WHIPLASH INJURIES, NOT ONLY A PROBLEM IN REAR-END IMPACT

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Paper # 214

ABSTRACT

Even though the risk of whiplash injury is the highest in rear-end impact, there is an increased focus on frontal and frontal-oblique impact during recent years. The amount of injuries in these directions may be larger than in rear-end impact. Therefore, a European project was initiated to investigate causes and countermeasures in this area, as was previously done for rear-end impact.

Accident studies showed that the amount whiplash cases was generally higher in frontal impact compared to rear-end. In all impact directions, the injury risk for female occupants was about twice the risk of male occupants. Given these results, there is a need for occupant protection against whiplash in frontal impact as well. Since there is no omni-directional whiplash dummy on the market, one of the aims was also to develop such a device. As a start several existing dummies, like THOR, Hybrid III, BioRID and RID2 were evaluated for this purpose. So far none of these dummies seemed fit to handle all the directions wished. The first start of more detailed development was to obtain typical human responses with human volunteers and Post Mortem Human Subjects. These tests will then be used for the whiplash dummy evaluation.

Future work will concentrate on dummy development and evaluation, test methods and evaluation of seats available on the European market and the definition of seat parameters, which could reduce whiplash injury risk.

INTRODUCTION

During recent years the main focus in whiplash research has been on rear-end impacts. Rear-end impacts have the largest risk of whiplash injury (Temming and Zobel, 2000) and therefore much effort is being spent on decreasing this injury risk. The total number of frontal whiplash cases may be higher, despite the smaller risk. According to German accident data (Temming and Zobel, 2000) 38% of the injury cases are single impact frontal accidents (589 of 1558), with an injury risk of 12% (100% are all belted occupants), while 15% of the injury cases are single impact rear-end accidents (233 of 1558), with an injury risk of 26%. A Swedish study by Von Koch et al. (1995) shows that 23% of all injury cases resulted from frontal impact, while 64% resulted from rear-end impact. Therefore, it is clear that also in frontal impact there is a need for improvement of whiplash protection.

In the first European Whiplash (Cappon et al., 2001) project the rear impact loading phase was the main focus. The research at the time was mainly limited to the loading phase of rear impact, since most of the proposed injury mechanisms assume whiplash to occur in the loading phase. On the other hand, some of the mechanisms of whiplash injury are suggested to originate from the rebound phase of rear impact (Von Koch et al, 1995). The rebound phase involves neck flexion, as in frontal impact. Therefore, the current research aims at reducing whiplash in frontal and oblique impact and studies the rear-end rebound phase.

The final aim of this three year study is to be able to advise on injury reducing measures. In the end a test method will be proposed for evaluation of seats and restraint systems with respect to their whiplash protection. In this evaluation stage also a dummy is needed in order to assess the protection of a system. Part of the current project is to recommend on a dummy design that can be used for this purpose. Resulting from the findings in this project, design guidelines for safer seat and restraint system design will be proposed.

In order to reach these goals, the workplan used is fairly similar to the Whiplash 1 workplan (Cappon et al, 2001). At the start accident and injury statistics are gathered in order to determine which parameters are important in the various impact directions. In order to save dummy development time a preliminary evaluation of existing dummies is performed. Then a series of human testing is carried out to find the more specific typical human responses in various loading conditions. This typical response is needed for the evaluation of a whiplash dummy, which should perform well in rear (and rebound), frontal and oblique impact. Finally, accident studies and dummy development will result in a test method proposal, which will be used for seat and restraint system benchmarking. This paper will discuss the accident analysis, the evaluation of existing dummies and will give an overview of the human testing within the project.

ACCIDENT ANALYSIS

The main aim of accident statistics is to determine the parameters of a crash, which have an influence on whiplash injury risk. Parameters like impact speed, deceleration, direction of impact, body size and gender may have influence on injury occurrence and injury severity. In the current project four different databases from different countries are used to determine which parameters and trends are important. Folksam Research, ETH Zurich, GDV and Volkswagen are responsible for this part of the program. This paper will not go into details about the analysis, but will summarise the overall trend found in the analyses.

Influence of Gender and Age

In each of the studies a significant higher risk for women to suffer a whiplash injury was found. VW found an almost double whiplash injury risk throughout the entire age range of women compared with men. The same study found that the risk for females increases from the age of approximately 18-27 years. After reaching this peak no further increase could be observed. The risk for male occupants increased to its highest level in the same age group (18-27 years). Here as well, no further striking increase of risk with rising age could be found in general, only a slight increase at the age class 67 years and over.

