EvaRID: a dummy model representing females in rear end impacts

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SUMMARY

The Seventh Framework project ADSEAT (Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants) aims at establishing the properties for a model of an average female and to implement those in a computational model in order to provide an improved tool for the development and evaluation of adaptive systems with special focus on protection against whiplash injuries. As such the project will result in a computational model of a female, in addition to the male model that already exists, for low severity testing. Both the female and the male model will then be used in be used in studies to design and evaluate adaptive seat systems that provide enhanced neck injury protection.

This paper will present the first version of the female dummy model, called EvaRID, as developed during the first year of the ADSEAT project. Background information on the size selection, anthropometry and the scaling method used will be described. The performance of the EvaRID V1.0 release is shown by comparing simulation results with volunteer data.

INTRODUCTION

Vehicle crashes causing Whiplash Associated Disorders (WAD), or 'whiplash injuries', is a worldwide problem. In Sweden, such injuries account for ~70% of all injuries leading to disability due to vehicle crashes (Kullgren et al. 2007). The majority of those who experiencing initial neck symptoms recover within a week of the car crash, however, 5-10% of individuals experience different levels of permanent disabilities (Nygren et al. 1985; Krafft 1998; the Whiplash Commission 2005). Whiplash injuries occur at relatively low velocity changes (typically <25 km/h) (Eichberger et al. 1996; Kullgren et al. 2003), and in impacts from all directions. Rear impacts, however, are most frequent in accident statistics (Watanabe et al. 2000).

It is well established that the whiplash injury risk is higher for females than for males, even in similar crash conditions (Narragon 1965; Kihlberg 1969; O'Neill et al. 1972; Thomas et al. 1982; Otremski et al. 1989; Maag et al. 1990; Morris recover & Thomas 1996; Dolinis 1997; Temming & Zobel 1998; Richter et al. 2000; Chapline et al. 2000; Krafft et al. 2003; Jakobsson et al. 2004; Storvik et al. 2009). 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 of the upper body with 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 seatback structures affects the plastic deformation and energy absorption as well as the dynamic head-to-head restraint distance and the rebound of the torso (Svensson et al. 1993; Croft 2002; Viano 2003). The motion of the head relative to the head restraint may be affected by sitting height in relation to the head restraint geometry. It has been reported that females, in comparison to males, have a somewhat different dynamic response in rear volunteer tests, such as higher head x-acceleration, higher (or similar) T1 x-acceleration, lower (or similar) Neck Injury Criterion (NIC) value and more pronounced rebound (Szabo et al. 1994; Siegmund et al. 1997; Hell et al. 1999; Welcher & Szabo 2001; Croft et al. 2002; Mordaka & Gentle 2003; Viano 2003; Ono et al. 2006; Carlsson et al. 2008; Linder et al. 2008; Schick et al. 2008, Carlsson et al. 2010).

In order to develop and evaluate the vehicle occupant protection performance crash test dummies are used. The 50th percentile male crash test dummy does not represent females in terms of mass distribution and dynamic response, and the size correspond to a ~90th -95th percentile female with regards to stature and mass (Welsh & Lenard 2001), resulting in females not being well represented by the existing low velocities 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 without consideration of female properties, despite higher whiplash injury risk in females. Existing whiplash protection concepts are thus more effective for males than females, with 45% risk reduction of permanent medical impairment for females and 60% for males, according to insurance claims records (Kullgren & Krafft 2010).

In view of the above a European research effort was started under the ADSEAT (Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants) project. The overall objective of ADSEAT is to provide guidance on how to evaluate the protective performance of vehicle seat designs aiming to reduce the incidence of whiplash injuries. The work concentrates on evaluating the protective performance of seats beneficial to female as well as male motor vehicle occupants. For this purpose a computational dummy model of an average female is being developed. This new research tool will be used in conjunction with the BioRID II dummy model when evaluating enhanced whiplash injury protection. Further information on ADSEAT can be found under www.vti.se/adseat

This paper will present the first version of the female dummy model, called EvaRID. The model was obtained by scaling an existing BioRID II model in LS-Dyna. Background information on the size selection, anthropometry and the scaling method used are described. The performance of the EvaRID V1.0 release is shown by comparing simulation results with volunteer data.

