SEAT OPTIMISATION CONSIDERING REDUCTION OF NECK INJURIES FOR FEMALE AND MALE OCCUPANTS – APPLICATIONS OF THE EVARID MODEL AND A LOADING DEVICE REPRESENTING A 50th PERCENTILE FEMALE

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ABSTRACT

Neck injury due to low severity vehicle crashes is of worldwide concern and the injury risk is greater for females than males. However, whiplash protection systems have shown to be more beneficial for males than females. Hence there is a need for improved tools to address female protection.

One objective of the European 7th Framework, project ADSEAT was to develop a finite element model of a rear impact dummy representing females for application in seat optimization studies along with the BioRID II. In support of this injury risks for females were studied revealing target size for the dummy model. Related anthropometric data were derived from literature and dynamic volunteer tests comprising females performed to set biofidelity targets. On this basis a finite element model representing females was developed and relevant injury criteria and thresholds identified. For the latter use was made of a prototype loading device consisting of a modified BioRID dummy that better matches the female anthropometry.

This paper article documents the development of the female whiplash dummy model called EvaRID (Eva female, RID – Rear Impact Dummy) and its application to a series of production seats. The loading device BioRID50F and initial test results are also presented herein.

INTRODUCTION

Motivation

Whiplash Associated Disorders (WAD), or 'whiplash injuries', sustained in vehicle crashes is a worldwide concern. In Sweden, such injuries account for about 70% of all injuries leading to disability due to vehicle crashes [1]. The majority of those experiencing initial neck symptoms following a car crash recover within a few weeks or months after the crash as reported by The Whiplash Commission [2]. However, 5 to 10% experience varying degrees of permanent disabilities [2] to [4]. Whiplash injuries may occur at relatively low velocity changes, typically less than 25 km/h [5], [6], and in impacts from all directions. Rear impacts occur most frequently out of all recorded impacts in accident statistics [7].

It is well established that the whiplash injury risk is higher for females than for males, even in similar crash conditions [8] to [18]. These studies concluded that the female injury risk was 1.5 to 3 times higher than the male injury risk. Females and males have different anthropometry and mass distribution, which may influence the interaction between the upper body

and the seatback/head restraint, and thus the injury risk. For example, the deflection of the seat frame, seatback padding and springs may depend on the mass and/or the centre of mass of the upper body with respect to the lever about the seatback hinge. The deflection of the structures of the seatback affects the plastic deformation, energy absorption and the dynamic head-to-head restraint distance, as well as the rebound of the torso [19] to [21]. The motion of the head relative to the head restraint may be affected by seated height in relation to the head restraint geometry. It has been reported that females have a somewhat different dynamic response in rear volunteer tests, such as a higher head forward acceleration, a higher (or similar) T1 forward acceleration, a lesser (or similar) Neck Injury Criterion (NIC) value and a more pronounced rebound than males [20] to [31].
Crash test dummies are used when developing and evaluating occupant protection performance of a vehicle. For whiplash injury risk assessment the BioRID II dummy is being used which represents a 50th percentile male. However, the dummy size corresponds to a ~90th–95th percentile female with regards to stature and mass [32], resulting in females not being well represented by this tool. Consequently, the current seats and whiplash protection systems are primarily adapted to the 50th percentile male with little or no consideration of female properties. Existing whiplash protection concepts are approx. 30% more effective for males than for females according to insurance claims records [33]. The difference between protection for females and males has effectively increased although the overall whiplash injury risk has decreased in rear impacts. Further investigations into these differences and understanding of the reason behind them are needed in order to achieve better protection for both genders.

Objectives

In view of the above, the ADSEAT (Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants) project was initiated. The overall objective of ADSEAT is to provide guidance on the protective performance evaluation of vehicle seats, aiming to reduce the incidence of whiplash injuries. The work focussed on evaluating the protective performance of seats for female and male occupants. Hence the development of an average female size finite element (FE) crash dummy model was undertaken. The new research tool, EvaRID, is intended as a complement to the BioRID II dummy when evaluating enhanced whiplash protection systems.

Approach

Figure 1 depicts the approach used to develop the EvaRID model. As a first step the size for the model was identified. Injury statistics were extracted from insurance databases revealing that a 50th percentile female dummy would correlate in size to the females most frequently suffering whiplash injury. Anthropometric data were then collected to define the geometry and mass. Based on these data a BioRID II dummy model was scaled to result in the EvaRID model that represents females. Extensive validations were made at volunteer level. Corridors from two datasets were used in an interactive procedure to fine tune and validate the model response.
Injury criteria and thresholds were derived. Amongst others an analysis of insurance data comparing risk for females with that of males was made to give thresholds related to NIC. In addition a new mechanical loading device called BioRID50F, crudely representing the anthropometry of a 50th percentile female, was developed [34] and applied in sled tests. Results for BioRID50F and BioRID II were compared for a range of seats to provide confidence in the thresholds established.
Finally the EvaRID model was applied to a range of seats under various loading conditions. Predictive injury outcomes of EvaRID were compared with those for BioRID II.

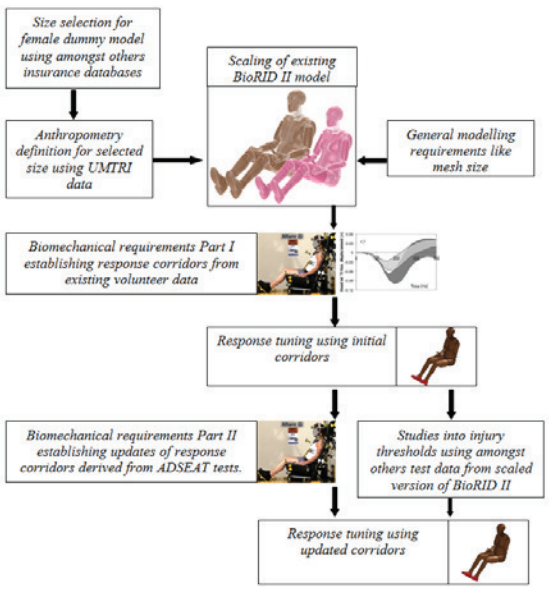

Figure 1 –EvaRID development process.

