BioRID, a Crash Test Dummy for Rear Impact: A Review of Development, Validation and Evaluation

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ABSTRACT
Neck injuries in rear-end car collisions is a problem on the increase. It causes severe pain and suffering to the subjected individuals and huge societal costs. The lack of a biofidelic crash dummy for rear-end impact testing has made it difficult to assess the function of the protective systems in cars, mainly the seats and head restraints. A Biofidelic Rear Impact Dummy (BioRID) was developed in several steps and validated against volunteer and cadaver test results and compared to the Hybrid III. The new dummy was partly based on the Hybrid III dummy. It had a new articulated spine with curvature and range of motion resembling that of a human being. A mathematical model (Madymo) of the head and neck was also developed and used during the development of the dummy. The BioRID was found to have more humanlike kinematics than the Hybrid III. This was found for the angular, vertical and horizontal displacement of the upper torso. It was also found for the head relative to upper torso horizontal and angular displacement. For future rear impact testing, the BioRID is an important step towards a more biofidelic dummy.

INTRODUCTION
Low velocity impacts causing soft tissue neck injuries are frequent and increasing both in total number and in relative frequency van Kampen (1993; Ono and Kanno, 1993; von Kock et al., 1994; Morris et al., 1996; Ono and Kaneoka, 1997; Krafft, 1998; Watanabe et al., 2000). For rear end impacts these injuries occur at low velocity changes, typically between 10-25 km/h (Hell et al., 1998; Eischberger et al., 1996). To be able to assess the protection performance and develop safety system that protects against soft tissue neck injuries, human-like crash test dummies are needed.

The most commonly used dummy in crash tests is the Hybrid III. Hybrid III was developed as a biofidelic tool for high-velocity frontal-impact testing. The thoracic and lumbar spine of the Hybrid III consists of three rigid elements joined together and the neck consists of rubber block joined together by aluminium blocks. The Hybrid III is stiff and unlikely to interact with the seat back in the same complicated way as a human. Foret-Burno et al. (1991) concluded that the human head can move relative to the torso with low stresses in the neck, but this is not the case for the Hybrid III. The Hybrid III has also a different contour of the back and mass distribution of the torso than a human. For rear-end collision testing the Hybrid III can supplemented by a RID-neck (Svensson and Lövsund, 1992) or by a TRID-neck (Thunnissen et al., 1996) to improve the head angular response in rear-end collision testing. However limitations still remain with the design. The Hybrid III thoracic spine that does not replicate the straightening of the spine and vertical acceleration of the head and T1 that occur in volunteer tests (Scott et al., 1993; Ono and Kaneoka, 1997; Davidsson, 1999) and limitations of the RID neck compared to human subject test has been reported by Geigl et al. (1995). There is thus a need for a complete new dummy with an articulated spine that is able to reproduce the kinematics of an occupant.

The aim of this study was to develop, validate, and evaluate a new crash test dummy for rear end low velocity rear impact testing. The development of the dummy focused on the head, neck and torso kinematics.

METHODS AND MATERIALS
To develop a new dummy, called the BioRID, a consortium was formed. It consisted of industry partners with Autoliv AB Research, Volvo Car Corporation and Saab Automobile AB and Chalmers University of Technology. The total cost for the project was $ 1.3 million (AU), which was equally shared between the industry and the Swedish government. The project ran for 4 year and ended in 1999.

When designing the BioRID following strategic decisions were made.
- The dummy should represent a 50th percentile male and its motion should be restricted to the sagittal plane,
- the dummy spine should consist of the same number of vertebrae as a human spine,

- the range of motion of the spine should be biofidelic and contain both a lordosis of the neck and the kyphosis of the thoracic spine,
- the dummy should have a human like mass distribution of the torso,
- the models should be simple in terms of number of components and the design of the components.

For the developing of the neck of the BioRID first a mathematical model was developed to evaluate a mechanically useful combination of components for the mechanical neck model. Neither the documented model in the literature nor the commercially available mathematical models contained basic information on what components a biofidelic mechanical neck model should consist of. Therefor the need for the development of a mathematical model was identified. The mathematical neck model was implemented in MADYMO 2D (TNO, 1997), which is capable of simulating planar motion. Motion in the mathematical neck model was restricted to the sagittal plane by revolute joints connecting the vertebrae. The mathematical neck was developed using the complete dummy model presented by Jakobsson et al. (1994). Jacobsson's model was chosen due to its basic structure and delimitations similar to those applying for the current neck model design. All elements of the mathematical neck model were transferred to physical parts in the BioRID.

