BioRID I - A New Biofidelic Rear Impact Dummy

Johan Davidsson[1], Mats Y Svensson[1], Anders Flogård[1], Yngve Håland[2], Lotta Jakobsson[3], Astrid Linder[1], Per Lövsund[1], Kristina Wiklund[4]

[1]Department of Machine and Vehicle Design, Chalmers University of Technology, Göteborg, Sweden
[2]Autoliv AB Research, Vårgårda, Sweden
[3]Volvo Car Corporation, Göteborg, Sweden
[4]Saab Automobile AB, Trollhättan, Sweden

ABSTRACT

Although most seat systems offer limited protection against neck injuries in rear-end collisions, there is currently no established method for performance testing of these systems in rear-end impacts. The most important component for such a test method is a crash test dummy. Several investigators have noted limitations of the most commonly used dummy in rear impact testing, the Hybrid III.

The objectives of this study have been to develop a new dummy for low speed rear-end collision testing and validate it against volunteer data. The dummy has a new articulated thoraco-lumbar and cervical spine and a torso of silicon rubber. The neck and the thoraco-lumbar spine consist of 24 vertebrae, the same number of vertebrae as in the human, which are connected by hinge joints. The motion of the head and neck is partly controlled by muscle substitutes. Linear torsion springs and polyurethane bumpers provide the resistance to flexion and extension in the thoracic and lumbar spine. The dummy is equipped with Hybrid III legs, arms, head and a modified Hybrid III pelvis.

The complete dummy prototype was validated against volunteer test data and its performance compared to that of the Hybrid III dummy. The kinematics of this dummy prototype showed more human like kinematics in rear end impacts at ΔV=7 km/h compared to the Hybrid III.

STATISTICS FROM several countries have shown an increase in traffic related occurrence of neck injuries during the last decades (Lundell et al., 1998). These injuries lead to long term consequences and are therefore very costly for society (v Koch et al., 1994).

The risk of sustaining a neck injury is higher in rear-end impacts than in any other crash type (Lundell et al., 1998). Currently there is no adequate tool for testing the performance of car seats and head-restraints in rear impacts. The best available dummy is the Hybrid III. Its neck and spinal structure is stiff and unlikely to interact with the seat-back in the same compliant way as the human spine.

In a comparative study between a human driver and Hybrid III dummy in low speed rear-end impacts by Scott et al. (1993), the human's head motion tended to be more complex than that of the Hybrid III and the human subject's torso appeared to ramp up the seat back while that of the Hybrid III did not. Foret-Bruno et al. (1991) compared the Hybrid III dummy to a cadaver in simulated rear-end impact using a headrestraint closely fitted to the head to minimize the relative movement between head and torso. The cadaver showed no sign of injury. However, very large shear forces at occipital level were registered in the Hybrid III test. The authors concluded that the human head can move relative to the torso with very limited stresses to the neck, but this is not the case for the Hybrid III.

Svensson and Lövsund (1992) developed and validated a Rear Impact Dummy-neck (RID-neck) that can be used on the Hybrid III dummy. Their neck was designed for rear-end collision testing at low impact velocities. It consists of seven cervical and two thoracic vertebrae. The RID-neck was validated using data from a test series with volunteers (Tarriere and Sapin., 1969). These validation data only included the angular displacement of the head relative to the torso but did not allow for validation of the initial rearward translational motion of the head (retraction motion or head lag).

Thunnissen et al. (1996) developed a new rear impact dummy neck, the TRID-neck (TNO Rear Impact Dummy-neck) based partly on the RID-neck design. The TRID was subjected to a more extensive validation, but which was still restricted to the angular displacement between head and torso. The number of pin joints had been reduced from nine (RID) to seven (TRID) and efforts had been made to achieve adequate repeatability and reproducibility, which were weak points in the RID-neck design. The dynamic responses of the two neck types appear to be very similar.

The aim of the present study is to develop a crash test dummy for evaluation of the performance of car-seat systems in rear-end collisions, and to compare the dummy performance to volunteer test data and to the standard Hybrid III. In the first instance, the dummy is designed primarily as a research tool. The dummy has been given the name Biofidelic Rear Impact Dummy (BioRID). It has a new articulated thoraco-lumbar spine, neck and flexible torso.

