

EvaRID - A 50th Percentile Female Rear Impact Finite Element Dummy Model

Anna Carlsson¹, Fred Chang², Paul Lemmen²,
Anders Kullgren^{1,3}, Kai-Uwe Schmitt⁴, Astrid Linder⁵, Mats Y. Svensson¹

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. The objective is to develop and evaluate a 50th percentile female rear impact crash dummy FE model.

The model was based on the same design concept as the BioRID II. A scaling approach was developed and the first version, EvaRID V1.0, was implemented. Its dynamic response was compared to rear impact tests with female volunteers.

The EvaRID model and volunteer tests showed good correlations until ~250 ms of the head and T1 accelerations, linear displacements and head angular displacement. Considerably less T1 angular displacement was found for the EvaRID; similar results were obtained for the BioRID II. Thus, the EvaRID V1.0 and BioRID II models have limitations at low Δv (7km/h).

The EvaRID model demonstrated the potential to become a valuable tool when evaluating and developing seats/whiplash protection systems, however, this will require updating the joint stiffness. The model may be used as a template for the development of a physical female dummy.

Keywords Anthropometry, Dummy, Female, FE model, Rear Impact

I. INTRODUCTION

Whiplash Associated Disorders (WAD), or ‘whiplash injuries’, sustained in vehicle crashes is a worldwide concern. In Sweden, such injuries account for ~70 percent of all injuries leading to disability due to vehicle crashes [1]. The majority of those who experienced initial neck symptoms following the car crash recovered within a few weeks or months after the crash [2]. However, 5 to 10 percent of individuals experienced varying degrees of permanent disabilities [2]–[4]. Whiplash injuries may occur at relatively low velocity changes (Δv), typically <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]–[22]. 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 [23]–[25]. 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 [24]–[35].

Crash test dummies are used when developing and evaluating the occupant protection performance of a vehicle. The 50th percentile male crash test dummy size corresponds to a ~90th–95th percentile female with regards to stature and mass [36], resulting in females not being well represented by the existing low velocity rear impact male dummies; the BioRID and the RID3D. Consequently, the current seats and whiplash protection systems are primarily adapted to the 50th percentile male with little consideration of female properties. Existing

A. Carlsson, PhD, Researcher at Chalmers University of Technology, Sweden (+46 31 772 3650, anna.carlsson@chalmers.se); F. Chang, PhD, is Project Manager in the CAE Department at Humanetics Innovative Solutions, USA; P. Lemmen is Manager of the European Engineering group at Humanetics, the Netherlands; A. Kullgren is head of Folksam Research and Adjunct Professor at Chalmers University of Technology, Sweden; K.-U. Schmitt, PhD, works for AGU Zurich (Switzerland) and the Swiss Federal Institute of Technology (ETH Zurich); A. Linder, PhD, is Research Director of Traffic Safety at The Swedish National Road and Transport Research Institute (VTI), Sweden; M.Y. Svensson is Professor in Vehicle Safety in the Department of Applied Mechanics at Chalmers University of Technology, Sweden.

whiplash protection concepts are approximately 30 percent more effective for males than for females according to insurance claims records (**Fig. 1**) [37]. The difference between females and males has effectively increased even though the overall whiplash injury risk has decreased in rear impacts. It is important to further investigate these differences and to understand the reason behind them in order to achieve better protection for both females and males.

In view of the above, the European research project ADSEAT (Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants) was initiated. The overall objective of ADSEAT is to provide guidance on the protective performance evaluation of vehicle seats, aiming at reducing the incidence of whiplash injuries. The work is focussed on evaluating the protective performance of seats for female as well as male occupants. For this purpose the development of an average female size finite element crash dummy model is a part of the ADSEAT project. This new research tool will be used in parallel with the BioRID II dummy model when evaluating enhanced whiplash injury protection systems.

The objective of this study is to develop and evaluate a finite element (FE) model of a 50th percentile female rear impact crash dummy.

II. METHODS

This study was divided into four subtasks: 1) selecting the size of the EvaRID V1.0 model 2) establishing anthropometric specifications of the model 3) model development 4) model evaluation.

Selecting the size

Different types of sources were assessed in the EvaRID dummy model size selection process, such as injury statistics, anthropometric data and previous publications on dummy development. Injury statistics were extracted in order to verify that a 50th percentile female dummy would correlate in size to the females most frequently suffering whiplash injury in rear impacts. Anthropometric data and previous publications on dummy development were studied in order to define the stature and mass of the 50th percentile female.

The injury statistics were collected from two different sources; the Working Group on Accident Mechanics (AGU) Zurich database (Switzerland) and the insurance company Folksam's database (Sweden). The AGU Zurich database was initiated in 2005 and contains records of technical as well as medical information of persons who have sustained WAD in car crashes. Insurance claims made to the Swiss Accident Insurance Fund, the largest accident insurer in Switzerland covering most of the working population, forms the basis for these records. Researchers at AGU follow up most insurance claims by victims suffering neck symptoms following a car crash once the victims are absent from work for more than four weeks. Police reports, vehicle specific information as well as medical files are added to the AGU Zurich database. These records also include basic anthropometric measures, such as stature and mass of the injured persons. The Folksam in-depth database consists of reported car crashes in Sweden involving cars fitted with crash pulse recorders to record car acceleration-time history. Occupant data such as age, gender, stature and mass are also noted in the database. The data used for age, gender, stature and mass distributions cover front seat occupants aged 18 years and above involved in reported car crashes between 1992 and 2010, irrespective of crash direction or occupant injury. In total 1610 female and 2093 male front seat occupants were included. The basic anthropometry of the injured females was compared to the average stature and mass of the female population in Switzerland (year 2007: 164.7 cm/63.4 kg, obtained by written communication from Swiss Statistical Office) and Sweden (year 2006: 166.2 cm/66.1 kg [38]).

Two main sources were studied for reference when selecting the size for the 50th percentile female model; the University of Michigan Transportation Research Institute (UMTRI) study [39]–[41] and the WorldSID project [45]. The purpose with the UMTRI study was to develop specifications for crash test dummies. Anthropometric data were initially collected and analysed for four adult body sizes; the 5th and 50th percentile females, and the 50th and 95th percentile males. The stature, mass and seated height (**TABLE I**) was defined based on the National Health and Nutrition Examination Survey (HANES) of 1971–1974 [42]–[43]. These data were collected

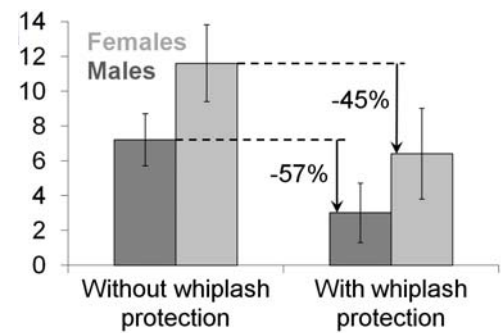


Fig. 1. Whiplash injury reduction for females and males including 95% CI. Based on [37].

on 13,645 individuals representing the 128 million persons aged 18–74 in the US population. Due to limited funds it was however decided that the 50th percentile female should be excluded from the latter part of the study. The purpose with the WorldSID project was to design a new generation side impact crash test dummy [45]. Based on anthropometric data (weighted by road fatality rates) across eight regions comprising OECD countries it was concluded that the size of a world-harmonized 50th percentile adult male would correspond well with the size of the 50th percentile adult male as was defined by the UMTRI project [39]–[41].

TABLE I

STATURE, MASS, AND SEATED HEIGHT OF THE
FOUR ADULT BODY SIZES – UMTRI [39].

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

Anthropometric specifications

The anthropometric data for the 50th percentile female was mainly collected from two references [44][46]. The study by [46] was based on data from several military and civilian sources. Emphasis was placed on the most important surveys, giving due consideration to their accuracy, sampling size and how recently they were performed. The study by [44] was part of a series of studies designed to obtain information about mass distribution characteristics (including moment of inertia and centre of volume) of the living human body and its segments, and to establish reliable means of estimating such properties from easily measured body dimensions. Their study was based on 46 adult female subjects, selected to approximate the range of stature and mass combinations found in the general US female population. The sampling plan was to achieve a stature and mass distribution comparable to that found in the civilian female US population as reported in the HANES study of 1971–1974 [42]–[43].