SIZE SELECTION FOR EvaRID MODEL

Within the scope of the ADSEAT project, several sources were evaluated to establish the anthropometry of females sustaining WAD most frequently [35]. An extensive literature review, searching for risk factors and injury criteria for males and females in published literature was performed. The review revealed that, until now, anthropometric measurements like body height, weight and head to neck ratio have not been established as a risk factor. Older studies associate a taller stature with an increased WAD risk [36] and [37], although it should be noted that those studies include seats not equipped with whiplash protection systems and conditions have changed since protection systems were introduced in vehicles. For instance, the mid- and long-term risk of WAD tend to decrease for increasing statures in vehicles equipped with the SAHR system [38], while in vehicles equipped with the WhiPS system stature does not appear to influence the risk of sustaining WAD [39].

A review on injury criteria showed that there are no gender specific injury criteria. Furthermore, no validated methods to adequately scale proposed threshold values were found. Nonetheless real-world data analysis reveals existing whiplash protection concepts to be more effective for males than for females, at a 45% risk reduction in permanent medical impairment for females and 60% for males [33]. For this reason insurance data were used to establish the size for the female model. Records of females who have sustained whiplash injuries in rear impacts were extracted from the AGU Zurich database, Switzerland (N=2,146), and the Folksam database, Sweden (N=1,610). Stature and mass distributions of the injured females are shown in Figure 2. The injured females in the AGU Zurich database had an average stature/mass of 165.3 cm/65.2 kg, which is close to the average size of the female population in Switzerland, 164.7 cm/63.4 kg (verbal confirmation by Swiss Statistical Office). Correspondingly, the average stature/mass of the injured females in the Folksam database was 165.3 cm/65.2 kg for, which correlate well with the average size of the female population in Sweden, 165.9 cm/65.9 kg [40]. Thus, it was considered that the 50th percentile female dummy would correlate best in size to the females that are most frequently injured in rear impacts. A comparison of these measures with data of the general female population of other European countries indicates that the weight and height found for the females that most frequently sustain WAD corresponds quite well with the average anthropometry among European countries; that is 165 cm and 66 kg (Table 1).

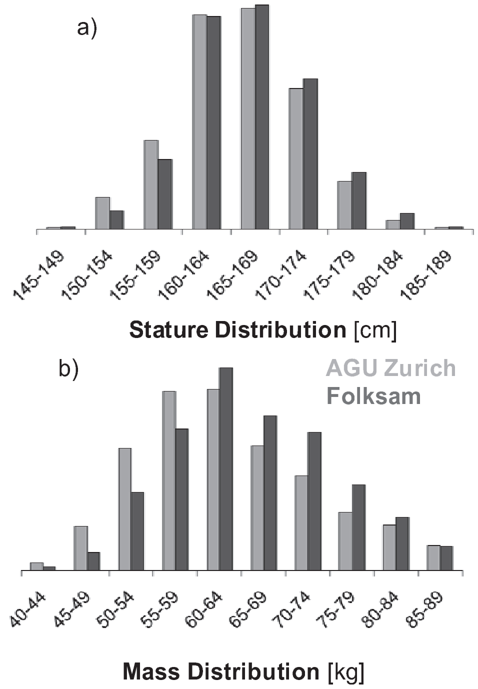

Figure 2 – Stature and mass distributions of whiplash injured female occupants in Sweden (Folksam database) and Switzerland (AGU Zurich database).

Table 1 – "Average" female anthropometry of the general population in different European countries

Country	Height [cm]	Weight [kg]	Age [years]
Austria [e, g]	167	67	43.2
Czech Rep. [e, f]	167.3	-	41.9
Germany [c, e]	165	67.5	45.2
Finland [e, f, h]	164.7	69-83	43.7
France [b, e, g]	161.9	62.4	40.9
Italy [e, g]	162	-	44.8
Netherlands [d, e]	166.8	68.1	41.2
Spain [e, f]	161	-	42.5
Sweden [e, i]	166.8	64.7	42.6
Switzerland [a, e]	164	49-67	42
UK [e, h]	161.6	67	41.3
Average	164.6	66.3	42.5

[a] www.statistik-bs.ch/kennzahlen/integration/A/a2
[b] www.insee.fr/fr/ffc/docs_ffc/es361d.pdf
[c] www.wissen.de/wde/generator
[d] dined.io.tudelft.nl/en,dined2004,304
[e] www.cia.gov/library/publications/the-world-factbook
[f] www.disabled-world.com/artman/publish/height-chart.shtml
[g] www.imas.at/content
[h] psychology.wikia.com/wiki/Body_weight
[i] www.nordstjernan.com/news/sweden/776/

In order to make a decision on the size to be used including a reference to a dataset that includes all required anthropometry information for defining in detail the dimensions of the female dummy model reference is made to assumptions made when defining the WorldSID dummy. For defining the anthropometry of that dummy it was concluded [41] that the size of a world-harmonized 50th percentile adult male would correspond well with the size of the 50th percentile adult male as defined by UMTRI [42] to [44]. For this reason it was regarded appropriate to assume the same for the 50th percentile adult female. Thus, it was decided to base the EvaRID model on the anthropometric measures of the 50th percentile female from the UMTRI study with a stature of 161.8 cm and a mass of 62.3 kg. Table 2 compares main dimensions with those from other dummies.

ANTHROPOMETRY SPECIFICATIONS

Having established the stature, mass and seated height of the EvaRID model, the next step was to specify the dimension and mass of different body segments and the distance between joints for the 50th percentile female. The UMTRI study [42] to [44] described in detail how the anthropometry and properties were specified for the 5th percentile female, as well as for the 50th and 95th percentile male crash test dummies. The same method was used in this study, if appropriate, when establishing the anthropometry of EvaRID. However, the actual data had to be found elsewhere since the UMTRI study did not contain relevant information for the 50th percentile female.

The anthropometric data for the 50th percentile female was mainly collected from the studies described by Diffrient et al. [45] and Young et al. [46]. In addition, anthropometric data extracted from the ergonomic software programmes GEBOD [47] and RAMSIS [48] was used to validate the collected data. Product Information from Humanetics (previously FTSS) was used to collect information on the BioRID II hardware dummy for direct comparison of anthropometric data. Finally, parts of the 50th percentile male data from McConville et al. [49] were used for comparative purposes.

Table 2 – Stature, mass and seated height of dummy family [42].