This paper attempts to address four issues: 1) to describe the most recent BioRID prototype and the rationale for the design, 2) to validate this dummy prototype with volunteer data, 3) to compare the BioRID with the Hybrid III in low speed rear-end impacts, and 4) to propose improvements for the next generation of BioRID.

MATERIALS AND METHODS

A new dummy for rear end collision testing at low velocity changes was developed (Figure 1). The dummy has a new torso, arm attachments, articulated spine, neck-muscle substitutes and pelvis, which has been fitted on Hybrid III legs, arms and head. The work was carried out in several stages where increasingly refined prototypes were developed and evaluated. This paper presents the results of the most recent prototype. The new dummy is further described in a companion paper (Davidsson 1998b).

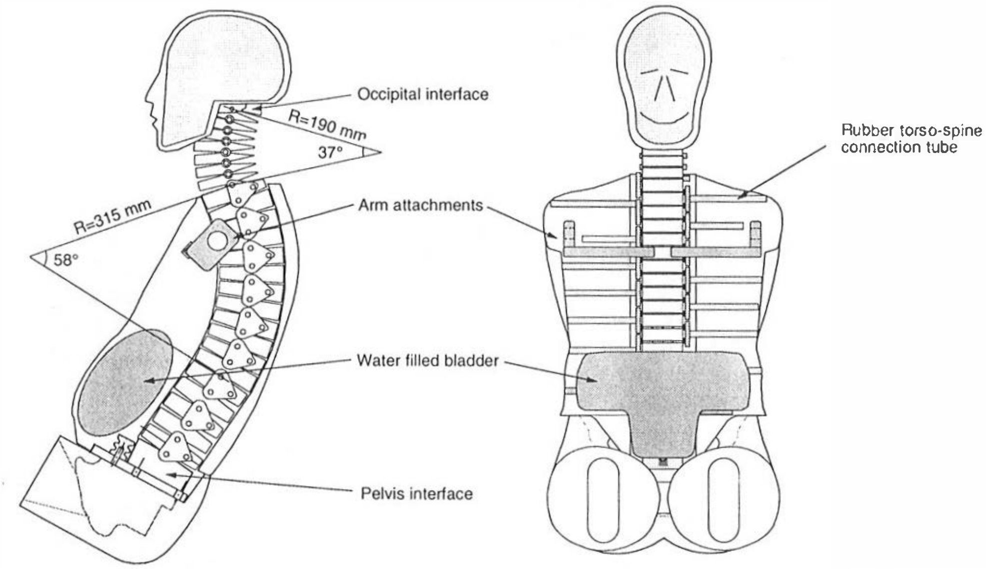

Figure 1: Schematic drawing of the new dummy torso, arm attachments, spine, neck and modified pelvis with Hybrid III head in seated position.

THE SPINE - In order to resemble the human spine, the BioRID spine consists of 7 cervical, 12 thoracic and 5 lumbar vertebrae. The thoracic spine has a kyphosis and the lumbar spine is straight as the human in seated posture (Schneider et al., 1983) (Figure 1). In seated posture the BioRID neck has a lordosis.

An occipital interface piece is rigidly mounted to a modified version of a Denton Hybrid III upper neck load cell. The top cervical vertebra and the occipital interface were designed to allow the head to be horizontal while maintaining the same joint characteristics as the rest of the neck joints. The top thoracic vertebra is a hybrid; its upper side is designed like a cervical vertebra and the bottom surface as a thoracic vertebra. The upper surface of the top lumbar vertebra matches the thoracic vertebra design. The bottom lumbar vertebra is connected to a pelvis interface which in turn is mounted to the pelvis.

The vertebrae are made of durable plastic and connected with pin joints which only allow for angular motion in the sagittal plane. The cervical, thoracic and lumbar vertebrae have the same joint-to-joint center distance: 17.5 mm, 26.5 mm and 30.5 mm respectively.

The cervical vertebrae and the occipital interface, thoracic and lumbar vertebrae have the same angular range of motion relative to the nearest inferior vertebra (Table 1). The chosen angular range of motion of the lumbar, thoracic and cervical spine were based on data from the literature (Table 1). In the BioRID, the range of angular motions were adjusted for seated posture according to Andersson et al. (1979).

Table 1: The range of motion between two adjacent vertebrae in the cervical, thoracic and lumbar spine compared to literature data [deg].