In addition to the above sources, anthropometric data taken 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 anthropometry data. Finally, parts of the 50th percentile male data [49] were used for comparative purposes.

EvaRID V1.0 – Model development

The EvaRID V1.0 model was developed by scaling an existing BioRID II LS-DYNA model (DYNAmore GmbH). The goal of the scaling was to make sure that the mass and length data of each body segment match the anthropometric data for the 50th percentile female [44][46]. In the present study, we choose to scale mass and length dimensions of each body segment according to equations (1)–(2) to obtain dimensions representative of the 50th percentile female:

$$\text{Mass Ratio:} \quad MR = \frac{M_{\text{EvaRID}}}{M_{\text{BioRID}}} \quad (1)$$

$$\text{Scale Factor Length:} \quad SFL = \frac{L_{\text{EvaRID}}}{L_{\text{BioRID}}} \quad (2)$$

Width and depth dimensions for the EvaRID were then established based on scaling of each body segment (**TABLE II**).

Apart from the geometrical scaling, stiffness and damping properties of those parts representing the neck and spine response (i.e. torsion pin stiffness, bumper stiffness, discrete damping elements as well as friction elements included in the model) were scaled to a value of 70 percent of the original values in the BioRID II model. The chosen reduction of the stiffness and damping properties was based on reported differences between females and males in static neck flexion and extension muscle strength [50]. Due to the non-linear response under dynamic loadings and large displacements, the selected reduction should be regarded as an initial estimate for further correlation against

TABLE II

EQUATIONS FOR SFB (SCALE FACTOR BREADTH) AND SFD
(SCALE FACTOR DEPTH) FOR DIFFERENT BODY PARTS.

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

test data.

Model evaluation

The EvaRID V1.0 model was simulated and compared to the responses in the volunteer rear impact test conditions at Δv 7 km/h [35]. The data were taken from six volunteers with an average stature similar to the EvaRID stature (161.8 cm). The average age was 23 years; the stature varied from 162 to 166 cm with an average of 164 cm; and the mass varied from 54 to 64 kg with an average of 59 kg.

A seat model representative of the test set-up was developed for the initial evaluation of the dynamic response of the EvaRID V1.0 model. In the sled tests, a Volvo 850 seat-base dating from the early 1990's was used. In the model, however, a public Ford Taurus seat-base was used during the EvaRID evaluation, assuming differences in the seat-base having minimal influence. The seatback consisted of four stiff panels, each suspended in the stiff seatback frame in four coil springs (**Fig. 2**) [35]. The panels were covered in a 20 mm thick layer of medium quality Tempur foam and lined with plush fabric (Volvo 850, year model 1993). The panels and foam were fitted according to the specified dimensions of the Volvo seat. The stiffness of the coil springs were measured and implemented in the finite element model. The head restraint consisted of one coil spring suspended stiff panel which was covered by 20 mm thick soft and 20 mm thick medium Tempur foam. The seatback frame inclination was adjusted to 24.3°. The volunteers wore a lap belt during the test. An angled plate, resembling a passenger floor pan surface of a standard car, was mounted on the target sled (**Fig. 2**).



Fig. 2. The test setup [35].

Dynamic response corridors were provided for x-accelerations, x-displacements and angular displacements of the head, T1, as well as head relative to T1 generated from the averages $\pm$ one standard deviation (SD) [35].

In addition, three tests with a BioRID dummy were performed in the same test setup as the tests with the female volunteers.

III. RESULTS

EvaRID - Selection of size

Records involving females who have sustained whiplash injuries in rear impacts were extracted from the AGU Zurich database, Switzerland (N=2,146), and from the Folksam database, Sweden (N=1,610). Basic anthropometric measures were then extracted from these records. The stature and mass distributions of the injured females are summarised in **Fig. 3**.

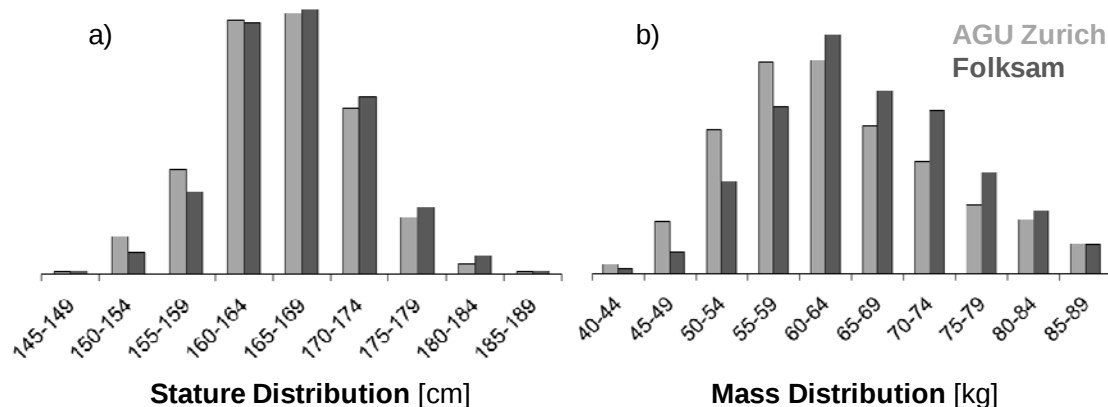


Fig. 3. The stature and mass distributions of whiplash injured female occupants in a) Sweden (from the Folksam database) and b) Switzerland (from the AGU Zurich database).

In the AGU Zurich database, the injured females 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 (obtained by written communication from Swiss Statistical Office). Correspondingly, in the Folksam database the average stature/mass was 165.3 cm/65.2 kg for the injured females, which correlate well with the average size of the female population in Sweden, 165.9 cm/65.9 kg [38]. Thus, the 50th percentile female dummy model would correlate in size to the females that are most frequently injured in rear impacts.

We found the anthropometry study of the WorldSID project [45] to be best available for defining an anthropometric size that is reasonably representative of the worldwide population at risk. Since it was concluded 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 the UMTRI project [39]–[41], we found it reasonable to make the same conclusion regarding the 50th percentile adult female. Thus, it was decided to base the EvaRID V1.0 model on the anthropometric measures of the 50th percentile female from the UMTRI study (stature 161.8 cm, mass 62.3 kg, **TABLE I**).

Anthropometry of the 50th Percentile Female

The stature, mass and seated height of the EvaRID model was thus established and the next step was to specify the body dimensions, mass of different body segments and the distance between different joints of the 50th percentile female. Since the UMTRI study only defined the stature, mass and seated height of the 50th percentile female, the data had to be found elsewhere. The studies [39]–[41] described in detail how the anthropometry and properties were specified for the 5th percentile female as well as the 50th and 95th percentile male crash test dummies. The same method was used in this study, when appropriate, in order to establish the anthropometry of the 50th percentile female.

The circumferences for different parts of the body of the 50th percentile female were summarised in **TABLE III** in order to compare the data from [44] and [46] with data from the software programmes RAMSIS and GEBOD. The table shows that in general there are good correlations between the different datasets.

In [44], the 50th percentile female stature was 161.2 cm and the mass 63.9 kg; i.e. 0.4 percent shorter and 2.6 percent heavier than that of the EvaRID. In [46], the 50th percentile female stature was 161.5 cm and the mass 65.8 kg; i.e. 0.2 percent shorter and 5.6 percent heavier than that of the EvaRID. No scaling was performed of the length dimensions [44][46], since the difference in stature between these two references and the EvaRID model was considered to be minor (0.4 percent and 0.2 percent). However, due to the somewhat greater difference in mass (2.6 percent and 5.6 percent), the depth and width dimensions and the circumferences [44][46] was scaled according to:

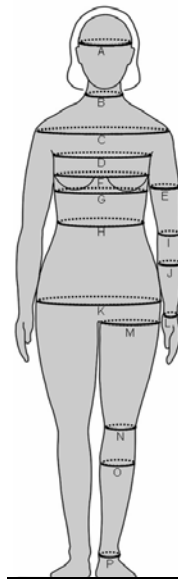
$$[44]: (63.9/62.3)^{1/3} = 1.008 \quad \Rightarrow 1 \text{ percent scaling}$$

$$[46]: (65.8/62.3)^{1/3} = 1.018 \quad \Rightarrow 2 \text{ percent scaling}$$

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) (**Eq. 1**) of body parts for the EvaRID and BioRID II dummy models are provided in **TABLE IV**. Additional data (input to the EvaRID V1.0 model) can be found in the **Appendix**, such as distances between joints (**Fig. A1**); torso details (**Fig. A2**) regression equations to compute segment volumes (**TABLE A1**); and anthropometric variables (**TABLE AII**).