%-ile	Sex	Stature [cm]	Mass [kg]	Seated Height [cm]
5th	Female	151.1	47.3	78.1
50th	**Female**	**161.8**	**62.3**	**84.4**
50th	Male	175.3	77.3	90.1
95th	Male	186.9	102.3	96.6

In [46] the 50th percentile female stature was 161.2 cm and the mass 63.9 kg; i.e., 0.4% shorter and 2.6% heavier than the 50th female values in Table 2. In [45] the 50th percentile female stature was 161.5 cm and the mass 65.8 kg; i.e., 0.2% shorter and 5.6% heavier than values in Table 2. Due to the small differences in stature, scaling was not made to the length dimensions in [45] and [46]. As mass differences were found to be greater, the depth and width dimensions or circumferences were scaled according:

- Young et al. (1983) [46]: 1% scaling
- Diffrient et al. (1974) [45]: 2% scaling

The EvaRID model was developed by scaling an existing BioRID II model from DYNAmore GmbH [52]. As described in the next section, this was done segment by segment according to the segments defined in [46]. The distances between joints were taken from [45] and summarised in Figure 3. Regression equations from [46] were used to compute the segment volumes [50].

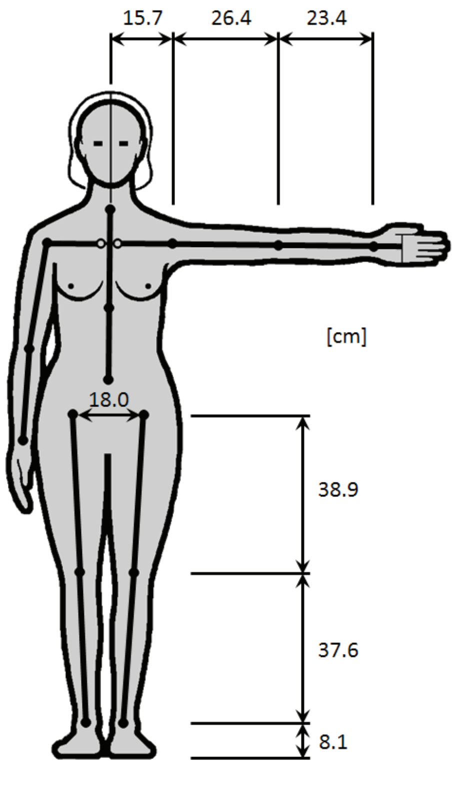

Figure 3 – Distances between joints of EvaRID [45].

Table 3 – Mass, mass distribution (in percentage of the total mass), and Mass Ratio (MR) (M_{EvaRID}/M_{BioRID}) of BioRID II and EvaRID.

Body Part	EvaRID		BioRID		MR
	Mass [kg]	% of total	Mass [kg]	% of total	Mass Ratio
Head	3.58	5.7	4.54	5.8	0.789
Upper Torso 1)	19.58	31.4	26.61	34.0	0.736
Pelvis 2)	15.84	25.4	15.80	20.2	1.003
Upper Arm	1.40	2.2	2.02	2.6	0.691
Lower Arm 3)	1.16	1.9	2.23	2.9	0.518
Upper Leg 4)	5.67	9.1	5.99	7.7	0.947
Lower Leg 5)	3.43	5.5	5.44	7.0	0.631
Total	**62.30**	**100**	**78.24**	**100**	**-**

1) The upper torso consists of the thorax, abdomen, spine and neck.
2) Flaps included.
3) Hand included.
4) Flap excluded.
5) Foot included.

The mass of each body segment was estimated based on its volume, assuming constant density of the body. The resulting masses (absolute and relative compared to overall mass) and the Mass Ratio (MR) of body parts for the EvaRID and BioRID II dummy models are provided in Table 3. Slight differences in mass distribution can be seen between the female EvaRID and the male BioRID; males having somewhat more mass in the torso region while the mass is greater in the pelvic region of females. Relevant anthropometry data in terms of segment volumes and main dimensions are provided in [50].

EvaRID MODEL DEVELOPMENT

When developing the EvaRID model by scaling the BioRID II model, the goal was to make sure that mass, inertia and length data of each body segment matched the anthropometric data for the 50th percentile female as closely as possible. To meet anthropometric requirements in terms of mass and dimension, firstly the longitudinal dimensions and mass were scaled according to equations (1) and (2) below. Breadth (width) and depth dimensions for the different EvaRID body parts were established based on the most appropriate scaling method for each body segment. For the purposes of this article, SFL is the Longitudinal Scale Factor, SFB the Breadth Scale Factor, and SFD the Depth Scale Factor.

Extremities – It was assumed that SFB and SFD for the extremities / limbs are equal. SFB / SFD then follow as the square root of Mass Ratio over Scale Factor Length (volumetric relationship), see Table 4.

Head - For the head, all data for breadth and width scaling directions were available in the anthropometry specifications. Due to the head´s importance in terms of loading to the neck it was decided to apply direct scaling in all directions to meet all the dimensional requirements.

Neck – Adequate sources were not found when collecting input data for the anthropometry defining the skeleton. Of particular relevance are the spine and neck, and due to the lack of data it was decided that EvaRID would maintain the same spine and back profile as in BioRID II. This was achieved by keeping the length and depth scaling factors, *SFL* and *SFD,* identical for both the neck and torso. Furthermore, it was assumed that breadth scaling factors SFB_{neck} and SFB_{torso} are identical, concluded by comparing the shoulder joint distance of EvaRID to the shoulder joint distance of BioRID.

Torso - The upper torso was defined as the torso without the pelvis, running from the cervical to the iliac crest. The mass of the upper torso was derived by subtracting the mass of the pelvis from the mass of the torso. The breadth scale factor, SFB, was obtained by comparing the distance between shoulder joints in the female data (31.50 cm) and the value for the BioRID II (34.60 cm). *SFD* was then calculated according to the equation in Table 4.
The outer shape of the male and female torso and pelvis segment body parts differ significantly. Breasts would be added to the female dummy and the shoulder/ waist ratio for both genders were quite different. Therefore, further refinements were made to the uniform scaling applying *SFL*, *SFB* and *SFD*. Using anthropometric data from Diffrient et al. [45] and Young et al. [46] the waist breadth was set at 310.5 mm, bust 288 mm; 10th rib 257 mm; buttocks 373 mm; and bust point distance 180 mm. Information on circumferences from these data sources was also used to further shape the geometry.