SIZE SELECTION FOR EvaRID MODEL

Within the scope of the ADSEAT project several sources were evaluated to establish the anthropometry of the female with highest frequency in sustaining WAD. One of those sources was the AGU Zurich database which records technical and medical information on persons who sustained WAD. 2146 data sets of females were analyzed. It was found that the median height and weight of those females were 165 cm and 65 kg, respectively. However, the data sources were limited to basic measures such as height and weight. More specific measures such as seating height or the dimensions of individual body parts were not available,

Comparing these measures with data of the general female population of different 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 next page).

ANTHROPOMETRY SPECIFICATIONS

The anthropometric data for the 50 percentile female were mainly collected from the following references:

1. Schneider et al. (1983): The goal of this study was to define the anthropometry of a crash test dummy family. Initially this dummy family consisted of two female dummy members (the 5th and the 50th percentiles), and two male dummy members (the 50th and the 95th percentiles). In the first part of the project, data was collected and analyzed for all four dummy members, but it was later decided that the 50th percentile female dummy member should be dropped. The statures, seating heights, and weights of the dummy family members were defined based on the National Health and Nutrition Examination Survey (HANES) of 1971-1974 by Abraham et al. (1979). According to Young et al. (1983), the HANES survey provides the most current and appropriate general population model available for US adult females. The HANES data was collected on 13,645 individuals representing the 128 million persons aged 18-74 in the US population.

2. Diffrient et al. (1974): This reference "incorporates extensive amount of human engineering data compiled and organized by Henry Dreyfuss Associates over the last thirty years, including the most up-to-date research of anthropologists, psychologists, scientists, human engineers, and medical experts."
3. Young et al. (1983): This research was a part of a series of studies designed to obtain information about mass distributions characteristics (including moment of inertia and centre of volume) of the living human body and its segments, and to establish reliable means for estimating these properties from easily measured body dimensions. The study was based on 46 adult female subjects, selected to approximate the range of stature and weight combinations found in the general United States female population. The sampling plan for this study was to achieve a stature and weight distribution comparable to that found in the civilian female US population as reported in the HANES of 1971-1974 by Abraham et al. (1979).
   It should be noted that Young et al. also derived stature, weight, and seating height of the 50th percentile female on the HANES data. However, as they only considered a limited age range (21-45 years) compared to Schneider et al. (18-74 years), the latter source was prevailed for deriving these anthropomic data.

In addition to these sources, anthropometric data from the ergonomic programs GEBOD and RAMSIS were generated to validate the collected data. Also Product Information from Denton ATD and FTSS was used to collect information on the BioRID II hardware dummy for direct comparison of anthropometry data. Finally some 50th percentile male data was based on McConville et al. (1980), again for comparative reasons.

The stature, weight, and seating height of the EvaRID were taken from Schneider et al. (1983) since this data set has defined the sizes of the existing dummies. Table 2 summarizes the suggested dimensions of the EvaRID in comparison to the recommended size based on frequency count in accident databases, the average female anthropometry derived from various national sources (Table 1) and the existing BioRID II dummy hardware.

Table 1 "Average" female anthropometries of the general population for different European countries:

Country	Height [cm]	Weight [kg]	Age [years]
Austria[f, h]	167	67	43.2
Czech Republic[f, g]	167.3	-	41.9
Germany[d, f]	165	67.5	45.2
Finland[f, g, i]	164.7	69-83	43.7
France[b, f, g]	161.9	62.4	40.9
Italy[f, g]	162	-	44.8
Netherlands[e, f]	166.8	68.1	41.2
Norway[c, f, g]	167.2	-	40.2
Spain[f, g]	161	-	42.5
Sweden[f, j]	166.8	64.7	42.6
Switzerland[a, f]	164	49-67	42
United Kingdom[f, i]	161.6	67	41.3
Average of the above given measures	164.6	66.3	42.5

