



Scaling head-neck response data
and derivation of 5th percentile
female side impact dummy head &
neck response requirements in
NBDL test conditions

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Publishable summary

Within the integrated European project APROSYS Sub-Project 5 'Biomechanics', a small female WorldSID prototype has been developed. It represents the small (5th percentile) female population, that is often at highest risk but yet not well accounted for in regulatory crash testing.

The head-neck biofidelity of side impact dummies can be assessed according to the response requirements for the head-neck system based on midsize male human subjects as published in ISO TR9790 (1999). These criteria are largely based on volunteer tests performed at the Naval Biodynamics Laboratory in New Orleans (NBDL) (Ewing *et al.*, 1977; Wismans *et al.*, 1986).

The first objective of this study is to provide a judgement on the validity of the scaling method for the head-neck system as proposed by Irwin *et al.* (2002). The second objective is to develop new scaling rules and new response requirements for the small female WorldSID head-neck, in case the existing scaling method would not to be valid.

In order to come to a judgement on the validity to apply Irwin's scaling method to the head-neck kinematics and dynamics the following steps were performed:

- analyses of Irwin's scaling method,
- literature review on gender related differences relevant to head-neck scaling,
- comparison of the NBDL volunteers head-neck anthropometry versus the head-neck responses in the NBDL tests.

From above analyses it was concluded that the scaling method developed by Irwin *et al.* (2002) to scale the midsize male requirements of the NBDL test condition of ISO TR9790 to small female is not valid for all requirements. The scale factors that were found not to be valid were updated using relations found in literature on head-neck biomechanics, and relations found in an analysis of the NBDL volunteer anthropometry and response.

The overall ISO TR9790 biofidelity rating of the small female WorldSID prototype for the NBDL test condition was not improved when using to the new requirements compared to Irwin's. However, the reason for this study was not to increase the biofidelity score of the 5th female WorldSID prototype, but to develop a scaling method for the head-neck in the condition based on literature of scientific research on neck biomechanics. And just as important, this study was performed to provide better targets for optimisation of the head-neck response of small female side impact dummies.

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Company	Representative	Chapters
TNO	R. Meijer	all

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1 Introduction

In car-to-car crashes, side impact is the most severe and second frequent traffic accident configuration (Samaha and Elliot, 2003). The head is often seriously injured in this crash scenario, due to interaction with the vehicle structure. Although neck injuries are generally not the most frequent injuries occurring in side impact, the behaviour of the neck is very important since it determines the trajectory of the head and contributes to the head loading conditions (Been *et al.*, 2004). To test the crash safety of cars in a side impact, the development of biofidelic side impact test devices is important.

A side impact test device with a good head-neck biofidelity is the recently developed Worldwide Side Impact Dummy (WorldSID). This dummy represents the midsize (50th percentile) male population. Within the integrated European project APROSYS Sub-Project 5 'Biomechanics', a small female WorldSID prototype has been developed. It represents the small (5th percentile) female population, that is often at highest risk but yet not well accounted for in regulatory crash testing.

The head-neck biofidelity of side impact dummies can be assessed according to the response requirements for the head-neck system based on midsize male human subjects as published in ISO TR9790 (1999). These criteria are largely based on volunteer tests performed at the Naval Biodynamics Laboratory in New Orleans (NBDL) (Ewing *et al.*, 1977; Wismans *et al.*, 1986). In ISO TR9790 the NBDL test condition is known as neck test 1. In addition also a test of Patrick & Chou (1976) is used. In ISO TR9790 the Patrick & Chou test condition is known as neck test 2. In earlier evaluations of the midsize male WorldSID (Been *et al.*, 2004) and the small female prototype (Been *et al.*, 2007), it was found that the requirements of neck test 2 are not very compatible with those of neck test 1. However, the tests results indicated that the head-neck response could be improved. From the two contradictory response requirements no clues could be derived for optimisation of the head neck response of the dummy. From the small female WorldSID prototype tests conclusions were derived, which are addressed in this report (reference Aprosyst test report APSP52-0036-C (Meijer *et al.*, 2007):

- Because of the incompatibility between test results, and the fact that the Patrick & Chou test does not have a requirement for the T1 lateral acceleration or displacement, and the fact that the requirements are based on a single volunteer, it is recommended that ISO/TC22/SC12/WG5 consider omission of the Patrick and Chou test condition. Instead of the Patrick & Chou requirements for the internal neck loads, it is recommended to adopt IHRA internal neck load requirements belonging to the NBDL test condition.
- It is recommended that the scaling of the NBDL responses should be reconsidered, and new requirements should be developed, taking also the time factor of the responses into account.
- The current responses of the head neck system should be compared to the newly defined response corridors. Decisions on design changes to the dummy head and neck should be based on the newly defined corridors and a comparison of the dummy responses to those.

In this study the Patrick and Chou conditions is no longer considered.

Since there are no side impact tests available of small female human subjects, the head-neck response requirements for a small female dummy are usually scaled from those of the midsize male dummy. The scaling can be done using the scaling rules proposed by Irwin *et al.* (2002). The scaling procedures of Irwin assume that the human neck behaves more or less like an elastic beam. But due to the large flexibility of the neck, particular if muscular activity is limited this assumption can be questioned.

The first objective of this study is to provide a judgement on the validity of the scaling method for the head-neck system as proposed by Irwin *et al.* (2002). The second objective is to develop new

scaling rules and new response requirements for the small female WorldSID head-neck, in case the existing scaling method would not to be valid.

In order to come to a judgement on the validity to apply Irwin's scaling method to the head-neck kinematics and dynamics the following steps were performed:

- analyses of Irwin's scaling method (Section 2),
- literature review on gender related differences relevant to head-neck scaling (Section 3),
- comparison of the NBDL volunteers head-neck anthropometry versus the head-neck responses in the NBDL tests (Section 4).

The findings from above analyses will be used to develop a new scaling method and resulting biofidelity requirements for the head-neck kinematics and dynamics, in case the Irwin based criteria significantly would deviate from the new findings (Section 5). The conclusion drawn from this study is described in Section 6.

It must be noted that the above mentioned analyses of the NBDL volunteers is based on the same volunteers as the ISO TR9790 head-neck response requirements are based on. However, there was no other data available of volunteers in a lateral impact in which similar responses were measured and the head-neck anthropometries were measured.

In Section 7 the responses of the small female WorldSID prototype were compared to the new requirements.

2 Analyses of Irwin's scaling method

Irwin *et al.* (2002) developed a scaling method to scale the ISO TR9709 lateral impact response requirements from midsize male to other size dummies. In this section this scaling method with respect to scaling of the midsize male head-neck response requirements to small female is described briefly.

