load limiter and increasing the airbag power such that the excursion of the models were kept identical for each combination of belt and airbag restraint. The Deq was found to increase with the increase of injuries on Humos2Lab human body model (Table 3). On the contrary, the rodpot deflection was not found to increase with the increase of injuries. This is due to the fact that the tolerance limit is different in terms of rodpot deflection for localized and distributed loading.

Table 3.
Humos2Lab injuries and HIII measurements at ISO excursion of T8

	Number of Rib Fractures (45 y/o)	**Number of Rib Fractures (65 y/o)**	**Drodpot (mm)**	**Deq quadratic based on upper shoulder belt load**	**Deq linear based on upper shoulder belt load**
2kN + 90% AB	0	3	35.3	27	37.4
4kN + 55% AB	0	6	40.6	36.1	50
6.5 kN	4	8	35.2	50.7	56.4

Another series of simulations were run with different kinds of restraining systems, in order to verify their effect on the prediction of fractures using either the rodpot or the Deq. Simulations included hub and airbag tests, belt-only or combined airbag and belt sled tests. All configurations were conducted at different severities leading to different injury outcomes.
The effect of the restraining system (shown in Figure 4) confirmed the observations made by Kent et al. (2003) on the relationship between the rodpot deflection and the number of fractures. On the contrary, Deq LIN was very efficient to reduce the effect of loading type.

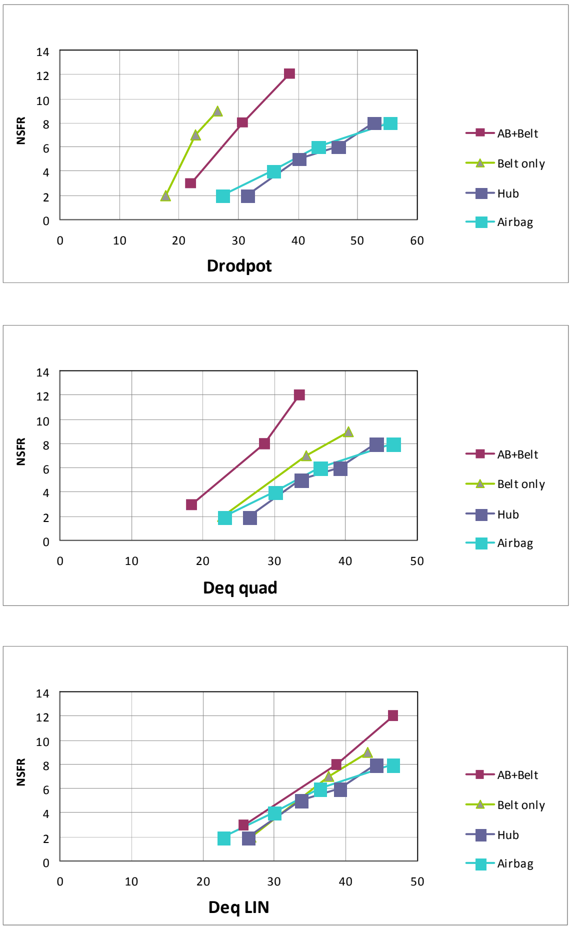

Figure 4. HBM/HIII simulations.

Injury Risk Curve

The Deq IRC was constructed using Foret-Bruno sample because it is a large sample, based on living subjects and representative of the crash situations. The risk, as a function of Deq and age is defined in Equation 11.

The quality index of this IRC is presented in Table 4. It demonstrates a good to fair ability to predict the risk.

$$Risk_{50th}(AIS3+)$$
$$= 1 - \exp\left[-\exp\left(\frac{\ln(Deq) - 4.99 + 0.0174 \times age}{0.246}\right)\right]$$

Eq. 11

Table 4.
Quality index of the IRC for Deq

	5%	**25%**	**50%**
45 y/o	Good	Good	Fair
60 y/o	Fair	Good	Good

HIII 5th

There is not enough 5th percentile PMHS tests allowing to build injury risk curves as a function of the Deq. However, the principle of the Deq thoracic injury criterion is also applicable to the Hybrid III 5th dummy, given some correspondences are done between the Hybrid III 50th and 5th. The values to be used for the different parameters have to be checked in order to adapt the Deq to the small female.