Dummy/ Reference:	BioRID		White & Panjabi, 1978	Kampanj, 1974*			Moffatt et al., 1979	Snyder et al., 1975*	
Direction:	Extension	Flexion	Total RoM	Extension	Flexion	Total RoM	Total RoM	Extension	Flexion
Cervical	11.5	4.5	8-17 (12.3)	-	-	-	13-21 (16.5)	10.0	6.9
Thoracic	3.0	3.0	4-12 (6.3)	2.1	3.8	-	-	-	-
Lumbar	10.0	5.0	12-20 (15.6)	6.0	8.0	11-24 (16.6)	-	-	-

* The body segment range of motion in extension and in flexion for the human in standing posture evenly distributed on the joints included in the particular segment (cervical 8, thoracic 12 and lumbar 5 joints).

In the interspaces between all vertebrae, there are blocks of polyurethane rubber glued to the nearest inferior vertebra. Two blocks are in the neck: the first contributes to the overall joint characteristics while the second is activated only when the spine is hyper-extended or hyper-flexed. The thoracic and lumbar spine are only equipped with blocks of the latter type. The size, hardness and position of the rubber blocks determine their contribution to the joint stiffness characteristics. In the thoracic and lumbar spine, the steel pin joints constitute linear torsion springs (Figure 2). The ends of the pins are connected on each side respectively to the superior and to the inferior pin by means of steel washers (Figure 2). By adjusting the torsion pin angle (i. e. changing the washer to washer angle) the spine curvature can be changed and thereby enable different initial seating posture. The choice of static joint characteristics in the cervical, thoracic and lumbar spine were based on MADYMO simulations (Linder et al., 1998; Eriksson, 1998). The static joint characteristics are depicted in Figure 3.

In order to better replicate the human head and neck retraction motion (headlag) and thus more precisely predict injury risk, the new neck is equipped with muscle substitutes. These consist of wires originating from the head, in the front and in the back of the occipital joint, guided through the cervical vertebrae and terminating at the T1. At the T1 the wire load is transferred, via nylon coated steel wires and wire housing, to a spring in parallel with a damper (Linder et al., 1998).

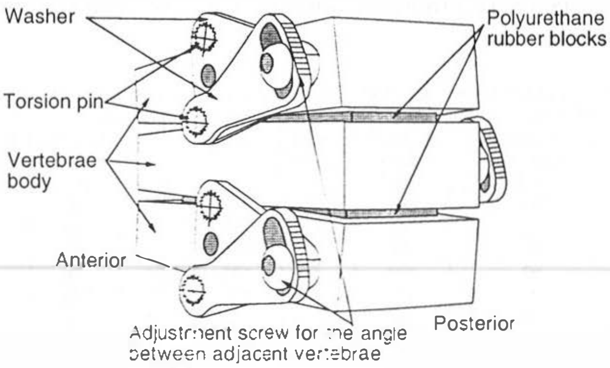

Figure 2: Schematic of three thoracic vertebrae with torsion springs/pin joints, washers and threaded holes for the pins which attach the spine and the rubber torso. (Oblique rear view)

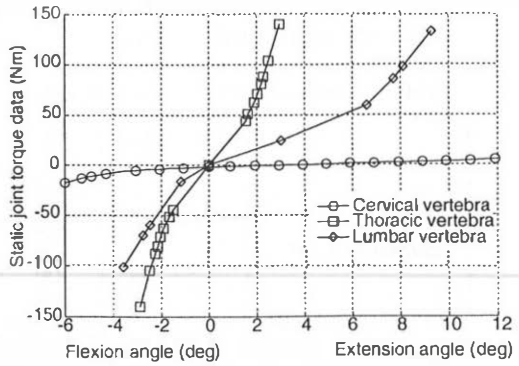

Figure 3: The static joint torque as a function of extension angle for the neck with polyurethane blocks but excluding muscle substitutes. Thoracic and lumbar spine data including torsion pins and polyurethane blocks.