Irwin *et al.* (2002) used the characteristic dimensions, masses, and material properties used to develop the Hybrid III child and CRABI dummies (Irwin and Mertz, 1997; Mertz *et al.*, 2001). The necks were assumed to be geometrically similar, with all dimensions proportional to the neck circumference (Mertz *et al.*, 1997). Irwin *et al.* (2002) assumed that the head mass scale factor is scaled with the third power of the dimension scale factor (Schneider *et al.*, 1983). The dimension scale factor from midsize male to small female equals 0.93 in all three directions, and so the mass scale factor equals 0.81. In the database People Size (1998), which includes measures of a huge amount of people, a ratio of 0.94 was found for the head breadth and 0.92 for the head length for small females compared to midsize males. Thus the ratios from the People Size database are comparable to that used by Irwin *et al.* (2002). Irwin *et al.* (2002) introduced a characteristic ratio for mass moment of inertia of the head to account for the inertial loading by the head in the neck sled tests. The scale factors for the length, mass, mass moment of inertia and stiffness of the head and neck are given in Table 2.1.

According to Irwin *et al.* (2002) there are two neck stiffness ratios which are needed for the neck response scaling, the lateral neck bending stiffness ratio and the neck twist stiffness ratio. To calculate the neck bending stiffness, the head-neck system was assumed to behave like a cantilever beam as described by Fenner (1989). Irwin *et al.* (2002) assumed the elastic modulus of bones of adults to be similar. To calculate the neck twist stiffness, the neck was assumed to behave like a cylindrical shaped beam around its length axis (Fenner, 1989). The shear modulus of bones of adults was also assumed to be similar, since it is based on the elastic modulus. The resulting scale factors for the neck bending stiffness and neck twist stiffness are shown in Table 2.1.

Table 2.1: Scale factors for length, mass, mass moment of inertia and stiffness for the small female relative to the midsize male according to Irwin *et al.* (2002).

Scale factor	Symbol	Formula	Factor
Head mass	$\lambda_m \text{ head}$	$(\lambda_x \text{ head})^3$	0.810
Head length	$\lambda_x \text{ head} = \lambda_y \text{ head} = \lambda_z \text{ head}$	$(C+W+H)_f / (C+W+H)_m$	0.932
Head inertia	$\lambda_{Iz} \text{ head}$	$\lambda_m \text{ head} * (\lambda_x \text{ head})^2$	0.704
Neck mass	$\lambda_m \text{ neck}$	$(\lambda_x \text{ neck})^3$	0.501
Neck length	$\lambda_x \text{ neck} = \lambda_y \text{ neck} = \lambda_z \text{ neck}$	$(NC)_f / (NC)_m$	0.794
Neck bending stiffness	$\lambda_k M_x \text{ neck}$	$\lambda_y \text{ neck}$	0.794
Neck torsional stiffness	$\lambda_k M_z \text{ neck}$	$(\lambda_y \text{ neck})^3$	0.501
Torso length	$\lambda_z \text{ torso}$	ESH_f / ESH_m	0.895
Torso stiffness	$\lambda_k t$	$\lambda_z \text{ torso}$	0.895
Torso total mass	$\lambda_m t$	mt_f / mt_m	0.597

_f = small female

_m = midsize male

Because drop tests and sled tests both involve the interaction of the subject's body and a significantly larger mass, Irwin *et al.* (2002) assumed that the scale factors for the peak T1 acceleration and displacement developed for cadaveric drop tests (Mertz, 1984) also apply to the sled tests.

To calculate the scale factors for the peak head flexion angle, peak lateral displacement, time of maximum lateral displacement and the peak accelerations, the neck was assumed to behave like a cantilever beam with a point mass on the free end. Using this model, the response scale factors could be derived from energy balance store in the neck at maximum flexion (the head's kinetic energy is converted to elastic energy in the neck). To derive the scale factor for the peak twist angle, the head-neck system was modelled as a cylindrical shaped beam with a point mass on the free end rotating around its length axis. The twist angle could be derived from the energy balance store in the neck at maximum twist. The sled velocity, the input to the impact response, was not scaled for the small female.

The scale factors in Table 2.1 were used to obtain the impact response scale factors given in Table 2.2. The upper and lower bounds were set at 11% for the lateral displacement and 19% for the vertical displacement of the head C.G. which are consistent with the midsize adult male spreads given in ISO TR9790. The resulting response requirements for ISO TR9790 for small female dummies in neck test 1 developed by Irwin *et al.* (2002) are given in Table 5.3.

Irwin *et al.* (2002) made a note that the sled tests of ISO TR9790 for assessing the neck biofidelity have been difficult to repeat with dummies. If the compliance of the dummy's shoulder and thorax are different than the cadaver or volunteers in the original tests, then the input to the neck will be different. With different input applied to the base of the neck, it is not possible to assess the biofidelity of the neck relative to the ISO TR9790 guidelines.

Table 2.2: Scale factors for the ISO TR9790 neck test 1 requirements for the small female relative to the midsize male according to Irwin *et al.* (2002).

Scale factor	Symbol	Formula	Factor
Sled velocity	λ_v	v_f / v_m	1
T1 lateral acceleration	R_{at}	$\lambda_v * \sqrt{(\lambda_k t / \lambda_m t)}$	1.224
T1 lateral displacement	R_d	$\lambda_v * \sqrt{(\lambda_m t / \lambda_k t)}$	0.817
Neck lateral flexion angle	R_θ	$\lambda_v * \sqrt{(\lambda_m \text{ head} / \lambda_k M_x) / \lambda_z \text{ neck}}$	1.272
Neck twist angle	R_ϕ	$\lambda_v * \sqrt{(\lambda_l z / \lambda_k M_z) / \lambda_x \text{ head}}$	1.272
Head lateral acceleration	R_{ahy}	$\lambda_v * \sqrt{(\lambda_k M_x / \lambda_m \text{ head})}$	0.990
Head lateral displacement	R_{dhy}	$\cos(R_\theta * \theta_m)$	0.808
Time peak head lat. disp.	R_{ht}	$\lambda_m \text{ head} / \lambda_k M_x$	1.010
Head vertical acceleration	R_{ahz}	$(\lambda_v^2) / \lambda_z \text{ neck}$	1.259
Head vertical displacement	R_{dhz}	$\sin(R_\theta * \theta_m)$	0.590

_f = small female

_m = midsize male

3 Gender related differences

3.1 Head-neck anthropometry

Mordaka (2004) performed a literature study on the differences of the neck between female and male and compared the neck circumference, height and length of different studies, see Table 3.1. The data (Irwin and Mertz, 1997, Mertz *et al.*, 2001) used by Irwin *et al.* (2002) was added to this table. From Table 3.1 it can be seen that the average ratio found for the neck circumferences between females and males vary between 0.83 and 0.93 between the studies. Since the ratio for the small female is expected to be smaller than for midsize females, the scale factor for the neck circumference used by Irwin *et al.* (2002) is in line with the findings in literature.

Also, in Table 3.1 it can be seen that the neck length ratio between females and males does not coincide with the ratio for the neck circumference. The neck height is defined as the distance between the occipital condyles and the last cervical vertebra (C7), and the neck length is defined as the length of the cervical lordosis, see Figure 3.1. Independent on whether the neck length or height was measured and how it was defined, the neck length of females and males seem to be similar, and the neck circumference of females seem to be more than 10% smaller than of males. This finding is not in line with the assumption of Irwin *et al.* (2002) to adopt the ratio for the neck circumference as a scale factor for the neck length.

Table 3.1: Neck related measurements (Mordaka, 2004) compared to the data used by Irwin *et al.* (2002).