TABLE III
COMPARISON OF ANTHROPOMETRIC DATA
(CIRCUMFERENCES) OF THE 50TH PERCENTILE FEMALE.
BASED ON [44], [46], GEBOD, AND RAMSIS.

Body Part	Circumference [cm]			
	[46]	[44]	GEBOD	RAMSIS
Stature [cm]	161.5	161.2	161.8	161.8
Mass [kg]	65.8	63.9	62.3	62.3
A Head	54.9	54.8	-	-
B Neck	35.1	32.9	34.3	-
C Shoulder	98.0	-	-	-
D Arm pit	89.2	-	-	-
E Arm ³⁾	29.0 ¹⁾	28.8 ¹⁾	27.1	21.7
F Bust	95.8	95.4	-	-
G Chest ⁴⁾	79.0	-	-	-
H Waist	74.2	-	-	74.6
I Elbow	28.2 ¹⁾	24.4 ²⁾	27.5	-
J Forearm	26.2 ¹⁾	21.2 ²⁾	24.2	23.7
K Hip	100.8	100.1	-	-
L Wrist	15.5	15.7	15.2	-
M Thigh	59.2	59.4	58.0	-
N Knee	38.1	37.0	38.5	-
O Calf	35.8	35.8	35.3	33.8
P Ankle	21.8	21.4	21.5	-



1) Flexed
2) Relaxed
3) Upper Arm

4) Below Bust
5) Upper Thigh

EvaRID V1.0 – Model development

The Scale Factor Length (SFL) was established for each body segment by taking the EvaRID's length over the BioRID's length (Eq. 2). The calculations of the Scale Factor Breadth (SFB) and Scale Factor Depth (SFD) for each body segment are described in detail below and the results are included in **TABLE V**. The masses and mass ratios for each body segment are listed in **TABLE IV**.

The head was scaled to meet three dimensional requirements for the EvaRID:

- Total length: 20.30 cm [46]
- Breadth: 14.58 cm [44]
- Depth: 18.69 cm [44]

where the total length is the vertical distance between the top of the head and the chin, the breadth is the maximum horizontal (lateral) distance above the ears, and the depth is the maximum distance between the glabella and the occiput. The corresponding dimensions of the BioRID's head were: total length 21.59 cm, breadth 15.76 cm and depth 19.99 cm. The same scaling principle was used when calculating SFB and SFD as for SFL (Eq. 2) (**TABLE II**). The mass requirement of the head (3.58 kg, **TABLE IV**) was met by adjusting the density of the skull.

The neck height was defined as the mastoid height less the cervical height. Considering the complexity of the neck modelling, the SFD_{neck} was selected to be the equivalent to the SFL_{neck} and the SFB_{neck} was assumed to be equivalent to the $SFB_{upper\ torso}$ (**TABLE II**). Due to lack of an accurate landmark of the mastoid and the cervical spine, the 50th percentile male data [49] was used for the neck height (12.04 cm). The mass ratio of 0.664 was derived from $(SFL \cdot SFB \cdot SFD)_{neck}$ and was slightly less than the mass ratio of the head (0.789) and the upper torso (0.736) (**TABLE IV**).

The upper torso was defined as the torso without the pelvis and ran from the cervical to the iliac crest. During scaling the EvaRID maintained the same spine and back profile as the BioRID II as the scaling factors for the SFL and SFD were kept identical. The mass of the upper torso was derived by subtracting the pelvis mass from the torso mass. The breadth, defined as the distance between shoulder joints, was 31.50 cm for the EvaRID and 34.60 cm for the BioRID II. Subsequently the SFD was derived from MR, SFL, and SFB (**TABLE II**). Thereafter, the torso shape was further modified based on data from either [44] or [46] since [39] only provides stature, mass and the seated height for the 50th percentile female. The model's depth at the bust point was measured in two different ways: 231 mm was measured from the bust point to the exact opposite point at the back of the jacket; 234 mm was measured from the bust point to the most rearward point on the back of the jacket. Data from [46] showed that the waist breadth was 22.4 cm, quite different from 31.05 cm [44]. In this model, 31.05 cm [44] was selected as well as the following breadth dimensions of the torso: bust 288 mm; 10th rib 257 mm; buttock 373 mm; and bust point distance 180 mm.

The seated height was defined as the standing height less 774 mm [46]. The height of the cervical, bust point, tenth rib, iliac crest and omphalion (waist) was based on [44].

The limb scaling was following basic scaling methodology. Firstly, the mass ratio of EvaRID over BioRID II was calculated (Eq. 1) (**TABLE IV**). Then the SFL of EvaRID over BioRID II was determined based on 50th percentile female data [46] and dimensions taken from the BioRID II model (Eq. 2) (**TABLE V**). The length of the upper arm

TABLE IV

THE MASS, THE MASS DISTRIBUTION (IN PERCENT OF THE TOTAL MASS), AND THE MASS RATIO (MR) (M_{EvaRID}/M_{BioRID}) OF THE BIORID II AND THE EVARID.

Body Part		EvaRID		BioRID		$\frac{M_{EvaRID}}{M_{BioRID}}$
		Mass [kg]	% of total	Mass [kg]	% of total	
Head	x1	3.58	5.7	4.54	5.8	0.789
Upper Torso ¹⁾	x1	19.58	31.4	26.61	34.0	0.736
Pelvis ²⁾	x1	15.84	25.4	15.80	20.2	1.003
Upper Arm	x2	1.40	2.2	2.02	2.6	0.691
Lower Arm ³⁾	x2	1.16	1.9	2.23	2.9	0.518
Upper Leg ⁴⁾	x2	5.67	9.1	5.99	7.7	0.947
Lower Leg ⁵⁾	x2	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, the abdomen, and the spine (including the neck). 3) Hand included.
 2) Flaps included. 4) Flap excluded.
 5) Foot included.

TABLE V

CALCULATION OF THE SCALE FACTOR LENGTH (SFL) ($=L_{EvaRID}/L_{BioRID}$) FOR DIFFERENT BODY PARTS. THE CORRESPONDING VALUES OF THE SCALE FACTOR BREADTH (SFB) AND THE SCALED FACTOR DEPTH (SFD) ARE GIVEN.

Body Part	Length		Scale Factors		
	L_{EvaRID} [cm]	L_{BioRID} [cm]	SFL	SFB	SFD
Head ¹⁾	20.30 ⁸⁾	21.59	0.940	0.925	0.935
Neck ²⁾	10.28 ⁸⁾	12.04	0.854	0.910	0.854
Upper Torso ³⁾	47.94 ⁸⁾	52.65	0.911	0.910	0.888
Pelvis	25.82 ⁸⁾	25.83	1.000	1.000	1.003
Upper Arm ⁴⁾	26.40 ⁸⁾	26.14	1.010	0.823	0.823
Lower Arm ⁵⁾	23.40 ⁸⁾	24.88	0.941	0.765	0.765
Upper Leg ⁶⁾	38.90 ⁸⁾	40.55	0.959	1.014	1.014
Lower Leg ⁷⁾	45.70 ⁸⁾	49.55	0.922	0.861	0.861

- 1) Top of head to chin. 6) Hip joint to knee joint.
 2) C0/C7 joint to C7/T1 joint. 7) Knee joint to bottom of heel along tibia.
 3) C7/T1 joint to mid-point of hip joints. 8) [46]
 4) Shoulder joint to elbow joint.
 5) Elbow joint to wrist joint.

was measured from shoulder joint to elbow joint; the lower arm from the elbow joint to the wrist joint; the upper leg from the hip joint to the knee joint; and the lower leg from the knee joint to the bottom of the heel (**TABLE IV**). The SFB and SFD were then derived by taking the square root of mass ratio over SFL (**TABLE II**).