[a] http://www.statistik-bs.ch/kennzahlen/integration/A/a2
[b] http://www.insee.fr/fr/ffc/docs_ffc/es361d.pdf
[c] http://www.ssb.no/english/yearbook/tab/tab-106.html
[d] http://www.wissen.de/wde/generator/wissen/ressorts/bildung/index,page= 3496378.html
[e] http://dined.io.tudelft.nl/en,dined2004,304
[f] https://www.cia.gov/library/publications/the-world-factbook/fields/2177.html
[g] http://www.disabled-world.com/artman/publish/height-chart.shtml
[h] http://www.imas.at/content/download/329/1288/version/1/file/05-03%5B1%5D.pdf
[i] http://psychology.wikia.com/wiki/Body_weight
[j] http://www.nordstjernan.com/news/sweden/776/

Table 2 EvaRID main dimensions and comparison with data for target size, "average" female anthropometry EU from Table 1 and BioRID II dummy

Variable:	50% Female EvaRID	Target size based on frequency count in accident databases (ADSEAT WP1 study)	Average female anthropometry EU (Table 1)	50% Male BioRID
Total stature:	161.8 cm	165 cm	164.6 cm	177 cm
Total weight:	62.3 kg	65 kg	66.3 kg	78.7 kg
Seating Height:	84.4 cm		-	88.4 cm

Data in Table 2 show that stature and weight of EvaRID are lower than values for the target size as derived from frequency count in the databases and the "average" female anthropometries as derived from various sources of different European countries. The difference between the data set used for dummy development and the "average" EU values might be explained by the fact that the population has grown in the meantime. However, since the differences are regarded small, the use of the 50% percentile reference values seems justifiable for the modeling and research purposes envisaged in the ADSEAT project.

The weights of body parts, absolute and relative compared to overall weight are provided in Table 3. It can be seen that the weight distribution of the EvaRID is somewhat different from the BioRID's. The female dummy has a relatively lighter torso, a heavier pelvis, and slightly heavier upper legs.

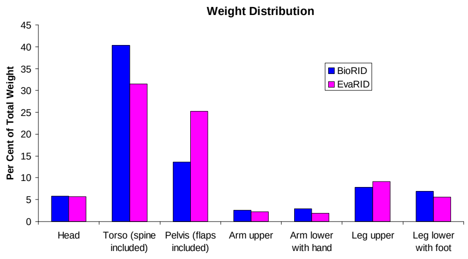
MODEL DEVELOPMENT

Since the goal was to develop a dummy model based on the existing BioRID II model, it became clear that mass and dimensional ratios of the 50th percentile female over the BioRID II should be used. To meet the anthropometric requirements in terms of mass and dimensions, first the longitudinal dimensions and mass were scaled to obtain values related to the 50th percentile female. Breadth and depth dimensions were then derived based on the scaling method for each body segment. This basic scaling methodology is depicted in Figure 1, where SFL is the Longitudinal Scale Factor, SFB is the Breadth Scale Factor, and SFD is the Depth Scale Factor.

Table 3 Comparison of Mass distribution (in per cent of the total weight) of the BioRID and the EvaRID

Body Part:		EvaRID		BioRID	
		Mass [kg]	% of total	Mass [kg]	% of total
Head	x1	3.5	5.7%	4.5	5.8%
Torso[1] (incl. neck/spine)	x1	19.6	31.5%	31.7	40.3%
Pelvis (incl. flaps)	x1	15.7	25.2%	10.7	13.6%
Arm upper	x2	1.4	2.2%	2.0	2.5%
Arm lower (incl. hand)	x2	1.2	1.8%	2.3	2.9%
Leg upper (excl. flaps)	x2	5.7	9.2%	6.2	7.8%
Leg lower (incl. foot)	x2	3.5	5.6%	5.4	6.9%
TOTAL		**62.3**	**100%**	**78.7**	**100%**