Parameter	Female		Male		Female/Male Ratio [-]
	Mean [mm]	SD [mm]	Mean [mm]	SD [mm]	
Neck circumference (Irwin and Mertz 1997, Mertz <i>et al.</i> 2001)	304 [^]		383		0.79
Neck circumference (Harty, 2004)	342	2.3	409	3.6	0.83
Neck circumference (Vasavada, 2001)	360	20.0	390	20.0	0.93
Neck circumference (People Size, 1998)	373	26.4	399	25.7	0.93
Neck height* (valkeinen, 2003)	64		62		1.03
Neck length* (Harty, 2004)	124	18.0	125	17.5	0.99
Height**-length*** ratio (Harrison, 1996)	0.9700	0.015	0.9695	0.016	1.00

[^] small female

* Occiput-C7 spinous process

** Height was defined as the length of chord of cervical lordosis

*** Length was defined as the length of arc of cervical lordosis arc

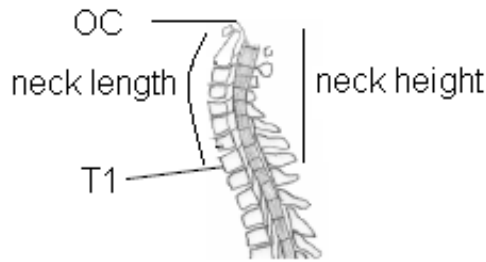


Figure 3.1: Neck length and height (www.neurosurgeon.org)

3.2 Head-neck responses

Schneider *et al.* (1975) measured the anthropometry and responses of 96 male and female volunteers of different age and size. The anthropometric values of the head, neck and whole body were measured as well as a couple of responses of the head-neck system. These responses were the three dimensional range of motion in quasi-static bending tests, response to low level acceleration, reflex time and voluntary isometric muscle force in lateral direction. The ranges of motion in lateral bending, also called lateral flexion, of young male and female subjects were found to be similar. However, the range of motion decreases with age for both males and females, and faster for males, see Table 3.2. This table also includes the rotation of the head-neck system around its vertical axis. In a voluntary head-pulling test, males showed 1.5 to 2 times greater strength of the neck muscles than females, and for both sexes the strength decreases with age. Reflex times to lateral head loading range from 30 to 70 ms and are smaller for females than for males. These differences may not be significant in complete surprise impact as the total time to maximum muscle force, including 100 ms contraction time, is in the order of 130-170 ms.

Table 3.2: Range of motion per sex and age category (Schneider *et al.*, 1975)

Subjects	Range of motion [degrees]			
	Lateral bending		Rotation	
Age	Male	Female	Male	Female
18 - 24	86.3	86.0	149.5	150.6
35 - 44	73.0	73.9	137.1	143.6
62 - 74	48.0	56.3	113.9	123.6
All	69.8	72.0	133.7	139.3
All of both sexes	71.0		136.5	

Youdas *et al.* (1992) measured the head and neck range of motion of 171 females and 166 males with ages ranging from 11 to 97 years in quasi-static bending tests. The difference between males and females for both the range of motion of the neck rotation about its length axis as well as the range of motion in lateral bending was only two to three degrees. This study also showed that the range of motion decreased with age.

Tilley (1993) found a range of motion in quasi-static lateral bending test of 54 degrees to either side for both males and females. He also stated that there is no difference in this range of motion between males and females of different body size.

Vasavada *et al.* (2001) measured the maximum flexion, extension, lateral bending and axial rotation moments in 11 male and 5 female subjects (aged 20 to 42 years) in quasi-static bending tests. The lateral bending moment measured on the male subjects was approximately two times larger than the moment measured on the females. These findings comply with the studies of Choi and Vanderby (1999) and Moroney *et al.* (1988).

Ono *et al.* (2007) conducted lateral shoulder impact tests with 5 male and 3 female volunteers. The impactor mass was 8.5 kg. Three levels of impact force were applied; 400, 500 and 600 N. The tests were performed with and without muscle tension. The volunteers were unbelted. For the same test conditions, without muscle tension, no difference between the peak T1 acceleration for males and females were found. However, the maximum acceleration of the head CG under these conditions was higher for females than for males. The presence of muscle tone resulted in a suppression of both the peak displacement of the head CG and the peak rotation of the head. This suppression was larger for males than for females. Also, it was also found that under the same test conditions, males and females with relaxed muscles showed approximately the same peak head CG displacements and peak head rotations.

Summarizing the above, the following was found to be important for scaling of the head-neck requirements of a lateral sled test:

- The neck length ratio between females and males is more than 10% smaller the neck circumference ratio.
- Males and females have approximately the same range of motion in quasi-static bending tests.
- The presence of muscle tone in lateral bending and in lateral shoulder impact tests results in suppression of the peak displacement and rotation of the head more in males than in females.
- In a relaxed condition in a lateral shoulder impact test the peak displacements and rotation of the head of males and females are approximately similar.
- In a relaxed condition in a lateral shoulder impact test the peak acceleration of the head CG is higher for females than for males.
- In a relaxed condition in a lateral shoulder impact test the T1 accelerations of males and females are similar.

4 NBDL volunteers head-neck anthropometry versus responses

4.1 NBDL volunteers anthropometries

The Naval Biodynamics Laboratory in New Orleans (NBDL) has conducted a large number of human volunteer tests in various impact directions. A number of the lateral impact tests have been analyzed here in order to investigate the possible relationship between head-neck anthropometric parameters and the actual performance in a dynamic test. Table 4.1 shows the NBDL volunteers whole body and head and neck anthropometries used for this analysis. The neck length was here defined as the distance between the T1 and head anatomical origin just before impact (Wismans *et al.*, 1986). The subject's head mass has been estimated based on measured head geometry data and using the regression equations proposed by McConville *et al.* (1980). The five measured neck circumferences are of subjects exposed to frontal tests (Thunnissen *et al.*, 1995). The neck circumferences of the rest of the volunteers were not available.

Table 4.1: NBDL Volunteers anthropometries (Wismans *et al.*, 1986).

Subject number	Standing height [m]	Weight [kg]	Initial neck length [m]	Neck circumference [m]	Head mass [kg]
H00118	1.86	73.8	0.172		4.79
H00120	1.73	83.0	0.172		5.14
H00127	1.72	62.1	0.162	0.355	4.40
H00130	1.80	72.6	0.180		4.75
H00131	1.67	67.6	0.156	0.394	4.98
H00132	1.73	79.8	0.141	0.395	5.05
H00133	1.62	61.2	0.165	0.377	4.70
H00134	1.78	75.3	0.158		4.81
H00135	1.72	68.9	0.150	0.376	4.32
H00136	1.85	88.9	0.173		4.77
H00138	1.86	78.9	0.174		4.87
H00139	1.74	72.6	0.164		4.94
H00140	1.77	86.2	0.173		4.88
H00141	1.83	80.7	0.175		4.57
H00142	1.82	87.5	0.161		4.75
average	1.77	75.9	0.165	0.379	4.78

4.2 Head responses as function of neck length

The peak head response values as function of initial neck length in the NBDL lateral impact tests are plotted in Figure 4.1. These peak response values were taken from the lateral sled tests conducted at 7.2 G (Wismans *et al.*, 1986), since the ISO TR9790 head-neck response requirements were derived from these tests.