VW found that in the whole range of body height classes (<157, 158-162, 163-167,..., >187 cm) the risk for male occupants to get whiplash was nearly constant and significant lower than the female risk. The taller the women were, the higher was their risk to suffer a whiplash injury.

Concerning the seating position, VW observed a significant higher whiplash risk for female front passengers. The injury risk at this position for female occupants was about 26% (versus 8% for males) while the injury risk for females in the driver seat was only 19% (versus 10% for males).

GDVfound that female drivers showed a much higher risk of whiplash injuries than males did (e. g.: Quebec Task Force (QTF) Grade II: 25% males, 39% females). Furthermore, the injury risk for front seat passengers and drivers was almost equal. Surprisingly, regarding the passenger seat males and females showed approximately the same incidence of QTF-Grade I-III in this study. So the higher risk for women to suffer whiplash could not be proved for the front seat passenger.

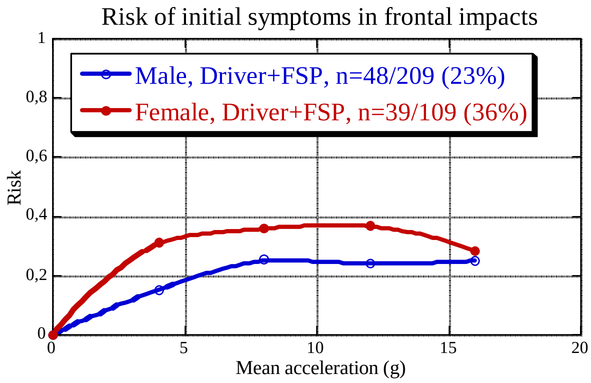

Figure 1 Folksam data shows a much higher risk for female occupants in frontal impact in the entire crash severity range

Folksam showed an almost doubled injury risk of females throughout the entire impact severity range (figure 3). They were also able to prove that in frontal impacts drivers in general had a 30% higher risk of initial symptoms than front seat passengers.

Accident Severity

Accident severity is often described with velocity change (Delta V) or acceleration (peak or mean impact acceleration).
In the study of VW, the risk curves for males and females steadily increased with increasing speed change until reaching a maximum risk value in frontal impact of 13-17 km/h for females and 18-22 km/h for males. After reaching this maximum, no further increase could be observed.

Folksam observed in their study that the mean acceleration better explained the risk of whiplash than the parameter Delta V did. The curves of risk versus mean acceleration are shown in Figure 2 and Figure 3, respectively, for rear and frontal impact. From these figures one can also conclude that the impact severity for longer term whiplash injury is higher than for short term injury.

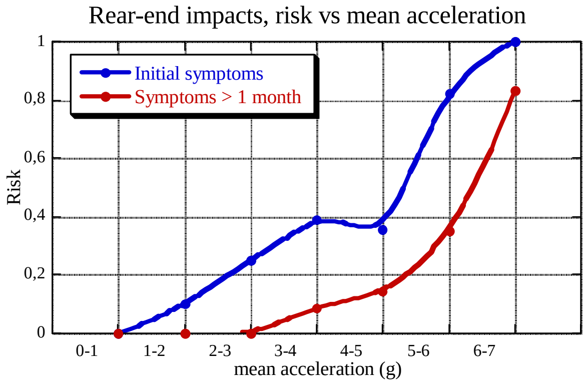

Figure 2 Injury risk as a function of mean impact acceleration in rear-end impact

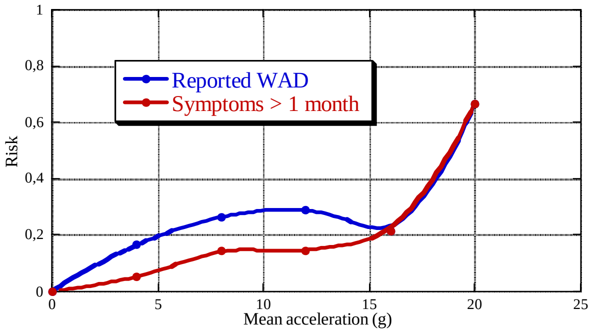

Figure 3 Injury risk as a function of mean impact acceleration in frontal impacts

In rear-end impacts the average change of velocity and mean acceleration for occupants with symptoms for more than one month were 20 km/h and 5.3g, respectively, and for occupants recovering within a month 10.3 km/h and 3.9g. In frontal impacts the average change of velocity and mean acceleration for occupants with symptoms for more than one month were 30.5 km/h and 7.9 g, respectively, for occupants recovering within a month this was 19.6 km/h and 5.4 g.