1) The torso consists of the thorax, the abdomen, and the spine (including the neck)



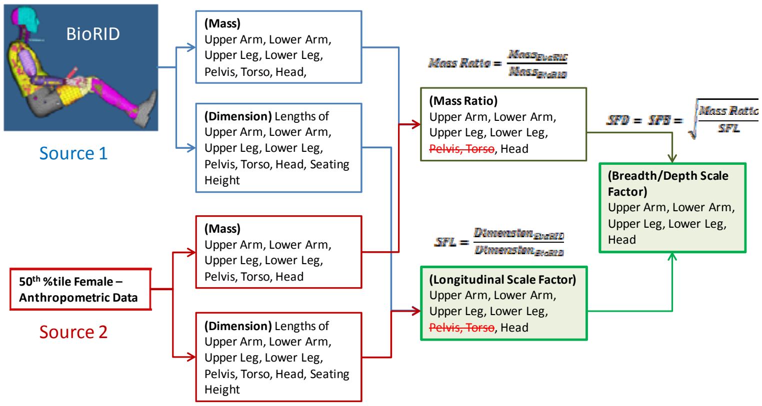


Figure 1 Scaling methodology for EvaRID

The above method was applied straightforward to all body parts. Some general remarks related to critical body parts are included below.

Since the size of the head is so important for rear impact analysis, this part was scaled to meet all three dimensional requirements. The mass requirement was met by adjusting the density of the skull.

The neck height was defined as the Mastoid height less the Cervicale height. Considering the complexity of the neck modeling, the SFD was selected to be the same as the SFL. The SFB was assumed to be the same as the SFB for the Torso, which was derived by comparing the shoulder joint distance of EvaRID to the shoulder joint distance of BioRID II. Due to lack of accurate landmark of the Mastoid and the Cervicale, the 50th %-tile male data from McConville et al. was used for the neck height. The mass ratio of 0.664 was derived from SFL*SFB*SFD and was slightly less than the mass ratios of the head (0.778) and the torso (0.737).

The limb scaling was following the Basic Scaling Methodology. First, the mass ratio of EvaRID over BioRID II was calculated. Then the SFL of EvaRID over BioRID II was determined based on the 50th percentile female data reported by Diffrient et al. (1974) and the dimensions measured from BioRID II model. The SFB and SFD were then derived by taking the square root of mass ratio over SFL.

Note that the longitudinal dimension of the limb is different from the total length of the limb. The longitudinal dimensions were measured as followed. For the upper arm, it was measured from shoulder joint to elbow joint; for the lower arm, it was measured from the elbow joint to the end of middle finger tip; for the upper leg, it was measured from the hip joint to the knee joint; and for the lower leg, it was measured from the knee joint to the bottom of the heel.

The torso was divided into two sections: the upper torso and the pelvis. The upper torso in this study was defined as the torso without the pelvis. It ran from the Cervicale to the Iliac Crest. The EvaRID maintains the same back profile as the BioRID II's as the scaling factors for the SFL and SLD were kept the same. The upper torso mass was derived by subtracting the pelvis mass from the torso mass. The breadth was defined as the distance between shoulder joints. The Depth Scale Factor was then derived from:

$$SFD_{Upper\ Torso} = \frac{Mass\ Ratio_{Upper\ Torso}}{SFL_{Upper\ Torso} \times SFB_{Upper\ Torso}}$$

Regarding the pelvis it was found that no significant difference was observed between the 50th percentile female pelvis and the 50th percentile male pelvis although the stature heights are quite different. From the data published by Diffrient et al. (1974), the 50th percentile female has a distance of 180 mm between hip joints, which matches the BioRID II's hip joint distance (179.6 mm). Also,

