Basics for developing a female occupant model for investigating Cervical Spine Distortion injury (CSD)

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Abstract - Females sustain Cervical Spine Distortion injury (CSD) more often than males. Most work dealing with the biomechanics background (e.g. injury mechanism/criteria) as well as the application in seat design/testing, focuses on the occupant model of an average male. Therefore the EU-Project ADSEAT (Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants) is aimed at adding a female model for gender balanced research of CSD and improving seat design. An extensive literature review, searching for risk factors and injury criteria for males and females, was accompanied by the evaluation of different databases containing CSD cases. The database evaluations suggests that an anthropometry quite close to the 50%ile female anthropometry as known from crash test dummy design is appropriate. The results presented here form the basis for the future development of a computational female model and the improvement of seat design for better protection of both males and females in the frame of the ADSEAT-Project.

NOTATION

CSD	Cervical Spine Distorsion
WAD	Whiplash Associated Disorder
ADSEAT	Adaptive Seat to Reduce Neck Injuries for Female and Male Occupants (EU-Project, 7th FRP)
WHIPS	Whiplash Protection System by Volvo
WIL	(Whiplash Injury Lessening) Whiplash Prevention System by Toyota
iiwpg	international insurance whiplash prevention group
IIHS	Insurance Institute of Highway Safety (US)
NIC	Neck Injury Criterion
IV-NIC	Intervertebral Neck Injury Criterion
NDC	Neck Displacement Criterion
WIC	Whiplash Injury Criterion
UMTRI	Transportation Research Institute at The University of Michigan

OBJECTIVE

The literature from accident analysis shows that females sustain Cervical Spine Distortion injury (CSD) more often than males. Most work dealing with the biomechanics background (e.g. injury mechanism/criteria) as well as the application in seat design/testing, focuses on the occupant model of an average male. Therefore it is aimed at adding a female model for gender balanced research of CSD. Here the anthropometric requirements as well as considerations with respect to injury criteria are addressed. By specification and quantification of risks for males and females in rear end crashes the basis for the development of a computational female model is given.

MATERIAL AND METHODS

An extensive literature review, searching for risk factors and injury criteria for males and females, was accompanied by the evaluation of different databases containing CSD cases. The possible anthropometry for a female model was to be derived from database evaluation and the recognition of high-risk groups. The literature review focused on scientific papers providing risk factors based on real world data and on papers from the field of anthropometry of high-risk groups and of crash test dummies. The databases of the ADSEAT WP1 Partners were used to calculate either risks and relative

rates or descriptive statistics. Three databases contain WAD cases only (GUT, AGU, LMU) so that differences between male and female patients can be retrieved. Two databases contain all kinds of crashes (Folksam, Volvo) so that risks for CSD injury are possible to calculate, in particular by concentrating on a sample of rear end crashes.
Both approaches provide the specification and quantification of risks for females and males. This information will be used for modelling a female computational model and to improve seat design in the frame of the ADSEAT project.

RESULTS

Literature review

Risk factors
The Literature review on risk factors included 38 references [1-37,52] presenting 113 associations between factors and risks for WAD and shows that males and females are susceptible to the same risk factors. The risk factors searched for stem from the fields "person-", "car-", "seat-", "crash-", and "interaction and situation- (between occupant, seat, vehicle and crash)" characteristics. Yet, the absolute risks for females are always higher compared to males. Table 1 gives an overview on the factors suspected to influence WAD risk.

Injury Criteria
Generally the term “injury criterion” is used for all different kinds of criteria which aim at quantifying the risk of sustaining injury or damage. In the context of rear-impact testing and or investigating the performance of different vehicle seats by sled testing, the criteria NIC and N_{km} [38, 39] are widely used. In addition measures of the “pure” loads like shear forces, axial forces or acceleration are used to characterize the loading situation.
Although it might seem that redundant measures are used – since the injury criteria also use forces/moments as input – it should be noted that the different criteria attempt to address different biomechanical hypotheses with regard to the injury mechanism.
The hypotheses mostly focus on injurious potential during the S-shape phase of the Cervical Spine without specifying the injured tissue. One hypothesis regarding the S-Phase concerns pressure aberrations inside the spinal canal leading to spinal ganglia nerve cell necrosis [38].
To mirror this phase the relative linear acceleration between T1 and head in x-direction is used (NIC, [38]), but also the flexion moment at OC (occipital condyle) and extension at lower neck (WIC, [40]), the relative head-to-torso motion [41], the relative displacement between head and torso (NDC, [42]), the linear combination of shear and y-moment (N_{km}, [39]), and intervertebral motions (IV-NIC, [43]).
Correlation to real life injury risk is best shown for NIC, N_{km}, and head to torso rotation [41, 44 – 47].
Also for frontal impacts injury criteria are suggested (N_{ij} [48], NIC protraction [49]) that could be used to mirror the rebound phase of rear impacts also. However, no good correlation to real life was shown up until now.
Generally approaches to scale currently used threshold values for males to females should be taken with care. In particular as long as fundamental biomechanical factors are not yet fully understood.

