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ABSTRACT

Given the serious consequences of neck injuries resulting from rear-end collisions, this collision type has gained much attention lately. The low g loading levels and diffuse injuries require a crash dummy with an improved response compared to the available crash dummies.

In the EC sponsored "Whiplash" program several sled tests with human subjects were performed, which can be used to evaluate dummies for low and mid severity rear-end collision testing. This paper shows the responses of the human subjects and compares the Hybrid III dummy with these responses. The Hybrid III dummy response was not found to be very biofidelic, resulting in the design of a new rear impact dummy: the RID2. Initial testing with the RID2- α prototype neck showed more human-like responses.

KEYWORDS: REAR IMPACTS, DUMMIES, BIOFIDELITY, SLED TESTS

REAR END IMPACTS are one of the main causes of low severity neck injuries (whiplash). In order to predict human kinematics and the neck loads occurring during rear end impacts, several attempts have been made to design a crash test dummy, which sufficiently describes the human body movements, including head movements. The generally used Hybrid III dummy has been evaluated by several researchers. Prasad et al. (1997) compared the Hybrid III response to 2 cadaver test performed by Mertz and found no significant difference between the dummy and human responses. Others conclude that the Hybrid III lacks biofidelity in rear impact, when comparing the responses to volunteer tests, as was shown by Scott (1993) and Davidsson (1998a & 1999b). Resulting from Davidsson's study, a Swedish consortium developed the BioRID (Davidsson, 1998a & 1999a), which has a multi-segment spine and shows biofidelic responses.

Parallel to the Swedish study, within the Brite-Euram Whiplash project, a whiplash dummy has been developed. This dummy, referred to as RID is, like the BioRID, intended for rear impact testing. The dummy design has been based on tests with human volunteers and P(ost) M(ortem) H(uman) S(ubject)s, performed within the Brite Euram Whiplash programme. The aim of this project was to generate new knowledge in order to reduce the occurrence of whiplash injuries. Within the project human body responses in rear-end impact were analysed, a Rear Impact Dummy and dummy models were developed, as well as test methods for rear impact seat and head restraint evaluations.

This paper focusses on the dummy performance, based on the volunteer and PMHS tests (Van den Kroonenberg, 1998 and Bertholon, 2000). A comparison of the Hybrid III with these tests is made and a preview is presented on the performance of the latest version of the RID dummy, referred to as the RID2- α prototype.

The RID2- α prototype has a newly designed pelvis, abdomen, torso and neck which is completed by the standard 50th percentile Hybrid III extremities and head. Furthermore, a specific instrumentation package is incorporated into the dummy, which is considered necessary to evaluate the performance of seat and restraint systems in rear impact conditions. This dummy is intended to be used in low and mid severity rear-end collision testing (up to $\Delta V = 16$ km/h), either with or without head restraint systems.

HUMAN TESTING

Within the whiplash project a number of sled tests were conducted. The following test series were judged to be most suitable to evaluate the responses of the dummy, based on completeness of the data, consistent test conditions and responses with soft and rigid seats.

- Volunteer tests performed at ΔV=9.5 km/h by the Institute of Vehicle Safety (GDV) at Allianz Zentrum für Technik in Ismaning, Germany (presented by Van den Kroonenberg et al. in 1998). These tests represent a very low severity rear end impact;
- PMHS experiments performed at ∆V=10 km/h for the Laboratory of Accidentology and Biomechanics (LAB), France (Bertholon 1999 & 2000). These were chosen, since they were performed in a well defined way on a rigid seat without a head restraint and each test was found to be very reproducible, thus allowing a strict comparison of human and dummy responses.

Table 1 shows a summary of the properties of the tests used in this study, as well as average test subject data.

	GDV	LAB	
Subjects	Volunteer	PMHS	
Seat Type	Standard	Rigid	
Head restraint	Yes	No	
No. of subjects	7	3	
No. of tests	7	6	
Mass [kg]	75	50	
Height	1.80	1.64	
Sled pulse [g]	5	12	
Velocity [km/h]	9.5	10	

	Table	1	- Properties	of	the	sled	tests
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In rear end impact the kinematics of head, T1 and pelvis are needed in order to determine the correct interaction with the seat and head restraint. When considering the head kinematics, these can be described with respect to the sled or with respect to T1. The difference for the definitions of rotations is shown in Figure 1; the T1 co-ordinate system rotates with the neck base (T1 location), while the sled co-ordinate system remains steady. Dummy neck performance is related to the interaction with the head restraint and the motion of T1, while T1 kinematics are a result of the interaction of the dummy back and pelvis with the seat. Unfortunately pelvis kinematics were not derived from the tests performed. Thus the kinematics are described with the following set:



Figure 1: Tl and sled co-ordinate systems.

