Development of injury risk functions for use with the THORAX Demonstrator; an updated THOR

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Abstract The thorax-shoulder complex of the THOR dummy was updated in the EU-project THORAX. The new dummy, the THORAX demonstrator, was evaluated in several biomechanical test conditions. In this study, selected data from these tests and injury information from the original tests with Post Mortem Human Subjects were used to develop injury risk functions in accordance with the guidelines defined within ISO/TC22/SC12/WG6. This included the use of survival analysis, distribution and quality assessments.

The results include draft injury risk functions for three THORAX injury criteria intended for frontal and oblique loading. The maximum peak deflection measurement (Dmax) and a new differential deflection criterion (DcTHOR) were found to have a good injury risk quality index. Furthermore, a new local strain-based concept, denoted Number of Fractured Ribs (NFR), appeared to be a potentially useful injury criterion as by its nature it is less sensitive to restraint conditions than deflection measures although it had a lower quality index compared with the displacement-based criteria.

Keywords Injury criteria, injury risk curves, THOR, THORAX

I. INTRODUCTION

The development of the THOR 50th percentile male dummy was initiated in 1992 by the National Highway Traffic Safety Administration with the objective of developing a more biofidelic frontal impact dummy. To date various studies [1]-3] have demonstrated an improved biofidelity of the THOR dummy over the currently used Hybrid III dummy. However, studies have also shown that the THOR, like the Hybrid III sternal displacement, lacks sensitivity to injury parameters such as peak chest deflection for typical restraints [4]-[5]. In particular, it has been shown for the Hybrid III that the relationship between injury risk and the injury criteria measured by the dummy is sensitive to experimental parameters such as the relative contributions of seatbelt and airbag loading to the overall restraint of the dummy [5]. This is a problem both of measurement (caused by the sensitivity of the dummy) and of interpretation (in that it becomes difficult to evaluate equitably different restraint system approaches attempting to provide an equal risk of injury). To reduce these limitations, the shoulder-thorax complex of the THOR was improved within the EU FP7 project THORAX. The design changes introduced were mainly the incorporation of slightly softer ribs, additional padding within the suit, new chest compression instrumentation and a new shoulder design. The new dummy version is referred to as the THORAX demonstrator and was presented by [6].

In parallel with hardware updates research has been conducted into the development of more robust, restraint independent, injury criteria using a finite element (FE) human body model (HMB) [7,8]. The FE-HBM was submitted to a wide range of loading types: impactor, static airbag, belt only restraint, airbag only restraint and combined belt and airbag restraint. For each loading type, different loading severities were applied to generate different levels of rib fracture from the absence of fractures to numerous fractured ribs. From these studies rib bending was identified as being the main loading mode resulting in fracture. Two injury criteria that were suitable for use with a crash test dummy and representing this pattern were formulated. The first one, called Combined Deflection (DC) criterion, uses chest displacements at four locations to compute overall and

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differential deflections. The second criterion, called Number of Fractured Ribs (NFR), uses locally measured strains on individual ribs to identify those ribs for which the bending strains at any location have exceeded a critical value.

Based on the results obtained in the studies into injury criteria, the THORAX demonstrator was fitted with instrumentation that measures 3-dimensional chest deformations (IR-TRACCS) at four different positions and fitted with strain gauges on the external side of each rib to record bending. Some of the final steps in the EU FP7 THORAX project were to adapt the injury criteria, Dc and NFR, for the EU FP7 THORAX demonstrator, construct injury risk curves (IRC) for these criteria and fundamental chest deflection measurements.

The objective of this paper is to report on the development of risk curves for usage with the THORAX demonstrator.

II. METHODS

This study followed the guidelines defined by ISO/TC22/SC12/WG6 [9] and those presented by [10] in the construction of IRCs and selection of injury criteria. In brief the following steps were undertaken:

- An in-depth literature review was conducted to identify available PMHS datasets for reconstructions.
- Criteria were developed for inclusion or exclusion of PMHS tests.
- Level of injury was determined and the PMHS injury was scored.
- Those PMHS tests regarded as being relevant were reproduced using THORAX demonstrator dummies.
- Tests for which the loading conditions were found to match those of the original tests were selected, data were normalised and injury criteria were defined and calculated.
- The paired-test data and PMHS injury score were used to construct IRCs using survival analysis. Data distribution and quality checks were undertaken.

Collect relevant data

In total 153 potential frontal and oblique impact tests conducted with PMHSs and reported in the literature were identified. These tests are listed in Appendix A. The tests were indentor impacts to the chest, out-of-position airbag (AB) inflation tests, inertia tests with harness and diagonal belt, sled tests in three (3-pt) and four (4-pt) belt systems and table-top tests. Some of these used a standard belt (SB), some a system to allow for pretension of the belt (PTB), some were fitted with a force-limiting system (FLB) whereas others a knee bar (KB). Both driver and passenger (pass) positions were used.

1) Inclusion and exclusion of PMHS data

Tests were included when the injuries were documented using at least x-ray imaging and an autopsy was carried out. No specific limits on the severity or type of fracture were set.

The following exclusion criteria were adopted in this study:

- Chest deflections measured using (trans-thoracic) rod techniques.
- PMHSs that were subjected to static chest compression tests prior to the dynamic test.
- PMHS stature, body mass index and weight outside the 95% confidence limits of the data sample.
- Tests with an early disruption of the normal impact.
- Configurations deemed to apply non-relevant loads to the ribcage i.e. some of the out-of-position tests.
- Table-top tests not considered to produce loads perfectly equivalent to those that are common in frontal collisions.
- Subjects exposed to multiple impacts that resulted in rib fractures.

A list of tests that were excluded from the 153 potential impact tests can be found in Appendix B.

2) Reproduction of PMHS tests using the THORAX demonstrator

The selected PMHS tests were reproduced in various laboratories using the THORAX demonstrator. These tests and the biofidelity score of the THORAX demonstrator in these tests were reported in [11].

Two THORAX demonstrators were used in the reproductions of the PMHS tests. A Cox regression [12] was used to ensure that there were no differences between the responses. The parameters assessed in this regression were the chest deflection measurements. No significant differences were observed between the two THORAX demonstrators used in this study.

THE FINAL DATASET

Table 1 presents the *final* dataset used in the construction of the IRCs. It contains only those tests for which the applied loads are representative of the loads common in a frontal collision when typical restraints are used. The tests were successfully reproduced with the THORAX demonstrator. Three sled tests, in which the belt slipped off the torso in the demonstrator tests but not in the PMHS tests, were thereby excluded from the dataset (see Appendix B). The final dataset includes a total of 59 tests, of which 26 are frontal and oblique impactor tests, 9 are airbag and inertia load tests, and 24 are sled tests.

TABLE 1
THE FINAL DATASET USED IN THE DEVELOPMENT OF RISK CURVES

Loading device	Information source	Test ref.	PMHS ref.
Frontal impactor	Kroell et al. [13]-[14]		11FF, 12FF, 13FM, 15FM, 18FM, 20FM, 22FM, 23FF
Frontal impactor	Neathery [15]		31FM, 34FM, 36FM, 37FM, 42FM,45FM, 53FM, 60FM, 62FM, 64FM
Frontal impactor	Trosseille et al. [16]		MS589
Frontal impactor	Bouquet et al. [17]	MRS03	MRT02
Oblique impactor	Yoganandan et al. [18]		PC101-105, PC107
AB membrane	Lebarbé et al. [19]	M13-1 and 2, M78-1 and 2	MS554, MS555, MS559, MS561
AB membrane and inertia	Trosseille et al. [16]	AB0-1, HRN-1, HRN-2, BLT-1, BLT-2	MS594, MS599, MS610, MS595, MS609
Sled pass 4.5 kN 3pt FL + AB	Forman et al. [20]	UVA577, UVA580	111, 105
Sled pass Lap belt + AB + KB	Bolton et al. [21]	UVA651, UVA652	121, 118
Sled pass 3pt SB	Forman et al. [20]	UVA1094-1096	322, 323, 327
Sled diver 3pt 4kN FLB + AB	Petitjean et al. [22]	SL4-1, SL4-2	MS536, MS542
Sled diver 3pt 6kN FLB	Petitjean et al. [22]	SL6-1, SL6-2	MS539, MS543
Sled driver 4 kN 3pt FLB + AB	Vezin et al. [23]		FID11, FID12, FID13
Sled driver 4 kN 3pt FLB	Vezin et al. [23]		FID14, FID15
Sled lab seat 3pt SB + KB	Shaw et al. [24]	1294, 1295, 1358-1360, 1378-1380	411, 403, 425, 426, 428, 443, 433, 441

Assign the censoring status

In this study only right and left censored data were used.