THE TORSO consists of chest and abdomen and is moulded in a soft silicon rubber. The static bending stiffness contribution of the rubber torso accounts for about 40 % of the overall upper-body stiffness. This, in conjunction with an adjustable spine, will facilitate forward and rearward out-of-position testing with a reasonable starting posture. The torso surface contour resembles a seated 50% male (Schneider et al., 1983). The spine is contained in a curved rectangular container inside the torso. Between the back of the vertebrae and the rubber torso is a Teflon foil to reduce friction between vertebrae and torso. A total of 15 steel tubes with a diameter of 10 mm connect the rubber torso to the spine (Figure 1). In order to reduce the bending resistance of the rubber torso, a water filled bladder (volume 2.05 liters) is enclosed in the abdominal region of the torso (Figure 1). The lower part of the rubber torso is connected to the sacrum, which in turn is mounted on the pelvis.

A modified Hybrid III shoulder joint is attached to a scapula-clavicle structure which is moulded into the silicon rubber (Figure 1). The shoulder joint torque is set to 8 Nm.

THE BIORID PELVIS weighs 8.8 kg which is 0.5 kg less than the Hybrid III pelvis. In the BioRID pelvis, the original Hybrid III anterior-superior iliac spine height has been decreased to conform with the modifications of the Advanced Anthropometric Test Dummy (Schneider et al., 1992) and to agree with the average male pelvis (Reynolds et al., 1981). The original pelvis front flesh has been removed to allow the abdomen to bulge forward. The pelvis flesh has been modified to reduce femur joint flexion/extension resistance.

MASS PROPERTIES of the BioRID, Hybrid III and anthropometric data are presented in Table 2.

Table 2: Mass of the new BioRID body parts compared with Hybrid III data and human anthropometric data.

Bodypart	BioRID (kg)	Hybrid III Backaitis et al. (1994) (kg)	Hybrid III Foster et al. (1977) (kg)	Human Robbins (1983) (kg)
Neck incl. muscle substitutes/Neck	0.9	1.5	1.5	1.0
Thoracic and lumbar spine	6.6	-	-	-
Rubber torso /Torso incl. abdomen	23.0	-	-	26.1
Pelvis	10.7	-	-	11.4
Pelvis, thoracic and lumbar spine	40.3	40.2	40.2	37.5
Head, arms, legs and feet	36.4	36.4	34.6	38.1
Total	77.6	78.2	76.3	76.6

VALIDATION DATA used in this work is from 5 tests, denoted 7V, a subset of a larger series of rear-end impact volunteer tests (Davidsson et al., 1998a). Table 3 presents the individual test conditions, selected anthropometric data of the subjects and the mean values of the data. The belted volunteers were placed in the passenger seat position and were asked to relax prior to impact. The sled acceleration and velocity change are shown in Figure 5.

The seat back had four stiff seat back panels and one headrestraint panel (Davidsson et al., 1998a). The panels were covered by a 20 mm layer of foam and lined with plush fabric. The panels were mounted in coil springs on a rigid seat-back frame (Figure 4). The springs gave the seat the same stiffness characteristics as a modern standard car seat. The seat bottom was a standard bucket seat.

Table 3: Anthropometric volunteer data and test conditions for the volunteer and the validation tests.

Series	Testdata			Head-headrestraint data			Anthropometric data			
	Subj. no.	Test no.	ΔV (km/h)	Horiz. distance x-direction (mm)	Contact time (ms)	Head pitch (°)	Stature (cm)	Age (year)	Weight (kg)	Seating height (cm)
Volunteer group 7V	A	6	6.69	80	80	5	181	35	85	93
	J	24	6.94	70	102	0	179	30	82	91
	K	25	6.84	120	94	0	177	29	65	90
	L	27	6.81	80	104	-5	190	26	75	95
	L	28	6.78	80	110	-8	190	26	75	95
Volunteer mean value			6.81 (.08)	86	98	-2	180	34	78	91
BioRID I	A	1 to 3	6.14 (.05)	90	94 to 95	0	-	-	78	-
	B	1 to3	6.17 (.07)	90	92 to 94	0	-	-	78	-
	C	1 to3	6.26 (.16)	90	92 to 95	0	-	-	78	-
Hybrid III	-	1 to3	6.23 (.03)	90	86 to 92	0	-	-	78	-

ΔV : Maximum sled Δv calculated from 9^{th} degree polynomial of video displacement data. The presented ΔV is the average and standard deviation of the maximum value for the three successive tests with each dummy.