No major difference was found between the dimensions of 50th percentile female and 50th percentile male pelvis [44][49]. The buttock depth was 241.2 mm/240.8 mm; the bitrochanteric breadth 31.63 cm/31.76 cm; and the pelvic length 258.20 mm/258.32 mm for the female and male, respectively. Furthermore, the distance between the hip joints was similar for the 50th percentile female and the BioRID II, 18.0 cm [46] and 17.96 cm, respectively. Accordingly, the pelvis mass (**TABLE IV**) was similar for the 50th percentile male (15.80 kg) and the 50th percentile female (15.84 kg). Thus, only minor changes were made to the pelvis, for instance the shape was adjusted to match the breadth dimensions [44]. The EvaRID V1.0 dummy model maintains the same pelvis angle of 26.5 degrees as the BioRID II.

A comparison between the EvaRID V1.0 and the BioRID II models is shown in **Fig. A3** in **Appendix**.

Model Evaluation

A pre-simulation was performed to establish the initial position of the sled simulation of the dummy model by dropping the EvaRID into the seat and allowing the gravity to find its balanced position. After the balanced position was achieved the head panel was adjusted, in this case closer to the head, to match the measured initial head-to-head restraint distance, as estimated from film analysis. An angled plate resembling the floor pan surface was introduced and a seatbelt was fastened before applying the measured acceleration pulse (**Fig. 4**).

Simulated results were compared with the dynamic response corridors obtained from the volunteer tests [35] (**Fig. 5**). In general, the simulated results correlated well for about ~250 ms with responses being inside or close to the corridors. However, the T1 rearward angular displacement was substantially less with values lower than 25 percent of the requirement set by the corridor. This may indicate that the thoracic spine is too stiff in extension. An extensive parameter study was conducted to explore these and other causes, however, these adjustments resulted only in a minor increase of the T1 rearward angular displacement.



Fig. 4. Test simulation with the EvaRID V1.0 model.

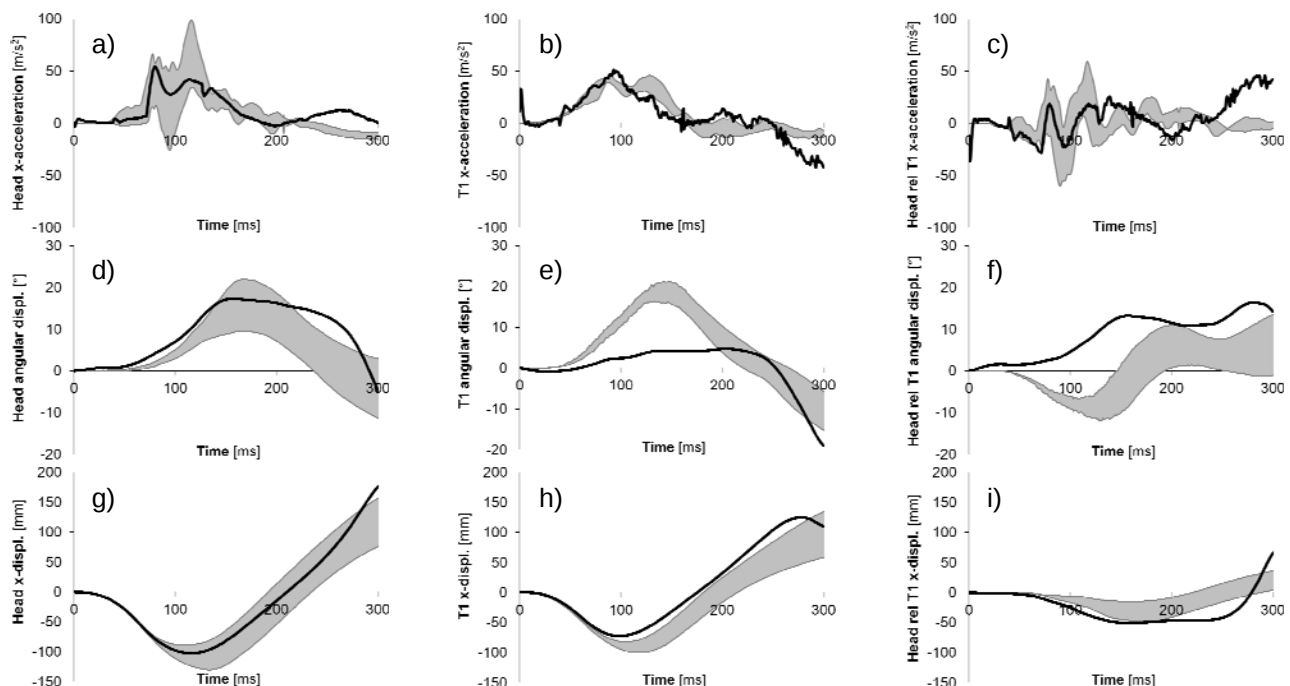


Fig. 5. X-accelerations of (a) the head, (b) the T1 and (c) the head relative to T1; angular displacements of (d) the head, (e) the T1 and (f) the head relative to T1; x-displacements relative to the sled of (g) the head, (h) the T1 and (i) the head relative to T1 for the 50th percentile female volunteers (grey corridor) and the EvaRID V1.0 (solid black line). The response corridors were calculated $\pm 1SD$ from the average response.

To investigate the model response in more detail, simulations using the original BioRID II dummy model were made under volunteer loading conditions. Experimental data, dynamic response corridors and simulated results are depicted in **Fig. 6**. It can be observed that the BioRID II model's responses are equivalent to the responses by EvaRID for these loading conditions, including the notably lesser T1 rotation.

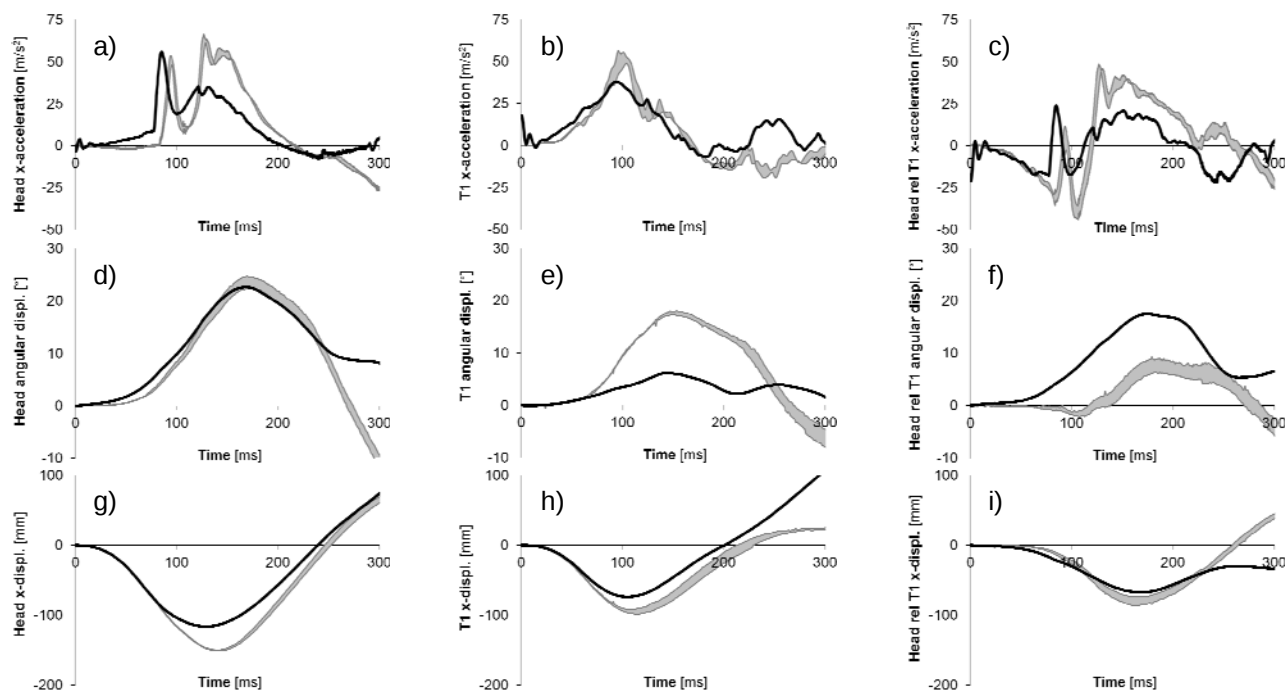


Fig. 6. X-accelerations of (a) the head, (b) the T1 and (c) the head relative to T1; angular displacements of (d) the head, (e) the T1 and (f) the head relative to T1; x-displacements relative to the sled of (g) the head, (h) the T1 and (i) the head relative to T1 for the BioRID dummy (grey corridor) and the BioRID II model (solid black line). The response corridors were calculated $\pm 1SD$ from the average response.