Table 1 – qualitative influence of factors or higher values of the considered parameters suspected to influence the WAD risk of females and males in rear end impacts derived from literature review (selection)

Keyword	Factor/parameter value	Influence on females' risk	Influence on males' risk	references
age	Especially 20 to 30 years compared to older (>50y)*	+	+	[3, 12, 13, 15, 18, 28, 34]
anthropometry	Body height	+/0[1]	+/0[1]	[5, 15, 16, 27, 34, 37]
anthropometry	Body weight	Not clear	Not clear	
anthropometry	BMI (Body Mass Index)	0	0	
anthropometry	Head to neck ratio**	0	0	
vehicle	car mass (struck car)	-	-	[1, 4, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16, 18, 20, 21, 22, 24, 26, 28, 29, 30, 31, 32, 35, 36, 51]
vehicle	Tow bar (struck car)	+	+	
seat	Stiff seat back	+	+	
seat	Good head restraint design	--	-	
seat	Good test result (iiwpg, IIHS)***	-	-	
seat	WHIPS[4]	-/--	--/-	
seat	Anti Whiplash Devices (other than WHIPS, e.g. SAHR, WIL, RHRs)	-	-	
Degree of damage	Degree of car damage	0/+[2]	+	
Delta v	Delta v	+	+	[3, 5, 7, 15, 17, 18, 20, 21, 25, 28, 29, 30, 32, 33, 34, 35, 52]
Delta v	EES (Energy Equivalent Speed)	0	0	
Delta v	Mean acceleration	+	+	
Direction of impact	Rear end impact	++	+	
Seating position	driver	+	+	[3, 5, 6, 13, 14, 15, 16, 17, 19, 23, 28, 30, 32, 33, 35]
posture	Turned head	+	+	
posture	Inclined head****	(+)?	(+)?	
posture	Seat belt	-	-	
Head restraint distance	Horizontal distance	0/+[3]	+	
Head restraint distance	Vertical distance	+	0	
Driving situation	roundabout	+	++	
Driving situation	intersection	++	+	

* different age classes used in studies
** in low energy volunteer tests
*** "good" rated compared to "poor" rated seats, no statement on acceptable/marginal ratings
**** only the number of symptoms in case of WAD is increased, not the risk of WAD occurrence
[1] In WHIPS seat no influence of body height found, in older seats higher body height → higher risk
[2] In one study a higher degree of damage is only associated to males risk, other studies combine males and females risk
[3] only one study shows no significantly increased risk for females
[4] one study shows even higher protection for females, one study shows even higher protection for males
0 no influence on risk for WAD when factor or higher value of parameter applies
+ higher risk for WAD when factor or higher value of parameter applies
- lower risk for WAD when factor or higher value of parameter applies
-- even lower risk for females compared to males/ or for males compared to females
++ even higher risk for females compared to males/ or for males compared to females

Database Analyses by ADSEAT Partners

Crash and Pulse characteristics

From the crash database by Folksam providing real world pulse measurements by crash recorders the following results are derived. The risk of both initial and long-term symptoms as well as grades of WAD is correlated to change of velocity and mean acceleration. At a change of velocity above 15 kph the risk of symptoms for more than 6 months was found to increase rapidly for the seats included in the study (Toyota). For mean acceleration the risk increases rapidly above 4.5 g.

The calculation of the risk curves show that females seem to have lower variations in risk factor susceptibility as the risk curves are steeper compared to males. Thus all females reach higher risks for WAD already at lower parameter values of delta v and mean acceleration, still when stratifying for different parameters. For instance the risk for symptoms > 1month is ~80% at 7g for females, for males the risk at 7g is ~60%; at 25 kph the risk for females is ~75% and for males ~50%.

The 50 % risk for initial symptoms of WAD for females lies at ~10 kph and 3.5 g, and for males at ~17 kph and ~4.7g. The 50 % risk for symptoms >1 month for females lies at ~21 kph and 5.8 g and for males at ~26 kph and 6.3 g.

Seat characteristics

The whiplash prevention system from Toyota (WIL) was found to reduce the whiplash risk. At a change of velocity of 20 kph the risk of symptoms lasting longer than 6 months was reduced with approximately 40 % for males and females together. No separation for gender was possible due to limited number of cases.