Thoracic response under localized loading

Linear stiffness and damping were calculated on a sample of Hybrid III 5th tests with belt only restraint (Table A 3). These tests were collected in the NHTSA Biomechanics Test Database.

The stiffness and damping were compared to those determined for the Hybrid III 50th. Figure 5 and Figure 6 show that the values found for the Hybrid III 5th are consistent with those found for Hybrid III 50th. Therefore the same coefficients were used to calculate the localized deflection from the shoulder belt force.

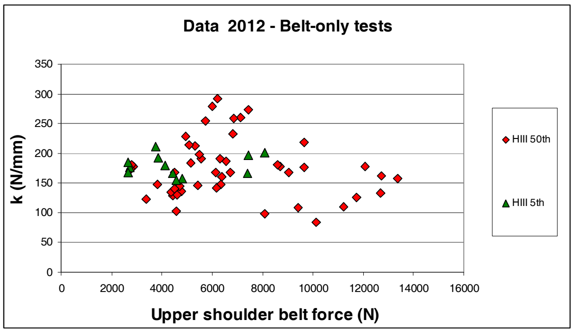

Figure 5. Comparison of the relationship between the upper shoulder belt load and the stiffness for the Hybrid III 50th and 5th.

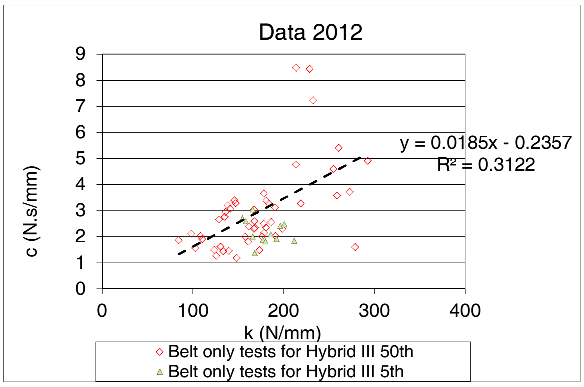

Figure 6. Comparison of the relationship between the damping and the stiffness for the Hybrid III 50th and 5th.

Thoracic response under distributed loading

The stiffness of the thorax should also be compared between the Hybrid III 50th and 5th for an impactor

test. This should be done for impactor test with a scaled impactor mass and impactor surface. Unfortunately, the only impactor tests available with the Hybrid III 5th are certification tests performed with a scaled impactor mass (13.98 kg) but with the same impactor surface as for the Hybrid III 50th (152.4 mm).
The stiffness ratio found based on the certification test corridors is close to 1 (Figure 7).

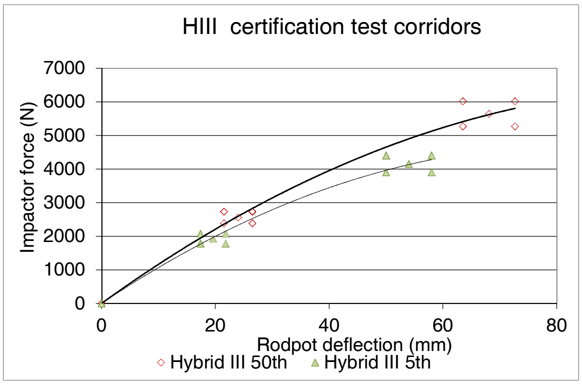

Figure 7. Comparison of the thoracic stiffness under distributed loading for the Hybrid III 50th and Hybrid III 5th.

Maximum upper shoulder belt load and upper shoulder belt load at the time of maximum deflection

Figure 8 shows that the relationship between the maximum upper shoulder belt load and the upper shoulder belt load at the time of maximum deflection was very consistent for the Hybrid III 50th and 5th.

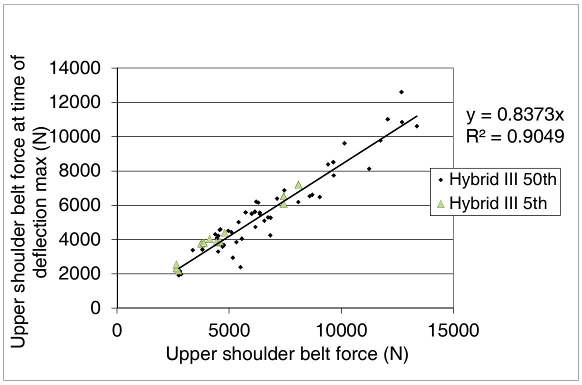

Figure 8. Comparison of the maximum upper shoulder belt load and of the upper shoulder belt load at the time of maximum deflection for the Hybrid III 50th and Hybrid III 5th.