Regression analysis was used to find relations between these anthropometry parameters and the head responses (Montgomery and Runger, 1999). The straight lines in the figures are the least squared functions resulting from this linear regression analysis. The coefficient of determination (R^2) and the correlation coefficient (ρ) were used to define the accuracy of the regression models. In this study it is assumed that if both R^2 and ρ are larger than 0.5 a linear relation is likely.

As is clear from Figure 4.1a and Figure 4.1b, a relation between the initial neck length with the peak head lateral flexion angle ($R^2 = 0.05$, $\rho = 0.22$) and with the peak head twist angle ($R^2 = 0.00$, $\rho = 0.04$) is not really present. From Figure 4.1 c and d it can be seen that a positive

correlation between the initial neck length with the peak lateral displacement ($R^2 = 0.77, \rho = 0.88$) and with peak vertical displacement ($R^2 = 0.55, \rho = 0.74$) does exist.

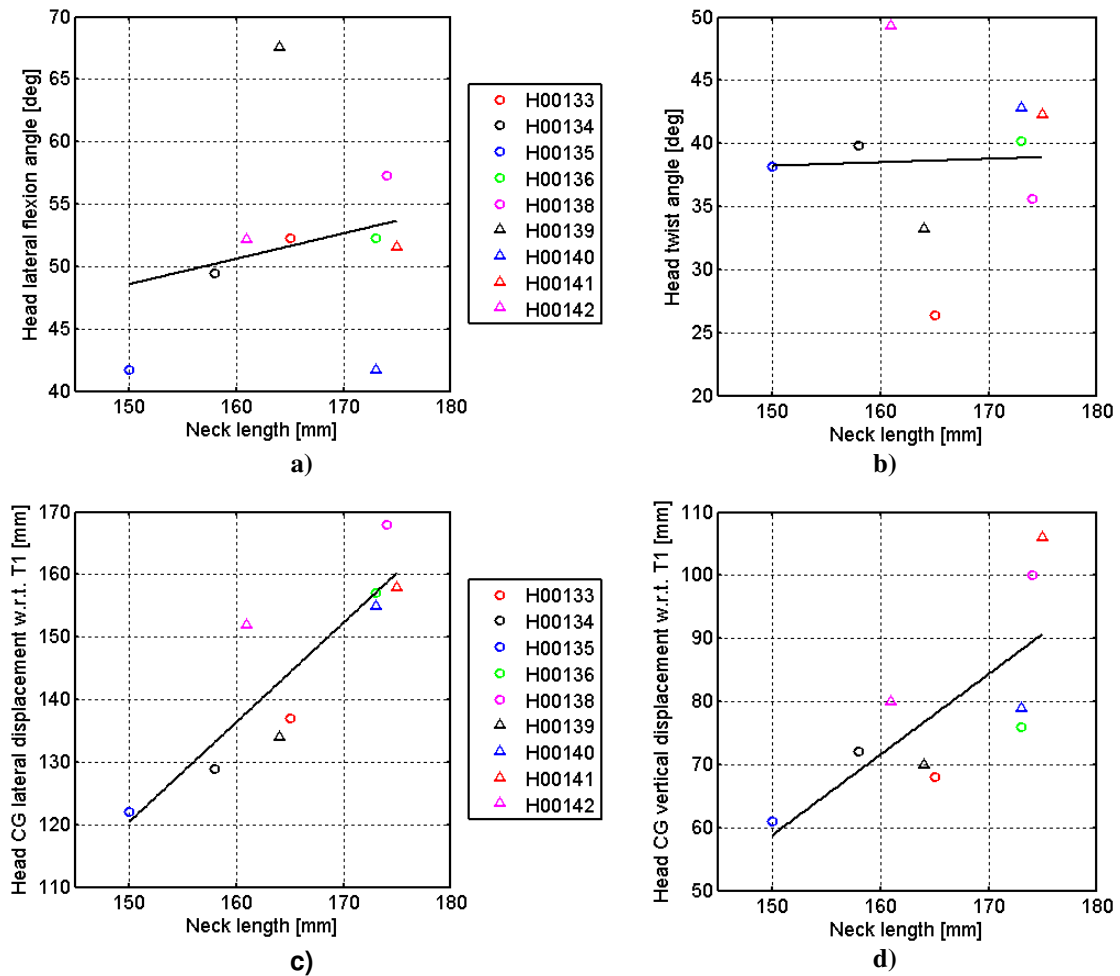


Figure 4.1: Peak lateral head flexion angle (a), peak head twist angle (b), peak lateral head displacement (c), and peak vertical head displacement (d) as function of initial neck length.

4.3 Head responses as function of head mass

The peak head response values as function of head mass in the 7.2 G NBDL lateral impact tests are plotted in Figure 4.2. From the regression analyses, no relation was found between the head mass with the peak head flexion angle ($R^2 = 0.31, \rho = 0.51$), peak head twist angle ($R^2 = 0.00, \rho = -0.06$), peak head lateral displacement ($R^2 = 0.15, \rho = 0.39$), peak head vertical displacement ($R^2 = 0.03, \rho = 0.17$).