Assign the level of injury

AIS coding protocols have changed over time. Hence the AIS codes as reported in original publications cannot be used as a consistent means of comparing injury severities. Therefore, the number of fractured ribs (NFR) was suggested to be used as a comparative measure instead of AIS. NFR was considered more appropriate to use for one of the injury criterion candidates as opposed to number of rib fractures (NRF). In order to relate NFR and NRF, NFR was plotted as function NRF for all PMHSs included in this study. The analysis of this plot provided that the NRF and NFR were nearly identical for NRF below 10.

With the full dataset considered for this study and with the MAIS for the thorax as reported by the original author, the NFR was 3.9 for MAIS=2 (n=18) and 7.4 for MAIS=3 (n=41). The limits used in this study were NFR ≥5 and NFR ≥7.

Injury criteria

1) Fundamental chest deflection measurements

The THOR fitted with 3D IR-TRACCS at four different measurement positions is able to generate x, y, z and resultant deflection measurements from each point throughout the event. Peak values from the IR-TRACCS were generated and simple combinations of these were compared with the basic measurements to determine the predictive value of such fundamental measures (most basic x, y, z and resultant output). Principal component analyses were performed on the peak deflection measures and differences from one measurement point to another. For example, one assessment showed that when considering the x-axis measurements, the peaks from the upper right, upper left, lower right and the peak of the top two points explained 68% of the variance, whilst the lower left peak explained another 22.5%. The results obtained from the component analyses were further investigated using logistic regression to identify which of the factors from the principal component analysis was most useful in predicting injury at the NFR ≥ 5 or NFR ≥ 7 levels.

The logistic regression analysis of the core dataset showed that the greatest correlations were found when using a combination of the maximum x-axis and resultant deflection measurements for all four quadrants to predict both the likelihood of sustaining a NFR ≥ 5 and ≥ 7. Further, the prediction of injury with the maximum deflection at any of the four points, both in the x-axis and the resultant, is not as complete as the prediction with measurements of deflection at all points. Finally, for some datasets, such as that considered here, the maximum peak x-axis measurement from any point offers a better injury risk prediction than the equivalent resultant measure, based on the Cox and Snell or Nagelkerke r^2 correlation values from the logistic regression.

Based on this, the maximum peak x-axis measurement from any of the four IR-TRACCS, referred to as Dmax, was used in the IRC constructions. In addition IRCs were constructed based on the resultant injury to check the validity of this statistical finding.

2) DC criteria for THORAX

The combined deflection "DC" was revised for use with the THORAX demonstrators instead of an FE-HBM. The new criterion, denoted DcTHOR, includes measurements of the general thoracic compression level (*Dm*) and the ribcage twisting level at the upper (*dDup*) and lower level (*dDlw*) and is defined as below:

$$DcTHOR = Dm + dDup + dDlw \tag{1}$$

where

$$Dm = (|ULX|max + |URX|max + |LLX|max + |LRX|max)/4 \tag{2}$$

$$dDup = |ULX - URX|max - 20;\ = 0\ if\ |ULX - URX| \leq 20\ or\ \min(|ULX|max, |URX|max) \leq 5 \tag{3}$$

$$dDlw = |LLX - LRX|max - 20;\ = 0\ if\ |LLX - LRX| \leq 20\ or\ \min(|LLX|max, |LRX|max) \leq 5 \tag{4}$$

ULX, URX, LLX and LRX are the IRTRACC X-component time histories, local coordinate system (mm).

3) Strain-based injury criterion NFR

Strain gauge instrumentation allowed for investigation of strain-based candidate criteria. The THORAX demonstrator ribs, from level two to seven, were fitted with six gauges per unit on each left and right side. An approach to derive a single value metric from the available gauge data has been described in [8]. This strain-based criteria takes into account additive effect of having several ribs loaded by counting how many ribs exceeds a value of 1.6 millistrain. This value has been found out by computing regressions relating number of PMHS rib fractures to the number of ribs on the dummy that exceeded a peak strain threshold. Regressions have been computed for various threshold values candidates and the 1.6 millistrain value was found to lead to the highest R^2 value. The number of dummy ribs exceeding this threshold, called NFR, was then used in the construction of IRC. It should be noted that the NFR metric is non-continuous and allowed values are integers ranging from 0 to 12.

Normalisation of crash test dummy data

The PMHSs are generally not mid-sized adult males. Therefore dummy responses were scaled, referred to as normalised, to account for the difference in anthropometry between a dummy and the individual PMHS. IRCs were constructed using data normalised for a dummy that represents a mid-sized adult male and using non-normalised data. For the impactor tests and table-top data a simple mass spring model analogy was used to derive normalisation equations. Sled test data were unscaled. Additional information on the normalisation of the dummy data is provided in Appendix C.

Statistical analysis

Parametric survival analysis was carried out using the R-script [25]. The analyses presented below were carried out.

1) Check for the effect of subject characteristics

The effect of subject characteristics on Cox regression survival curves was investigated. In this analysis, the outcome measures were the risk of receiving either NFR ≥ 5 or ≥ 7 and the input measures were either the resultant chest deflection measurements from the four IR-TRACCS or the x-axis measurements (the peak taken from any of the measurement points at any time and the peak of the mean of the top two measurement points). A p-value less than 0.05 inferred a statistical significance. The subject characteristics assessed were age, gender, mass, stature and chest depth.

2) Estimate the distribution parameters

When using the parametric survival analysis, several distributions should be evaluated in order to recommend the one that best predicts the true injury risk function. The distributions Weibull, log-normal and log-logistic were considered within these analyses as they ensure zero risk of injury at zero stimuli.

3) Identify overly influential observations

A measure of how much an observation has affected the estimate of a regression coefficient (DFBETA) was calculated to identify overly influential data points. The higher the DFBETA number, the more the point is considered to influence the estimate. A limit of 0.3 was used in this study. This was considered to be a reasonable approximation to the usual practice of considering a threshold around $2/\sqrt{n}$ (where n is the number of observations).

4) Check the distribution assumption

The estimated risk curve for each of the three distributions was compared with a spline function fitted to the PMHS-THORAX demonstrator data. If the curves from the three assumed distributions were substantially different from the spline, another distribution was considered.

5) Choose the distribution

The distribution with the best fit was chosen, based on the Akaike Information Criterion (AIC). Of the three available distributions considered, the one with the lowest AIC was chosen to be the best estimate.

6) Calculate the 95% confidence interval

The 95% confidence interval of each IRC was calculated via boot-strapping. The relative size of the confidence interval is defined as the width of the 95% confidence interval at a given injury risk relative to the value of the stimulus at this same injury risk. These were calculated at 5%, 25% and 50% risks of injury.

7) Assess the quality index of the IRCs

Based on the relative size of the 95% confidence interval, four categories of a quality index were used. For the quality good, fair, marginal and unacceptable, the relative size of the 95% confidence interval should be from 0 to 0.5, from 0.5 to 1.0, from 1.0 to 1.5 and over 1.5, respectively.

8) Study restraint dependency

Cox regression was used to investigate whether the type of test would influence the risk predictions for the fundamental chest deflection measurements from the THORAX demonstrators. For this analysis the tests from the *Core* dataset were divided into three categories: sled tests, pendulum tests and out-of-position or deploying restraint system tests. The effect of the three categories of test type and deflection measurement predictor variables were assessed with regard to the Cox regression survival curves predicting the number of rib fractures.

A logistic regression using a binomial distribution was carried out to evaluate restraint dependency of the DcTHOR criterion. The final dataset was classified into three loading configurations: distributed loading, belt loading and combined loading (belt and airbag).

For both the fundamental chest deflection measurements and the DcTHOR, the injury status was the variable to be predicted.