The study of ETH and GDV took into account the whiplash cases at certain changes of velocity or the average Delta v in different collision types. ETH found out that in rear-end impacts the occurrence of QTF Grade II was predominant in rear impact at a delta v of 8-13 km/h and at a delta v of 18-25 km/h in frontal impact.

Collision Type

All parties have studied the absolute numbers of whiplash cases resulting from either frontal or rear-end impact. Table 1 provides and overview of the results. All parties, except ETH, show a higher amount of frontal whiplash cases, than rear-end whiplash cases.

Table 1 Amount of whiplash injuries in the databases. Division between party and impact direction

Organisation	Total	Frontal	Rear
ETH	668	140	447
Folksam	62	47	15
GDV	754	332	246
VW	650	310	199

Concerning the injury risk and the direction of impact VW showed that the risk of whiplash was more than twice as high in rear-end collisions than in frontal and side impacts. For males: 20% versus 8% and 7% and for females: 46% versus 17% and 14%, respectively (100% is all injured occupants). Also here the risk for women was twice as high as for males in all collision types.

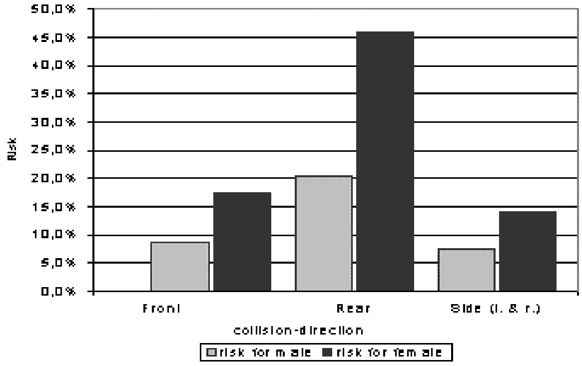

Figure 4 Injury risk related to gender and impact direction

Folksam reports an injury risk of 26% in frontal impact and 38% in rear-end impact for the driver (100% is all drivers in the included sample). For the front seat passenger, the figures are 20% and 57%, respectively (100% is all front seat passengers)

Concerning the pulse angle which is defined as the angle between the vehicle´s x-axis and the direction of the pulse induced during the collision, VW made an interesting discovery: In frontal collisions, the range of impact angles causing injury seemed to be much larger for female occupants than for male occupants (Figure 5)

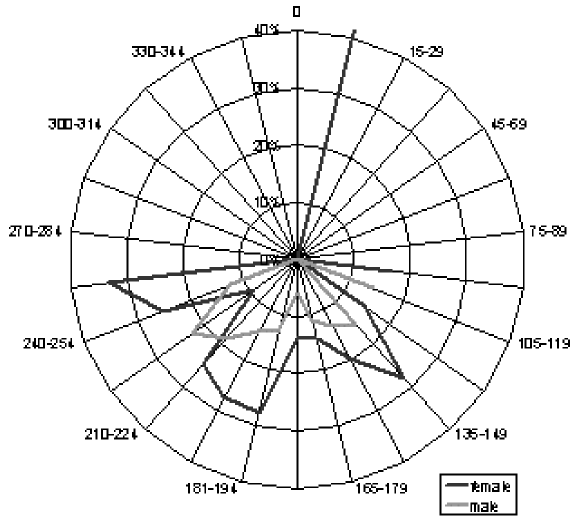

Figure 5 Risk to suffer whiplash by pulse angle and impact direction related to gender. The angle range of females is much larger than for males.

Airbag Use

Folksam is the only party considering the protection aspect of airbags in frontal whiplash injury cases. Injuries were divided in two categories: lasting less than one month (initial symptoms) and lasting more than one month. In the Swedish study in frontal impacts airbags were found to reduce the risk of initial symptoms by 24%, and the risk of symptoms for more than one month by 45%.