IV. DISCUSSION

It is well established that females have a higher whiplash injury risk in rear impacts compared to males [9]–[10], [14]–[16], [18]–[19]. There are, for example, differences in the neck anatomy and physiology in males and females [50]–[56], which may contribute to the greater whiplash injury risk in females. Furthermore, males and females have different anthropometry and mass distribution which may influence the interaction of the upper body with the seatback and head restraint, and thus the injury risk. Females tend to have greater head x-acceleration, greater (or similar) T1 x-acceleration, lesser (or similar) NIC value and more pronounced rebound compared to males in rear impact volunteer tests [24]–[35].

It has been reported that tall females have the highest whiplash injury risk in standard vehicle seats (i.e. no advanced whiplash protection systems fitted) in rear impacts [16], [58]–[59]. However, this study found that the females associated with the highest whiplash injury frequency in rear impacts are of average size (**Fig. 3**). Similar results have previously been reported [9]. Yet, only the extremes of the female population are accounted for by the existing dummies that may be used for rear impact crash testing; the 50th percentile male rear impact dummy, or possibly, the 5th percentile female frontal impact dummy. This may explain why existing whiplash protection concepts are approximately 30 percent more effective for males than females regarding permanent medical impairment [37] (**Fig. 1**). The assessment and development of whiplash prevention systems may thus benefit from an additional rear impact dummy – the 50th percentile female – since it would correlate in size to the females that are most frequently injured.

The anthropometry and mass data of the 50th percentile female was predominantly obtained from the UMTRI study [39] and two anthropometric studies [44][46]. The UMTRI study was based on anthropometric data collected in the early 1970's in the USA. Due to the secular trend (i.e. the variation in body size over time) the average statures and body masses have increased since then. However, the selected size for the EvaRID (stature 161.8 cm, mass 62.3 kg) correlates to the 50th percentile female in relation to the existing adult dummies. In addition, the selected size was less than 1 percent shorter than the average female (163.2 cm)

according to the WorldSID study [45], who based their data on anthropometric studies across eight regions comprising OECD countries (weighted by road fatality rates).

A computational rear impact dummy model, EvaRID V1.0, representing the 50th percentile female was developed (**Figs. A2, A3**). The model was obtained by scaling anthropometric, geometric and mass properties of an existing BioRID II dummy model (DYNAmore GmbH). The relative mass distribution of the EvaRID was somewhat different from the BioRID – the EvaRID had a slightly lighter torso, a heavier pelvis and slightly heavier thighs. Based on reported differences between females and males in neck muscle strength [50] the stiffness and damping properties of the neck and spine were scaled to 70 percent of the original values in the BioRID II model. Apart from the muscle strength, further factors may affect the stiffness of the spine, such as muscle reflexes [50][60], ligament properties [57][61], support area between vertebrae [57] and ageing [62]–[65]. These variables were not considered in the EvaRID V1.0 model.

The EvaRID model was validated with regard to rear impact tests comprising female volunteers. The volunteers were rather young at an average age of 23 years. However, several studies have shown that the whiplash injury risk is highest at younger (or middle) ages and tends to decrease at older ages [16][59][66]. The volunteers were thus fairly representative of the age group most at risk of sustaining a whiplash injury.

The simulated dynamic response correlated well until ~250 ms with responses being within or close to the corridors; however, the T1 rearward angular displacement was less than 25 percent of the requirement set by the corridor (**Fig. 5**). In spite of an extensive parametric study of the T1 angular displacement, the general response did not improve significantly. In addition to the initial reduction in stiffness and damping characteristics, values were reduced further down to 50 percent of the original values in the BioRID II model, stiffness of the spring coils in the lower seat segments was increased, and elements representing the breasts were removed. Although each of these adjustments resulted in some increase of the T1 angular displacement, the general response did not show any significant improvement, even in different combinations.

As a further check it was decided to run the BioRID II model in the same test setup as in the volunteer tests. Experimental test data and dynamic response corridors were obtained from tests with the BioRID dummy. The BioRID II and the EvaRID V1.0 models displayed identical trends, including the notably lesser T1 rearward angular displacement (**Fig. 6**). The results suggest that the biofidelity of the EvaRID V1.0 model and the BioRID II models have limitations at low velocity changes (7 km/h) which may be explained by the fact that the BioRID II model was validated against dummy test results in the range of consumer test load conditions (EuroNCAP).

Based on these observations it is advisable to further evaluate and improve the BioRID II and EvaRID models at low velocity changes. In addition, further studies of the performance of the BioRID II model at higher velocity changes are recommended. In defining the test set-up it is noted that the head restraint was relatively close to the head in the volunteer tests [35], which indicates that the head response is largely governed by the head restraint properties and not entirely by the neck properties. Thus, these volunteer tests are less suitable for fine tuning the neck parameters, stressing the importance of using greater head restraint gap in future volunteer tests. Once improved correlation is obtained for T1 rotational response, further fine tuning of the stiffness and damping characteristics could be considered next. It is also advisable to establish the curvature of the spine and its relation to the HR distance for seated 50th percentile female occupants. These results need to be implemented to further improve the EvaRID model.

V. CONCLUSIONS

The EvaRID V1.0 model showed good correlations until ~250 ms for most parameters except for the T1 rearward angular displacement. When running the BioRID II model and comparing it with dummy data under the same loading conditions, identical results were found for that model. This may indicate that both models have limitations at lower velocity changes (7 km/h). Further work on the stiffness properties is needed for the model to achieve a response fully within the corridors in the volunteer tests. This may include a profound survey of the elemental design of the BioRID II and EvaRID models. Furthermore, additional volunteer data with a greater initial distance between the head and the head restraint would be valuable to further improve the dynamic response of the dummy model. Such studies are included in the ADSEAT project. Once fully validated, the dummy model will be utilised in the design and evaluation of adaptive seat system concepts in order to provide enhanced neck injury protection for female occupants.

VI. ACKNOWLEDGEMENT

This study is part of the ADSEAT (Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants) project funded by the European Commission within the 7th Framework Programme. Additional funding has been received from the Swedish Transport Agency.

The authors would like to thank DYNAmore GmbH for providing the BioRID II dummy model as basis for the EvaRID model developments.