Pelvis - Although the outer shapes are different for the pelvis, no significant difference between the main dimensions of the 50th percentile female and the 50th percentile male pelvis were found in the anthropometric studies described in [46] and [49]. Furthermore, the distance between the hip joints was similar for the 50th percentile female and the BioRID II. The pelvis mass was also found to be similar for the 50th percentile male (15.84 kg) and the 50th percentile female (15.80 kg). Consequently, the shape of this body part was the only one adjusted to match

Table 4 – SFB and SFD equations for body parts

Part	SFB	SFD
Head	$\frac{\text{Head Breadth}_{EvaRID}}{\text{Head Breadth}_{BioRID}}$	$\frac{\text{Head Depth}_{EvaRID}}{\text{Head Depth}_{BioRID}}$
Neck	$= SFB_{upper\ torso}$	$= SFL_{neck}$
Upper Torso	$\frac{\text{Shoulder Breadth}_{EvaRID}}{\text{Shoulder Breadth}_{BioRID}}$	$\frac{MR_{upper\ torso}}{(SFL \times SFB)_{upper\ torso}}$
Pelvis	1	$\frac{MR_{pelvis}}{(SFL \times SFB)_{pelvis}}$
Extremities	$\sqrt{\frac{MR_{limb}}{SFL_{limb}}}$	$\sqrt{\frac{MR_{limb}}{SFL_{limb}}}$

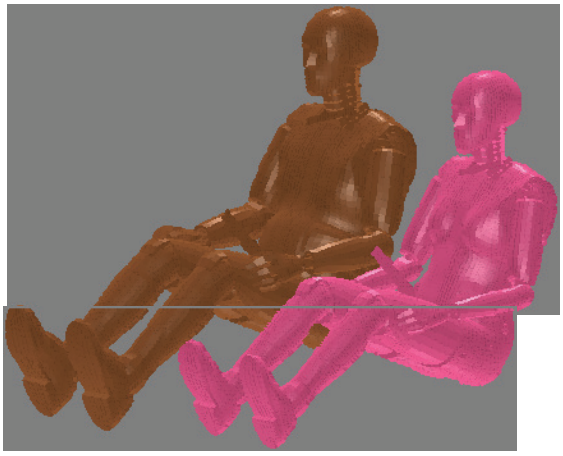

Figure 4 – Comparison EvaRID and BioRID II

the breadth dimensions in [46]. Finally, it was assumed that the EvaRID will maintain the same pelvis angle as the BioRID II at 26.5 degrees.

The scaling factor formulas are shown in Table 4 and resulting scale factors are provided in [50]. The EvaRID model is depicted in Figure 4 together with the BioRID II model.
Based on information collected on muscle tension between males and females [51] the stiffness and damping properties of discrete elements in neck and spine were scaled to a value of 70% of the original values in the BioRID II model [52].

BioRID50F DEVELOPMENT

Following the model development a prototype rear impact loading device representing 50th percentile females was constructed by modifying parts from a BioRID II dummy. Target dimensions and masses of the BioRID50F's body segments were based on the EvaRID values included in Table 3. This tool was designed to initiate studies into injury thresholds for females as it seems unlikely that data obtained for a male dummy would be appropriate for female injury risk due to the difference in size, seated posture, physical distribution and kinematics.
Generally the structure of BioRID50F is similar to BioRID II. However, some modifications were introduced to closer match the anthropometry of a 50th female. The head of the BioRID50F was made of a BioRID head from which the anterior flesh had been removed. The lower arms were shortened and the wrist rotators, wrist pivots, and hands were removed. The upper and lower legs were shortened, and the ankles were replaced by aluminium square profiles, to which the shoes were attached and the flesh was sculpted to match the reduced length of the limbs. Furthermore, sections of the interior flesh were removed and oval holes were machined in different parts of the steel skeleton to reduce mass. The spine was shortened by removing two vertebrae and reducing the height of the sacral vertebra. Two sections (one horizontal and one vertical were cut out from the torso jacket followed by the reassembly of the remaining pieces, resulting in reduced shoulder joint distance. The interface pins (connecting the spine to the torso jacket) were shortened to match the modified torso jacket width. The size of the neck and spine polyurethane bumpers was decreased and the neck muscle substitute springs were replaced by softer springs. The spring cartridges and muscle substitute wires were replaced to match the length of the new springs. Resulting masses of the BioRID II and the BioRID50F's body segments are compared in Table 5. The BioRID50F prototype loading device is shown in Figure 5. Instrumentation is similar to the BioRID [52].

Table 5 – Masses of BioRID II and BioRID50F

Dummy Segment	BioRID II Mass [kg]	BioRID50F Mass [kg]
Head	4.44	3.32
Torso (incl. neck/spine)	27.16	22.43
Pelvis	11.67	12.03
Arm (upper)	2.02	1.46
Arm (lower)	2.26	1.25
Leg (upper)	6.86	5.72
Leg (lower)	5.80	3.83
Total	**77.15**	**62.30**

Figure 5 – BioRID50F prototype loading device.

EvaRID MODEL EVALUATION

Firstly, volunteer and BioRID II hardware tests from Carlsson et al. [31] were reproduced for the initial validation of the EvaRID model. A detailed description of the test set-up, volunteers and results is given in [31] and [50]. Figure 6 compares head and T1 accelerations and rotations of the EvaRID model with corridors and Figure 7 shows results for the BioRID model plotted against corridors constructed from tests with the BioRID II hardware dummy at volunteer loading levels. Both the EvaRID and the BioRID II model showed good to reasonable correlation with test data except for the T1 rotation which remains well below test data. It should be noted that in this first validation, correction to the characteristics of discrete elements related to muscle tension was not yet made.

To allow a more detailed analysis a new series of volunteer tests was performed. In this series a rigid seat base and larger head to head-restraint distance was introduced to eliminate some of the uncertainties for the correlation with the EvaRID model. In the new

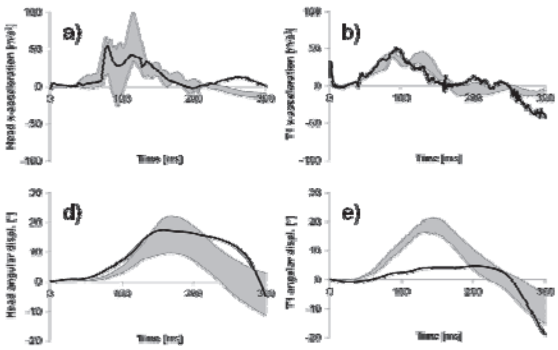

Figure 6 – Comparison of EvaRID against corridors from volunteer tests at velocity change of 7 km/h.

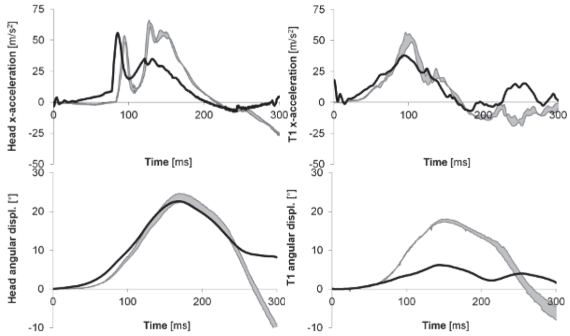

Figure 7 – Comparison of BioRID II model against corridors from hardware tests at velocity change of 7 km/h.

series tests with eight female volunteers, representing the 50th percentile female, were performed at a change of velocity of 6.8 km/h. The volunteer data are summarised in Table 6.