Validation

Occupant dynamics can be obtained from volunteer and post-mortem human-subject (PMHS) tests. Both of these test types have their advantages and disadvantages. For the PMHS tests, loads can be applied that represent load levels where injuries occur. However, the lack of muscle tone, internal pressure and other changes due to time after death limit the interpretation of the results. Volunteer tests have to be carried out at load levels that will not cause injuries. In volunteer studies, muscles are active even though their influence is difficult to interpret in terms of loads. When using occupant dynamics for validation it is essential that the test conditions can be reproduced and that detailed dynamic data is available for as many parameters as possible. For these reasons two set of PMHS data (Eichberger et al., 2000: Viano et al., 2000) was chosen as validation data for the dummy. Detailed volunteer test data was used for validation of the dummy (Davidsson et al., 1998; Linder et al., 1998; Davidsson et al., 1999a, Linder et al., 1999) The mathematical model was validated against volunteer data (Davidsson, 1999).

Running identical tests with the BioRID and the Hybrid III carried out the comparison between the dummies (Davisson et al., 1998, Linder et al., 1998, Davidsson et. al, 1999, Linder et al., 1999, Linder et al., 2000). Repeatability was tested by performing three identical tests with each dummy, and reproducibility was tested by running three identical dummies in the same sled test set-up as used for the validation (Davidsson et al., 1998).

RESULTS

The mathematical neck model (Linder, 2000) consisted of 7 identical vertebrae and the T1 vertebra. The motion of T1 was prescribed using displacement data from volunteer tests (Davidsson, 1999).

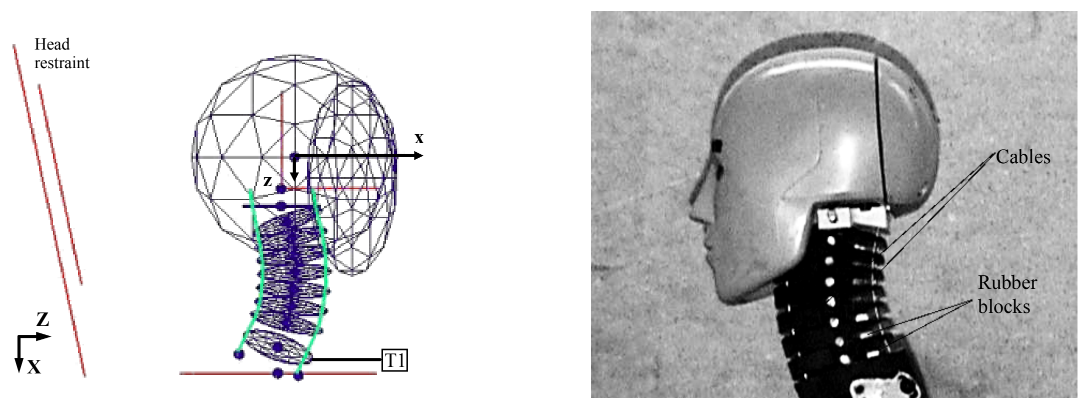


Figure 1. The mathematical model and the neck of the BioRID and the global (X, Z) and the local (x, z) co-ordinate systems used for the output parameters.

The mathematical neck model included muscle substitutes containing a combination of elastic stiffness and damping in the muscle substitutes, together with a non-linear progressive joint stiffness. The muscle substitutes were modelled in the BioRID with cables connected to springs and a damper (Figure 1).

BioRID

Technical decriptions of the BioRID has been presented in Davidsson et al. (1998) and Davidsson et al. (1999b). Here a short description of the BioRIDs main components (Figure 1 and 2) and their characteristics is given:

- Segmented spine consisting of 24vertebrae and a spine curvature resembling human seated in a car seat. The kyphoses of the spine can thus be straightened out and a human like motion can be obtained.
- A neck model consisted of 6 identical vertebrae representing C2 to C7. The vertebrae representing the C1 had a somewhat different upper geometry, so that it could be attached to the dummy head. The neck model had a combination of elastic stiffness and damping in the muscle substitutes.
- Torso moulded in on piece including a bladder representing the soft part of the stomach and shoulders.
- Enlarged hip joint motion compared to regular Hybrid III.
- Legs, arms and head from Hybrid III.