	Model	
	BioRID II (mm)	EvaRID (mm)
Head Total Height (top of head to chin)	215.9	203.0
Head Length	199.9	186.9
Head Breadth	157.6	145.8
Neck (C0-C1 joint to C7-T1 joint)	120.4	102.8
Torso (C7-T1 joint to Mid-point of hip joints)	526.5	479.4
Distance between shoulder joints	346.0	315.2
Upper Arm (shoulder joint to elbow joint)	261.4	264.0
Lower Arm (elbow joint to tip of middle finger)	248.8	234.0
Upper Leg (hip joint to knee joint)	405.5	389.6
Lower Leg (knee joint to bottom of heel along tibia)	495.5	457.0
Shoe Length	322.6	271.6

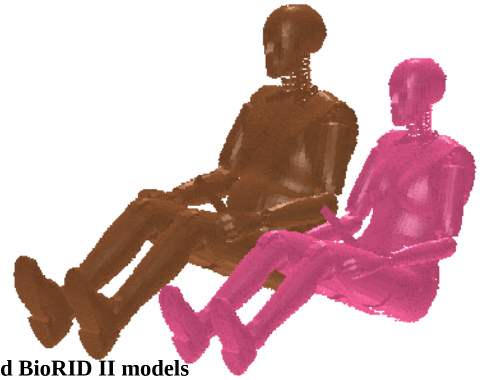


Figure 2 Comparison of EvaRID and BioRID II models

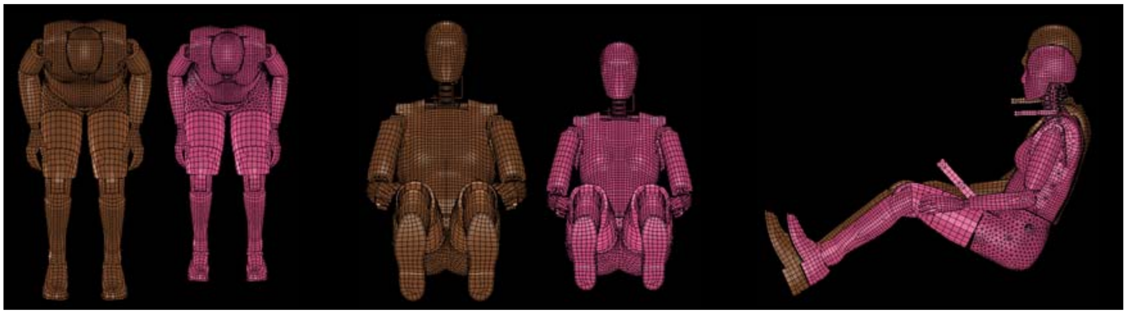


Figure 3 Comparison of EvaRID and BioRID II models

from the articles of Young's et al. and McConville's et al. there's very little difference between the 50th %-tile female pelvis and the 50th %-tile male pelvis.

In the EvaRID V1.0 joint properties were adopted from the BioRID II model. For this first validation no attempts were made to adjust spine, neck, or others. See also next sections. This resulting EvaRID model is compared with the BioRID II model in Figure 2 and Figure 3.

FIRST VALIDATION

To get an impression on how close the EvaRID model can be to real subject responses, volunteer tests described by Carlsson et al. (2008) were reproduced. A series of rear impact sled tests with eight female volunteers, representing the 50th percentile female, were performed at a change of velocity of 5 km/h and 7 km/h. The volunteer data are summarized in Table 4.

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. Two linear accelerometers, in x- and z direction, were placed on a holder that was attached to the skin at four points near the spinal process of the T1. The upper body was equipped with a harness with tri-axial accelerometers mounted at the chest. Linear accelerometers were placed on the bullet sled and

Table 4 Volunteer data

Female volunteers	Age	Stature	Weight	Seating height	Neck circumference
Average	24 years	1.66 m	60 kg	0.88 m	0.33 m