The set-up consisted of a stationary sled equipped with a laboratory seat designed to mimic a Volvo S80 seat [31] and [53]. This target sled was impacted from the rear by a bullet sled with an iron band mechanism dimensioned to create the mean acceleration of 2.1g of the target sled. Schematics of the test set-up can be seen in Figure 8. Dynamic response corridors for the x-accelerations, the x-displacements, and the angular displacements of the head, T1, and head relative to T1 were generated. For this purpose the head was equipped with a harness with tri-axial accelerometers mounted on the left side, and an angular accelerometer mounted on the right side, approximately at the centre of gravity of the head on each side. T1 accelerometers were mounted on a holder, which was attached to the skin at four points (one above each clavicle, and two bilateral and close to the spinal process of the T1). The volunteers were restrained by a standard three point seatbelt. See picture of volunteer in Figure 8.

The back of the seat consisted of four stiff panels, lined with a 20 mm thick layer of Tempur medium quality foam covered with a plush cloth. Panel and foam dimensions and stiffness's were derived from detailed measurements of each element. Furthermore, the stiffness of the supporting springs was derived from static measurements on each spring. The head-restraint consisted of a stiff panel and the initial Head Rest (HR) distance was adjusted to 15 cm by adding layers of padding, see Figure 8.

A pre-simulation was conducted by dropping the dummy into the seat and letting it find its balanced position in the simulation through gravity. The seat was fixed to the ground and the only external force

Table 6 – Age, stature, mass, sitting height, and neck circumference of the female volunteers

Test Subject	Age [years]	Stat. [m]	Mass [kg]	Sitting Height [m]	Neck circ. [m]
FA2	27	161.0	54.5	86.5	30.0
FB2		163.8	56.8	86.5	32.0
FC2	27	162.8	66.8	86.5	32.5
FD2	23	166.0	56.8	86.5	32.0
FE2	25	165.3	61.2	94.5	32.0
FF2	29	161.4	62.2	85.5	33.0
FG2	22	161.9	60.4	86.4	32.0
FH2	27	164.4	58.0	86.5	32.0
Mean	**26**	**163.3**	**59.6**	**88.6**	**31.9**
SD	**2**	**1.8**	**3.9**	**4.3**	**0.9**

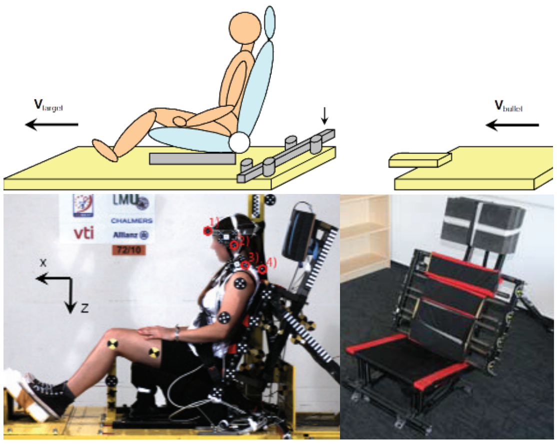

Figure 8 – Schematic of sled setup, volunteer with markers and seat with rigid seat based.

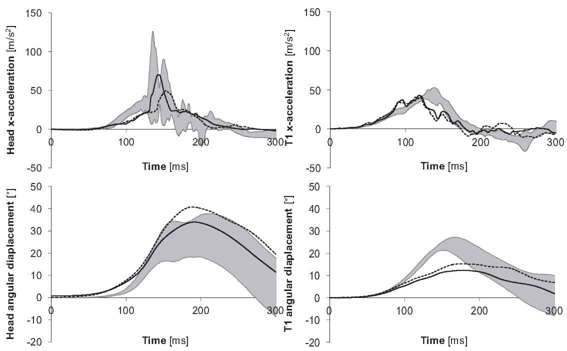

Figure 9 – Comparison of EvaRID against corridors from volunteer tests at a velocity change of 6.8 km/h.

was the gravity. The influence of dummy positioning on the seat was studied by applying a shorter and a longer run time for the pre-simulations resulting in head to headrest distances of 144 and 158 mm respectively.

Figure 9 shows some typical results. Head and T1 accelerations and angular displacements for position #1 (black line, 144 mm head-to-headrest distance) and position #2 (dotted lines, 158 mm head-to-headrest distance) compared against corridors from volunteer tests (indicated by grey lines and shaded area). Good correlation was obtained for most signals. The T1 rotation, however, remains below the corridor for the first 160 ms. Compared to results from the initial validations, improved performance was found, which is explained by clearer definition of the test conditions. This allowed for a more detailed modelling of the seat and thereby for better conditions to fine tune the EvaRID model in terms of stiffness reduction related to muscle tension.

Based on the above observations, it is advisable to further evaluate and improve the BioRID II and EvaRID models for use at low velocity changes. In this respect it is recommended to establish the curvature of the spine and its relation to the HR distance for seated 50th percentile female occupants. Such data were not available to the ADSEAT project when generating the model; therefore these results must be implemented to further improve the EvaRID model.

FEMALE NECK INJURY RISK

To apply the newly established EvaRID model in the context of seat performance assessment, it is crucial to derive parameters characterising the associated neck loading. While various criteria published to rate the male injury risk exist, of which NIC [54] and Nkm [55] are probably the most commonly applied, criteria specifically addressing the female injury risk are not yet available. Therefore, attempts were undertaken to establish initial suggestions on how to assess female injury risk. Assuming that the biomechanical basis for neck complaints is similar for male and females, injury criteria with similar underlying concepts were assumed to be appropriate. However, female specific threshold values for acceptable dynamic neck loading needed to be established.

An analysis of the Folksam Insurance data was made to compare injury risks between males and females and Figure 10 shows risk curves for both genders. From these results it was observed that the risk for females is approximately 20% higher compared to males. Kullgren et al. [6] considered a correlation between NIC and vehicle mean acceleration. Consequently, a provisional reduction of the NIC threshold value by 20%, i.e., a reduction of the threshold value from 15 (males) to 12 (females) was suggested.