Age adjustment

Age was used as a covariant in the survival analysis. The analyses set the probability of injury to be dependent on both the parameter being measured by the dummy and also the age of the occupant. Risk curves were constructed for a dummy representing a 45 year old male. However, as occupant age is known to be a key factor in the risk of thoracic injury [26], IRCs were also constructed for a dummy representing a 65 year old male.

III. RESULTS

Statistical analysis

1) Check for effect of subject characteristics

The Cox regression analysis for any effects of subject characteristics (age, gender, mass, stature and chest depth) revealed that there were no significant effects of any of the covariates on the survival function for any of the injury predictor variables (the four x-axis peak values, peak from any one of the four and peak of the mean of the top two, each of the 6 maximum resultant deflection measurements, 6 maximum x-axis deflection measurements).

2) Identify overly influential observations

In these analyses no justification could be found for further removal of data from the final dataset.

3) Study restraint dependency

For the maximum x-axis deflection measurement at any point, the study into restraint dependency provided that the risk of sustaining a NFR≥5 is 0.135 times lower with an impactor test compared with a sled test ($p = 0.001$). Furthermore, the risk of sustaining a NFR ≥ 5 is 4.545 times greater with a deploying test compared with a sled test ($p = 0.028$) and the risk of sustaining a NFR ≥ 7 is 0.194 times lower with an impactor test compared with a sled test ($p = 0.008$). Finally the analysis indicated that the risk of sustaining a NFR ≥ 7 is 4.913 times greater with an deploying test compared with a sled test ($p = 0.023$).

For the DcTHOR criterion a logistic regression study into restraint dependency gave the results that neither the age of the subject nor the restraint system type were significant coefficients in this estimate of risk (at the 5 % significance level; $p > 0.05$).

Injury risk curves

1) Recommended injury risk curves for sample age and average age

Skeletal thoracic IRCs recommended for use with the EU FP7 THORAX demonstrator were developed using non-normalised demonstrator chest deformation. Curves for a 65-year old occupant are provided in Fig. 1 and Fig. 2 and for a 45-year old occupant are provided in Fig. 3.

Table 2 provides the injury measures, confidence limits and the quality index that correspond to 5%, 25% and 50% risks of injury from the recommended IRCs.

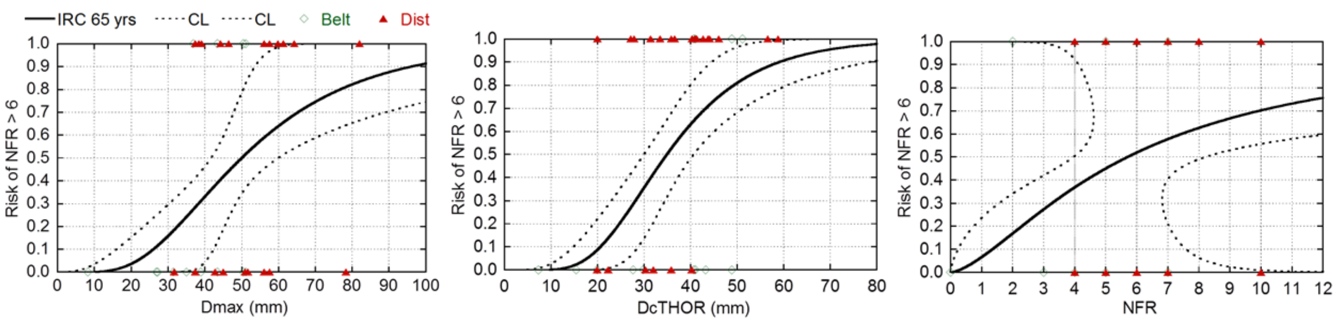

Fig. 1. IRC NFR7+ as a function of Dmax (left), DcTHOR (middle) and NFR (right) for the THORAX demonstrator.

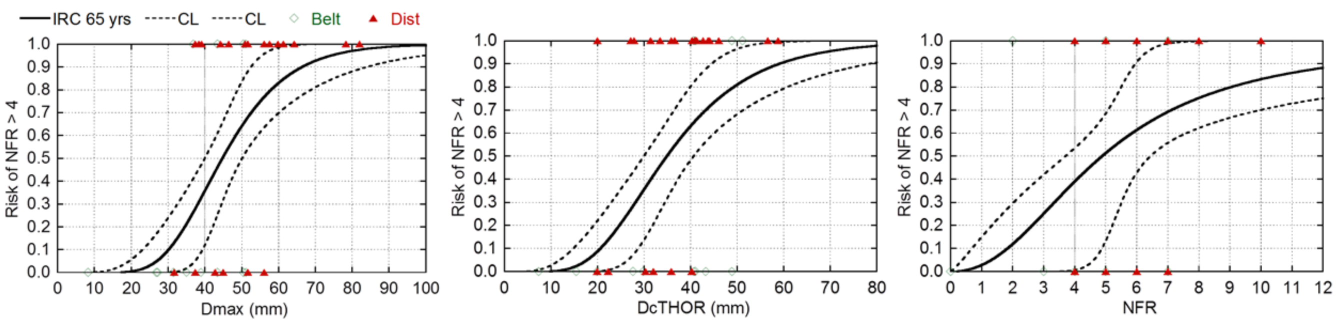

Fig. 2. IRC NFR5+as a function of Dmax (left), DcTHOR (middle) and NFR (right) for the THORAX demonstrator.

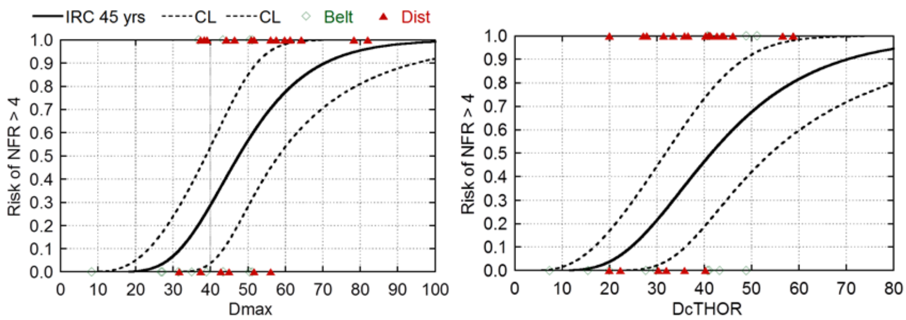

Fig. 3. IRC NFR5+ as a function of Dmax (left) and DcTHOR (right), for 45 years, for the THORAX demonstrator.

TABLE 2
INJURY RISKS AND QUALITY INDEX OF THE IRCS FOR RISK CURVES FOR 65-YEAR OLDS

Risk function	Risk (%)	Mean parameter value	Confidence limit, lower	Confidence limit, upper	Confidence error	Grade
Dmax NFR>6	5	21.6	7.9	35.4	1.3	Marginal
	25	35.5	25.4	45.5	0.6	Fair
	50	50.0	40.7	59.3	0.4	Good
Dmax NFR>4	5	27.0	18.0	35.9	0.7	Fair
	25	36.4	29.9	42.9	0.4	Good
	50	44.8	39.6	49.9	0.2	Good
DcTHOR NFR>6	5	19.3	12.7	29.3	0.9	Fair
	25	29.1	23.3	36.2	0.4	Good
	50	38.6	33.2	44.9	0.3	Good
DcTHOR NFR>4	5	17.8	11.9	26.6	0.8	Fair
	25	26.5	21.1	33.2	0.5	Good
	50	34.9	30.0	40.6	0.3	Good
NFR criteria NFR>6	5	0.8	0.1	8.2	9.88	Unacceptable
	25	2.8	1.1	6.9	2.09	Unacceptable
	50	5.7	4.0	8.2	0.75	Fair
NFR criteria NFR>4	5	1.3	0.4	4.6	3.22	Unacceptable
	25	3.0	1.7	5.4	1.23	Marginal
	50	4.9	3.7	6.4	0.56	Fair

Equations 5 and 6 with the coefficients given in Table 3 provide the thorax skeletal IRCs with the survival analysis for the THORAX demonstrator. The risk according to the Weibull distribution is:

$$Risk\ (\%) = 1 - exp(-(\frac{Injury\ criteria}{exp(int + age * coef\_age)})^{\frac{1}{exp(log\_scale)}}) \quad (5)$$

The risk according to the log-normal distribution is:

$$Risk\ (\%) = \frac{1}{2} + \frac{1}{2} erf\, \frac{ln(injury\ criteria) - (int + age * coef\_age)}{\sqrt{2 * (exp(log - scale))^2}} \quad (6)$$

TABLE 3
DISTRIBUTION AND PARAMETERS FOR THE RECOMMENDED INJURY RISK FUNCTIONS FOR THE THORAX DEMONSTRATOR.