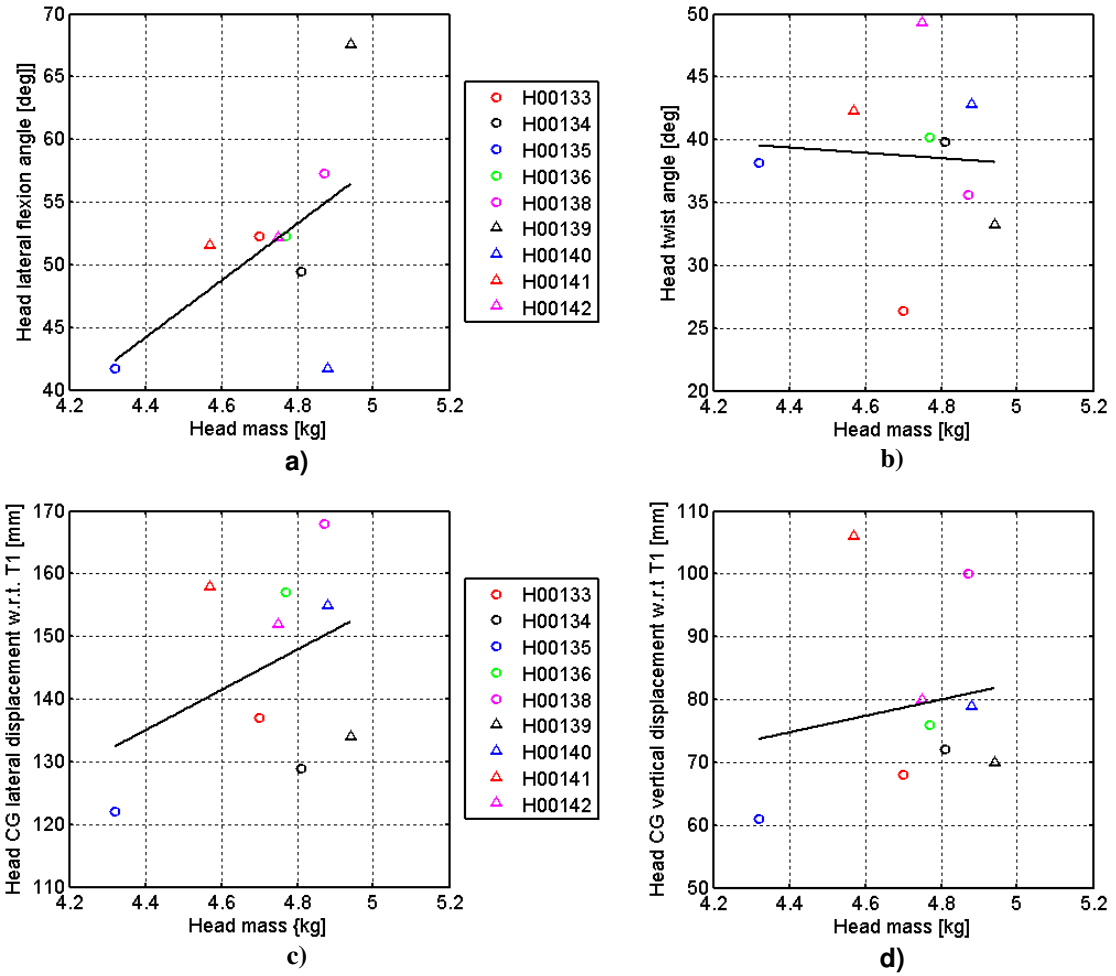


Figure 4.2 Peak lateral head flexion angle (a), peak head twist angle (b), peak lateral head displacement (c) and peak vertical head displacement (d) as function of head mass.

5 Discussion

The assumption of Irwin *et al.* (2002) to scale the neck in all directions with the same factor is in contrast with the literature findings that the neck circumference is smaller in midsize female than in midsize male, but the neck length is not (Valkeinen, 2003, Harty 2004). Also, in Figure 5.1a it can be seen that the neck length and the neck circumference does not have a positive relation ($R^2 = 0.37, \rho = -0.61$). The number of subjects is too small to conclude that there is a negative correlation between the neck circumference and the neck length. Probably, it is more or less randomly distributed.

As females on average have a shorter body length than males, their neck is proportionally longer than in men. From an anatomical point of view, the neck length is positively related to the erect seating height. The erect seating height was also used by Mertz *et al.* (1984 and 1989) to scale the neck length. In Figure 5.1b the erect seating height of the NBDL human subjects is plotted as function of their neck length. There is no strong positive correlation ($R^2 = 0.29, \rho = 0.54$), but the erect seating height seems to be a better scale factor than the neck circumference.

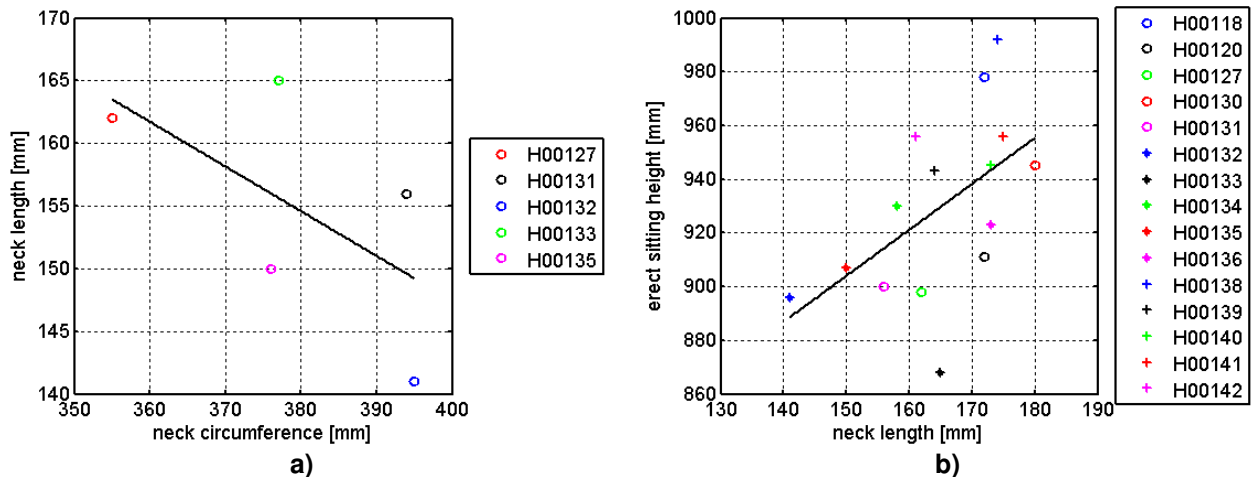


Figure 5.1: Initial neck length as function of neck circumference (a), and erect seating height as function of initial neck length (b).

Irwin *et al.* (2002) assumed the neck bends like a cantilever beam as described by Fenner (1989) in lateral direction, and the neck is assumed to behave like a cylindrical shaped beam around its length axis (Fenner, 1989). With the elastic modulus and the shear modulus both assumed to equal 1, the bending and the twist of the neck both depend on the neck length and circumference. Since in the NBDL volunteer analysis in section 4, the head flexion angle and the head twist are not related to the neck length, the cantilever beam model was found not to be a good approximation for the head kinematics in the NBDL test.

From the NBDL volunteer analysis in section 4, it can be seen that the head kinematics (lateral flexion, head twist, lateral and vertical displacements) are not related to the head mass. Also, the head mass seems to be strongly positively related to the neck circumference in the group of NBDL volunteers of which the neck circumference was available, see Figure 5.2. Since the NBDL volunteers were all young and trained people, their neck circumference is probably depending on the amount of muscles, and thus the neck strength, and not so much on the skin and fat tissue. So, this suggests that the neck strength is proportional to the head mass. It must be noted that in a group of people of different age and proportions, the neck circumference will not be a good

measure for the neck strength. Considering further that males and females of the same age have similar range of motion of the head-neck system (Schneider *et al.* 1975; Tilley, 1993; Youdas *et al.*, 1993), and that the difference in neck stiffness between females and males does not have to be taken into account in unexpected impacts (Schneider *et al.*, 1975; Ono *et al.*, 2007), the relation between the head mass and neck strength is assumed to be valid regardless of the gender.

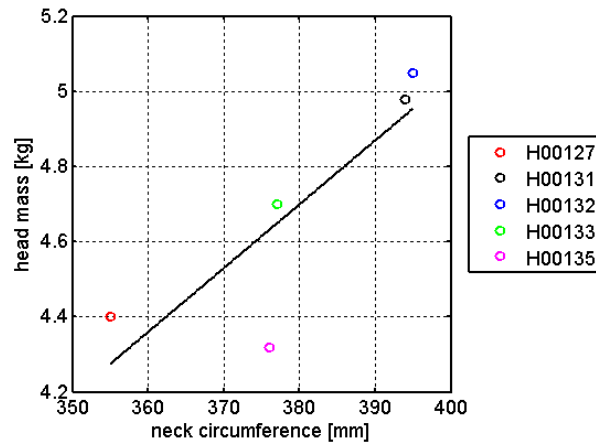


Figure 5.2: Neck circumference as function of head mass.