The behaviour of the HIII 5th female being close enough to the HIII 50th male, it was considered that the same formula should be applied for the Deq calculation.

IRC for the Hybrid III 5th

Identically, the injury risk curve described in Equation 11 can be used for the prediction of the risk as a function of the Deq scaled to the Hybrid III 5th percentile.
The Deq scaled to the HIII 5th is the Deq divided by the length ratio. The length ration is the ratio of the chest depth of the Hybrid III 5th (182.9 mm) and the chest depth of the Hybrid III 50th (221 mm). It equals 0.83.
Therefore, Equation 12 defines the IRC for the HIII 5th female.

$$Risk_{5th}(AIS3+)$$
$$=1-\exp\left[-\exp\left(\frac{\ln(Deq/0.83)-4.99+0.0174\times age}{0.246}\right)\right]$$

Eq. 12

DISCUSSION

Upper shoulder belt force measurement

Belt force transducers are not conventional and concerns were raised about the calibration of these transducers and their ability to provide accurate measurements.

A calibration procedure is required and is under development at ISO TC22/SC12/WG3. The following steps are necessary:

- Linearization (as rodpot)
- Calibration with an harmonized standard belt strap

A round robin is in progress and ISO expects a range of +/- 5%.

As a comparison, the deflection measured by the rodpot in calibration tests has to fall in a range of +/- 10% at low severity (Figure 9).

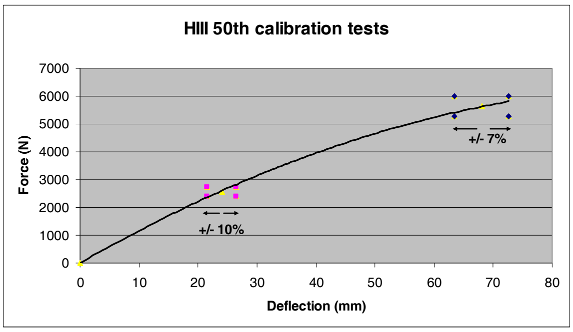

Figure 9. HIII 50th calibration tests.

Speed sensitivity and effect of the lower body restraint

Another concern about Deq was its sensitivity to the test speed and its ability to detect changes in the pelvis retraint. The rational of this objection was that the Deq is highly driven by the upper shoulder belt force which is often limited. This was true with the 2003 version and the 2012 version was modified to account for this concern. In particular, the use of a linear form of the Deq, by providing a higher contribution of the distributed deflection, increased the speed sensitivity and the effect of the pelvis restraint. However, the need to take this latest effect is not fully validated.

Simulations performed by LAB on Humos2Lab / HIII (Table 5) show that:

- HIII simulations are not very sensitive to pelvis restraint
- Rodpot variations are often opposite to Humos2Lab injury outcome
- Both Drodpot, Deq quad and Deq LIN are sensitive to the velocity

Table 5.
Humos2Lab injuries and HIII measurements at different velocities

Velocity	Drodpot	USBF	LSBF	Deq	Deq LIN	NFR
40	38.5	4.1	3.1	33.5	46.6	2.0
45	40.6	4.1	3.4	35.7	49.7	4.0
60	45.0	4.2	4.0	38.2	53.6	12.0
45/40	6%	0%	11%	7%	7%	100%
60/40	17%	2%	30%	14%	15%	500%

Geometry sensitivity

It was said that Deq may be insensitive to the restraint geometry, in opposite to the injury outcome.
Simulations performed by LAB on Humos2Lab / HIII with different anchorage geometries (Table 6) show that:

- Deq Lin and Rodpot increase while injuries remain the same.
- Deq quad is less sensitive to the geometry

Table 6.
Humos2Lab injuries and HIII measurements for different geometries

Configuration	Drodpot	USBF	LSBF	Deq	Deq LIN	NFR
base	40.1	4.1	3.7	36	49.8	5
lower B3	46.2	4.1	3.7	38.7	54.6	5
Lower & rear B3	47.9	4.1	3.8	40.1	56.5	5

Effect of the Rodpot deflection and the upper shoulder belt force

In order to better understand the contributions of the rodpot deflection and the upper shoulder belt force, the Deq formula was simplified. The viscous component was removed and only the relationship between Fbelt_max and Fmax at the time of maximum deflection was kept. The stiffness was considered as constant over Fbelt (the value was chosen at Fbelt = 5 kN).