The WHIPS seat in Volvo cars offers a statistical significant injury reduction as compared to the comparable models without this system (reference seat). Overall injury reducing effects of 25 % for initial symptoms and 40 % for symptoms lasting more than one year are seen. The injury reducing effect varies depending on impact severity. For moderate impact severity the mean effectiveness are as high as 30 % (initial) and 49 % (>1 year), respectively and for minor impact severity, 26 % and 36 %, respectively.

Table 2 summarizes the literature results and new analyses towards protective potential by seat design

Table 2 - literature results and new analyses towards protective potential by seat design

Factor	change of WAD Risk	Reference
geometric head restraint redesign	37% lower risk for Ford Taunus and Mercury Sable for females, not for males (models with "standard" and "improved" seat/head restraint design)	[9]
active head restraints	55% lower risk for active head restraints (except WIL and WHIPS) for females (sig.), 43% overall (sig.) (males reduction n.sign.) (models with "standard" and "improved" seat/head restraint design)	[9]
WHIPS	absolute risk reduction for females 29%, for males 10%; at moderate impact severity 45% reduction for females, (all sig.) and n.sig. 24% reduction for males	[15]
WHIPS	reduction of 22% for initial risk and 34% reduction of long term risk	[16]
WHIPS	60% relative risk reduction for long term (>1 month) WAD in two car crashes	[26]
WHIPS	reduction of 25% for initial risk and 40% reduction of long term risk, absolute risk reduction for initial symptoms by 18% for males, and 17% for females	(Jakobsson 2010 for ADSEAT)
WHIPS	35% relative risk reduction for long term (>1 month) WAD in two car crashes compared to cars with standard seats	[51]
SAHR	absolute Risk Reduction of 14% (from 18% to 4%) risk of CSD >1 week	[36]
SAHR	55% relative risk reduction for long term (>1 month) WAD in two car crashes	[26]
SAHR	50% relative risk reduction for long term (>1 month) WAD in two car crashes compared to cars with standard seats	[51]
WIL	30% relative risk reduction for long term (>1 month) WAD in two car crashes	[26]
WIL	40% relative risk reduction for more than 1 month and more than 6 months at 20 kph	(Kullgren et al. 2010 for ADSEAT)
WIL	20% relative risk reduction for long term (>1 month) WAD in two car crashes compared to cars with standard seats	[51]
WHIPS, RHR, WIL	Relative risk for long-term (> 1 month) neck injury in seats with a system is about 50% of the risk in seats without a system, absolute Risk Reduction of 7% (from around 14% to 7%)	[25]
other than WHIPS, SAHR, WIL	25% relative risk reduction by whiplash protection systems for long term (>1 month) WAD in two car crashes	[26]
All Whiplash Protection concepts	45% risk reduction for females, 60% risk reduction for males (for WAD > 6months)	[51]

Profile of male and female WAD patients

The CSD databases show that male and female patients do not differ significantly in their symptom severity or duration. The cars the females were sitting in when hit from the rear were of lower weight compared to the males. On average the females' vehicles had a mass between 1000 and 1200 kg and the males' vehicles around 1300 kg (all crashes from 2000 to 2009, including vehicle models from 1985 on). Only one database could show a significant difference between males and females concerning the crash pulse (reconstructed, PC-Crash), which was higher for the females. Further differences from vehicle, seat, and crash circumstances could not be found.

Anthropometry

In accordance with the literature the database containing anthropometric data on CSD cases by AGU found that the typical female patient does not differ to the general population (Switzerland) in terms of body height and body weight (165 cm, 65 kg). The anthropometric data of the general female population reported from several European countries lies at 164.6 cm and 66.3 kg (not weighted average). The results found do not differ much from the 50%ile specifications for females used in dummy design (162 cm, 62 kg) [50].

DISCUSSION

Risk factors

For the purpose of the ADSEAT project to improve protection from WAD in rear end crashes for both males and females the focus was laid on possible risk factors that can be influenced by seat design.

Of course the person characteristics cannot be influenced, but influences from their side could be taken into account when designing seats (seating height e.g.). However, no definite hints what to take into account were found from published Real World data studies.

With respect to vehicle characteristics it has to be pointed out that the occupants' risk or protection is a consequence of crash behaviour and the installed seat. Therefore only hints towards stiffness of rear structures influencing the crash pulse seem useful for further considerations. The seat itself was found to have a high potential for the protection of occupants. All seats fitted with Anti Whiplash Devices perform better than conventional seats from the 90s up to 2006. For females an even higher protection is seen by improved head restraint design [9] and by the WHIPS seat [15], whereas another study finds a higher protection potential by WHIPS for males [51].