Displacement data for the volunteer head was recalculated to the head center of gravity (Davidsson et al., 1998a). The volunteer T1 linear displacement data used in this validation was calculated as a weighted value from the T1 skin and clavicle skin marker data (Figure 4) (Davidsson et al., 1998a). The volunteer T1 angular displacement was calculated from the T1 and clavicle skin markers. In the volunteer test V6A, the T1 marker was invisible after 60 ms and is therefore excluded in the calculation of the average of the linear and angular displacements.

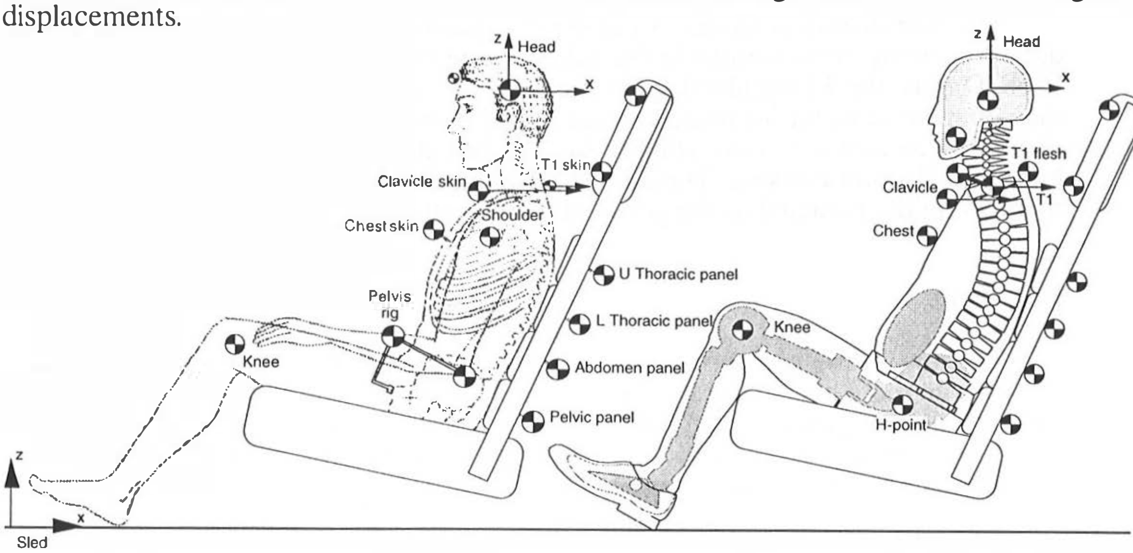

Figure 4: Schematic drawing of the volunteer and BioRID in the special seat used in this study. Two different coordinate systems were defined. One moving with the sled, the x-axis parallel to the sled track and the vertical z-axis. The second, the anatomical coordinate system, is positioned at the accelerometer-mount, and the axis rotates according to the mounting plane.

VALIDATION TESTING was carried out by means of a target and bullet sled at Chalmers University of Technology. In the experiments, the target sled acceleration profiles and velocity change are similar to those used in the volunteer tests (Table 1, Figure 5).

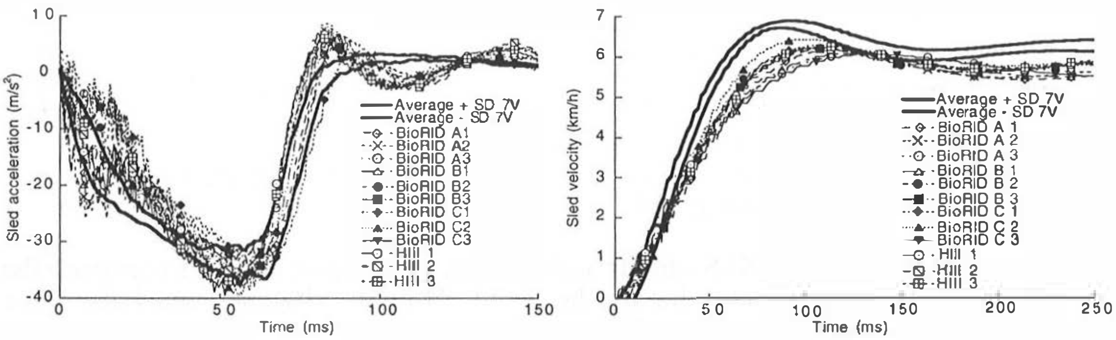

Figure 5: Typical dummy test sled acceleration and velocity change for the dummy tests depicted together with the average ± standard deviation of the volunteers in series 7V.