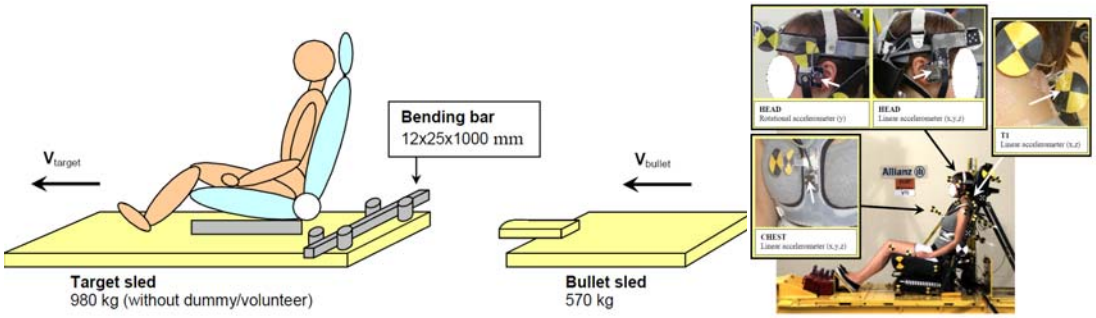


Figure 4 Sled set-up and position of markers

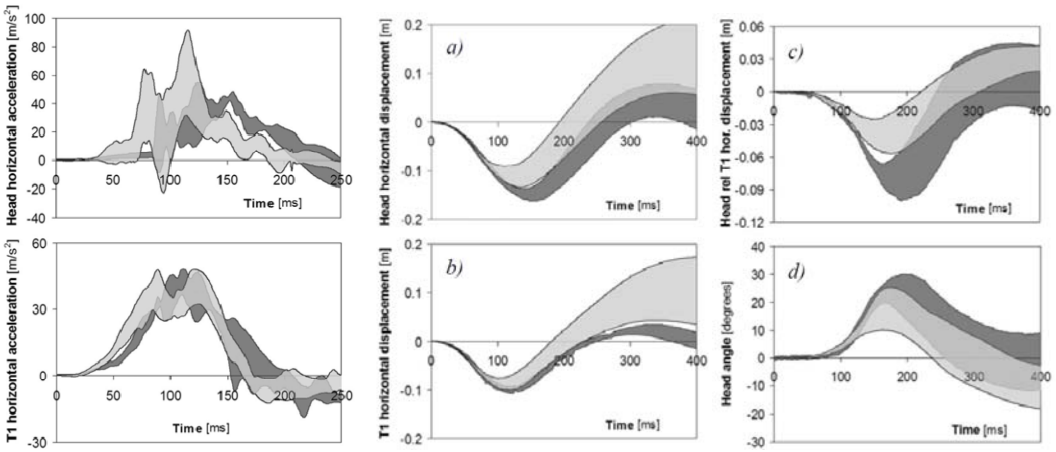


Figure 5 Examples of response corridors constructed (Carlsson et al. 2008). The dark corridors represent tests with males and the light corridors represent tests with females.

on the target sled. The setup is depicted in Figure 4. Additionally, the parameters head-to-head restraint distance and contact time, and Neck Injury Criteria (NIC), were extracted from the data set. To avoid the interaction with the chest harness, the volunteers wore only the lap belt during the test.

Some resulting corridors constructed from the tests are shown in Figure 5.

For this first validation of EvaRID a sled model representing the test set-up was constructed since this was not available. The seat used in the test has a seat base from a Volvo 850 dating from the early 90's. Since the seat base variation was considered less influential on the validation, an available Taurus seat base provided by Chalmers was used for the validation. The seat back of the seat consisted of four stiff panels, which were covered by a 20 mm thick layer of Tempur medium quality foam and lined with a plush cloth (Volvo 850, year model 1993). The panels and foam were modelled in detail according to the dimensions of the Volvo seat. The stiffnesses of the supporting springs were derived directly from the seat. The head-restraint consisted of a stiff panel which was covered by a 20 mm thick soft Tempur foam and a 20 mm thick medium Tempur foam.

A pre-simulation was conducted by dropping the dummy into the seat and letting the gravity find its balanced position in the simulation. The seat was fixed to the ground and the only external force was the gravity. Correlation of the initial position of the EvaRID in comparison to the volunteers was carefully checked. A representative example is shown in Figure 6.