Injury risk	Injury criteria	Distribution	int	coef_age	log_scale
NFR>6	Dmax (mm)	Log-normal	4.169848571	-0.003966626	-0.674641945
	DcTHOR (mm)	Log-normal	4.129902140	-0.007329849	-0.864286536
	NFR	Weibull	2.655028616	-0.009309372	-0.205841639
NFR>4	Dmax (mm)	Log-normal	3.996502432	-0.003003672	-1.17874 0290
	DcTHOR (mm)	Log-normal	4.114066034	-0.008639173	-0.891652927
	NFR	Weibull	2.439855004	-0.009523969	-0.613812056

2) Effect of normalization of data on the risk curves

IRCs were also developed using normalised demonstrator chest deformation. Normalisation of demonstrator data prior to risk curve construction provided risk close to those constructed with non-normalised data (Fig. 4).

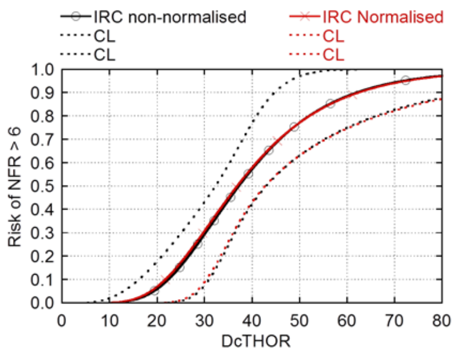

Fig. 4. Thoracic skeletal IRC NFR7+ as a function of the DcTHOR criteria adjusted to 65-year old person for the THORAX demonstrator. Non-normalised data (black) and normalised data (read).

IV. DISCUSSION

Selection of matched PMHS-THORAX demonstrator tests

The number of matched PMHS-THORAX demonstrator tests selected for IRC construction was considered fair to good in comparison to other studies that used a similar approach. Despite this a few concerns related to the matched dataset that may have influenced the results were identified. These are discussed below.

1) Type of restraints used

Several of the PMHS tests, reproduced using the THORAX demonstrator, were carried out several years ago, before state-of-the-art restraints were readily available. Therefore, PMHS test data generated using modern restraints were rare. The approach adopted here was to reproduce all PMHS test series for which the loading induced to the thorax was mainly from the frontal direction. The available test series included both hard contacts and out-of-position tests along with more typical sled tests. Despite the shortcomings of PMHS test data, we believe that the dataset chosen also reflects modern restraints since several tests were carried out with some of the systems commonly installed in modern cars.

For 44% of the 59 matched tests included in the final dataset the chest was struck by an impactor. These tests loaded the chest symmetrically and the loads were concentrated to a restricted area. These tests were not fully representative of the loads produced by typical modern car restraints (airbag combined with belts). This large proportion of impactor tests within the dataset may have influenced the analyses since the development of a risk function that takes asymmetric loading into account would most likely have benefited from additional sled tests with diagonal belts. However, these tests are to some degree representative of airbag loads. In addition, using an impactor is a well-controlled means of loading the chest and as such is generally considered to be very useful in IRC construction. These reasons justify the inclusion of the impactor tests, although for the future we encourage that additional sled tests with instrumented PMHSs are carried out and data made available for thoracic IRCs.

2) Effect of additional matched tests in injury risk curves

The number of matched PMHS-THORAX demonstrator tests included in the final dataset and used to produce the IRCs appeared to be sufficient. The analysis provided risk curves for DcTHOR and for Dmax with fair to good confidence limits for 50% and 25% risk of NFR ≥5 and NFR ≥7. For DcTHOR the confidence limits were also fair for 5% injury risks. However, an attempt to include additional matched PMHS-dummy tests was made; this dataset was denominated *Extended* and included, in addition, eight table-top tests by [28]-[29] and four sled tests [30]. The risk curves based on the *Extended* dataset had, unfortunately, wider confidence limits than those based on the original dataset. We speculate that the ribcage loading in the table-top tests were rather different from those that occur in sled tests and as such inflated the confidence limits. Other reasons for larger confidence limits could be the inclusion of four additional sled tests. In these tests the PMHS upper body kinematics and chest compressions were very different from those observed in the THORAX demonstrator tests.

3) Reproduction of the original PMHS tests

The quality of the developed IRCs is to a large degree a function of how well the actual PMHS tests were reproduced. Not all tests that were carried out with the intention to be used for IRC construction could be included; some were excluded due to excessive belt slippage along the clavicle and some were excluded due to upper body kinematics considered to be dissimilar to those of the original PMHSs. To assess how well the actual PMHS tests were reproduced, additional tests with the Hybrid III dummy were carried out and the responses were compared to Hybrid III tests that had been carried out in conjunction with the original PMHS tests. These tests are reported in [11]. The analyses indicated that the loading modality was well reproduced for most test conditions included in the dataset. For a few test conditions there was a lack of Hybrid III data. For these conditions the biofidelity assessment comparisons were used to judge how well the original test conditions were reproduced.

Level of injury

In this study we were unable to use the AIS coding as supplied in the original work because the code has changed over the years. Therefore the number of fractured ribs, NFR, was used in this study. To suggest limits to be used, the relationship between the original AIS code assigned to each PMHS following the tests and the NFR were established for AIS 2 and AIS 3. The results attained indicated that an AIS 2+ injury was equivalent to 5 or more fractured ribs while AIS3+ was equivalent to 7 or more fractured ribs. Compared to the AIS 2005 scale, these limits appear to be rather high. However, the AIS scale is intended to be used to classify injuries in healthy persons who have been subjected to crashes and were alive at the time of impact. It is expected that AIS coding in PMHSs is quite different to those for traffic victims.

Preferably risk curves for costal cartilage injuries and clavicle and sternum fractures should be established. Unfortunately, records of costal cartilage fractures in the original PMHS studies were considered too few for costal cartilage IRC developments. Similarly, limited reporting of clavicle and sternum fractures prevented robust risk functions being developed for those injuries.

On closer inspection of the DcTHOR curves provided in Fig. 2, it can be seen that below 60 mm the two curves fall within the confidence limits of one another. This suggests that the curves for the two different injury levels will not be significantly different from each other at low deflection levels. A similar response is evident in the Dmax curves. The assertion that an NFR ≥ 7 injury can occur at a deflection below that for an NFR ≥ 5 injury is not statistically robust. This situation has arisen because of the poorer balance of injured and uninjured data at the NFR ≥ 7 level compared with NFR ≥ 5.

Injury criteria

There was a concern that chest displacement measurements could become inadequate as an injury predictor when the velocity of deformation exceeds 3 m/s. However, the typical rib cage deformation rate is today normally less than 3 m/s. Therefore, having a compression measurement alone should be adequate.

For the DcTHOR injury criteria, it is to be noted that a threshold of 20 mm (in Equation 3 and 4) was applied to moderate the contribution of the total differential deflections |ULX-URX| and |LLX-LRX|. This moderation allows the DcTHOR to achieve a reasonable restraint independency, i.e. a unique risk curve for all loading types, on the one hand, and a relatively good confidence interval for the injury risk curves on the other hand. Besides, a threshold of 5 mm (in Equation 3 and 4) was also introduced to determine whether upper and lower ribcage differential deflections are effective to generate ribcage twisting: a localised loading, such as the Yoganandan oblique hub impact for example, may generate high differential deflection without twisting the ribcage.

The strain-based injury criterion NFR displayed a lower quality index than the displacement-based criteria. Nevertheless, we encourage additional research into this criterion. Local rib strains as the metric is expected to be intrinsically linked more closely to the rib fracture mechanism than the rib end deflection. Indeed, for a given deflection various stress states were observed. From this perspective, considering the local peak stress is theoretically more relevant than using deflection.