VII. REFERENCES

- [1] Kullgren A, Krafft M, Lie A, Tingvall C. The Effect of Whiplash Protection Systems in Real-Life Crashes and Their Correlation to Consumer Crash Test Programmes. *Proc. 20th ESV Conf.*; 2007; Lyon (France)
- [2] The Whiplash Commission. The Whiplash Commission Final Report. 2005. ISBN 91-975655-4-7. Available at: http://www.whiplashkommissionen.se/pdf/WK_finalreport.pdf. Accessed July 7, 2011
- [3] Nygren Å. Injuries to Car Occupants - Some Aspects of the Interior Safety of Cars, *Akta Oto-Laryngologica*, Supplement 395, ISSN 0365-5237; 1984; Almqvist & Wiksell, Stockholm, Sweden.
- [4] Galasko CSB, Murray PA, Pitcher M. Whiplash Associated Disorders. *Proc. 15th ESV Conf.*; 1996; Melbourne (Australia)
- [5] Eichberger A, Geigl BC, Moser A, Fachbach B, Steffan H. Comparison of Different Car Seats Regarding Head-Neck Kinematics of Volunteers During Rear End Impact. *Proc. IRCOBI Conf.*; 1996; Dublin (Ireland)
- [6] Kullgren A, Eriksson L, Boström O, Krafft M. Validation of Neck Injury Criteria Using Reconstructed Real-Life Rear-End Crashes With Recorded Crash Pulses. *Proc. 18th ESV Conf.*; 2003; Nagoya (Japan)
- [7] Watanabe Y, Ichikawa H, Kayama O, Ono K, Kaneoka K, Inami S. Influence of Seat Characteristics on Occupant Motion in Low-Velocity Rear-End Impacts. *Accid Anal Prev.* 2000;32:243–250
- [8] Narragon EA. Sex Comparisons in Automobile Crash Injury. CAL Report No. VJ-1823-R15; 1965; Cornell Aeronautical Laboratory, Inc. of Cornell University, Buffalo, New York, USA.
- [9] Kihlberg JK. Flexion–Torsion Neck Injury in Rear Impacts. *Proc. 13th AAAM Conf.*; 1969; Minneapolis (Minnesota)
- [10] O'Neill B, Haddon W, Kelley AB, Sorenson WW. Automobile Head Restraints—Frequency of Neck Injury Claims in Relation to the Presence of Head Restraints. *Am J Public Health.* 1972;62:399–405
- [11] Thomas C, Faverjon G, Hartemann F, Tarriere C, Patel A, Got C. Protection Against Rear-End Accidents. *Proc. IRCOBI Conf.*; 1982; Cologne, Germany
- [12] Otremski I, Marsh JL, Wilde BR, McLardy Smith PD, Newman RJ. Soft Tissue Cervical Injuries in Motor Vehicle Accidents. *Injury.* 1989;20:349–351
- [13] Maag U, Desjardins D, Bourbeau R, Laberge-Nadeau C. Seat Belts and Neck Injuries. *Proc. IRCOBI Conf.*; 1990; Bron (France)
- [14] Morris AP, Thomas PD. Neck Injuries in the UK Co-operative Crash Injury Study. *Proc. 40th Stapp Conf.*; 1996; Albuquerque (New Mexico)
- [15] Dolinis J. Risk Factors for “Whiplash” in Drivers: a Cohort Study of Rear-End Traffic Crashes. *Injury.* 1997;28:173–179
- [16] Temming J, Zobel R. Frequency and Risk of Cervical Spine Distortion Injuries in Passenger Car Accidents: Significance of Human Factors Data. *Proc. IRCOBI Conf.*; 1998; Göteborg (Sweden)
- [17] Richter M, Otte D, Pohlemann T, Krettek C, Blauth M. Whiplash-Type Neck Distortion in Restrained Car Drivers: Frequency, Causes and Long-Term Results. *Eur Spine J.* 2000;9:109–117
- [18] Chapline JF, Ferguson SA, Lillis RP, Lund AK, Williams AF. Neck Pain and Head Restraint Position Relative to the Driver's Head in Rear-End Collisions. *Accid Anal Prev.* 2000;32:287–297
- [19] Krafft M, Kullgren A, Lie A, Tingvall C. The Risk of Whiplash Injury in the Rear Seat Compared to the Front Seat in Rear Impacts. *Traffic Inj Prev.* 2003;4:136–140
- [20] Jakobsson L, Norin H, Svensson MY. Parameters Influencing AIS 1 Neck Injury Outcome in Frontal Impacts. *Traffic Inj Prev.* 2004;5:156–163
- [21] Storvik SG, Stemper BD, Yoganandan N, Pintar FA. Population-Based Estimates of Whiplash Injury Using NASS CDS Data. *Biomed Sci Instrum.* 2009;45:244–249
- [22] Carstensen TB, Frostholt L, Oernboel E, Kongsted A, Kasch H, Jensen TS, Fink P. Are There Gender Differences in Coping with Neck Pain Following Acute Whiplash Trauma? A 12-month follow-up study. *Eur J Pain.* 2011 (Epub ahead of print).

- [23] Svensson MY, Lövsund P, Håland Y, Larsson S. Rear-End Collisions—A Study of the Influence of Backrest Properties on Head–Neck Motion Using a New Dummy Neck. SAE/SP-93/963, Paper No. 930343;1993; *Society of Automotive Engineers, Inc.*, Warrendale, PA, USA
- [24] Croft AC, Haneline MT, Freeman MD. Differential Occupant Kinematics and Forces Between Frontal and Rear Automobile Impacts at Low Speed: Evidence for a Differential Injury Risk. *Proc. IRCOBI Conf.*; 2002; Munich (Germany)
- [25] Viano DC. Seat Influences on Female Neck Responses in Rear Crashes: A Reason Why Women Have Higher Whiplash Rates. *Traffic Inj Prev.* 2003;4:228–239
- [26] Szabo TJ, Welcher JB, Anderson RD, Rice MM, Ward JA, Paulo LR, Carpenter NJ. Human Occupant Kinematic Response to Low-Speed Rear End Impacts. *Proc. 38th Stapp Conf.*; 1994; Fort Lauderdale (Florida)
- [27] Siegmund GP, King DJ, Lawrence JM, Wheeler JB, Brault JR, Smith TA. Head/Neck Kinematic Response of Human Subjects in Low-Speed Rear-End Collisions. *Proc. 41st Stapp Conf.*; 1997; Orlando (Florida)
- [28] Hell W, Langwieder K, Walz F, Muser M, Kramer M, Hartwig E. Consequences for Seat Design due to Rear End Accident Analysis, Sled Tests and Possible Test Criteria for Reducing Cervical Spine Injuries After Rear-End Collision. *Proc. IRCOBI Conf.*; 1999; Sitges (Spain)
- [29] Welcher JB, Szabo JS. Relationships Between Seat Properties and Human Subject Kinematics in Rear Impact Tests. *Accid Anal Prev.* 2001;33:289–304
- [30] Mordaka J, Gentle RC. The Biomechanics of Gender Difference and Whiplash Injury: Designing Safer Car Seats for Women. *Acta Politechnica.* 2003;43:47–54
- [31] Ono K, Ejima S, Suzuki Y, Kaneoka K, Fukushima M, Ujihashi S. Prediction of Neck Injury Risk Based on the Analysis of Localized Cervical Vertebral Motion of Human Volunteers During Low-Speed Rear Impacts. *Proc. IRCOBI Conf.*; 2006; Madrid (Spain)
- [32] Linder A, Carlsson A, Svensson MY, Siegmund GP. Dynamic Responses of Female and Male Volunteers in Rear Impacts. *Traffic Inj Prev.* 2008;9:592–599
- [33] Schick S, Horion S, Thorsteinsdottir K, Hell W. Differences and Commons in Kinetic Parameters of Male and Female Volunteers in Low Speed Rear End Impacts. *Proc 2nd TÜV SÜD Conf., Whiplash – Neck Pain in Car Crashes*; 2008, Erding (Germany)
- [34] Carlsson A, Siegmund GP, Linder A, Svensson M. Motion of the Head and Neck of Female and Male Volunteers in Rear Impact Car-to-Car Tests at 4 and 8 km/h. *Proc. IRCOBI Conf.*; 2010; Hanover (Germany)
- [35] Carlsson A, Linder A, Davidsson J, Hell W, Schick S, Svensson M. Dynamic Kinematic Responses of Female Volunteers in Rear Impacts and Comparison to Previous Male Volunteer Tests. *Traffic Inj Prev.* 2011;12:347–357
- [36] Welsh R, Lenard J. Male and Female Car Drivers—Differences in Collision and Injury Risks. *Proc. 45th AAAM Conf.*; 2001; San Antonio (Texas)
- [37] Kullgren A, Krafft M. Gender Analysis on Whiplash Seat Effectiveness: Results From Real-World Crashes. *Proc. IRCOBI Conf.*; 2010; Hanover (Germany)
- [38] Hanson L, Sperling L, Gard G, Ipsen S, Olivares Vergara C. Swedish Anthropometrics for Product and Workplace Design. *Appl Ergon.* 2008;40:797–806
- [39] Schneider LW, Robbins DH, Pflüg MA and Snyder RG. Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family. Final Report, UMTRI-83-53-1; *University of Michigan Transportation Research Institute*; 1983; Ann Arbor, Michigan, USA.
- [40] Robbins DH. Anthropometric Specifications for Mid-Sized Male Dummy. Final Report, UMTRI-83-53-2; *University of Michigan Transportation Research Institute*; 1983; Ann Arbor, Michigan, USA
- [41] Robbins DH. Anthropometric Specifications for Small Female and Large Male Dummies. Final Report, UMTRI-83-53-3; *University of Michigan Transportation Research Institute*; 1983; Ann Arbor, Michigan, USA
- [42] Abraham S, Johnson CL, Najjar F. Weight and Height of Adults 18-74 Years of Age. Vital Health Statistics, Series 11, Number 211; 1979; *National Center for Health Statistics*, Hyattsville, MD, USA
- [43] Abraham S, Johnson CL, Najjar MF. Weight and Height and Age for Adults 18-74 Years. Vital Health Statistics, Series 11, Number 208; 1979; *National Center for Health Statistics*, Hyattsville, MD, USA
- [44] Young JW, Chandler RF, Snow CC, Robinette KM, Zehner GF, Lofberg MS. Anthropometric and Mass Distribution Characteristics of Adult Female Body Segments. Federal Aviation Administration, *Civil Aeromedical Institute*; 1983; Oklahoma City, OK, USA
- [45] Moss S, Wang Z, Salloum M, Reed M, van Ratingen M, Beusenbergh M. Anthropometry for WorldSID a World-Harmonized Midsize Male Side Impact Crash Dummy. SAE, Paper No. 220-01-2202; 2000; *Society of Automotive Engineers, Inc.*, Warrendale, PA, USA