- 1. Head response:
 - Head angle w.r.t. T1 versus time;
 - OC displacements w.r.t. T1 versus time;
 - Head linear and angular accelerations;
- 2. T1 response:
 - Tl angle w.r.t. sled versus time;
 - T1 displacements w.r.t. sled versus time;

Additionally the head angle with respect to the sled offers a very quick insight in the dummy's overall response (Tl plus head). Therefore this parameter will also be included.

SOFT SEAT TEST SETUP- In the GDV experiments a standard car seat, has been used, which was selected in the Brite-Euram Whiplash Project. The car seat was mounted on a sled. The seat back angle was set to 25 degrees using an H-point manikin according to regulation SAE J826 §4.3. The head restraint was positioned so that the top of the head and the head restraint are aligned. If this was not possible due to the subject's height, the maximum head restraint height was taken.

The volunteers were asked to take a normal automotive posture (Figure 2). No position of the pelvis was measured, and so no specific position is available for the H-point of a dummy. The Frankfort plane was initially horizontal, which implies an initial head angle of 0 degrees.



Figure 2 - Volunteer test setup

The sled acceleration pulse is a 10 km/h rear-impact pulse with a peak of about 4.5 g (Figure 3).



Figure 3 – Sled pulses soft seat

RIGID SEAT TEST SETUP – The experimental set-up was designed to be both simple and reproducible, using a rigid seat without a head restraint. The seat back and seat pan had an inclination of 25° and 10° respectively. Three subjects were tested in this configuration; each subject was tested twice. The subjects were restrained to the seat by three belts, restraining the thighs, pelvis and thorax tightly to the seat. The seat was mounted on a reverse sled and the pulse, shown in Figure 4, was applied to the sled through a pneumatic piston.



Figure 4 - Sled pulses rigid seat

Since the head-neck position was not stable, an electromagnet was used to keep the head in the initial position (i.e. Frankfort plane horizontal). Details of this test series are given by Bertholon (1999 & 2000).

DUMMY PERFORMANCE

This section shows the responses of the volunteers and the human subjects. These responses will be used in the evaluation of a Rear Impact Dummy (RID), which will be tested in the same conditions. The tests with the rigid seat can be used to evaluate the performance of the RID, while the tests with the soft seat are only used to compare the responses of volunteers and dummies using one specific seat. Furthermore, the Hybrid III dummy was tested in the same conditions as both test series given above. A comparison is made between the Hybrid III and the volunteer and PMHS.

Note that there was a great difference in the sled pulses applied in both series. The pulse applied to the rigid seat was a short and high pulse, resulting in a ΔV of 10 km/h. The soft seat pulse was much lower, but resulted in almost the same ΔV of 9.5 km/h. The differences between these tests, i.e. rigid seat versus soft seat, high pulse versus low pulse, volunteer versus PMHS, do not allow a comparison of responses of both test series. It is expected that the rigid seat tests with the high pulse will result in larger head rotations and head accelerations of the dummy.

SOFT SEAT TESTS – The head angle with respect to the sled and T1 are given in Figure 5. These two plots illustrate that the head starts its backward rotation later than T1 does, resulting in a forward rotation of the head relative to T1. Contact of the volunteer's head with the head restraint occurs between 70 and 120 ms, so a large amount of head rotation occurs while the head is already in contact with the head restraint.

Comparison with the Hybrid III dummy shows that the amount of head rotation with respect to the sled is sufficient, but the timing is somewhat too early. Since the Hybrid III shows no T1 rotation, the initial forward rotation of the head with respect to T1 is not visible.



Figure 5 – Head angle w.r.t. the sled (left) and w.r.t. T1 (right)

The Tl angle versus time is shown in Figure 6. The volunteers' Tl responses relative to the sled shows a similar shape as the head responses, although the timing is about 40 ms earlier and the magnitude is about half as large. The accuracy of the Hybrid III data was 1 degrees, rotations of Tl were found to be smaller than that, resulting in the straight line shown. This would mean that the Hybrid III spine is too stiff.



Figure 6 – Tl angle w.r.t. the sled

The displacements of T1 with respect to the sled are presented in Figure 7. The volunteers show a consistent rearward motion of T1. Very relevant is vertical upward displacement of T1 (due to ramping up) which was found in the experiments, which indicates that the vertical position of the subject's head relative to the head restraint increases during impact. This phenomenon was not found in the Hybrid III dummy test. On the contrary, the dummy tends to move further down into the seat, instead of showing ramping up, which shows that the interaction with the seat is not as realistic as it should be.



Figure 7 - T1 displacements w.r.t. the sled

Figure 8 shows the displacements of the OC joint with respect to T1. Both displacements show a rather small amount of movement of the OC for the volunteers; a few centimeters for both the x- and z-displacement. The OC x-displacement with respect to T1 found in the Hybrid III is larger than for the volunteers.