Three identical BioRID prototypes (A, B and C) and a Hybrid III were each tested three times. The same seat and similar sled configurations were used in the BioRID and Hybrid III tests as in the volunteer study (Davidsson et al., 1998a; Davidsson, 1998b). The curvature of the BioRID back is based on data from the study conducted by Schneider et al. (1983). In that study the subjects were seated in a selection of standard seats. The seat used in the volunteer study probably had a harder lumbar support than did the seats used in the study conducted by Schneider et al. To enable the same load between the average test subject and the seat panels at all levels, the lowest seat panel was mounted 9 mm in front of the original panel position in the BioRID tests.

The dummies were belted and their arms were placed on their thighs to resemble the volunteer conditions. The femur joint torque was reduced to a very low level, approximately 30 Nm in flexion and extension. The shoulder joint torque was set to a level that held the upper arm horizontal with the elbow flexed at 90 degrees, approximately 8 Nm. The BioRID was dressed in two layers of elastic nylon/Lycra shirt and pants to mimic the low friction observed between the human skin and normal clothing. The initial BioRID pelvis angle, defined as the angle between the horizon and the lumbar spine mounting surface on the Hybrid III pelvis, was 29 degrees. The initial head to headrestraint distance was 90 mm to resemble the volunteer tests. The initial H-point position was constant in all dummy tests.

The film marker positions, accelerometer positions, data acquisition, film analysis and data processing were similar in the validation tests and volunteer tests (Figure 4). In the BioRID tests, the T1 angular displacement was calculated from the T1 vertebra markers. In the volunteer tests, the T1 angle was calculated from two markers mounted on the volunteer skin at T1 and clavicle bone (Figure 4). The dummy femur angle was calculated from the knee and H-point markers. The dummy H-point displacements were calculated from two markers rigidly mounted on the pelvis' aluminum structure.

RESULTS

The aim of the present study was to design a crash test dummy for rear-end impact testing with more human like kinematics than that of the Hybrid III. In the following section, the kinematic responses of the BioRID are compared to volunteer and Hybrid III kinematic responses for a sled velocity change of 7 km/h. Results from the repeatability and reproducibility study are also presented.

REPEATABILITY AND REPRODUCIBILITY TESTS - Three BioRIDs of the most recent version were manufactured and each dummy was tested three times under identical conditions ($\Delta V \pm sd$ 6.19±0.11 km/h). In the reproducibility test, the same head, pelvis, upper and lower extremities were used in the different BioRIDs.

The repeatability of the BioRID was taken as the difference between the peak rearward displacement for one test and the average peak rearward displacement value for three tests with the same BioRID. For all three BioRIDs the head x-displacements were within ±2 %, the T1 x-displacements were within ±3 % and the T1 angular displacements were within ±6 %. The BioRIDs showed good repeatability.

The reproducibility of the BioRID was taken as the difference between the average peak rearward displacement for one dummy and the average peak rearward displacement value for three different dummies. The average head x-displacements were within ±2 %, the average T1 x-displacements within ±2 % and the average T1 angular displacements within ±1 %. The three different BioRIDs showed good reproducibility.

The T1 x-displacements for three tests of each of the three BioRID dummies and for the Hybrid III are depicted in Figure 6.

VALIDATION TESTS - In the validation tests, we have chosen to compare the linear and angular displacements for the head, T1, H-point, shoulder and knee since these parameters are good indications of dummy performance.

The linear displacements as a function of time, for the head, T1, H-point and head relative to T1 are compared to the volunteer results in Figure 6.

The maximum T1 x-displacement for the BioRID was 20 mm lower than the average volunteer T1 x-displacement. The Hybrid III T1 x-displacement was very low compared to the volunteer data. The BioRID T1 rebound velocity was more representative of the volunteer data than was the Hybrid III. The BioRID head relative to T1 x-displacement was within the volunteer data corridor for most of the impact time history. The Hybrid III gave a peak head relative to T1 x-displacement which was rather low.

There appeared to be a large difference in the head and T1 z-displacements between the dummies and the volunteers. The Hybrid III was less prone to ramp up the seat back, as can be concluded from the H-point z-displacements, than were the volunteers and the BioRID. The BioRID T1 z-displacement curve was somewhat closer to the volunteer data than the Hybrid III, but still 25 mm lower than desired.