Normalisation of crash test dummy data

For normalisation of table-top and impactor data we adopted a *Length* based assumption (see Appendix C) as length measurements were available for all subjects included in the dataset used here.

Statistical analysis

Survival analysis groups the techniques used into parametric, semi-parametric or non-parametric. In this study the parametric technique was used. This was justified by the sample size. With a reasonably large sample size (n > 30), it is likely that estimated parameters will be normally distributed.

1) Check for effect of subject characteristics

The check for any effects of subject characteristics provided that the risk functions derived for the fundamental deflection measurements will not be significantly influenced by the subject characteristics. This means that additional efforts to control for these variables in the risk construction work are probably not necessary. These results were unexpected and are not supported by past research. It was expected that age-specific risk curves would be produced to aid occupant diversity considerations in future frontal impact protection developments. Despite the insignificant effect of age, the direction of the age effect was as expected, with a reduction in tolerance being associated with an increase in age. Therefore, age was still included as a covariant in order to produce risk estimates for both 45 and 65-year old occupants.

2) Study restraint dependency

The THORAX demonstrators were fitted with four IR-TRACCS and strain gauges to calculate the criteria Dmax, DcTHOR and NFR. The Dmax recorded the maximum x-deformation at any of the four measurement points. The DcTHOR also used the chest deformations but includes terms for relative right and left chest compression.

The results obtained in the restraint dependency analysis demonstrated that both the resultant and x-axis peak measurement injury predictions were dependent on the loading type. The risk curves derived specifically for each type of loading were significantly different from one another. Therefore, it is possible to infer from this outcome that the peak deflection measurements are unlikely to be restraint system independent. It implies that for a given chest deflection measurement from the dummy the predicted risk of injury would be different depending on whether the loading in the test had been applied by a sled, impactor or by deploying restraint system. The risk of injury prediction for a given deflection was slightly lower from impactor tests than from sled tests. This may support the hypothesis that localised belt loading is more injurious than distributed loading. However, it seems to demonstrate a difference between the different types of test that have been reconstructed. In these varied test types we might expect the inertia of the body in the sled, impactor or deploying restraint tests to influence the potential for injuries occurring. Ideally, the dummy measurement would offer equivalent risk assessments in all types of loading to which it is likely to be exposed during future testing.

The results obtained in the study into restraint dependency for DcTHOR show that: 1) the DcTHOR criterion is a significant predictor of the injury status; and 2) the influence of the restraint types is not significant. Nevertheless, it is important to stress that these conclusions should be viewed with caution since it may be conditioned by the database limitations. However, the confidence limits for the Dmax were rather similar to those obtained for the DcTHOR. The reason for this may be due to the large proportion of tests with symmetric chest loading in the final dataset; about half of the tests included in the dataset mainly loaded the chest symmetrically.

NFR is a measure of the number of ribs for which strain in the ribs reached a predefined limit; roughly it is a measure of the number of ribs that were exposed to a specified curve change. As such, the NFR was expected to predict injuries for belted occupants even better than the deflection measurements when the chest was exposed to local and asymmetric loads. Whilst this was not the case based on the assessed dataset and the discontinuous nature of the measure, NFR showed sufficient discriminatory power to suggest it for further development and evaluation.

Injury risk curves for other ages

Age did not have a significant effect on the survival functions and a lower AIC estimate was obtained if age was excluded as a covariant. As such, the estimate was a better representation of the original PMHS data. One reason for this could be limited PMHS age distribution. In addition, the bulk of the PMHSs were above 65 years of age while three PMHSs were very young at the time of death. It may well be that the three PMHSs were more fragile than the average of their age group. These three subjects may therefore have vastly influenced the survival functions and the AIC values. Nevertheless, the direction of the age effect was as expected, with a reduction in tolerance being associated with an increase in age. Therefore, age was still included as a covariant in order to produce risk curves for a 45 year old occupant (Fig. 3).

Comparison between predicted risk and real-life injury risk

In this study IRCs were constructed using matched crash test dummy and PMHS data. Additional studies are required to determine the relation between predicted thoracic injury risk, using the THORAX demonstrator, and injury risk in real-life accidents. A first study on this was carried out by [31]. In that study the THORAX demonstrator and Hybrid III injury risks were calculated for several injury criteria and compared to expected injury risk reductions based on trends observed in real-life data. For this, sled tests were performed in a body-in-white representing a family car using different restraint combinations. Their results show that the expected injury risk reduction, going from predicted high to low risk, was obvious for THORAX demonstrator, unlike the Hybrid III. Their study concludes that the large variations in injury risk and the sensitivity to crash severity indicate that the THORAX demonstrator and the new IRCs should be the preferred tools for evaluation of frontal impact occupant protection.

V. CONCLUSIONS

The results include thoracic injury risk functions for a number of parameters and a criterion developed specifically for the THORAX demonstrator. Two displacement-based criteria including the maximum peak deflection measurement (Dmax) and a differential deflection criterion (DcTHOR) were found to have a good injury risk quality index. In addition to these global displacement criteria, a local strain-based concept was introduced using strains measured in six positions around each of the lower six ribs. Strain values were converted into a prediction of the number of fractured ribs. Although the quality index for the related risk curves was not as good compared to the displacement-based criteria, the strain-based criterion appears to be a potential injury criterion candidate as by nature it is less sensitive to restraint conditions. The full-scale test results demonstrate that the THORAX demonstrator and these draft injury risk functions are suitable to be used in tests in which various types of vehicle restraints are used.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX A – AVAILABLE PMHS DATA