Figure 8 - Occipital Condyle displacements w.r.t. T1

Figure 9 and Figure 10 show the head accelerations of the Hybrid III dummy in comparison to the volunteer tests. The head x-acceleration correlates well considering the timing, but the peak is somewhat too high. The head z-acceleration and the angular acceleration, show the right magnitude but the signals start too early. Note that these tests were performed with a head restraint, which decelerated the head during its rearward movement.



Figure 9 - Head x- and z-accelerations



Figure 10 - Head angular accelerations

RIGID SEAT TESTS – The selected rigid seat tests used had no head restraint included. The conditions in which these tests were performed were very reproducible, resulting in rather consistent responses of the human subjects. Furthermore seat performance is not an issue using rigid seats, which means that the dummy's performance is evaluated apart from any seat performance.

Figure 11 shows the head angle with respect to the sled and T1. Two tests with each subject showed the reproducibility of the tests. Furthermore the three subjects behaved rather similar. The head rotation of the Hybrid III deviates considerably from the human subjects, indicating that the neck and the thoracic spine of the Hybrid III are rather stiff. Unfortunately, T1 rotations were not measured in this test. The human responses are shown anyhow, since they are relevant for the evaluation of a dummy in rear impact.



Figure 11 - Head angle w.r.t. the sled (right) and T1 (left)

The kinematics of T1 are shown in Figure 12 and Figure 13. Again the consistency of the responses of each subject are clearly visible. Note that one subject behaved differently and hardly showed any ramping up; the T1 z-displacement remains rather small. Since the T1 kinematics of the Hybrid III dummy were not measured, but the T1 accelerations were, the dummy's T1 displacements were derived from the acceleration signals, assuming the T1 rotations to be negligible, since the dummy was strapped to the seat rather securely and the Hybrid III spine is very stiff.



Figure 12 - T1 angle w.r.t. the sled



Figure 13 - T1 x- and z-displacements w.r.t. the sled

Figure 14 shows the OC position with respect to T1. The human subject which showed a rather small ramping up in the previous figure, shows a positive OC z-displacement. The OC x-displacement is consistent for all human subjects and the Hybrid III shows a similar behaviour.



Figure 14 - OC x- and z-position w.r.t. T1

The head accelerations found in the rigid seat tests are shown in Figure 15 and Figure 16. Note that especially the x-accelerations of the Hybrid III dummy differ considerably from the human subjects. The head z-accelerations and angular accelerations also show considerable differences with the human responses.



Figure 15 - Head x- and z-accelerations



Figure 16 - Head angular accelerations

RID GENERAL OVERVIEW

The results of the evaluation of the Hybrid-III against the human data have shown that the dummy may be improved to better mimic the human occupant in a rear impact. Biofidelic neck performance and realistic interaction between dummy and seat are important for a correct prediction of the human head and neck kinematics in rear impact. The dummy enhancements are:

- A more articulated spine and improved anthropomorphic back shape to improve the interaction with the seat, promote ramping up and prevent unrealistic 'grabbing' of dummy parts in the seat;
- A less stiff spine and neck to better represent the head/neck kinematics.

The initial position of the subject is expected to have major effects on the responses in low severity rear impacts. Because seats and head restraints can require different initial dummy orientations, more freedom in dummy positioning is desirable, in particular at the lumbar spine-pelvis junction (lumbar bracket) and at the dummy's T1 level (neck bracket) assuring correct orientation of the pelvis, spine and head.

The above enhancements form the basis for the Rear Impact Dummy, RID, that has been developed in the Whiplash project on the 50th perc. Hybrid-III platform. The current prototype, RID2- α , includes additional instrumentation options next to standard instrumentation available. This instrumentation consists of a load sensing skull cap, load-sensing capability at T12 level, head angular and linear acceleration sensor and tilt sensors, which measure the initial orientation of different body parts. Most critical part of the dummy, however, is the new neck design as described in the next section.

DUMMY NECK - The RID2- α prototype neck (Figure 17) should comply with response requirements of the volunteer and PMHS tests carried out within the Whiplash programme. The neck consists of

seven aluminium discs, which are clamped to a steel cable running through the neck in longitudinal direction. Rubber discs between the aluminium discs give the neck its basic stiffness. At the back and side of the neck, rubber buffers are inserted, providing additional bending stiffness where necessary. To meet the required dynamic performance dictated by the PMHS and volunteer tests, the initial neck flexion stiffness has been reduced, causing the head-neck assembly to fall forward without support. Therefore, a mechanical support device is used to support the head in pre-test conditions. To assess and optimise the neck performance, a separate head-neck component test has been defined, based on the rigid seat PMHS tests described earlier.