Wismans and Spenny (1983) were able to describe the head motion well using a model of 2 pivots, one located in the torso with the rotation axis perpendicular to the impact plane and one located near the occipital condyles rotating about the axis perpendicular to the impact plane and rotating about the axis parallel to the head anatomical z-axis. Taking in mind that the peak head lateral and vertical displacements were found to depend on the neck length and most of the volunteers have an almost similar head flexion and twist, see section 4, a simple version of this model could be used for scaling the neck test 1 requirements from midsize male to small female, see Figure 5.3. The first pivot is assumed to be located at the T1 rotating perpendicular to the impact plane. The second pivot is assumed to be located at the occipital condyles (OC) rotating about the z-axis parallel to the head anatomical z-axis.

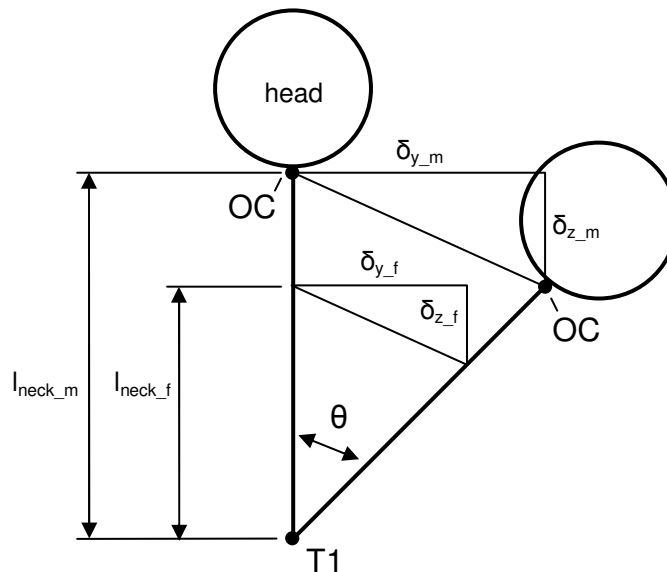


Figure 5.3: Model for scaling the head lateral and vertical displacements, assuming that the flexion angle θ is similar for midsize male and small female and the head displacements depend on the neck length.

Unfortunately, no relations could be found for the peak T1 lateral acceleration to the anthropometry, since the peak T1 accelerations per NBDL volunteers were not available. Irwin's scaling of the peak T1 accelerations was based on the body response in blunt impact, resulting in higher T1 accelerations for small female than for midsize male. However, Ono *et al.* (2007) found the peak T1 lateral acceleration to be similar in blunt lateral impact. In ISO TR9790 neck test 1 the dummy is sitting against a plate and is tied to the seat due to which the impact on the shoulder is small compared to the inertia effects of the head. Therefore, it is here assumed that the peak T1 lateral acceleration is similar for small female and midsize male. It is assumed that the sled acceleration is the dominant parameter for T1 acceleration in this test condition, rather than anthropometry. No sufficient data is available to find a proper scale factor for the peak T1 accelerations and more research is needed in this area. In this paper the following theory is applied based on comparison of T1 and sled accelerations. The T1 lateral acceleration is lagging to sled acceleration in loading phase. The theory is that the human body acts as spring-mass system. During acceleration the spring (body lateral stiffness) is compressed (T1 displacement) until sufficient force is build up to accelerate the mass (human body mass). After the loading phase and compression of the chest the T1 acceleration is following the sled acceleration. In this phase the sled acceleration is dominant for the peak T1 acceleration and not the anthropometry. Therefore, it is proposed to apply Irwin's scaling formula based on chest stiffness and body mass for T1 displacement, and NBDL volunteer peak T1 acceleration without scaling.

The head dynamics and time of the peak head lateral displacement of the small female are scaled taking into account the scaling method for the kinematics as described above. The scale factors according to the new method for the length, mass, mass moment of inertia and stiffness of the head and neck are given in Table 5.1. The new scale factors to scale the requirements of ISO TR9790 neck test 1 for the midsize male to small female are given in Table 5.2.

The corridors of ISO TR9790 neck test 1 were scaled according to the new scale factors in Table 5.2 and are given in Table 5.3. The corridor widths for small female were assumed to be relatively the same as for the midsize male, as was assumed by Irwin *et al.* (2002). The authors

recommend that ISO/TC22/SC12/WG12 review and adopt the new requirements for the small female dummy in ISO TR9790 neck test 1.

Summarising, the differences between the new method for scaling the midsize male neck test 1 requirements to small female and the scaling method of Irwin *et al.* (2002) are:

- The neck length is scaled with the erect seating height. In Irwin’s it was scaled with the neck circumference.
- The peak T1 acceleration is not scaled. In Irwin’s it was scaled using the scaling method developed for cadaveric drop tests by Mertz (1984).
- The peak head displacements, flexion angle, and accelerations are determined by a simple one pivot (at T1) theory. In this one pivot theory the passive neck strength is proportional to the head mass resulting in similar peak flexion angles for small female as for male, and the peak head displacements scale with the neck length. In Irwin’s they were derived from the energy balance store in the neck at maximum flexion, with the neck modelled as a cantilever beam with a point mass on the free end.
- For the same reason as for the peak flexion angle, the peak twist angle is not scaled. In Irwin’s it was derived from the energy balance store in the neck at maximum twist, with the neck modelled as a cylindrical shaped beam with a point mass on the free end.

Table 5.1: Scale factors for length, mass, mass moment of inertia and stiffness for the small female relative to the midsize male according to the scaling method developed in this study.

Scale factor	Symbol	Formula	Factor
Head mass	$\lambda_m \text{ head}$	$(\lambda_x \text{ head})^3$	0.810
Head length	$\lambda_x \text{ head} = \lambda_y \text{ head} = \lambda_z \text{ head}$	$(C+W+H)_f / (C+W+H)_m$	0.932
Head inertia	$\lambda_{Iz} \text{ head}$	$\lambda_m \text{ head} * (\lambda_x \text{ head})^2$	0.704
Neck mass	$\lambda_m \text{ neck}$	$(\lambda_x \text{ neck})^3$	0.501
Neck length	$\lambda_x \text{ neck} = \lambda_y \text{ neck} = \lambda_z \text{ neck}$	$\lambda_z \text{ torso}$	0.895
Neck bending stiffness	$\lambda_k M_x \text{ neck}$	$\lambda_m \text{ head}$	0.810
Neck torsional stiffness	$\lambda_k M_z \text{ neck}$	$\lambda_m \text{ head}$	0.810
Torso length	$\lambda_z \text{ torso}$	ESH_f / ESH_m	0.895
Torso stiffness	$\lambda_k t$	$\lambda_z \text{ torso}$	0.895
Torso total mass	$\lambda_m b^*$	$m_{b_f} / m_{b_m^*}$	0.597*

Figure 5.4

$_f$ = small female

$_m$ = midsize male

* Note that the scale factor for the total body mass is similar to that of the torso mass, see Table 2.1.