Deq = dlocalized + Fn * ddistributed

Dlocalized was replaced by (Fshoulder* λ_F)/kl
Ddistributed was replaced by Drodpot-(Fshoulder* λ_F)/klr
With λ_F =Fbelt@dmax/Fbelt_max

Deq LIN = 6.6*USBF(kN) + 0.84*(Rodpot(mm) - 3.7*USBF(kN))

Then Deq can be written as a linear combination of Fshoulder and Drodpot.

Deq LIN = 3.5*USBF(kN) + 0.84*Rodpot(mm)

The smaller the shoulder belt force is, the higher the rodpot deflection can be for the same risk.

This simplified version of the Deq is illustrated in Figure 10. It gives the iso-Deq in terms of Rodpot deflection as a function of the Shoulder belt force.
The airbag limit (in black) is the limit under which the rodpot does not measure properly the deflection. This figure illustrates the fact that the DEQ IRC has nothing to do with the Rodpot IRC, because the Deq accounts for the maximum deflection and generally not the rodpot. For instance for a belt-only restraint, 5kN of Shoulder belt force generate a rodpot deflection of 22 mm as a mean. In that case, the Deq is equal to 36, which is much higher than the rodpot deflection.

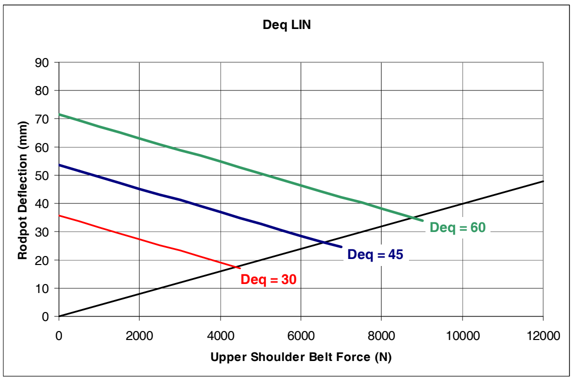

Figure 10. Iso-Deq curves.

This simplified version of Deq allows getting a good approximation of the final result, within a margin of generally 1 or 2 points, sometimes up to 5 points of Deq. This is the reason why a more sophisticated routine for the Deq calculation is needed, which takes into account the viscous component of the chest.

Deq versus Deflection

The Rodpot deflection is known to be a criterion which depends on the restraining system. An injury risk curve based on the rodpot is therefore only valid for a given contribution of the belt and the airbag. Mertz et al. (2003) proposed a curve for distributed loading and another one for belt loading. Laituri et al. (2005) mixed all kind of loading systems and therefore proposed a curve for an undefined balance of belt and airbag. Consequently, the same rodpot deflection gives different risks, depending on the belt force (Figure 11):

- 5% Laituri goes from 0.3% to 15% risk
- 50% Laituri goes from 15% to 90% risk

When looking at some equivalence between the rodpot and the Deq, it is then necessary to define at which shoulder belt force the risk should be equal.

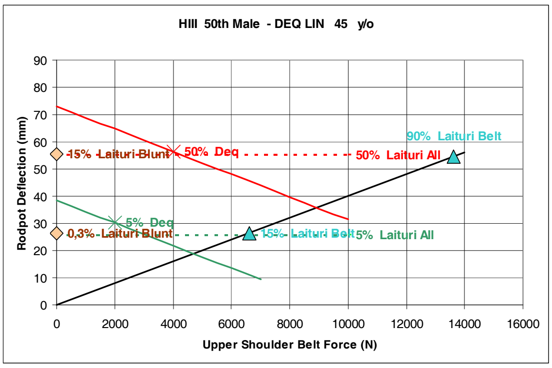

Figure 11. Risks associated with Rodpot deflection compared to Deq.

Deq limits

The risks used to calculate Deq limits should be calculated in order to promote load limitation and give enough room for airbag loading.