After the balanced position was achieved by pre-simulation the head panel was adjusted to match the measured initial head-to-head restraint distance, as estimated from film analysis, and a seatbelt was routed before applying the measured acceleration pulse.

Figure 6 Finite element model of test configuratio and comparison of initial posture with one of the volunteers

Figure 7 compares simulated results using EvaRID with response corridors and volunteer #50 which had closest fit with EvaRID in terms of mass and initial position. Head & T1 Acceleration, Head & T1 Displacement and Head & T1 Rotation are depicted.

- *Head and T1 Accelerations*

The head and T1 accelerations were close to the test results and mostly within the test corridors. The T1 acceleration has similar response compared to the test, but with higher peak values, which was partly due to the little T1 rotation (2 degrees @ 100ms) in the simulation as compared to the one in the test (13 degrees @ 100ms)

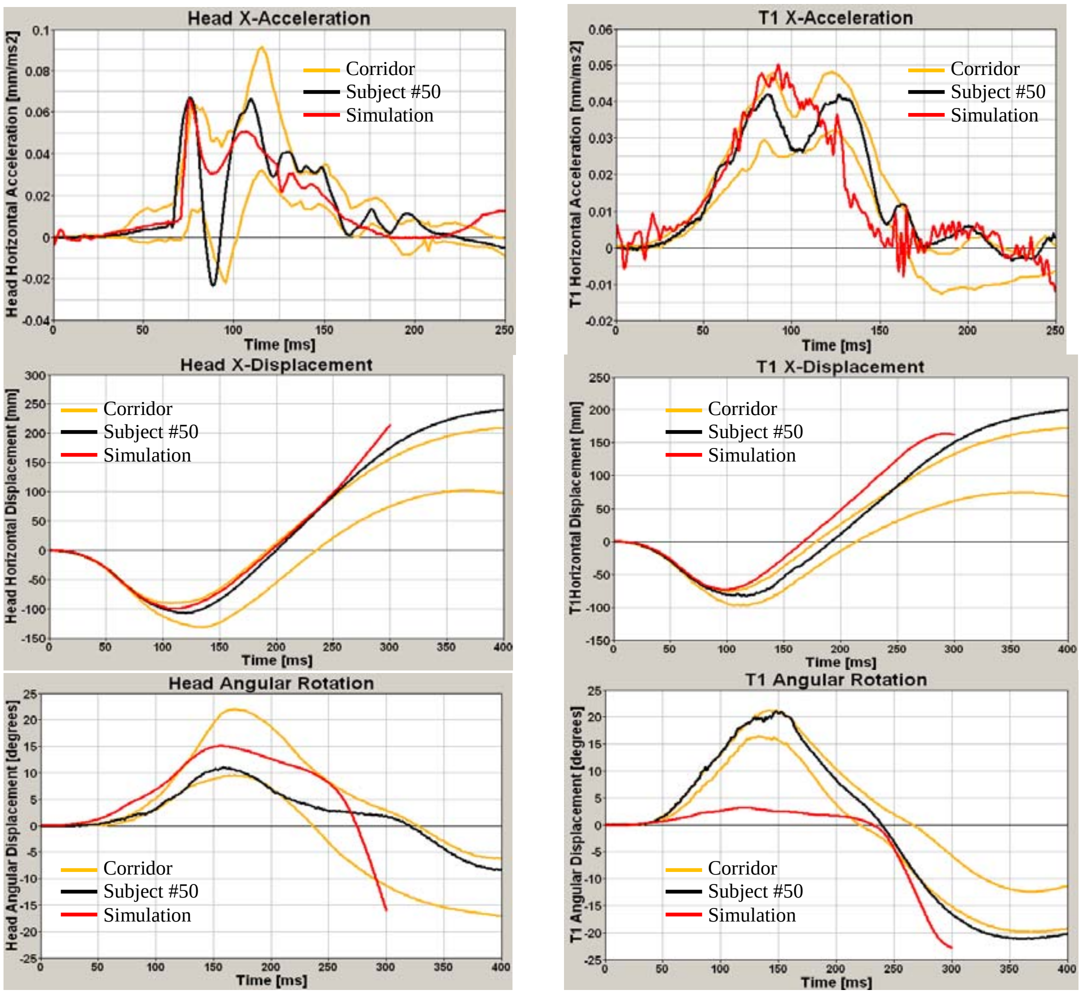


Figure 7 Comparison of EvaRID reponse (red) with corridors constructed from all volunteer test data (orange corridors) and volunteer #50 which has closest fit with EvaRID in terms of mass and initial position (black)