Additionally, the Nkm criterion was adapted by adjusting the intercept values used to determine the criterion. Considering a scaling approach of neck properties as described in FMVSS 208 related to the Nij criterion, as well as in Viano [21] it was suggested to reduce the intercept values for females to 60% of the corresponding values for males.

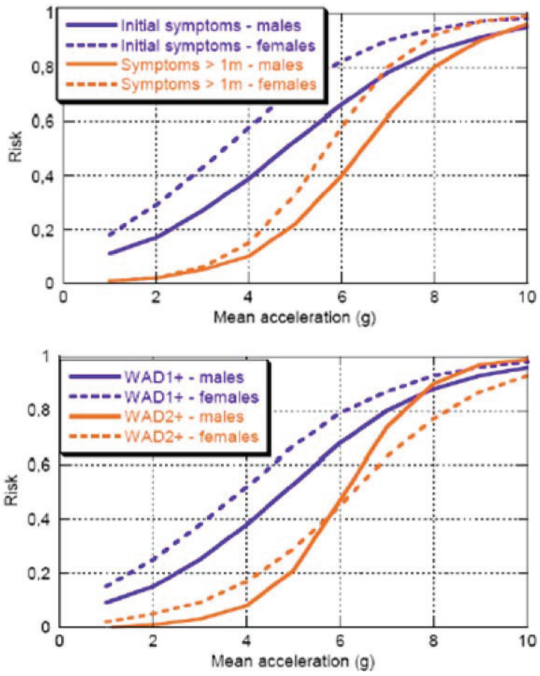

Figure 10 – Injury risk curves for males and females as derived from Folksam database.

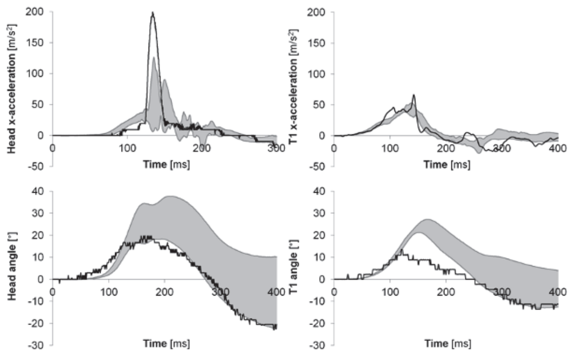

Figure 11 – Comparison of BioRID50F against corridors from volunteer tests at velocity change of 6.8 km/h.

To investigate whether these suggestions for female injury criteria are reasonable, sled tests were performed utilising the BioRID50F. Initially, the loading device was validated against the female volunteer data, see Figure 11. The overall response of the BioRID50F resembled the female volunteer response corridors. The lower thoracic and lumbar joint stiffness of the BioRID II was replicated in the BioRID50F; therefore it is possible that the spine segments were stiffer than in an average female.

Secondly, a series of sled tests adhering to Euro NCAP whiplash test procedure was performed (IIWPG 16km/h delta-v). Four commercially available vehicle seats rated by Euro NCAP were used: A, B and D awarded good rating while seat C performed marginally. Seats A and B were equipped with re-active systems to reduce the neck loading. Two seats of each model were tested, i.e., a total of 8 sled tests comprising 8 seats were performed with the new loading device BioRID50F. The tests were evaluated similar to Euro-NCAP evaluations and results are summarised in Figure 12 in terms of absolute values normalised with respect to corresponding Euro NCAP tests using the BioRID II, i.e., 1.0 representing the baseline as obtained using a BioRID.

Despite various limitations e.g., related to the new loading device, its seated posture or the seat position, the tests clearly illustrate that assessing current seats focusing on female anthropometry will lead to different results. Poorly performing seats in BioRID II tests can produce much better results under the new setting and vice versa. In seat C, for example, the smaller dummy managed to fit in between the seat frame leading to completely different kinematics associated with lower loading. Likewise, the outcome for injury criteria differed. Evaluating the modified versions of NIC and Nkm reflected the different performance of the seats as described above. Hence, it was decided to use the modified versions in the computer simulations, as well, to test their applicability to the EvaRID model.

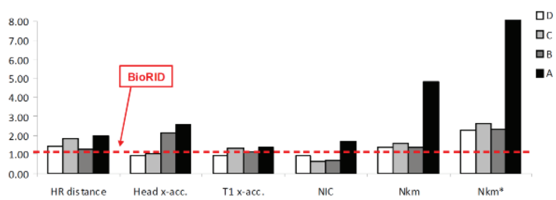

Figure 12 – Test results normalized with respect to the corresponding Euro-NCAP results.

SIMULATIONS OF VEHICLE SEATS

The new female dummy model EvaRID and limits proposed by ADSEAT were used to compare the efficacy, for males and females, of the whiplash protection systems currently on the market. Three different kinds of seats were selected to represent a wide range of typical automotive vehicle seats and head restraints. All had been awarded medium to good performance in the Euro NCAP whiplash rating.

Description of seats

The seats used in this study are shown in Figure 13. Seat A represents a middle class vehicle seat of an older generation still in serial production. The head restraint is a classic passive adjustable up/down type. Although the height in the upper most position is lower than for the latest generation of vehicle seats the dynamic performance of the seat is excellent. Seat C is a recent middle class vehicle seat awarded 3 out of the 4 possible points in the Euro NCAP whiplash rating. The headrest is adjustable up/down and has an integrated plastic insert covered by foam. Seat D is a recent vehicle seat for a small vehicle awarded 3 points in Euro NCAP ratings. This seat has an integrated head restraint at fixed height.

Seat model validation

Initially the available models for these seats were validated by comparing simulation results for the BioRID II dummy model with dummy hardware test in SRA16, IIWPG16 and SRA24 pulses. The BioRID model was positioned in line with the Euro NCAP protocol and recorded test pulses were applied.

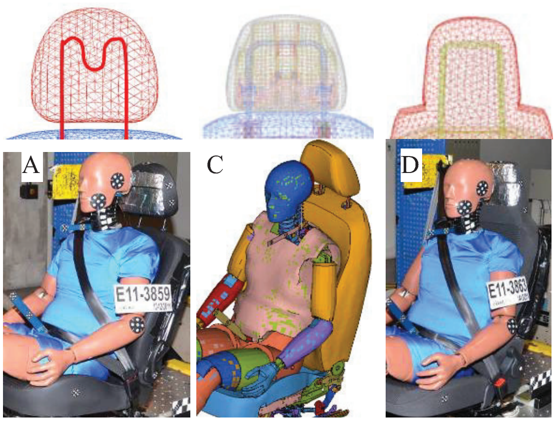

Figure 13 – Seats used in numerical study and details of the headrest.