A strategy should be to define the upper performance limit for the 5th female and the lower performance limit for the 50% male, the existing limits as defined by EuroNCAP (Rodpot @ 18mm for the 5% female as an upper limit and 50mm for the 50th male as a lower limit) being defined for instance at 4.5kN and 5.5 kN respectively (5.5kN scaled for the small female gives 4.5 kN). This would mean that systems at 4.5 kN of load limitation would be evaluated identically with the rodpot and the Deq for the small female and systems at 5.5 kN Load limitation would be evaluated identically with the rodpot and the Deq for the mid male. Then lower load limitation would be encouraged while higher load limitation would be discouraged. This would be an improvement for the elderly.

Following this strategy, the limits for Deq at 45 y/o would be set at 10% and 50% of risk.

The upper limit (10% risk @ 45 y/o for a 5th female) would correspond to 37% risk at 65 y/o for a 5th female.

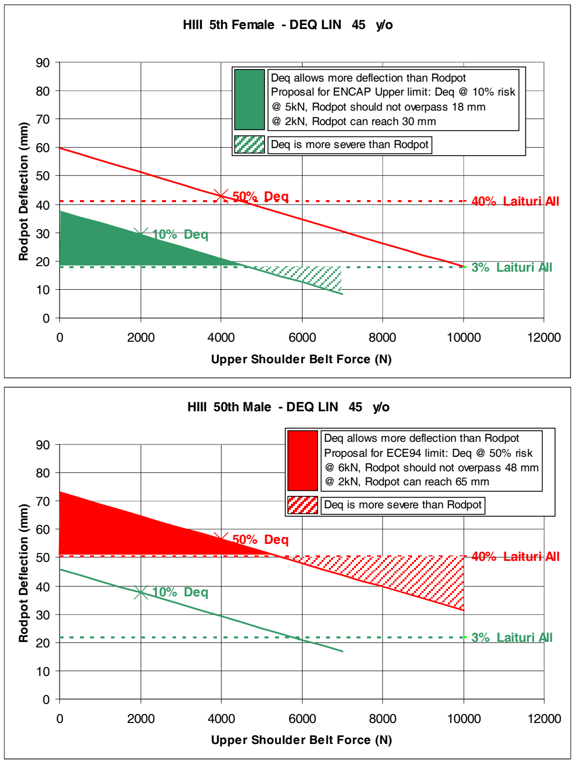

Figure 12. Deq limits compared to Rodpot limits.

CONCLUSIONS

What we know

- The only proven effect on the injury outcome is the belt load limitation, especially for elderly
- The limitation is made possible by means of the combination with an airbag

What DEQ is NOT

- A universal criterion (apply only to belt and airbag systems)
- A perfect criterion (does not solve all HIII concerns)

What is DEQ

- A way to better balance belt and airbag contributions
  - Lower belt loads
  - Higher bag loads, but limited
- The only criterion on HIII that take into account the effect of belt load limitation
- An interim solution, waiting for THOR dummy with associated criteria

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Table A 1.
PMHS impactor tests (Kroell et al. (1971, 1974)) used in the 2012 update for the construction of the injury risk curve for the distributed deflection

PMHS test number	Chest compression	PMHS age	Rib fractures	Impactor mass (kg)	Impactor velocity (m/s)	Hybrid III rodpot deflection (mm)
12FF	0.42	67	22	22.86	7.24	83.2
13FM	0.44	81	21	22.86	7.42	88.7
14FF	0.44	76	7	22.86	7.33	86.6
15FM	0.39	80	13	23.59	6.88	77.0
18FM	0.42	78	14	23.59	6.70	82.7
19FM	0.38	19	1	23.59	6.70	72.9
20FM	0.35	29	0	23.59	6.70	67.2
21FF	0.56	45	18	23.59	6.84	115.5
22FM	0.42	72	17	23.59	6.70	82.5
23FF	0.43	58	23	19.50	7.73	85.0
31FM	0.46	51	14	23.04	10.19	92.1
32FM	0.46	75	20	22.86	9.92	91.8
34FM	0.45	64	13	18.96	8.22	89.6
36FM	0.35	52	7	18.96	7.20	66.2
37FM	0.33	48	9	22.86	9.83	62.0
42FM	0.32	61	0	22.86	4.87	60.5
45FM	0.32	64	10	23.00	5.05	59.1
46FM	0.31	46	0	19.28	7.33	58.0
53FM	0.26	75	3	22.95	5.23	45.9
54FF	0.41	49	7	19.55	9.92	80.1
55FF	0.41	46	8	19.55	9.92	80.4
60FM	0.27	66	9	22.95	4.34	48.6
63FM	0.37	53	4	23.00	6.93	72.2
64FM	0.37	72	6	23.00	6.93	72.0