TABLE 4

ORIGINAL PMHS THORAX IMPACTOR TESTS

Information source	Hub mass (kg)	Hub velocity (m/s)	Test/PMHS ref.	Age	Gender	Body weight (kg)	Stature (m)	Chest depth (mm)	Body mass Index	NRF wo Cartilage fractures	NFR wo Cartilage fractures
Nahum et al. [32]	19.3	5.1	05FM	60	M	86	1.85	257	25	2	2
Nahum et al. [32]	19.3	5.1	06FM	83	M	77	1.82	254	23	11	11
Nahum et al. [32]	19.3	4.0	07FF	86	F	38	1.67	200	13	11	
Nahum et al. [32]	19.3	5.1	09FM	73	M	76	1.85	238	22	0	
Nahum et al. [32]	19.3	4.9	10FF	82	F	43	1.60	168	17	12	
Kroell et al. [13]-[14]	19.5	6.3	11FF	60	F	59	1.60	208	23	11	11
Kroell et al. [13][14]	22.9	7.2	12FF	67	F	63	1.63	187	24	22	14
Kroell et al. [13]-[14]	22.9	7.4	13FM	81	M	76	1.68	246	27	21	12
Kroell et al. [13]-[14]	22.9	7.3	14FF	76	M	58	1.56	216	24	7	6
Kroell et al. [13]-[14]	23.6	6.9	15FM	80	M	53	1.65	200	19	13	9
Kroell et al. [13]-[14]	23.6	6.7	18FM	78	M	66	1.77	219	21	14	11
Kroell et al. [13]-[14]	23.6	6.7	19FM	19	M	71	1.96	203	19	0	0
Kroell et al. [13]-[14]	23.6	6.7	20FM	29	M	57	1.80	203	17	0	0
Kroell et al. [13]-[14]	23.6	6.7	22FM	72	M	75	1.74	226	25	17	10
Kroell et al. [13][14]	19.5	7.8	23FF	58	F	61	1.63	226	23	23	11
Kroell et al. [13]-[14]	22.9	9.7	24FM	65	M	82	1.83	251	24	24	16
Neathery [15]	23.0	10.2	31FM	51	M	75	1.83	238	22	14	11
Neathery [15]	22.9	9.9	32FM	75	M	54	1.71	248	19	20	13
Neathery [15]	19.0	8.3	34FM	64	M	59	1.78	241	19	13	11
Neathery [15]	19.0	7.2	36FM	52	M	75	1.83	226	22	7	7
Neathery [15]	22.9	9.8	37FM	48	M	74	1.79	248	23	9	6
Neathery [15]	22.9	4.9	42FM	61	M	54	1.83	216	16	0	0
Neathery [15]	23.0	5.1	45FM	64	M	64	1.81	254	20	10	10
Neathery [15]	19.3	7.4	46FM	46	M	95	1.78	286	30	0	0
Neathery [15]	23.0	5.2	53FM	75	M	77	1.74	241	25	3	3
Neathery [15]	19.6	6.7	54FF	49	F	37	1.63	205	14	7	7
Neathery [15]	19.6	9.9	55FF	46	F	81	1.77	241	26	8	8
Neathery [15]	23.0	4.3	60FM	66	M	79	1.80	222	25	9	9
Neathery [15]	10.0	6.9	62FM	76	M	50	1.74	245	17	9	9
Neathery [15]	23.0	6.9	64FM	72	M	63	1.63	216	24	6	6
Trosseille et al. [16]	23.7	4.4	MS589	88	M	60	1.69	200	21	14	11
Trosseille et al. [16]	23.7	4.4	MS621	82	M	78	1.71	230	27	9	9
Bouquet et al. [17]	23.4	3.4	MRS01-MRT01	76	M	82	1.73	250	27	*na*	*na*
Bouquet et al. [17]	23.4	3.4	MRS03-MRT02	57	M	76	1.74	230	25	1	1
Bouquet et al. [17]	23.4	5.8	MRS04-MRT02	57	M	76	1.74	230	25	1	1
Bouquet et al. [17]	23.4	3.4	MRS05-MRT03	66	M	69	1.72	230	23	*na*	*na*
Bouquet et al. [17]	23.4	5.9	MRS06-MRT03	66	M	69	1.72	230	23	11	11
Bouquet et al. [17]	23.4	3.4	MRS07-MRT04	69	M	52	1.64	220	19	*na*	*na*
Bouquet et al. [17]	23.4	5.8	MRS08-MRT04	69	M	52	1.64	220	19	11	11
Stalnaker et al. [33]	10.0	5.8	11M	70	M	56	1.67		20		
Stalnaker et al. [33]	10.0	5.8	14M	73	M	55	1.68		19		
Stalnaker et al. [33]	10.0	5.8	15M	65	M	35	1.57		14		
Stalnaker et al. [33]	10.0	5.8	16M	88	M	68	1.73		23		
Stalnaker et al. [33]	10.0	5.8	17M	49	M	70	1.80		22		
Stalnaker et al. [33]	10.0	5.8	18F	65	F	45	1.61		17		
Stalnaker et al. [33]	10.0	5.8	20F	75	F	40	1.42		20		
Stalnaker et al. [33]	10.0	5.8	21M	62	M	51	1.83		15		
Stalnaker et al. [33]	10.0	5.8	22M	63	M	58	1.70		20		
Stalnaker et al. [33]	10.0	5.8	23M	58	M	70	1.78		22		
Yoganandan et al. [18]	23.5	4.3	PC101	72	M	82	1.70	234	28	4	4
Yoganandan et al. [18]	23.5	4.3	PC102	81	M	63	1.75	219	21	4	4
Yoganandan et al. [18]	23.5	4.3	PC103	84	M	68	1.68	233	24	0	0
Yoganandan et al. [18]	23.5	4.3	PC104	86	M	56	1.70	211	19	2	2
Yoganandan et al. [18]	23.5	4.3	PC105	62	M	61	1.74	240	20	3	3
Yoganandan et al. [18]	23.5	4.3	PC106	70	M	91	1.69	312	32	4	4
Yoganandan et al. [18]	23.5	4.3	PC107	68	M	83	1.78	282	26	6	6

TABLE 5
ORIGINAL TEST SERIES OF PMHS AIRBAG, OUT-OF-POSITION, HARNESS AND BELT TESTS

Information source	Test condition	Airbag dist. (mm)	Test/PMHS ref.	Age	Gender	Body weight (kg)	Stature (m)	Chest depth (mm)	Body mass Index	NRF wo Cartilage fractures	NFR wo Cartilage fractures	NRF with Cartilage fractures	NFR with Cartilage fractures
Lebarbé et al. [19]	membrane	13	MS554	76	M	77	1.70	235	27	12	12	12	12
Lebarbé et al. [19]	membrane	13	MS555	67	M	65	1.75	220	21	15	15	15	15
Lebarbé et al. [19]	membrane	78	MS559	73	M	67	1.74	205	22	11	11	11	11
Lebarbé et al. [19]	membrane	78	MS561	72	M	83	1.73	235	28	0	0	0	0
Lebarbé et al. [19]	membrane	128	MS560	74	F	73	1.60	195	29	0	0	0	0
Lebarbé et al. [19]	punch out	52	MS557		M	79	1.66	190	29				
Lebarbé et al. [19]	punch out	52	MS558		F	80	1.58	200	32				
Lebarbé et al. [19]	complete	52	MS562		M	80	1.67	200	29				
Lebarbé et al. [19]	complete	52	MS565		M	72	1.70	225	25				
Trosseille et al. [16]	membrane	13	MS607	84	M	56	1.75	190	18				
Trosseille et al. [16]	membrane	78	MS594	78	M	65	1.70	230	22	3	3	8	8
Trosseille et al. [16]	harness		MS599	73	M	72	1.82	230	22	2	2	3	3
Trosseille et al. [16]	harness		MS610	70	M	60	1.70	230	21	3	3	3	3
Trosseille et al. [16]	diagonal belt		MS595	74	M	69	1.74	220	23	0	0	3	2
Trosseille et al. [16]	diagonal belt		MS609	69	M	71	1.70	250	25	0	0	0	0

TABLE 6
ORIGINAL TEST SERIES OF PMHS TABLE-TOP TEST DATA (DATA ON NRF AND NFR WITH CARTILAGE FRACTURES WAS NOT AVAILABLE)

Information source	Loading device	Hub mass (kg)	Hub velocity (m/s)	Test/PMHS ref.	Age	Gender	Body weight (kg)	Stature (m)	Chest depth (mm)	Body mass Index	NRF wo Cartilage fractures	NFR wo Cartilage fractures
Cesari and Bouquet [28]	D-B	22.4	3.4	K	72	M	53	1.83	180	16	0	0
Cesari and Bouquet [28]	D-B	22.4	3.1	L	71	M	41	1.70	180	14	0	0
Cesari and Bouquet [28]	D-B	22.4	2.8	M	40	M	56	1.83	190	17	0	0
Cesari and Bouquet [28]	D-B	22.4	2.9	Q	64	F	49	1.64	160	18	0	0
Cesari and Bouquet [28]	D-B	22.4	3.1	R	43	M	54	1.86	200	16	0	0
Cesari and Bouquet [28]	D-B	22.4	2.7	S	67	M	67	1.80	229	21	0	0
Cesari and Bouquet [28]	D-B	22.4	3.1	T	63	M	56	1.76	229	18	0	0
Cesari and Bouquet [28]	D-B	22.4	9.3	A	47	F	93	1.70	180	32	8	8
Cesari and Bouquet [28]	D-B	22.4	6.8	B	17	F	59	1.64	175	22	0	0
Cesari and Bouquet [28]	D-B	22.4	4.1	C	86	F	43	1.60	170	17	2	2
Cesari and Bouquet [28]	D-B	22.4	7.1	D	69	M	82	1.73	220	27	17	12
Cesari and Bouquet [28]	D-B	22.4	8.1	E	60	M	69	1.77	200	22	3	3
Cesari and Bouquet [28]	D-B	22.4	7.5	F	59	F	62	1.70	200	21	4	3
Cesari and Bouquet [28]	D-B	22.4	7.8	G	71	M	75	1.77	210	24	7	7
Cesari and Bouquet [28]	D-B	76.1	3.2	H	67	M	47	1.74	200	16	6	6
Cesari and Bouquet [28]	D-B	76.1	2.5	I	83	F	43	1.55	215	18	4	4
Cesari and Bouquet [28]	D-B	76.1	3.1	J	70	M	63	1.60	190	25	18	12
Cesari and Bouquet [28]	D-B	76.1	3.5	K	72	M	53	1.83	180	16	4	4
Cesari and Bouquet [28]	D-B	76.1	2.8	L	71	M	41	1.70	180	14	10	9
Cesari and Bouquet [28]	D-B	76.1	3.0	M	40	M	56	1.83	190	17	0	0
Cesari and Bouquet [29]	D-B	76.1	2.9	P	60	M	45	1.60	200	17	6	6
Cesari and Bouquet [29]	D-B	76.1	2.7	Q	64	F	49	1.64	160	18	6	6
Cesari and Bouquet [29]	D-B	76.1	3.7	R	43	M	54	1.86	200	16	3	3
Cesari and Bouquet [29]	D-B	76.1	2.8	S	67	M	67	1.80	229	21	2	2
Cesari and Bouquet [29]	D-B	76.1	3.1	T	63	M	56	1.76	229	18	10	10
Kent et al. [34]	Various			176	85	F	58	1.57		24		
Kent et al. [34]	Various			182	80	F	65	1.57		26		
Kent et al. [34]	Various			177	79	F	48	1.61		19		
Kent et al. [34]	Various			155a	71	F	54	1.66		20		
Kent et al. [34]	Various			173	67	F	57	1.62		22		
Kent et al. [34]	Various			147	63	F	45	1.61		17		
Kent et al. [34]	Various			186	58	F	61	1.78		19		