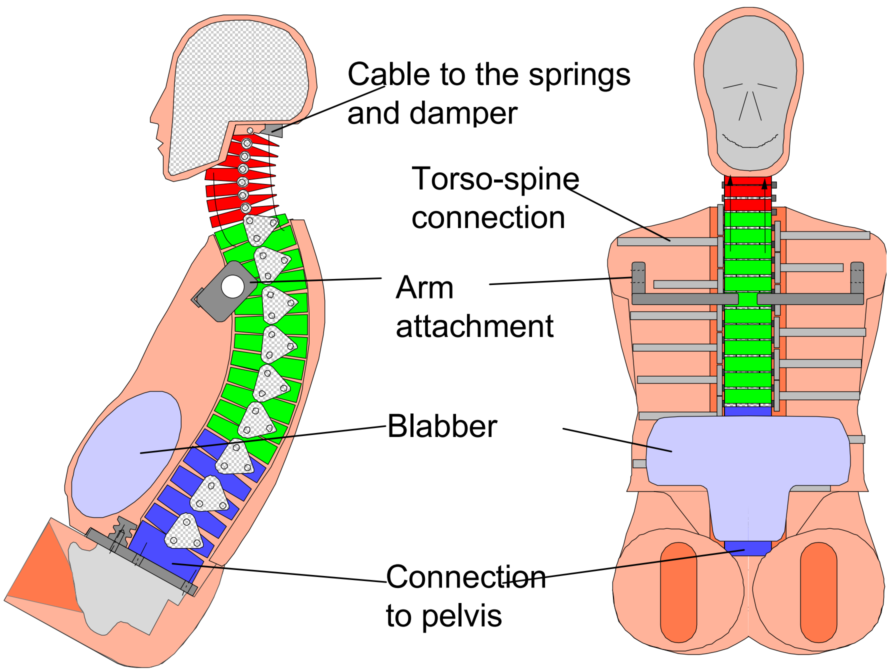


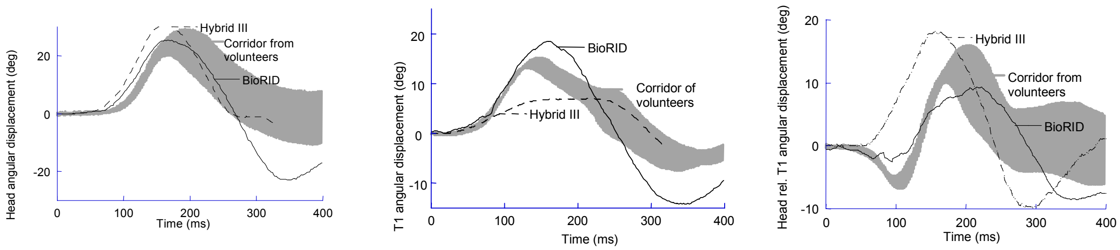
Figure 2. Schematic description of the BioRID, side and front view (from Davidsson et al. 1998).

Validation

The BioRID has been evaluated against data obtained from volunteer tests (Davidsson et al., 1998; Linder et al., 1998; Davidsson et al., 1999a). From volunteer and PMHS test (Linder et al., 1999) and toward PMHS test (Linder et al., 2000). The mathematical model was evaluated toward volunteer test (Linder, 2000).

The validation of the mathematical model (Linder, 2000) showed that the kinematic of the head relative to the T1 agreed well with volunteer data. This was found for horizontal, vertical and angular displacement. The results of the mathematical neck model development showed that muscle substitutes containing a combination of elastic stiffness and damping in the muscle substitutes, together with a non-linear progressive joint stiffness, was required to obtain the head kinematics found in volunteer tests. Without the muscle substitutes the duration of the neck motion was shorter when a similar rearward peak angular displacement as the neck model containing muscle substitutes was reached.

In Davidsson et al. (1998) and Linder et al. (1998) the BioRID was validated in sled tests toward a series of volunteer test. The response of the volunteers was presented as corridors representing ± sd of the average volunteer. In this study the BioRID was also compared with the response of the Hybrid III. In sled test at an impact velocity of 7 km/h and at peak acceleration 3.2g. It was found that the head relative to T1 motion of the BioRID was similar to that of the volunteers, where as the Hybrid III showed lower peak values and shorter duration of the horizontal displacement and angular displacement than the volunteers (Figure 3).



(a) (b) (c)

Figure 3. Angular displacement of the head (a), T1 (b), and head relative to T1 (c) for the BioRID, the Hybrid III and the corridor from the volunteers (Linder et al., 1998).