- [46] Diffrient N, Tilley AR, Bardagjy JC. Humanscale 1/2/3 – A Portfolio of Information. *The MIT Press*; 1974; Cambridge, MA
- [47] Cheng H, Obergefell L, Rizer A. Generator of Body (GEBOD) Manual. Report No. AL/CF-TR-1994-0051; 1994; Human Effectiveness Directorate, Crew Survivability and Logistics Division, *Wright-Patterson Air Force Base*, Ohio, USA
- [48] Seidl A. RAMSIS – A New CAD Tool for Ergonomic Analysis of Vehicles Developed for the German Automotive Industry. SAE Paper No. 970088; 1997; *Society of Automotive Engineers, Inc.*, Warrendale, PA, USA
- [49] McConville JT, Churchill TD, Kaleps I, Clauser CE, Cuzzi. Anthropometric Relationships of Body and Body Segment Moments of Inertia. AMRL-TR-80-119; 1980; *Wright-Patterson AFB*, Aerospace Medical Research Laboratory, Yellow Springs, OH, USA
- [50] Foust DR, Chaffin DB, Snyder RG, Baum JK. Cervical Range of Motion and Dynamic Response and Strength of Cervical Muscles. *Proc 17th Stapp Conf.*; 1973; Oklahoma City (Oklahoma)
- [51] Pettersson K, Kärrholm J, Toolanen G, Hildingsson C. Decreased Width of the Spinal Canal in Patients With Chronic Symptoms After Whiplash Injury. *Spine*. 1995;20:1664–1667
- [52] Vasavada AN, Li S, Delp SL. Three-Dimensional Isometric Strength of Neck Muscles in Humans. *Spine*. 2001;26:1904–1909
- [53] DeSantis Klinich K, Ebert SM, Van Ee CA, Flannagan CA, Prasad M, Reed MP, Schneider LW. Cervical spine Geometry in the Automotive Seated Posture: Variations With Age, Stature, and Gender. *Stapp Car Crash J*. 2004;48:301–330
- [54] Tatarek NE. Variation in the Human Cervical Neural Canal. *Spine*. 2005;5:623–631
- [55] Vasavada AN, Danaraj J, Siegmund GP. Head and Neck Anthropometry, Vertebral Geometry and Neck Strength in Height-Matched Men and Women. *J Biomech*. 2008;41:114–121
- [56] Stemper BD, Yoganandan N, Gennarelli TA, Pintar FA. Toward a Lower Neck Rear Impact Injury Criterion – Correlation of Lower Neck Loads With Spinal Kinematics. *Proc. IRCOBI Conf.*; 2007; Maastricht (The Netherlands)
- [57] Stemper BD, Yoganandan N, Pintar FA, Maiman DJ, Meyer MA, DeRosia J, Shender BS, Paskoff G Anatomical Gender Differences in Cervical Vertebrae of Size-Matched Volunteers. *Spine*. 2008;33:E44-E49
- [58] Lundell B, Jakobsson L, Alfredsson B, Jernström C, Isaksson-Hellman I. Guidelines for and the Design of a Car Seat Concept for Improved Protection Against Neck Injuries in Rear-End car impacts. SAE, Paper No. 980301, 1998; *Society of Automotive Engineers, Inc.*, Warrendale, PA, USA
- [59] Jakobsson L, Lundell B, Norin H, Isaksson-Hellman I. WHIPS-Volvo's Whiplash Protection Study. *Accid Anal Prev*. 2000;32:307–319
- [60] Siegmund GP, Sanderson DJ, Myers BS, and Inglis JT. Awareness Effects the Response to Single Whiplash Perturbations. *Spine*. 2003;28:671–679
- [61] Osakabe T, Hayashi M, Hasegawa K, Okuaki T, Ritty TM, Mecham RP, Wachi H, Seyama RP. Age- and Gender-Related Changes in Ligament Components. *Ann Clin Biochem*. 2001;38:527–532
- [62] Hanten WP, Lucio RM, Russell JL, Brunt D. Assessment of Total Head Excursion and Resting Head Posture. *Arch Phys Med Rehabil*. 1991;72:877–880
- [63] Youdas JW, Garrett TR, Suman VJ, Bogard CL, Hallman HO, Carey JR. Normal Range of Motion of the Cervical Spine: an Initial Goniometric Study. *Phys Ther*. 1992;72:770–780
- [64] Hanten WP, Olson S L, Russell JL, Lucio RM, Campbell AH. Total Head Excursion and Resting Head Posture: Normal and Patient Comparisons. *Arch Phys Med Rehabil*. 2000;81:62–66
- [65] Seacrist T, Maltese MR, Balasubramanian S, Garcia-Espana JF, Arbogast KB, Sterner R, Saffioti J, Kadlowec J. Comparison of Passive Cervical Spine Flexion in Children and Adults. *Proc. 21st ESV Conf.*; 2009; Stuttgart, (Germany)
- [66] Farmer CM, Wells JK, Werner JV. Relationship of Head Restraint Positioning to Driver Neck Injury in Rear-End Crashes. *Accid Anal Prev*. 1999;31:719–728

VIII. APPENDIX

TABLE AI

REGRESSION EQUATIONS FOR ESTIMATIONS OF THE VOLUME OF DIFFERENT BODY PARTS OF FEMALES [44].
THE CALCULATED VOLUME AND MASS OF DIFFERENT BODY PARTS OF THE 50TH PERCENTILE FEMALE.