Overall Result

Despite the different inclusion criteria, some general trends can be observed in all databases:

- Females have a double risk of whiplash injury (VW, Folksam, GDV)
- Frontal impact with whiplash occurs most frequently (VW, Folksam, GDV)
- The average impact severity (Delta V and G level) resulting in whiplash in frontal impact is twice as high as in rear impact (all databases)
- Great portion of frontal impacts is angled (Folksam, ETH, VW)
- Vast majority of rear impacts is not angled (GDV)

HUMAN BODY RESPONSES

Reference Seat

The first task of this part of the project was designing and building a reference seat, which was needed later on in the project, as will be explained. A limiting factor in many volunteer and PMHS tests is the use of a specific car seat. Most of the time this car seat is not available anymore after a few years and it is very difficult to perform dummy tests in similar conditions as the original volunteer or PMHS tests. Therefore, it was decided to build a well defined flexible seat, which could be used for all human testing and dummy evaluations and which could be copied easily by any other party wishing to do similar testing.

The needs for this specific seat were defined as follows:

- The seat should have adequate durability. It had to be capable of sustaining a large number of crash tests with maintained dynamic properties.
- The seat should have geometrical properties that resembled a typical car seat.
- The seat should have a design that was possible to reproduce in an uncomplicated mathematical model.
- If possible, the seat should also have dynamic properties that resemble those of a typical (future) production seat.

The resulting seat (Figure 6) has four flexible back panels, each with individual stiffness properties. The inner frame with the panels can rotate in the outer rear frame. This should simulate the plastic deformation of the seat back during overload. The plastic deformation is obtained by using a stiff indentor and a metal strip, which can be replaced when overload has occurred. The head restraint was initially flexible, but inertia caused the system to be too stiff during impact. Therefore, the head restraint has been fixed to the inner seat back frame and soft padding with known characteristics was applied to safely test the volunteers later on. The seat back panels were only covered with an overall thin layer of plastic in order to decrease friction between subject and seat and to prevent grabbing of the panels in the subject's skin. Foam was applied at the panel side rims only in volunteer testing, to prevent hard contact between legs, arms and the metal sheeting.

Figure 6 Reference seat used for human and dummy testing

Human Testing

For the development of a whiplash dummy, insight is needed into the typical human behaviour in loading conditions which closely resemble the real life scenarios causing whiplash. Clearly, one cannot use volunteers in harmful conditions. Therefore, the testing has been split up in two series:

1. Human volunteer testing at impact levels below the injury threshold
2. Post Mortem Human Subject (PMHS) testing at impact levels above the injury threshold

The injury threshold is determined by the detailed analysis of accident material. Especially the crash recorder data of Folksam are extremely valuable at this stage. Based on their findings and the other accident studies, it was decided that a voluntary frontal impact should not exceed the speed of 12 km/h and a g-level of 4G. Practically speaking this means that a test with a volunteer will start at a very low level (7 kph) and the level is increased as soon as it is clear that the volunteer experiences no inconveniences after the test. In this situation the reference seat was used and it became clear that the low seat friction combined with the belt system was the limiting factor. The volunteers experienced large belt tension in frontal impact, which became inconvenient around 10 km/h.

The accident analysis results pointed out that the injury chance for females is larger than for males. For this reason, both males and females were tested. The experiments were performed at three different laboratories in various test conditions:

- TRL performed rear impact oblique (15 degrees) tests at low velocity (7 km/h) with their own rear impact seat (Figure 7). They measured accelerations at head, T1, chest and pelvis. Loads in the seat back and head restraint were recorded, EMG data of the neck muscles was measured and pressure distribution patterns of the interaction between the volunteer's back and the seat back were obtained.
- GDV performed rear impact rebound and frontal impact tests with the reference seat at a velocity of approximately 9 km/h. These volunteers were equiped with accelerometers at the head CG, T1 and sternum. EMG measurements were obtained for the major neck muscles in order to monitor muscle activity during loading phase and rebound. In order to track the displacements of head and spine, markers were attached to head and T1. The rebound phase was also monitored completely, contrary to the analysis by Van den Kroonenberg et al (1997) earlier.
- Graz University did frontal, frontal oblique (30 degrees) and rear impact rebound tests with the reference seat at speeds up to 12 km./h for frontal tests. Accelerations were measured at head, T1, sternum and pelvis. Markers were applied at head, sternum and T1.