Table 7 – Comparison of NIC and Nkm for hardware tests and simulations with the BioRID model

Seat	Pulse	NIC		Nkm	
		Test	Simu.	Test	Simu.
A	SRA16	13.01	13.65	0.23	0.16
A	IIWPG16	16.41	15.62	0.22	0.17
A	SRA24	19.86	13.26	0.35	0.27
C	SRA16	8.80	10.72	0.26	0.21
C	IIWPG16	17.99	16.35	0.24	0.17
C	SRA24	14.24	17.57	0.43	0.31
D	SRA16	9.10	10.10	0.19	0.28
D	IIWPG16	14.35	17.14	0.28	0.28
D	SRA24	14.20	19.20	0.45	0.34

A comparison was made on the basis of signals and injury criteria. Table 7 shows NIC and Nkm as an example to illustrate correlations obtained. Whereas NIC (see Table 7), Fz upper and T1 for seats A and C are comparable, the outcome on Nkm (see Table 7) and Fx differ. Also the HR contact times differ and head rebound velocities appear higher in simulation than in real test. For seat D the head contact times are aligned between FEA and the tests. Regarding the behaviour of the criteria over the time, NIC, Fx upper and T1 are the values which correlate the best between test and simulation. Head rebound velocity is again overestimated in simulations. Despite the differences observed between simulations and tests the correlations found gave sufficient confidence in applying the seat models to a comparison between the performance for males and females.

EvaRID positioning

For the simulation runs with the female dummy model it was decided not to change the seat adjustments except for the head restraint height. This allows for a comparison without any other influence factor. Where the head restraint was adjusted to the mid height position for the BioRID, it was adjusted to its lowest position for the EvaRID (see Figure 14). As no seating procedure was available the aim was to keep the EvaRID H-point in the same position as for the BioRID model. To avoid interference with the seat base the same femur orientation as for the BioRID was applied which was realised by directing the tibia in a more upward position i.e., heel further back (see Figure 15). The pelvis angle was set to 26.5+/- 2.5° (BioRID 26.5+/- 2.5°), the head angle to 0° (+/-1°) and the occiput of the EvaRID head was aligned to the occiput of the BioRID.
The seating procedure appeared to be feasible for all

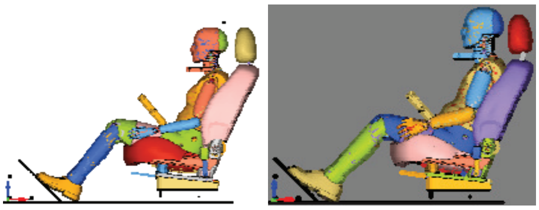

Figure 14 – Head restraint position for EvaRID (left) in lowest position and BioRID (right) in mid position.

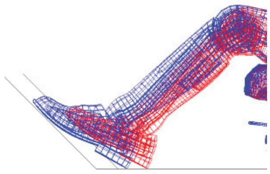

Figure 15 – Leg positioning EvaRID (red) in comparison to BioRID (blue)

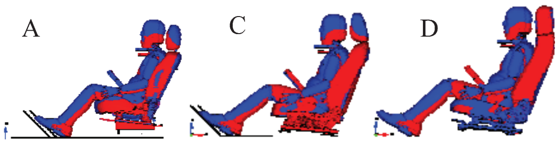

Figure 16 – Comparison of seated position for EvaRID (red) and BioRID (blue) for each seat.

seats and resulting postures and seat settings for the EvaRID in relation to the BioRID are depicted in Figure 16. Although feasible, it is to be noted that the seating procedure requires further research. Volunteer studies have shown that females and males tend to adjust the seatback differently; women´s seat back angulation being 3 degrees less than males [56].

EvaRID simulations and performance comparison for males and females

Simulations comparing the performance of the three seats for EvaRID and BioRID II were made applying the SRA16, IIWPG16 and SRA24 pulses. Figure 17 show head displacements and rotations for the IIWPG16 pulse as example. Figure 18 and Figure 19 provide results for NIC and Nkm respectively. Notable differences were observed for seat D. This is explained by the fact that the EvaRID head is not contained by the headrest due to lack of support; firm support is missing at the contact location between the occiput and the headrest for the female dummy. When considering the thresholds for NIC (12) and Nkm as identified for the EvaRID it is evident that all seats perform better for the BioRID than for the EvaRID.

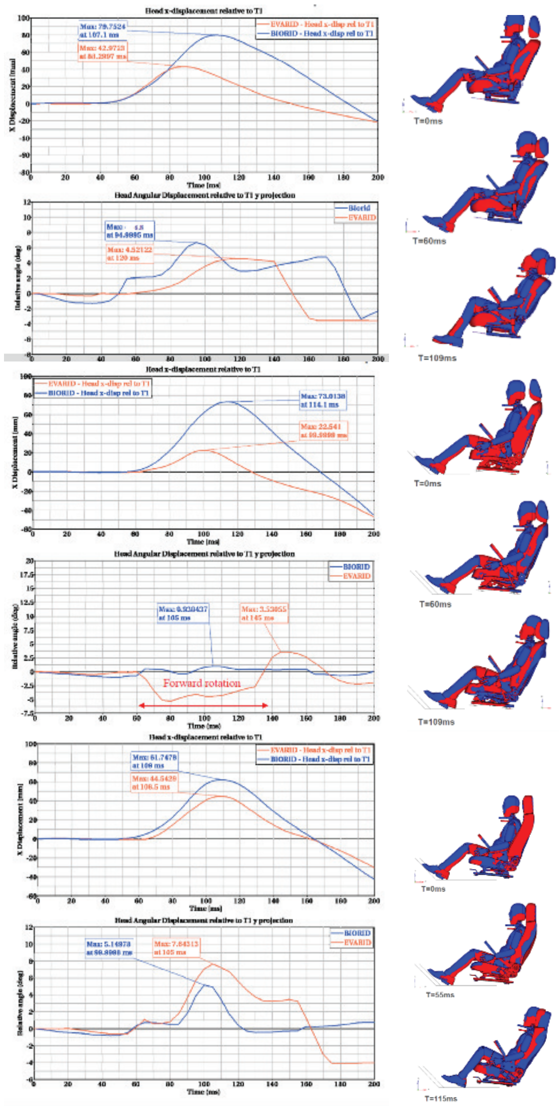

Figure 17 – Head x displacements and relative angles for EvaRID (red) and BioRID (bleu) for IIWPG16 pulse: seat A (top); seat C (middle) and seat D (bottom)

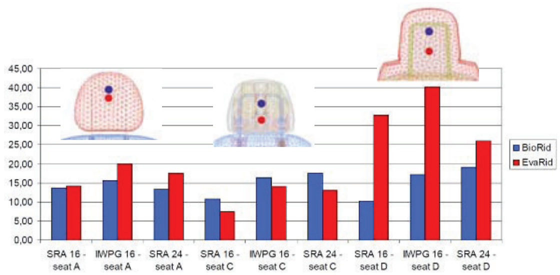

Figure 18 – NIC values for EvaRID (red) and BioRID II (blue) in three different seats and at three different pulses. Contact point between head and headrest indicated for each seat.