Body Part	Volume Regression Equation	Volume [cm ³]		Mass [kg]	
		From [44]	Scaled variables	Based on [44]	Based on Scaled variables
Head	$V=132.85C_{head}+163.75H_{head}-13.73S-3,722.51$	3,894	3,886	3.51	3.58
Neck	$V=9.44S+23.57C_{neck}+14.26L_{neck}-1,658.86$	737	735	0.66	0.68
Thorax	$V=33.08M+285.77C_{bust}+422.96L_{thorax}-29,046.39$	18,175	17,782	16.38	16.36
Abdomen	$V=572.45L_{abdomen}+184.72C_{tenth\ rib}-323.75B_{tenth\ rib}-5,727.80$	2,817	2,760	2.54	2.54
Pelvis	$V=107.20M-84.30S+528.80F_{suprailiac}+7,637.48$	10,128	9,685	9.13	8.91
Upper Arm	R $V=7.33M+67.89C_{elbow}+19.49L_{acrom_rad}-1,714.08$	1,557	1,513	1.40	1.39
	L $V=3.64M+65.37C_{biceps_fl_left}+47.57L_{acrom_rad}-2,241.29$	1,556	1,524	1.40	1.40
Lower Arm	R $V=61.12C_{elbow}+53.42C_{wrist}+18.99L_{rad_stylium}-1,835.29$	935	912	0.84	0.84
	L $V=30.56C_{elbow}+36.41L_{rad_stylium}+49.49C_{mid\ forearm}-1,713.20$	923	932	0.83	0.86
Hand	R $V=25.14C_{wrist}+36.37B_{hand}+16.83L_{meta\ III_dact}-484.95$	344	337	0.31	0.31
	L $V=50.64B_{hand}+12.84C_{wrist}+12.67L_{hand}-476.78$	334	328	0.30	0.30
Flap	R $V=90.90C_{upper\ thigh}+177.39L_{thigh\ flap}+18.77S-7,823.86$	3,792	3,748	3.42	3.45
	L $V=98.20C_{upper\ thigh}+153.06L_{thigh\ flap}+23.37S-8,522.40$	3,832	3,786	3.45	3.48
Upper Leg (flap excl)	R $V=173.68C_{mid\ thigh}+57.90S+29.81C_{buttock}-15,058.42$	6,278	6,191	5.66	5.70
	L $V=253.27C_{mid\ thigh}+80.63S-141.89B_{bitroch}-15,450.17$	6,211	6,126	5.60	5.64
Lower Leg	R $V=137.20C_{calf_right}+47.91C_{knee}+33.92L_{calf}-4,740.57$	3,111	3,045	2.80	2.80
	L $V=128.09C_{calf_left}+64.32C_{knee}+37.69L_{calf}-5,166.17$	3,151	3,081	2.84	2.83
Foot	R $V=38.27L_{foot}+121.67H_{sphyrion}+22.70C_{ankle}-1,475.74$	673	668	0.61	0.61
	L $V=32.65C_{ball\ of\ foot}+93.42H_{sphyrion}+32.44L_{foot}-1,409.56$	682	675	0.61	0.62
TOTAL:		69,130	67,714	62.3	62.3

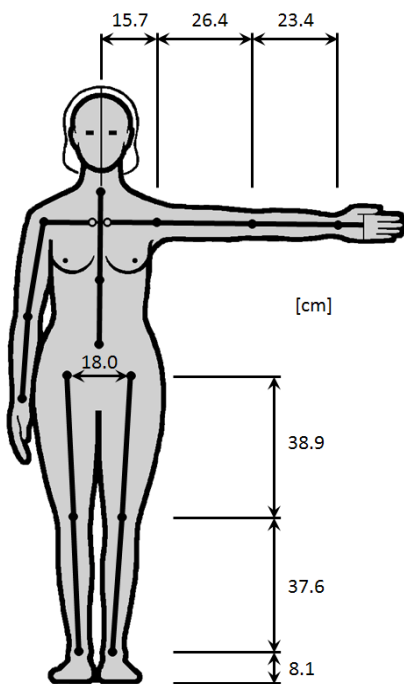


Fig. A1. Distances (in cm) between joints of EvaRID based on [46].

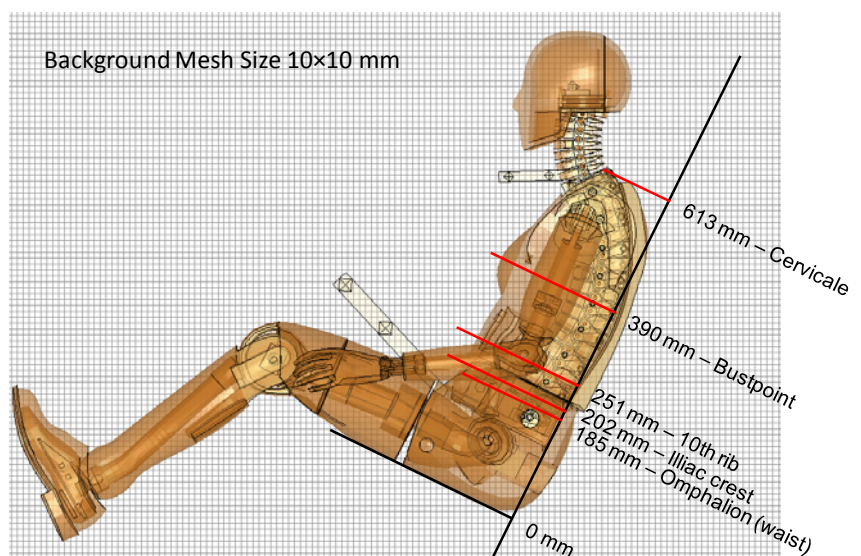


Fig. A2. Torso details – heights of major landmarks.

TABLE AII

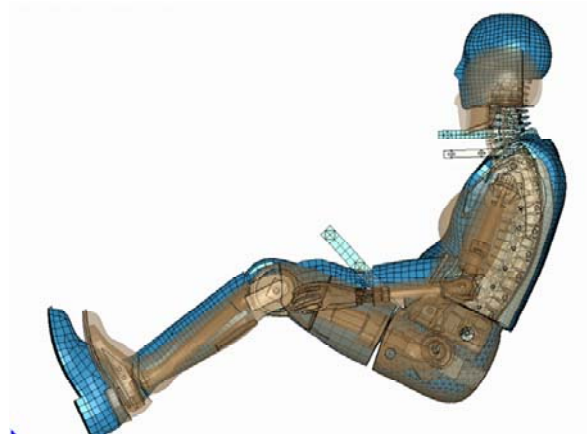
ANTHROPOMETRIC DATA USED FOR CALCULATIONS OF THE VOLUME FOR DIFFERENT BODY PARTS (TABLE IV). BASED ON [44].

Measure	Unit	Body Part	Variable ¹⁾	Value ²⁾	Scale Factor	Scaled Value ³⁾
Stature	[cm]	Body	S	161.2	-	161.8
Mass	[punds]	Body	M	140.9	-	137.3
Circumference	[cm]	Head	C _{head}	54.78	1	54.78
		Neck	C _{neck}	32.86	0.99	32.53
		Bust	C _{bust}	95.41	0.99	94.46
		Tenth rib	C _{tenth rib}	75.94	0.99	75.18
		Buttock	C _{buttock}	100.08	0.99	99.08
		Upper thigh	C _{upper thigh}	59.44	0.99	58.85
		Mid thigh	C _{mid thigh}	51.92	0.99	51.40
		Knee	C _{knee}	36.97	0.99	36.60
		Calf (right)	C _{calf_right}	35.43	0.99	35.08
		Calf (left)	C _{calf_left}	35.79	0.99	35.43
		Ankle	C _{ankle}	21.45	0.99	21.24
		Biceps flexed (left)	C _{biceps_fl_left}	28.60	0.99	28.31
		Elbow	C _{elbow}	24.42	0.99	24.18
		Mid forearm	C _{mid forearm}	21.22	0.99	21.01
		Wrist	C _{wrist}	15.72	0.99	15.56
		Ball of foot	C _{ball of foot}	22.8	0.99	22.57
Height	[cm]	Head	H _{head}	15.59	1	15.59
		Sphyrion	H _{sphyrion}	6.26	1	6.26
		Neck	L _{neck}	6.98	1	6.98
		Thorax	L _{thorax}	36.16	1	36.16
		Abdomen	L _{abdomen}	4.94	1	4.94
		Thigh flap	L _{thigh flap}	17.96	1	17.96
		Calf	L _{calf}	35.95	1	35.95
		Foot	L _{foot}	23.51	1	23.51
		Acromion-radiale	L _{acrom_rad}	29.74	1	29.74
		Radiale-styilion	L _{rad_styilion}	23.07	1	23.07
		Metacarpale III - Dactylion	L _{meta III_dact}	8.99	1	8.99
		Hand	L _{hand}	17.08	1	17.08
Breadth	[cm]	Tenth rib	B _{tenth rib}	25.67	0.99	25.41
		Bitrochanteric	B _{bitroch}	31.63	1	31.63
		Hand	B _{hand}	7.76	0.99	7.68
Skinfold	[mm]	Suprailiac	F _{suprailiac}	1.85	0.99	1.83

1) Variables in the regression equations (Table A1).

2) Average values from Young et al. (1983).

3) Input to the calculations of volume/mass of the EvaRID model (Table A1)

**Fig. A3.** Comparison of the EvaRID and the BioRID II models.