Table A 2.
PMHS tests performed with different restraints used of the validation of the Deq in the 2012 update

PMHS test number	Source	HIII test number	Restraint type	PMHS age	Number of rib fractures	USBF (N)	Defl (mm)	Deq LIN
1386	Forman et al. (2009)	1316, 1317, 1318	Lap and Shoulder Belt, Dual stage load limiter	67	12	4446	22.9	36.1
1387	Forman et al. (2009)		Lap and Shoulder Belt, Dual stage load limiter	69	2	4446	22.9	36.1
1389	Forman et al. (2009)		Lap and Shoulder Belt, Dual stage load limiter	72	17	4446	22.9	36.1
Humos 3	Humos (2000)	Dummy 3, Dummy 4	Lap and Shoulder Belt, shoulder load limiter	58	19	4457	15.6	37.0
Humos 4	Humos (2000)		Lap and Shoulder Belt, shoulder load limiter	70	9	4457	15.6	37.0
Humos 1	Humos (2000)	Dummy 1, Dummy 2	Lap and Shoulder Belt, shoulder load limiter	76	26	6126	25.9	48.7
Humos 2	Humos (2000)		Lap and Shoulder Belt, shoulder load	66	24	6126	25.9	48.7

PMHS test number	Source	HIII test number	Restraint type	PMHS age	Number of rib fractures	USBF (N)	Defl (mm)	Deq LIN
			limiter					
C17	Petitjean et al. (2002)	C11, C12, C19, C21	Lap and Shoulder Belt, shoulder load limiter	76	25	6557	20.6	48.6
C23	Petitjean et al. (2002)		Lap and Shoulder Belt, shoulder load limiter	75	18	6557	20.6	48.6
1262	Forman et al. (2009)	1210, 1211, 1212	Lap and Shoulder belt	51	13	8774	32.8	59.5
1263	Forman et al. (2009)		Lap and Shoulder belt	57	29	8774	32.8	59.5
1264	Forman et al. (2009)		Lap and Shoulder belt	57	13	8774	32.8	59.5
102	Kent et al. (2001)	101	Shoulder belt	60	19	9405	56.7	81.8
9013	Kent et al. (2001)	9002D	Lap and Shoulder belt	34	0	9661	28.3	65.7
114	Kent et al. (2001)	112	Shoulder belt	60	27	10141	75.3	102.3
227	Kent et al. (2001)	226	Shoulder belt	53	12	11747	63.4	95.8
228	Kent et al. (2001)		Shoulder belt	47	16	11747	63.4	95.8
1094	Forman et al. (2006)	1023, 1024, 1025	Lap and Shoulder belt	49	0	4722	23.3	36.0
1095	Forman et al. (2006)		Lap and Shoulder belt	44	0	4722	23.3	36.0
1096	Forman et al. (2006)		Lap and Shoulder belt	39	0	4722	23.3	36.0
1110	Forman et al. (2006)	1108, 1109	Lap and Shoulder belt	44	0	6262	30.3	48.3
577P	Kent et al. (2001)	571P, 572P, 576P	Lap and Shoulder Belt, shoulder load limiter, airbag	57	0	5318	29.2	45.7
580P	Kent et al. (2001)		Lap and Shoulder Belt, shoulder load limiter, airbag	57	0	5318	29.2	45.7
665P	Kent et al. (2001)	663P, 664P	Lap and Shoulder Belt, airbag	55	3	7979	39.8	63.3
666P	Kent et al. (2001)		Lap and Shoulder Belt, airbag	69	3	7979	39.8	63.3
667P	Kent et al. (2001)		Lap and Shoulder Belt, airbag	59	13	7979	39.8	63.3
668P	Kent et al. (2001)		Lap and Shoulder Belt, airbag	54	23	7979	39.8	63.3
C05	Petitjean et al. (2002)	C03, C13, C18, C20	Lap and Shoulder Belt, shoulder load limiter, airbag	78	6	3988	25.0	35.9
C22	Petitjean et al. (2002)		Lap and Shoulder Belt, shoulder load limiter, airbag	81	19	3988	25.0	35.9
651P	Kent et al. (2001)	648P, 649P	Lap belt, airbag	70	0	0	19.4	16.3
652P	Kent et al. (2001)		Lap belt, airbag	46	0	0	19.4	16.3
9014C	Kent et al. (2001)	9003D	Airbag	31	0	0	12.6	10.6
9207C	Kent et al. (2001)		Airbag	25	0	0	12.6	10.6
9212C	Kent et al. (2001)		Airbag	38	0	0	12.6	10.6
554-M13-PCH1597	Lebarbé et al. (2005)	PCH1640, PCH1641	Airbag	76	15	0	45.2	38.0
555-M13-PCH1598	Lebarbé et al. (2005)		Airbag	67	15	0	45.2	38.0
559-M78-PCH1624	Lebarbé et al. (2005)	PCH1628, PCH1629	Airbag	73	11	0	37.3	31.3
561-M78-PCH1658	Lebarbé et al. (2005)		Airbag	72	0	0	37.3	31.3
594-M78-SEB144	Lebarbé et al. (2005)		Airbag	78	3	0	37.3	31.3
560-M128-PCH1625	Lebarbé et al. (2005)	PCH1627, PCH1643	Airbag	74	0	0	27.7	23.2