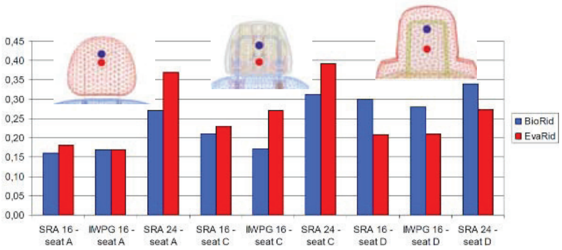

Figure 19 – Nkm for EvaRID (red) and BioRID II (blue) in three different seats and at three different pulses. Contact point between head and headrest indicated for each seat.

DISCUSSION

Real-world car crash records shows that females have a higher risk of sustaining whiplash injuries, than males. An analysis of insurance data conducted in the ADSEAT project showed that females associated with the highest whiplash injury frequency in rear impacts are of average size [33]. Related anthropometry data were collected and used to scale an available BioRID II model. The resulting model, called EvaRID, is meant to represent females in rear impact studies. The EvaRID model was validated against two sets of response corridors obtained from female volunteer tests. Despite a reasonably good overall correlation the EvaRID model showed a notably low T1 rotation compared to the volunteer data from the first test series, see Figure 6. Comparison between the BioRID II model and hardware tests in the same conditions showed identical behaviour, see Figure 7. The results suggest that the biofidelity of both the EvaRID and the BioRID II model have limitations at low velocity changes in the range of 7 km/h. This may be explained by the fact that the BioRID II model is mostly used and therefore largely validated against dummy test results in the range of consumer test load conditions.

In the second series of female volunteer tests a seat with rigid base and larger head to head restraint distance was applied allowing for more accurate reproduction in simulations. In this condition better correlation was obtained although the T1 rotation remained below the corridors, see Figure 9.

Based on these observations it is recommended to further evaluate and improve the virtual BioRID II and EvaRID models for performance in low velocity changes. In this respect it is advisable to establish the curvature of the spine and its relation to the HR distance for seated 50th percentile female occupants in the EvaRID. Such data were not available to the ADSEAT project when generating the model.

For the injury criteria and thresholds to be used with the EvaRID model it was assumed that the biomechanical basis for soft tissue neck injuries is similar for male and females. As a consequence criteria previously established for the BioRID II were adopted. A comparison of injury risks between males and females [6] indicates that the risk for females is approximately 20% higher compared to males. On this basis a reduction of the NIC threshold value by 20% was proposed as a first estimate. For the Nkm reduced intercept values of 29 Nm for extension moment, 53 Nm for flexion moment and 507 N for shear force for females were proposed. These values are based on a scaling approach of neck properties as described in FMVSS 208 (related to the Nij criterion) as well as a publication by Viano [21] which would suggest reducing the intercept values for females to 60% of the corresponding values for males.

The appropriateness of these thresholds was investigated by sled tests comparing the performance of seats using the BioRID II dummy and a newly established loading device called BioRID50F. The BioRID50F was developed by modifying components from the BioRID II to make a closer match to the anthropometry of the 50th percentile female. Comparative tests on four different production seats revealed differences in outcome of the tests due to the differences in anthropometry of both loading devices. In one of the seats the smaller dummy managed to fit in between the seat frame leading to completely different kinematics resulting in lower values of the neck loadings. Evaluation of the adopted thresholds for NIC and Nkm reflected the differences in behaviour. Although the approach applied has many limitations including the correctness of the loading device applied and the lack of an adequate seating procedure it was decided to use the proposed lowered values for NIC and Nkm for the EvaRID model. However, further work in this field is much needed.

Simulations with production seats using the BioRID II and the EvaRID model showed that significant differences may occur between the response of the BioRID II and EvaRID models. As seat and headrest designs respond to actual consumer procedures which favour a mid-height position of the head restraint at the height of the BioRID II dummy, the EvaRID response may suffer in those situations where the head cannot be fully retained by the head restraint due to lack of support. The head restraint needs to provide firm support at the height of the occipital point of the average female. This could for instance be realised by adding additional inserts within the head restraint or alternatively by allowing the head restraint to be aligned with the top of the head of the EvaRID. The real world data and the research findings in the ADSEAT project are expected to become essential input for future updates of test protocols such as IIHS and Euro NCAP. In terms of usage of the EvaRID model it is to be noted that future studies into the seat adjustments and seating procedure for females are required to reflect for the fact that females tend to apply different seat adjustments than males [56].

CONCLUSION

A computational dummy model, called EvaRID, Eva female, RID – Rear Impact Dummy, of a 50th percentile female for use in rear impact tests was developed based on anthropometry data found in the literature. To evaluate how close the dummy model´s response was to that of a human, the EvaRID was compared to the corridors and response curves gained in volunteer tests comprising females. Good overall correlation was found except for the T1 rotation, indicating that further refinement to the spine geometry is needed possibly in conjunction with stiffness optimisation to achieve a response fully within the corridors.

With respect to injury criteria it was concluded that it would be appropriate to begin by using NIC (with a lower threshold value of 12 m2/s2) and Nkm (with reduced intercept values of 29 Nm for extension moment, 53 Nm for flexion moment and 507 N for shear force for females). Evaluation of these values using a new experimental loading device called BioRID50F reflected the different behaviour observed in tests comparing seat performance for the BioRID50F and the BioRID II. The same was true for simulations comparing seat performance for males and females using the EvaRID and the BioRID models. Further work in this field is needed though.

Virtual impact simulations with seats showed that for some seats significant differences may occur between the response of the BioRID II and EvaRID model. The initial results of the simulations showed that in similar conditions the female occupant behaves less favourably in terms of loading to the neck, than male occupants. To improve the validity of such simulations a seating procedure including related tools, specifically for females are to be developed.

ACKNOWLEDGEMENT

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