For the further use in the ADSEAT project it is also interesting to see that real world data correlate with seat ratings. Yet, the existing seat ratings (taking into account geometry and the dynamic parameters T1x, upper neck tension, lower neck shear forces, and contact time) can only mirror differences between "good" and "poor" ratings, not so for the in-between rated seats that perform differently in real world.

From the crash characteristics the mean acceleration seems to be the most important risk factor, yet, only two studies examined real world outcome [20,52]. At mean accelerations of 1 g females already show a risk of 40 % to sustain WAD (any duration) whereas males still show nearly no WAD. Rising delta v also indicates higher risks for WAD. The delta v of highest risk (for WAD occurrence and WAD symptoms duration up to 1 month, respectively) seems to lie in the range between 13 to 15 kph when combining the results of two studies [20,35]. Yet, this is based on different samples and measurement techniques. New results are provided by the database analysis by Folksam for ADSEAT confirming that mean acceleration and delta v increases lead to risk increases for WAD for males and females, which is steeper for females. No studies based on real world data could show that e.g. angled impacts or impacts with small overlap bear higher risks. The impact direction with the highest risk for WAD, especially for females, is the rear end impact.

Regarding posture, only the interaction with the head-restraint seems to be important. A higher vertical and horizontal distance to the head restraint bears higher risks, and so does a turned head posture compared to looking straight. The latter is based on the recalled memories of the crash situation of the occupants.

Furthermore, all studies found that the driver position entails highest risks for males and females compared to other seating positions. No further studies based on real world data examined other

posture influencing factors like distance to steering wheel and arm/hand position or seat back inclination, which might influence shoulder positions and spine curvature.
Especially for seat characteristics and for the direction of impact differences in relative risk changes between males and females can be found in literature. Risk factors from anthropometry cannot be proven. Body height was discussed as a risk factor for both females and males. However, one newer study can show that by adequate seat design no risk differences from different body height can be expected. Further, databases did not show a different anthropometric profile for WAD patients compared to the general population. Especially females can profit from improved seat design.

The anthropometry of the female WAD patient does not differ from the general population in terms of stature and weight. In addition, no different risks were identified for the males or for the females when analysis was separated by stature or weight classes. Thus, there seems to be no necessity to model a female of special anthropometry as no group of higher risk would be represented by some special characteristics. The anthropometrical measures that were used to define the currently used dummy sizes are slightly smaller and of lower weight compared to the values based on AGU data. For acceptance of the ADSEAT female model by target groups and for the project preceding it was decided to use the 50%ile UMTRI data for the female model.

Females seem to be more vulnerable to loads occurring during rear end impact. They reach higher risks compared to males already at lower mean accelerations and delta v values.
The WHIPS, WIL, and the SAHR systems are able to decrease the risk for WAD significantly. In addition other Anti Whiplash Designs were shown to also reduce injury risk [26,36]. For improved seat design these concepts should be improved to protect both males and females in all crash situations. However, it seems to be important to focus on protection of the most dangerous crash pulses for females and males that start at delta v level of around 15 kph and mean accelerations of 4.5 g.
One request evolving from CSD database analyses seems to be to improve especially seats in low weight cars as those seem to provide higher loads in general when involved in rear end impacts.

The review on injury criteria shows that especially the first phase until head restraint contact is seen as the vulnerable phase for WAD. However, only in animal experiments nerve cell degeneration due to pressure gradients inside the spinal canal could be detected correlating to the injury criterion NIC. Correlation to real world injury data was shown for NIC, N_{km}, and head to torso rotation. The rebound phase as bearing injurious potential is only suggested up until now. Yet, as there seem to be high frequencies of WAD after frontal impacts also, and an influence of the seat belt also in rear impacts was found, there might evolve a need for keeping the rebound phase under consideration. It is to be noted that some of the injury criteria are already part of regulations and test procedures, respectively. However, some criteria require the use of particular anthropometric test dummies to be able to determine the physical measures needed to establish the injury criteria.
Threshold values for females are not given in literature concerning Injury Criteria and no scaling advices are retrievable.

CONCLUSION

For the preceding in the ADSEAT Project towards a computational female model the use of the 50%ile UMTRI data is suggested. Seats should provide protection from WAD for males and females especially at crash pulses of at least 15 kph and 4.5 g.
The review on injury criteria shows, that there are no gender specific injury criteria. No methods are validated to adequately scale proposed threshold values of postulated injury criteria. As seat ratings can already separate good protection potential from poor protection potential in real life the used criteria should be taken into account, but criteria choice and weightings should be improved.
For the further ADSEAT Project volunteer, animal, PMHS and dummy test set-ups have to imply these findings. Further research based on real world data is needed on the anthropometric influences on WAD and on the validation of injury criteria.

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