- *Head and T1 Displacements*

The head and T1 displacements were close to the test results. The correlation was pretty good before the rebound at around 95 ms. From the T1 rebound and the simulation animation, it was observed that EvaRID by design had a torso with much stiffer properties in extension then in flexion. Another possible cause may be from the un-validated seat model.

- *Head and T1 Rotations*

The head rotation response falls within the corridor very well for the first 250 ms, but the T1 rotation response was off for the first 240 ms. Again, this shows that EvaRID by design had a torso with much stiffer properties in extension. Un-validated seat and seatbelt models may also contribute some of the discrepancies.

Hence from this first validation it can be observed that EvaRID has a stiffer torso/spine in extension as compared to the subjects'. This is due to the fact that it inherits the design and properties of the BioRID II dummy model: no adjustments in joint characteristics were made in this V1.0 model. With that, the T1 rotation is expected to be much less as compared to the response of the real subjects during the extension motion. The rotation of head relative to the T1 suggests that further improvement on the T1 (or spine) flexibility is important to correct neck motion.

FUTURE ACTIVITIES

The EvaRID was obtained from the BioRID II model by scaling anthropometry, geometry and mass properties. Up to now no efforts were made to tune the stiffness properties of spine, torso and neck. In fact, the new dimensions with shorter torsion pin springs may have made the spinal joints stiffer in the EvaRID compared to BioRID. This is confirmed by comparison of T1 displacement curves between EvaRID and volunteer tests.

In order to obtain a reasonable T1 angular motion the EvaRID model will need stiffness tuning. It is the intention to start with a simple parameter study where the spinal stiffness (all joints from C1 to L5) and rubber-torso stiffness is reduced in a few steps. The literature review of ADSEAT indicates a reduction down to 2/3 or 1/2 of the male stiffness.

Regarding the tuning of the neck stiffness it is noted that the headrest was very close to the head in volunteer tests by Carlssen et al. (2008). Therefore the head response is largely governed by the head restraint properties and only to a somewhat lesser extent by the neck properties. As a consequence these volunteer tests are less suitable for fine tuning the neck parameters, stressing the importance of making the upcoming volunteer tests in ADSEAT with a much larger headrest gap. Such tests would give valuable information for tuning the neck stiffness.

CONCLUSIONS

A computational dummy model, called EvaRID, representing the mid-size female in rear end impacts was developed in the ADSEAT project from anthropometry data. Geometry and mass data for this size were taken from sources that served as basis for the anthropometry of crash dummies (Diffrient et al. and Schnieder et al.). The model was obtained by scaling anthropometry, geometry and mass properties of an existing BioRID II dummy model. In the initial EvaRID version stiffness and damping properties of materials and discrete elements were unchanged compared to BioRID II.

To get an impression on how close the model can be to real subject responses the V1.0 model of EvaRID was compared to the corridors and response curves from female volunteer tests. The comparison showed that a relatively good correlation was obtained. However, the new dimensions with shorter torsion pin springs have made the spinal joints stiffer in the EvaRID compared to BioRID. This was confirmed by comparison of T1 displacement curves between EvaRID and volunteer tests. Hence stiffness tuning is needed to obtain a more human-like response of the model, as expected. This will require additional volunteer data with larger initial gap between the head and the headrest. These tests are part of future studies of the ADSEAT project. Once fully validated, the model will be applied in the design and evaluation of adaptive seat systems in order to provide enhanced neck injury protection from the seat.

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