Figure 7 Volunteer 3D setup at TRL, rear impact oblique testing

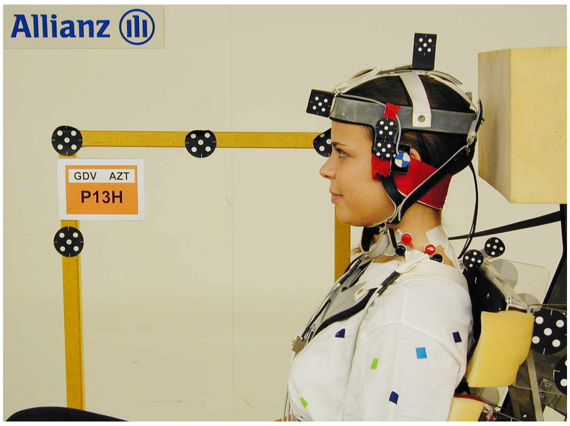

Figure 8 Volunteer 2D test setup at Allianz in cooperation with GDV, rear and frontal impact

The analysis of these tests is currently ongoing. The typical responses will be used in a later stage to evaluate the biofidelity of the whiplash dummy, which is part of the subsequent task.

DUMMY DEVELOPMENT

The aim of this task is to provide a whiplash dummy, which shows biofidelic behavior in rear-end, frontal and oblique impacts. This task consists of several smaller tasks:

a) A series of human testing is chosen to act as a reference for dummy biofidelity. These are translated into a series of biofidelity requirements for the dummy;
b) A set of existing dummies is evaluated against these biofidelity conditions in order to find out whether an already existing dummy (part) may comply to the desired targets;
c) Based on the evaluation a (omni-directional) whiplash dummy design is proposed;
d) This dummy design is then evaluated against newly defined criteria derived from the human testing of the present project (described above).

This paper reports on task a) and b).

Initial Biofidelity Requirements

An omni-directional whiplash dummy design must be based on existing knowlegde of crash conditions, materials and performance. In order for the dummy to be used for whiplash reducing measures, it is necessary that the dummy reflects the human response as close as possible, the so called biofidelity of the dummy. The response of the dummy to a crash event has to match the response of an average human in all relevant impact directions and loading phases. The best way to set up biofidelity requirements for a dummy is using existing tests on human subjects, either volunteers or Post Mortem Human Subjects (PMHS).

Frontal and Oblique Impact - In case of frontal impact the human test data which are available and relevant for this subject are rather limited. Several researchers have performed frontal tests using PMHSs with airbags at high impact severity, causing more serious injuries than whiplash trauma. Therefore these are not relevant for the current whiplash research, in which an impact severity of 25 km/h and 6G mean acceleration are average. The only extensive set of frontal impacts in reasonably well defined conditions, causing no serious injury are the tests of the Naval BioDynamics Laboratory (NBDL). The pulse of these tests is longer, resulting in a large Delta V of 60 km/h, but the acceleration rate is comparable to the ones found in typical, whiplash related, frontal impacts. The frontal and oblique impact test are used for the dummy evaluation. Results are not fully available at this stage of the project, but mainly focus on dummy kinematics with respect to time.

Rear Impact and Rebound - For rear impact the biofidelity requirements are based on a set of rear impact tests performed by the Laboratory of Accidentology and Biomechanics (LAB) in France (Bertholon, 2000), also used for the development of the RID2 dummy (Cappon, 2002), and by Chalmers University in Sweden, used for the development of the BioRID dummy (Davidsson, 1998). The LAB tests used for the biofidelity requirements were done without a head restraint, which is usually not the case in a real life accident. However, one can consider this a worst case scenario, in which the future dummy should still perform well.

The biofidelity requirements derived from the Chalmers data were used for the development of the BioRID dummy. It was originally developed within a Swedish research project on whiplash. At the time BioRID I was based on a series of volunteer tests in a flexible laboratory seat with a head restraint, which resembles a reproducible version of a standard car seat. Since the volunteers were not to be harmed, the delta-V was chosen to be low severity 7 km/h, 3.5 G peak acceleration. A total of 11 subjects were subjected to 23 tests in this setup at the given speed. For the biofidelity requirements a well defined set of 5 tests was used (Davidsson, 1998).