Table A 3.
Hybrid III 5th belt tests of the sample used to determine the relation between the belt load and the sternal deflection

HIII 5th test number	Source of the tests	Type of belt restraint	Maximal upper shoulder belt load (N)	Optimised stiffness (N/mm)	Optimised damping (N,s/mm)	Upper shoulder belt load at the time of maximal rodpot deflection (N)
UVA1218	NHTSA b09319	Lap and shoulder	4429	166	3,0	3823
UVA1219	NHTSA b09320		4794	158	2,6	4383
UVA1220	NHTSA b09321		4581	155	2,7	3880
UVA1221	NHTSA b09322		7419	166	2,0	6072
UVA1222	NHTSA b09323		7429	196	2,4	6515
UVA1223	NHTSA b09324		8089	201	2,5	7187
UVA1297	NHTSA b10008	Lap and Shoulder, Shoulder Dual Force limiter	2738	177	1,9	2167
UVA1298	NHTSA b10009		2652	186	2,1	2306
UVA1299	NHTSA b10010		2644	168	1,4	2533
UVA1300	NHTSA b10011		3744	212	1,8	3740
UVA1301	NHTSA b10012		4124	180	1,8	4028
UVA1302	NHTSA b10013		3859	192	1,9	3800

Deq calculation process

For the belt deflection calculation

- the stiffness and damping are calculated as follow:
  - k1 = 135.78 – 0.0018*Max_Upper_Shoulder_Belt_Force
  - c1 = 0.0185*k1 – 0.2357
- The belt deflection (Dbelt) is calculated by solving the differential equation
  - USBF = k1*Dbelt + c1*dDbelt/dt

For the airbag deflection calculation

- the initial stiffness and damping are calculated as follow:
  - ki = 238.14 – 0.0023* Max_Upper_Shoulder_Belt_Force
  - ci = 0.0185*k1-0.2357
- The belt deflection is calculated by solving the differential equation
  - USBF = ki*Dbelt + ci*dDbelt/dt
- The airbag deflection (Defl_airbag) is calculated by substracting the belt deflection from the rodpot deflection
- Then the stiffness is increased until the difference between the localized calculated deflection and the measured sternal deflection is less than 5mm at any time,

DEQ is calculated as follows:

- DEQ LIN = Defl_belt + (Fn*Defl_airbag)
- With Fn =0.84

The risks for M50 and F05 are calculated with the following formulas:

- Risk DEQ M50 = (1-exp(-exp((log(DEQ_max)-intercept-fage*age)/scale)))*100
- Risk DEQ F05 = (1-exp(-exp((log(DEQ_max/F05)-intercept-fage*age)/scale)))*100
  - With scale=0.246
  - intercept=4.9908
  - fage=-0.0174
  - F05=0.83