In Linder et al. (1999) the BioRID and the Hybrid III were run in different seats given the same impact and compared to the results from volunteer at an impact velocity of 10 km/h and at a peak acceleration of 3.5g and from previus run PMHS tests. The results showed that the BioRID had a more flexible and human like motion than the Hybrid III. The results shoved that the Hybrid III is a more sensitive tool for rear end low velocities than the Hybrid III. In the same study an evaluation toward PMHS test data was also carried out. The acceleration pulse used in these human cadaver tests, however, could not be sufficiently reproduced.

In Davidsson et al. (1999) the BioRID and the Hybrid III was evaluated toward volunteer data from Jari. These test were conducted in a rigid seat at a delta v of 8 km/h and a maximum acceleration of 4 g. The results showed that the BioRID very well mimics the motion of a volunteer with sufficient straightening out of the spine and a human like head neck motion. In a forward leaning position (10 degrees) the BioRID was somewhat softer than the volunteers were. In the evaluation of the dummies the Hybrid II was much to stiff and loads the seatback in an unhuman way it was very clear that a flexible pine is necessity to obtain the s-shape of the neck.

In Linder et al (2000) the BioRID and the Hybrid III has evaluated in pendulum impacts to the back and compared to data from previous cadaver tests. The test set-up impacting seated cadavers was reproduced with a pendulum impacting seated dummies (Figure 4) at the level of T6 (6th thoracic vertebra). The pendulum mass was 23 kg and the impact velocity 4.6 m/s. The displacement corridors for the low-severity T6 test contained data from seven cadavers. The typical cadaver response falls within the corridor. The corridors were calculated by overlaying all of the similar test results and selecting points that bounded the responses.

Figure 4. Initial dummy position and film marker position for the BioRID (left) and Hybrid III (right).

Figure 5 shows head relative to T1 angular displacement from Linder et al. (2000). The response of the BioRID was closer to that of the corridor than was the Hybrid III. The time for the positive peak value of the head relative to T1 angular displacement differs between the Hybrid III and the BioRID. The peak value for the BioRID fell within the corridor of the cadavers whereas the peak value for the Hybrid III occurs earlier than in the cadaver tests. The peak value occurs at 47 ms for the Hybrid III and at 85 ms for the BioRID.

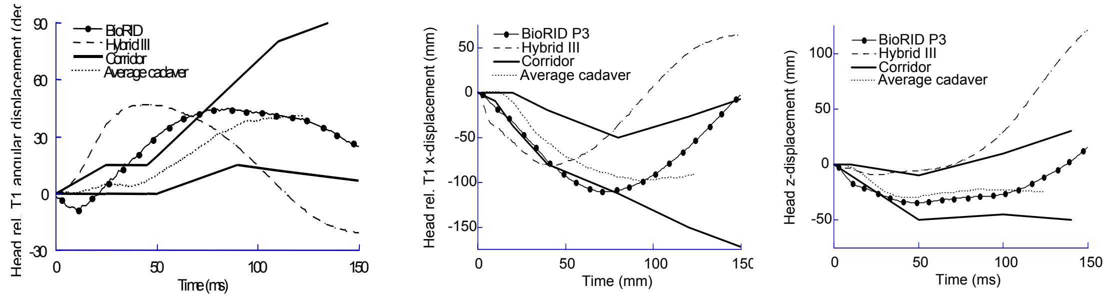


Figure 5. Head relative to T1 angular displacement, head rel. T1 x-displacement and head z-displacement of the corridor of the seven cadavers, Hybrid III and BioRID.

The results showed that the BioRID was more biofidelic than the Hybrid III in terms of the peak responses and the temporal window of the head and head relative to T1 horizontal, vertical, and angular displacement. This study is an evaluation of both the BioRID and the Hybrid III against a recently available set of human subject data. The study meets the need for validation of the BioRID at a higher impact severity than has been previously accomplished.

Crash-test dummies should not only provide a biofidelic response. For practical testing reasons they should also be able to withstand series of tests without requiring maintenance. They should also be reproducible. The dummies should have a consistent, repeatable response when subjected to identical test conditions. These are important features when designing components and choosing materials for mechanical models of humans. The BioRID showed sufficient results for both repeatability and reproducibility (Davidsson et al., 1998 and Linder et al., 1998).

CONCLUSIONS

A Biofidelic Rear Impact Dummy (BioRID) was developed in several steps and validated against volunteer and post mortem human subjects test results and compared to the Hybrid III. The BioRID was found to have more human-like kinematics than the Hybrid III in low velocity rear end testing. This was found both in comparison to volunteers and post mortem human subjects. This was found for the angular, vertical and horizontal displacement of the upper torso. It was also found for the head relative to upper torso horizontal and angular displacement.

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