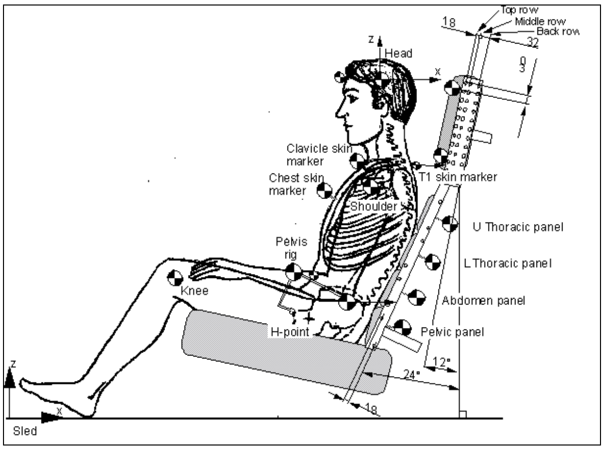

Figure 9 Chalmers volunteer setup as used for BioRID requirements

The biofidelity targets, which were used for the BioRID dummy development also take into account some spinal influences and do not only consider the head-neck complex. The requirements were chosen as follows (Davidsson, 1998):

- Head x-displacement with respect to the sled coordinate system
- Head x-displacement with respect to the T1 coordinate system
- Head angle with respect to the sled and with respect to T1
- T1 x- and z displacement and T1 rotation with respect to the sled coordinate system
- Hip z-displacement (ramping up)
- Change of distance between the hip and T1 (spine straightening)
- Head CG x-acceleration

Additionally, for the Whiplash II project the following signals were chosen as well:
- Head CG z-acceleration
- T1 x-acceleration
- Pelvis x-acceleration

None of the requirements in any of the biofidelity test condition focus on seat back interaction and thorax-belt interaction. Nevertheless, these are important to obtain the correct input for the head-neck system. The human testing in Whiplash II has to take this missing information into account and go a few steps further in order to find these missing data.

Dummy Evaluation

The dummy evaluations performed at LAB using several dummies were already presented earlier by Cappon (2002), as were the Chalmers tests. The latter did not include the evaluation of THOR and the rebound phase. Therefore, some typical responses will be presented here.

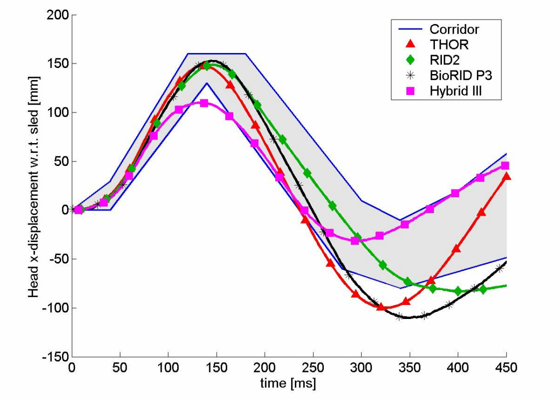

Figure 10 Head x-displacement in the sled coordinate system, volunteer corridor and dummy responses

In this setup the BioRID P3, the RID2, Hybrid III and THOR were used. Figure 10 displays the head CG x-displacement with respect to the sled. Positive displacement is in the posterior direction. The shapes of all dummy responses are very good. Maximum forward rebound displacement occurs at 300-350 ms. The Hybrid III forward motion turns too early and the RID2 slightly late. The THOR and the BioRID have the best timing but somewhat too large excursions.

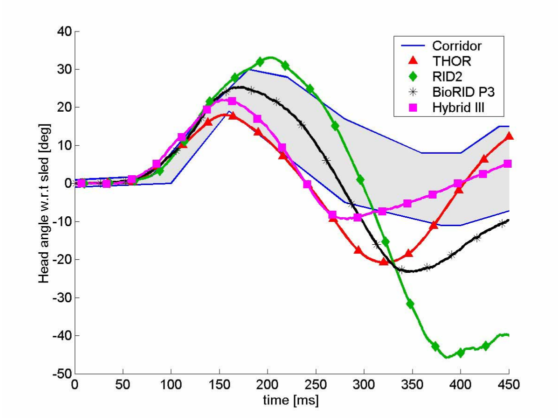

Figure 11 Head angle in the sled coordinate system, volunteer corridor and dummy responses

The rotation of the head is given in Figure 11. During the first 150 ms the head angle of all dummies rises slightly too early with respect to the volunteer tests, which means the translation phase of the head before rotation (head lag) is a bit too short. BioRID performs best and RID2 overestimates the maximum head rotation of the volunteers slightly and has a very large rebound (for which it was not designed). Hybrid III shows an early, but correct maximum head rotation when related to the sled, while THOR and BioRID have better rebound timing though the maximum forward excursions are somewhat too large.