Figure 17 - Head-neck system of RID2- α prototype

NECK COMPONENT TEST

The results from the experiments at LAB were transformed into a set of corridors, taking the mean plus and minus the standard deviation for each resulting signal. In order to get an indication of the dummy's performance and repeatability, two RID2- α prototype necks were made and tested in exactly the same configurations. A Hybrid III 50-th percentile head was mounted to the RID2- α neck. The neck in turn was mounted on a rotating base (Figure 19), which approximated the T1 rotation (Figure 20) and T1 vertical displacement found in the PMHS experiments. The combination of rotation and vertical displacement was obtained due to the fact that the centre of T1 was situated in front of the centre of rotation of the rotating base. The rotating base was attached to a Servo Hydraulic Sled (Figure 18).



Figure 18 - Dummy head and neck on a rotating sled mount at T1 level



Figure 19 - Simulated T1 angle compared to LAB corridor

The sled acceleration of the SHS was derived from the x-acceleration of the LAB PMHS experiments. The envelope and the pulse used in the neck tests are shown in Figure 20. OC and CG positions were visualised with markers attached to the RID parts, which were monitored with high speed video at 1000 frames/s.



Figure 20 - Sled pulse applied to the rotating base

RESULTS

The head angle is presented in Figure 21. From both responses it is the head angle does not increase immediately as soon as the T1 rotation starts; there is a 40-50 ms delay. The maximum head angles are too large eventually, due to the fact that the prescribed T1 rotation was also too large in the end.



Figure 21 - Head angles with respect to the sled and T1

In Figure 22 the Occipital Condyle movements are given. Both responses are very close to the defined corridor. The z-displacement corridor seems relatively wide, since one test subject behaved differently from the others in the LAB experiments (Figure 14).



Figure 22 - Time traces of the Occipital Condyle with respect to a rotating T1

DISCUSSION

Two test series were presented which will be used for the evaluation of a newly developed Rear Impact Dummy: the RID2. One series involved human volunteer tests on a standard soft car seat, including a head restraint, while the second series used Post Mortem Human Subjects on a rigid seat without a head restraint. These different test conditions resulted in larger displacements and rotations in the PMHS tests compared to the volunteer tests.

The tests with the rigid seat were meant to test the performance of the dummy. Using soft seats implies that the response is also influenced by the performance of the seat. However, if the dummy is tested in exactly the same configuration as the human subjects, a comparison of responses is legitimate and does contribute to the evaluation of biofidelity.

The widely used Hybrid III dummy was evaluated as well with these tests. Davidsson (1998a & 1999b) found that the displacements and rotations of T1 in the Hybrid III were not realistic, as well as the head kinematics found, since the Hybrid III is meant to be a frontal impact dummy. The

comparison presented in this paper supports these findings. Ramping up, which is very usual in human volunteer testing, hardly showed in the Hybrid III dummy response. The amount of head rotation and OC x- and z-displacement was found to be sufficient using a Hybrid III in the standard car seat configuration. The head rotation itself starts immediately in the Hybrid III, whereas the human subjects show a rotation of T1 first and the head rotation follows after about 40-50 ms. These different phenomena, however, do influence the further response considerably. For instance, ramping up causes the head of the subject to contact the head restraint at a different level, which means the direction of head restraint forces on the head are different and thus the loads experienced in the upper and lower neck. Even when no head restraint is used, the head accelerations, which are directly related to the neck loads and thus may be injury related, show considerable deviations, when comparing the Hybrid III response to the responses of the human subjects. The reason for this non-biofidelic behaviour of the Hybrid III dummy is thought to be the unrealistic interaction of the dummy with the seat back and the stiff spine and neck of the Hybrid III.

The RID2 should deal with these shortcomings, although the entire evaluation is not yet finished. Full dummy sled tests with rigid and regular car seats at 10 and 15 km/h were performed during spring this year, although no results are available yet. In order to get an initial idea on the dummy's performance, the RID2- α dummy neck was evaluated using the set of PMHS test results. It was found that the general trend of the evaluation was good compared to the PMHS results. The RID2- α showed the correct amount of head rotation and head displacement. The maximum head rotation turned out to be somewhat too large due to a large prescribed T1 rotation in the end. In case of the head z-displacement, the PMHS tests on which the corridors were based showed some inconsistent behaviour, resulting in a wide corridor.

CONCLUSIONS

- Experiments with both human subjects and the Hybrid III dummy showed the need for a more biofidelic dummy in rear impact testing. Especially the interaction of the Hybrid III dummy with the seat was not satisfactory.
- A RID2-α dummy neck was developed and two prototype necks were used in a preliminary evaluation, comparing the responses to PMHS tests performed earlier. The head and neck response of the dummy necks were found to be in reasonably good correspondence with the experimental results.
- The head was found to rotate later than T1 in the new developed neck, but the delay was still somewhat too small. No such delay was found in the Hybrid III responses.

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