Table 5.2: Scale factors for the ISO TR9790 neck test 1 requirements for the small female relative to the midsize male according to the scaling method developed in this study.

Scale factor	Symbol	Formula	Factor
Sled velocity	λ_v	v_f / v_m	1
T1 lateral acceleration	R_{at}	λ_v	1
T1 lateral displacement	R_d	$\lambda_v * \sqrt{(\lambda_m b / \lambda_k t)}$	0.817
Neck lateral flexion angle	R_θ	$\lambda_v * \sqrt{(\lambda_m \text{ head} / \lambda_k M_x)}$	1
Neck twist angle	R_ϕ	$\lambda_v * \sqrt{(\lambda_{lz} / \lambda_k M_z) / \lambda_x \text{ head}}$	1
Head lateral acceleration	R_{ahy}	$(\lambda_v^2) / \lambda_z \text{ neck}$	1.117
Head lateral displacement	R_{dhy}	$\lambda_z \text{ neck}$	0.895
Time peak head lat. disp.	R_{ht}	$\lambda_z \text{ neck} / \lambda_v$	0.895
Head vertical acceleration	R_{ahz}	$(\lambda_v^2) / \lambda_z \text{ neck}$	1.117
Head vertical displacement	R_{dhz}	$\lambda_z \text{ neck}$	0.895

Table 5.3: ISO TR9790 neck test 1 requirements for the midsize male, the small female requirements scaled according to Irwin *et al.* (2002), and the new small female requirements.

Response	Requirements 50th male		Requirements 5th female Irwin <i>et al.</i> (2002)		Requirements 5th female New	
	Lower	Upper	Lower	Upper	Lower	Upper
Peak horizontal acceleration of T1 [G]	12	18	15	22	12	18
Peak horizontal displacement of T1 rel. sled [mm]	46	63	38	51	38	51
Peak horizontal displacement of head CG rel. T1 [mm]	130	162	121	151	116	145
Peak vertical displacement of head CG rel. T1 [mm]	64	94	80	118	57	84
Time of peak head excursion [s]	0.159	0.175	0.161	0.177	0.142	0.157
Peak lateral acceleration of head [G]	8	11	8	11	9	12
Peak vertical acceleration of head [G]	8	10	10	13	9	11
Peak flexion angle [deg]	44	59	56	75	44	59
Peak twist angle [deg]	32	45	41	57	32	45

6 Conclusions

From this study it was concluded that the scaling method developed by Irwin *et al.* (2002) to scale the midsize male requirements of ISO TR9790 neck test 1 to small female is not valid for all requirements. The scale factors that were found not to be valid were updated using relations found in literature on head-neck biomechanics, and relations found in an analysis of the NBDL volunteer anthropometry and response. The requirements of the midsize male, the requirements scaled to small female according to Irwin *et al.* (2002), and the new requirements for the small female are given in Table 5.3. More research is needed on scaling of the T1 displacement.

7 Comparison of the small female WorldSID prototype head-neck responses to the new requirements

The responses of the small female WorldSID in the neck test 1 set-up used in the evaluation of the small female WorldSID (Been *et al.*, 2007) are compared to the new small female requirements in Figure 7.1 to Figure 7.8. Three tests were performed with the small female WorldSID impacting its right side to the rigid board. Each test had a different belt configuration, because the tying of a volunteer is different than a dummy and hard to compare:

- **Original test:** Tight 5-point belt with lateral torso belt
- **Second test:** Tight 5-point belt, no lateral torso belt
- **Third test:** 5-point belt with slack, no lateral torso belt

The dummy head angles were calculated according to the definition of head angles of Philippens *et al.* (2004) due to which the head twist angle had another sign (positive) than the requirement (negative). However, the absolute value of the twist angle in a pure lateral impact should be approximately similar. The definition of the flexion angle here is similar to that measured on the NBDL volunteers.

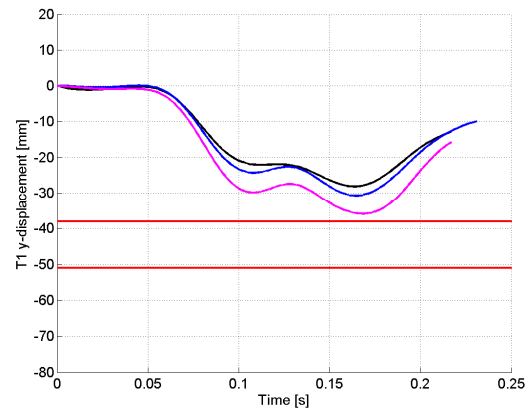
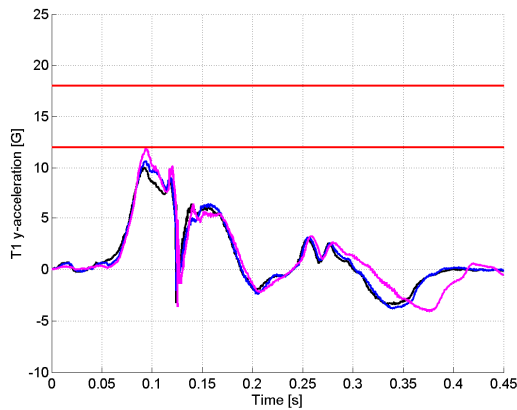


Figure 7.1: T1 y-acceleration (right=positive). Figure 7.2: T1 y-displacement.

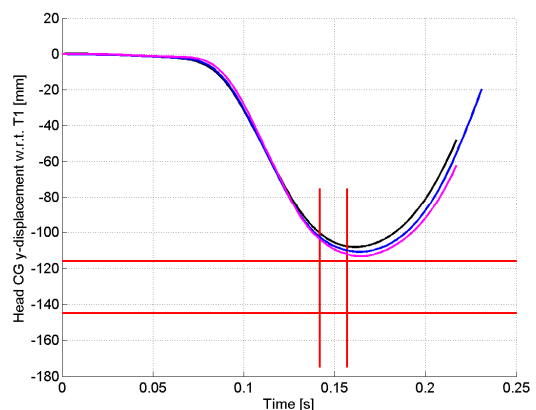
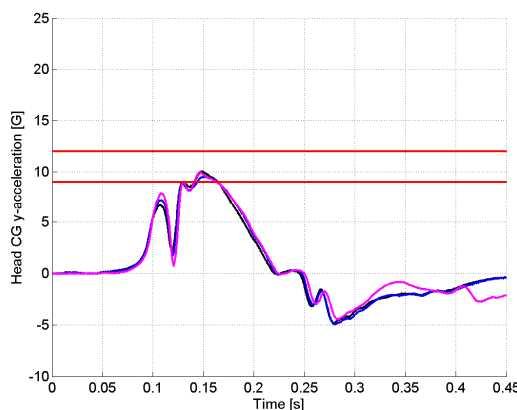


Figure 7.3: Head y-acceleration (right=positive).

Figure 7.4: Head y-displacement.