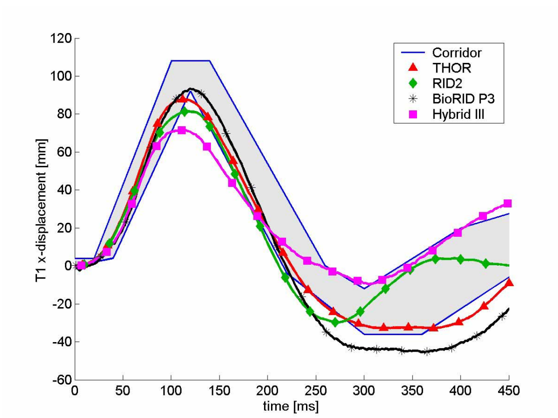

Figure 12 T1 x-displacement in the sled coordinate system, volunteer corridor and dummy responses

In Figure 12 and Figure 13 the linear displacements of the T1 vertebral body are shown. The rearward T1 x-motion is too small in the Hybrid III. In the end phase, the T1 x-displacement is well reproduced by THOR. The RID2 rotates a bit early and BioRID is somewhat soft. The Hybrid III shows too little forward T1 x-displacement. The T1 z-displacement is under estimated by all dummies, BioRID shows half of the displacement required, while RID2 shows very little upward motion and tends to sink into the seat, as does the Hybrid III. THOR performs the worst in this case. Note that this parameters is heavily related to pelvis ramping up and spine straightening. The friction and surface shape between the dummy and the seat-back influences the ramping. The RID2 and the BioRID designs incorporate smooth back shapes and the BioRID back has reduced friction, in contrast to the Hybrid III and the THOR.

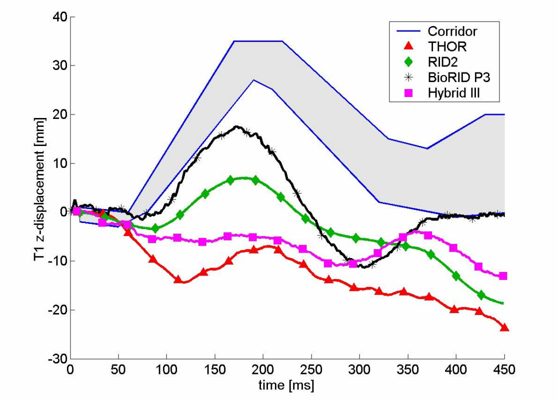

Figure 13 T1 z-displacement in the sled coordinate system, volunteer corridor and dummy responses

Figure 14 and Figure 15 show the ramping up and spine straightening, respectively. The ramping up of BioRID is within the defined corridor, while both THOR and RID2 show similar behavior having too little ramping. Initially, the spine straightening for BioRID is good as well, but its rebound in that sense seems to be too fast. RID2 shows the right timing, but too little straightening as such and THOR shows no spine straightening at all. Unfortunately, data concerning the pelvis are not known for the Hybrid III dummy.

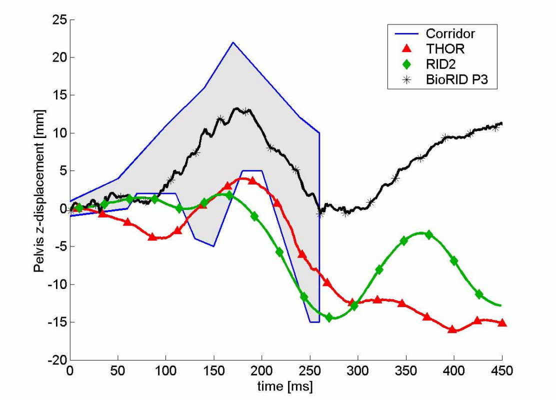

Figure 14 Ramping up (pelvis z-displacement), volunteer corridor and dummy responses