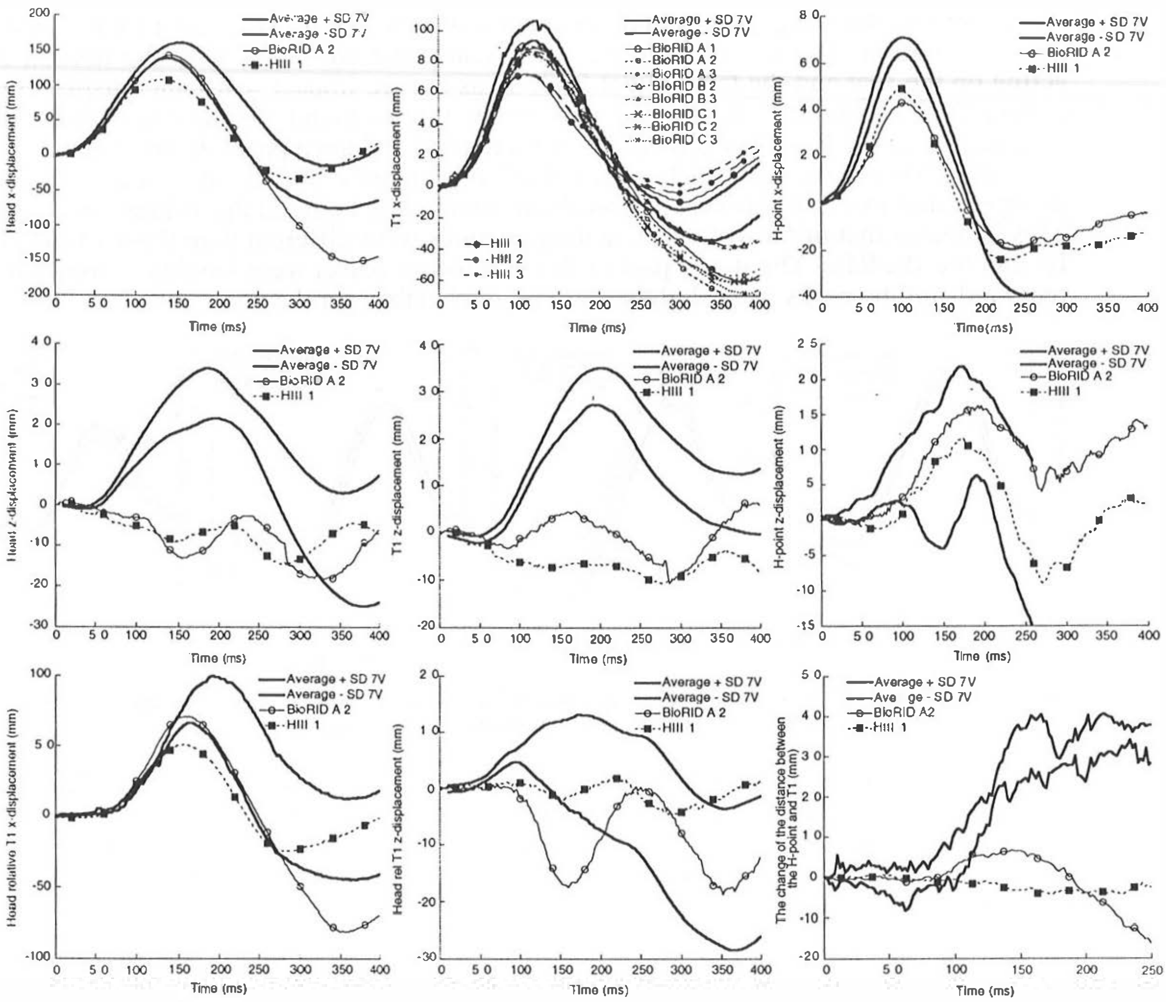

Figure 6: Linear displacement for the dummy head, T1, H–point and head relative to T1 compared to volunteer response corridors (average ± standard deviation) at 7 km/h ΔV in sled x- and z-coordinates.

For the same impact situation, the angular displacements of the dummy head, T1 and head relative to T1 are compared to volunteer data (Figure 7). The T1 angular displacement and angular velocity for the BioRID were similar to that of the volunteers for the first 160 ms. The maximum T1 rearward angular displacement was the same for the BioRID and the average volunteer while the maximum T1 rearward displacement was 11 deg less for the Hybrid III. The head relative to T1 angle for the BioRID resembled the volunteer data but was unfortunately not within the volunteer corridor in the rear phase.