Kent et al. [34]	Various	157	55	F	74	1.68	26	
Kent et al. [34]	Various	189	79	M	57	1.59	23	
Kent et al. [34]	Various	190	79	M	73	1.73	24	
Kent et al. [34]	Various	170	75	M	65	1.78	21	
Kent et al. [34]	Various	178	73	M	81	1.82	24	
Kent et al. [34]	Various	188	71	M	85	1.73	28	
Kent et al. [34]	Various	145	54	M	88	1.92	24	
Kent et al. [34]	Various	187	54	M	113	1.78	36	
Shaw et al. [35]	Indentor	343	72	M	66	1.80	20	15
Shaw et al. [35]	Indentor	342	75	M	73	1.83	22	10
Shaw et al. [35]	Indentor	320	48	M	68	1.68	24	4
Shaw et al. [35]	Indentor	319	52	M	77	1.79	24	17
Shaw et al. [35]	Indentor	203	67	M	77	1.70	27	15

D-B Diagonal belt

TABLE 7
ORIGINAL TEST SERIES OF PMHS SLED TEST DATA

Information source	Loading device	Vel. change (km/h)	Test/PMHS ref.	Age	Gender	Body weight (kg)	Stature (m)	Chest depth (mm)	Body mass Index	NRF wo Cartilage fractures	NFR wo Cartilage fractures	NRF wo Cartilage fractures	NFR wo Cartilage fractures
Forman et al. [20]	Pass 4.5 kN 3pt FL + AB	48	111	57	M	70	1.74	185	23	0	0	0	0
Forman et al. [20]	Pass 4.5 kN 3pt FL + AB	48	107	69	F	52	1.55	205	22	4	4	8	8
Forman et al. [20]	Pass 4.5 kN 3pt FL + AB	48	105	57	F	57	1.77	200	18	0	0	0	0
Bolton et al. [21]	Pass Lap belt + AB + KB	49	124	40	M	47	1.50	156	21	4	4	4	4
Bolton et al. [21]	Pass Lap belt + AB + KB	49	121	70	M	57	1.76	177	18	0	0	0	0
Bolton et al. [21]	Pass Lap belt + AB + KB	49	118	46	M	74	1.75	222	24	0	0	0	0
Forman et al. [20]	Pass 3pt SB + AB	48	112	55	M	85	1.76	231	27	3	3	0	0
Forman et al. [20]	Pass 3pt SB + AB	48	115	69	M	84	1.76	192	27	3	3	3	3
Forman et al. [20]	Pass 3pt SB + AB	48	120	59	F	79	1.61	202	30	13	12	13	12
Forman et al. [20]	Pass 3pt SB	29	322	49	M	58	1.78	200	18	0	0	0	0
Forman et al. [20]	Pass 3pt SB	29	323	44	M	77	1.72	180	26	0	0	0	0
Forman et al. [20]	Pass 3pt SB	29	327	39	M	79	1.84	220	23	0	0	0	0
Petitjean et al.[22]	Driver 3pt 4kN FLB + AB	64	MS536	78	F	70	1.69	na	25	5	4	6	4
Petitjean et al.[22]	Driver 3pt 4kN FLB + AB	64	MS542	76	M	67	1.74	na	22	10	9	17	11
Petitjean et al.[22]	Driver 3pt 6kN FLB	64	MS539	81	M	60	1.70	na	21	14	10	21	12
Petitjean et al.[22]	Driver 3pt 6kN FLB	64	MS543	75	M	70	1.69	na	25	9	7	17	12
Vezin et al. [23]	Driver 4 kN 3pt FLB + AB	50	FID11	46	M	63	1.83	210	19	11	8	na	na
Vezin et al. [23]	Driver 4 kN 3pt FLB + AB	50	FID12	83	M	69	1.68	265	24	6	5	na	na
Vezin et al. [23]	Driver 4 kN 3pt FLB + AB	50	FID13	74	M	67	1.68	240	24	0	0	na	na
Vezin et al. [23]	Driver 4 kN 3pt FLB	30	FID14	78	M	82	1.80	250	25	2	2	na	na
Vezin et al. [23]	Driver 4 kN 3pt FLB	30	FID15	81	M	58	1.67	175	21	4	3	na	na
Vezin et al. [23]	Driver 4 kN 3pt FLB	30	FID16	90	M	45	1.77	200	14	0	0	na	na
Rouhana et al. [30]	Pass 3pt SB	40	206	75	M	72	1.75	na	24	29	14	29	14
Rouhana et al. [30]	Pass 3pt SB	40	474	72	M	82	1.78	na	26	4	3	16	9
Rouhana et al. [30]	Pass 4pt FL + PTB	40	853	75	M	81	1.80	na	25	7	7	12	11
Rouhana et al. [30]	Pass 4pt FL + PTB	40	247	41	M	82	1.75	na	27	0	0	0	0
Rouhana et al. [30]	Pass 4pt FL + PTB	40	639	60	M	91	1.83	na	27	0	0	3	2
Rouhana et al. [30]	Pass 4pt FL + PTB	40	683	69	F	42	1.52	na	18	9	8	11	10
Rouhana et al. [30]	Pass 4pt FL + PTB	40	657	79	F	59	1.52	na	26	1	1	3	3
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	411	76	M	70	1.78	210	22	2	2	7	6
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	403	47	M	68	1.77	260	22	23	17	27	17
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	425	54	M	79	1.77	na	25	15	10	15	10
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	426	49	M	76	1.84	na	22	7	7	9	8
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	428	57	M	64	1.75	na	21	3	3	5	5
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	443	72	M	81	1.84	na	24	8	7	9	7
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	433	40	M	88	1.79	na	27	9	8	10	8
Shaw et al. [24]	Lab seat 3pt SB* + KB	40	441	37	M	78	1.80	na	24	0	0	2	2

IX. Appendix B – Inclusion and Exclusions of PMHS tests

Exclusions from the final dataset

Tests with PMHS 05FM, 06FM, 07FF, 09FM and 10FF are excluded from the dataset in the analysis. Chest deflections were measured using a rod technique and this may have reduced the integrity of the chest and as such the number of rib fractures may have been influenced by the instrumentation. With the exception of one test, these PMHSs were subjected to static chest compression prior to the impactor test.

Stature, body mass index (BMI) and weight were considered important and data outside the 95% confidence limits of the data sample were excluded from both datasets. These were:

- Outside stature range for subjects
  - Frontal impactor, subject 14FF and 19FM.
- Outside BMI range for subject:
  - Frontal impactor, subject 46FM and 54FF
  - Oblique impactor, subject PC106.
  - Sled, subject FID16.
- Outside mass range for subjects:
  - Sled, subject 683

Other test-related reasons for exclusions from both datasets:

- Early disruption of the normal impact event occurred:
  - Frontal impactor, subject 24FM, 32 FM, 54FF and 55FF.
- Force deflection curves used to compute effective mass are missing:
  - Frontal impactor, subject MS621.
- Airbag gas generator malfunction:
  - Airbag test AB0_2 with subject MS607.

Sled test data UVA665. UVA666 and UVA667 were excluded due to excessive belt slip in the demonstrator tests.