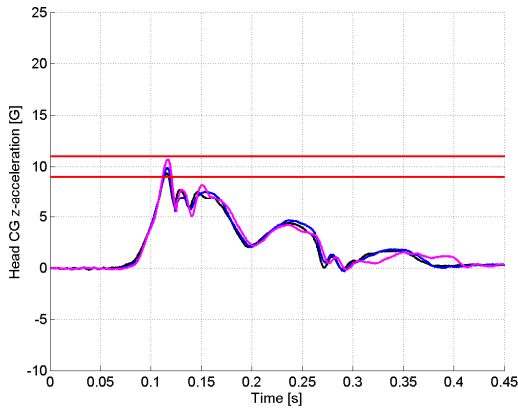


Figure 7.5: Head z-acceleration (downward=positive).

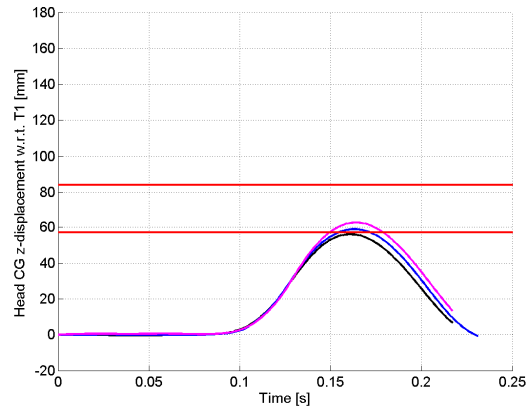


Figure 7.6: Head z-displacement.

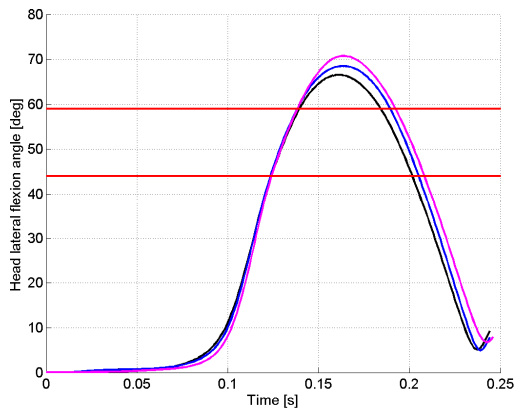


Figure 7.7: Head lateral flexion angle. (right rotation=positive)

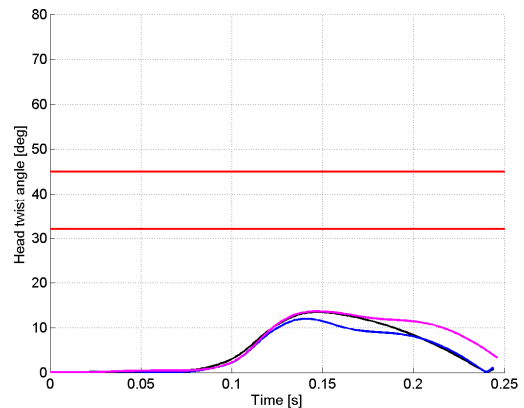


Figure 7.8: Head twist angle. (right rotation=positive)

For objective rating of the small female WorldSID head-neck system the ISO TR9790 rating system was applied to the test results. In this rating system 10 points are given if the response meets the requirement, 5 if the response lies within one corridor width of the requirement, 0 if neither is met. The overall biofidelity is defined by the average of the rating per response, so lies between 0 and 10, taking into account the weighting factors of each response. The rating results using the corridors scaled according to Irwin *et al.* (2002) as well as the new corridors are given in Table 7.1. Comparing the scores using the new corridors to the scores using the Irwin scaled corridors, it can be seen that for some responses the biofidelity score became better and some scores were reduced. The overall biofidelity rating of the small female WorldSID is lower for the new corridors than for the Irwin scaled corridors. However, five of the nine responses were just outside the new corridor (Figure 7.1, Figure 7.2, Figure 7.4 and Figure 7.6) and one was just outside one corridor width (Figure 7.2).

Also, if the T1 lateral acceleration would have been inside the corridors, the six responses that were now below the corridors are anticipated to get closer to or inside inside the corridors. When increasing the T1 lateral acceleration, the head flexion angle would exceed its maximum requirement even more. This could be an indicator that the neck bending stiffness of the small female WorldSID prototype is too small.

The overall ISO TR9790 biofidelity rating of the small female WorldSID prototype for neck test 1 was not improved when applying the new requirements compared to Irwin's. Also, the overall ISO TR9790 biofidelity rating of the small female WorldSID prototype for the NBDL test condition was not improved when applying the new requirements compared to Irwin's. However, the reason for this study was not to increase the biofidelity score of the 5th female WorldSID prototype, but to

develop a scaling method for the head-neck in the condition based on literature of scientific research on neck biomechanics. And just as important, this study was performed to provide better targets for optimisation of the head-neck response of small female side impact dummies. Omission of Neck Test 2 (Patrick and Chou) from ISO TR9790 would bring the head-neck response much closer to the target of body segment biofidelity exceeding $B_{neck} > 6.5$.

Table 7.1: ISO TR9790 biofidelity score of the small female WorldSID prototype for neck test 1.

Response	Original test	Second test	Third test	Weighting factor	Old Score	New Score
Peak horizontal acceleration of T1 [G]	10.0	10.7	11.9	5	5.0	6.7
Peak horizontal displacement of T1 rel. sled [mm]	-28.1	-30.7	-35.9	5	5.0	5.0
Peak horizontal displacement of head CG rel. T1 [mm]	-108.2	110.9	113.3	8	5.0	5.0
Peak vertical displacement of head CG rel. T1 [mm]	56.0	58.9	62.6	6	5.0	8.3
Time of peak head excursion [ms]	161	164	164	5	10.0	5.0
Peak lateral acceleration of head [G]	10.1	9.5	10.0	5	10.0	10.0
Peak vertical acceleration of head [G]	9.4	9.9	10.7	5	8.3	10.0
Peak flexion angle [deg]	66.5	68.5	70.7	7	10.0	5.0
Peak twist angle [deg]	13.5	12.0	13.7	4	0.0	0.0
Overall biofidelity rating for ISO neck test 1:					6.6	6.2

From the comparison of the dummy responses and the new corridors the following dummy measures are proposed to further improve the head-neck responses:

1. Improve the twist response by replacing the rear square neck buffers with a circular one which is similar to the ones used in lateral positions. The change will have insignificant effect on the lateral response. Human necks are more flexible in neck extension (backward bending) than in flexion. The frontal response (not validated so far) will not be affected with this change. The twist motion may be doubled by this measure, with a potential to approach the lower boundary of 32° and increasing the score from 0 to 5.
2. The revision 1 updated dummy will have a reduced stiffness of the shoulder, thorax and abdomen ribs, with a potential to improve T1 acceleration and T1 displacement, and head lateral displacement. However, potential negative effects could be that the head lateral and vertical accelerations and the head flexion angle will increase.

It is recommended to repeat neck test 1 with revision 1 updated dummy to review its response to the newly develop corridors and to perform neck pendulum tests in frontal test conditions according to Mertz OC angle moment relationship (Mertz and Patrick, 1971).

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