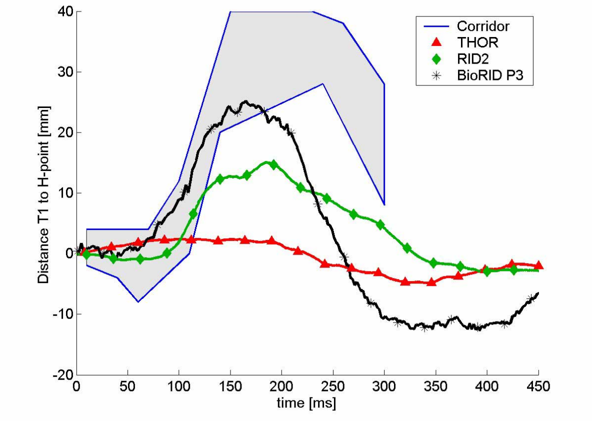

Figure 15 Spine straightening, volunteer corridor and dummy responses

The dummy evaluation showed the major areas where certain dummies lack performance or biofidelity. Hybrid III has large problems in rear-end impact and also THOR has limitations. BioRID has the best biofidelity in this rear impact evaluation, but is not able to bend in oblique direction, as it has a 2D spine. It was not used in the severe frontal NBDL test program due to the risk of damage. RID2 has limitations in ramping up and it is soft in forward rebound, but is in principle a 3D design. It was not designed for frontal impact and would have to be redesigned to get adequate stiffness and to meet the higher durability requirements in that crash direction.

DISCUSSIONS AND CONCLUSIONS

Whiplash in frontal impact has been generally overlooked in past research. A large focus was granted to whiplash injury associated to rear impact. Yet, the figures in this study point out that the problem in frontal and frontal oblique impact may be even larger, even though the injury risks are lower than for rear impact. Accident statistics in this study have again shown that the whiplash risk of females is almost twice as large as for males. This is not only the case in rear-end impact. Furthermore, the age group at risk are the young adults (18-27 years) for both sexes. Another observation was that females sustain whiplash over a larger range of impact angles than males do.

In the current dummy development task, a two phase approach was used, in order to save development time. Initially dummies were evaluated against existing data of PMHS tests and volunteer tests. As indicated in previous studies Hybrid III is not a good candidate for rear impact. THOR was also found to have limitations in rear impact, especially where T1 z-motion is concerned. BioRID was not considered for severe frontal and frontal oblique impact. The RID2 is able to handle oblique impact, but its neck is too compliant for frontal impact. Note that all existing dummies that may be suitable for whiplash are based on 50th percentile male anthropometry, and hence represent the average male driver. This is a consequence of the research which has been done since the mid-nineties with a focus on the mid-size male. At this moment, further development work will be based on this size of dummy, although it is recognised that a need exists for a female whiplash dummy, since females are higher at risk.

In the mean while, more specific data for whiplash dummy evaluations were generated. A series of sled tests with volunteers were performed, which will be extended in a later stage with PMHS tests. An important improvement with respect to previous studies, is that a special reference seat with known characteristics and dimensions was constructed. It allows other parties to do similar testing on the short and long term without the need to buy a production car seat, which is no longer on the market. The detail with which the volunteer tests are performed, including pressure mapping and EMG data measurement, allows a more thorough analysis of the dummy performance later during the project.

Derived from the test data available and the accident statistics, a proposal for a test method will be made. Since the problem of whiplash in frontal impact is at least as large as in rear impact, this procedure has a good chance to start the discussion of regulatory measures in this field. Together with the whiplash dummy as a result of this project, it is expected that the entire whiplash problem can be addressed more adequately in the future.

FUTURE WORK

Since the project is not finished until 2004 there is a large part of the work yet to be done. Below the main activities are highlighted:

- Long term injury reports of the accident analysis task.
- PMHS tests using high speed X-Ray to be performed by Graz University
- Evaluation of the whiplash dummy versus the human testing at various laboratories
- Proposal for a test method procedure for whiplash in frontal impact
- Design guidelines for safer seat and restraint system and a demonstrator

ACKNOWLEDGEMENTS

The authors would like to thank the partners in the Whiplash2 program: PSA Peugeot/Citroën, Renault, Lear Corporation, FIAT Research Centre, GDV, Volkswagen, FTSS, Graz University of Technology, Faurecia Seating, DaimlerChrysler AG, TRL, Chalmers University of Technology and Folksam. Furthermore the European Commission and the Dutch Ministry of Transport are acknowledged for their support in this study.

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