The tests P52_1, P52_2, C52_1, C52_2 were excluded because the configuration was deemed to apply non relevant loads to the ribcage.

Clavicle fractures were present in five of the sled tests. It was anticipated that chest forces were stronger in these PMHS tests than in those where no clavicle fractures occurred. However, from the available data it is not possible to establish whether clavicle fractures occurred prior to or after the rib fractures occurred. For this reason, presence of clavicle fracture was not considered a reason for data exclusion.

Test series excluded from the final dataset

Test reported by Stalnaker et al. [32] were excluded due to differences in response to those reported by Kroell et al. [14]and Neathery et al. [15].

In the Rouhana et al. [30] sled tests a rod technique was used to study chest deformations. For this reason all these tests were excluded.

Table-top tests by [28][29][34][35] were not considered to produce loads perfectly equivalent to those that are common in frontal collisions.

Extended dataset

In the E*xtended* dataset table-top tests by [28][29] and sled test by [30] were included. Also for these test series a number of PMHSs did not meet the inclusion criterion and were excluded:

- Outside stature range for subjects
  - Table top, subject THC19.
- Outside BMI range for subject:
  - Table Top, subject THC11.
- Outside mass range for subjects:
  - Table Top, subject THC13.
- Belt pretensioner malfunction:
  - Sled test 222.

Some of the PMHSs were subjected to multiple exposures. The first sled test with PMHS No. 208 produced fractures and the second test with same subject produce additional fractures. Both tests with subject 208 were therefore excluded from the dataset. Also. Cesari and Bouquet [28]-[29] carried out two tests per subject. When the first test carried out was considered non-injurious and the following injurious, these subjects (subject K, L, M, Q, R, S and T) were excluded. This is also the case for tests carried out by Kent et al. [34] and Shaw et al. [35]

X. APPENDIX C - NORMALISATION OF CRASH TEST DUMMY DATA

The PMHSs are generally not mid-size adult males. Therefore, it is considered necessary to scale, in this study referred to as normalise, the dummy response to account for the difference in anthropometry between a dummy and the individual PMHS. In this report IRCs were constructed using data normalised for a dummy that represents a mid-size adult male and using non-normalised data. The following scaling methodology was adopted for impactor tests. For the table-top data the same model has been used and an infinite mass has been assumed for the PMHS.

A simple mass spring model is used to represent the Kroell impactor loading condition (Fig. 5). In the following sections, subscripts and p relate to the hub and PMHS characteristics respectively.

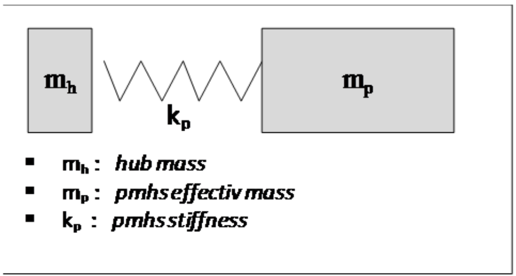

Fig. 5. Mass spring model to represent an impactor to thorax loading condition.

The governing equation for this system is:

$$x(t) = V_0 \cdot \sqrt{\frac{m_h \cdot m_p}{m_h + m_p} \cdot \frac{1}{k_p}}\ sin\left(\sqrt{\frac{m_h \cdot m_p}{m_h + m_p} \cdot \frac{1}{k_p}} \cdot t\right) \tag{1}$$

The peak deflection value is derived from the previous equation:

$$x = V_0 \cdot \sqrt{\frac{m_h \cdot m_p}{m_h + m_p} \cdot \frac{1}{k_p}} \tag{2}$$

Where:

- x is the PMHS deflection
- V_0 is the initial impactor speed
- m_p is the PMHS effective mass

Assuming that peak chest compression (chest deflection normalised to chest depth) is the injury criteria. two different tests lead to the same injury outcome if the following relation holds:

$$\frac{x_1}{L_1} = \frac{x_2}{L_2} \quad \Leftrightarrow \quad \frac{V_{01}}{L_1} \cdot \sqrt{\frac{m_{h1} \cdot m_{p1}}{m_{h1} + m_{p1}} \cdot \frac{1}{k_{p1}}} = \frac{V_{02}}{L_2} \cdot \sqrt{\frac{m_{h2} \cdot m_{p2}}{m_{h2} + m_{p2}} \cdot \frac{1}{k_{p2}}} \tag{3}$$

Introducing the following lambda coefficients:

$$\lambda_L = \frac{L_1}{L_2} \ ; \ \lambda_{m_p} = \frac{m_{p1}}{m_{p2}} \ ; \ \lambda_{m_h} = \frac{m_{h1}}{m_{h2}} \ ; \ \lambda_k = \frac{k_1}{k_2} \ ; \ \lambda_{m_h + m_p} = \frac{m_{h1} + m_{p1}}{m_{h2} + m_{p2}} \tag{4}$$

The previous equation simplifies into

$$\lambda_{V_0} = \lambda_L \cdot (\lambda_{m_p})^{-1/2} \cdot (\lambda_{m_h})^{-1/2} \cdot (\lambda_{m_p + m_h})^{1/2} \cdot (\lambda_k)^{1/2} \tag{5}$$

This λ_{V_0}coefficient is used to scale the dummy loading condition in order to compensate the PMHS for not being a 50^{th} subject. For instance, considering a subject exhibiting a 50^{th} stiffness and mass but with a larger chest depth, say L_1=300mm. Then using L_2=229mm as the 50^{th} value, the λ_{V_0}coefficient will be

$$\lambda_{V_0} = \frac{300}{229} \sim 1.31 \tag{6}$$

To account for this PMHS having a larger chest depth, the dummy should then be tested at a speed increased by 31% with regard to the actual PMHS speed.

Different options can be used in order to relate the λ_k coefficient to the PMHS characteristics.
In case the chest depth information is not available, the following assumption can be made

$$\lambda_k = (\lambda_{m_p})^{1/3} \text{ (Mass based assumption)} \tag{7}$$

In that case, the following is also assumed

$$\lambda_L = (\lambda_{m_p})^{1/3} \tag{8}$$

In case the chest depth is available then one can use

$$\lambda_k = \lambda_L \text{ (Length based assumption)} \tag{9}$$

WorldSID IRC have been developed using the mass based assumptions, whereas frontal biofidelity targets have used the length based one.

When mass based assumptions are used, the equation simplifies into:

$$\lambda_{V_0} = (\lambda_{m_h})^{-1/2} \cdot (\lambda_{m_p+m_h})^{1/2} \tag{10}$$

In case the length based assumptions are used the equation turns into:

$$\lambda_{V_0} = (\lambda_L)^{3/2} \cdot (\lambda_{m_p})^{-1/2} \cdot (\lambda_{m_h})^{-1/2} \cdot (\lambda_{m_p+m_h})^{1/2} \tag{11}$$

For Kroell type impactor tests and Yoganandan impactor tests, the 50th effective mass value has been computed from the *final* dataset sample in the following way: ratios between effective mass and total mass has been computed. The average value of these ratios have been considered as a 50th percentile value and used in conjunction with the 50th percentile physical mass to derive the 50th percentile effective mass value as being:

$$m_{\,eff.50^{th}} = m_{total\,50^{th}} \cdot \left(\sum_{i=1}^{n} \frac{m_{\,eff.\,i}}{m_{\,total\ i}} \right) \cdot \frac{1}{n} \tag{12}$$

For Kroell tests, this value is:

$$m_{\,eff.50^{th}} = 30.69\ kg \tag{13}$$

For Yoganandan tests, this value is:

$$m_{\,eff.50^{th}} = 21.70\ kg \tag{14}$$

When considering the Cesari table-top tests, the same model can be used but with the change to assume the PMHS (supported by the table) exhibited an infinite mass. Equations 10 and 11 then simplify in the following form:

$$\lambda_{V_0} = (\lambda_{m_h})^{-1/2} \quad \text{(mass based)} \tag{15}$$

$$\lambda_{V_0} = (\lambda_L)^{3/2} \cdot (\lambda_{m_h})^{-1/2} \quad \text{(length based)} \tag{16}$$

Lambda coefficients were calculated and used for frontal and oblique test as well as for Cesari and Bouquet table-top test.