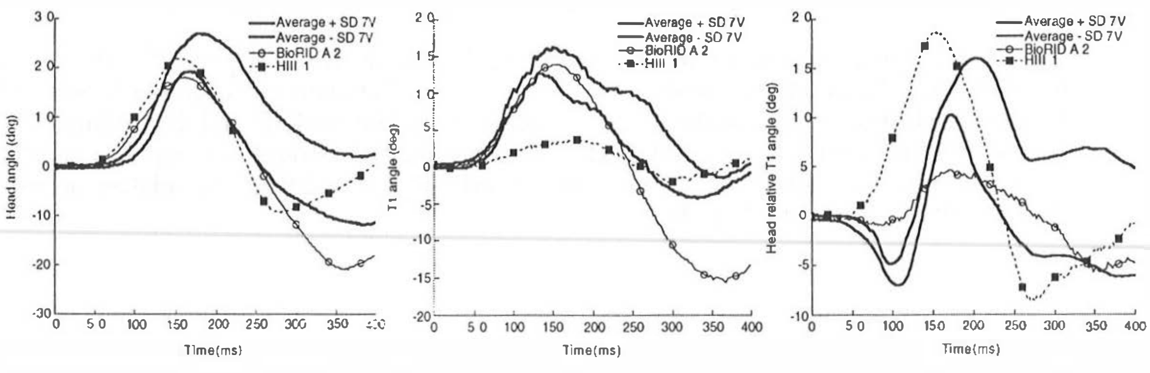

Figure 7: Rearward angular dummy displacements of the head, T1 and head relative to T1 compared to the volunteer response corridors (average ± standard deviation) at ΔV=7 km/h.

Figure 8 shows the dummy and volunteer x-displacement of the seat panels in the same impact situation. The x-displacement of the seat panel correlates with the normal forces acting on the seat and the test subject (as long as the pre-impact seat-panel displacement is constant). The Hybrid III showed less upper thorax panel displacement than do the volunteers and the BioRID but more lower thorax and abdomen panel displacement.

After 200 ms, the seat panels were unloaded in all tests. Initially, the dummies displaced the upper and lower thorax seat panels about 10 mm less than did the volunteers (Figure 8). This indicates that initial volunteer seating postures were different than those of the Hybrid III and the BioRID. The upper part of the volunteers' backs were leaning somewhat more rearward and the necks were slightly more protracted than for the dummies.

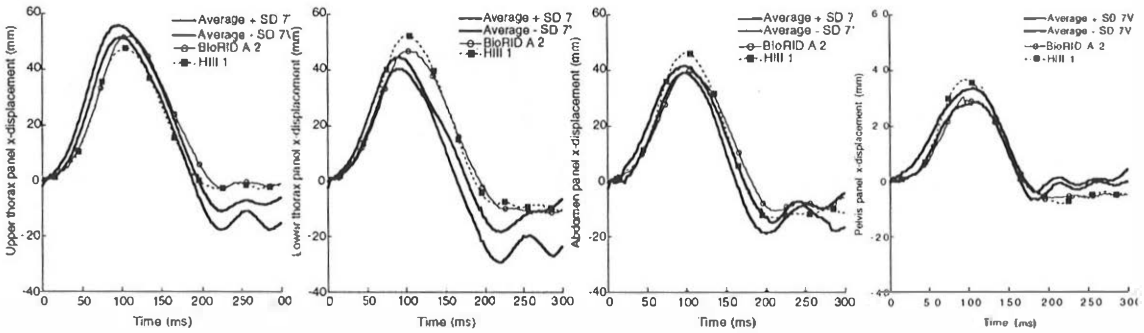

Figure 8: Linear x-displacement of pelvis, abdomen, lower torso and upper torso seat panels compared to volunteer response corridors (average ± standard deviation) at ΔV=7 km/h.

Figure 9 shows the response curves of the shoulder displacement for the BioRID, the Hybrid III and the volunteers. The BioRID is somewhat closer to the volunteer data.

For the first 100 ms the volunteers pressed their knees downward towards the seat cushion (Figure 9). In the validation tests, however, the Hybrid III and BioRID knees moved upward for the first 160 ms.

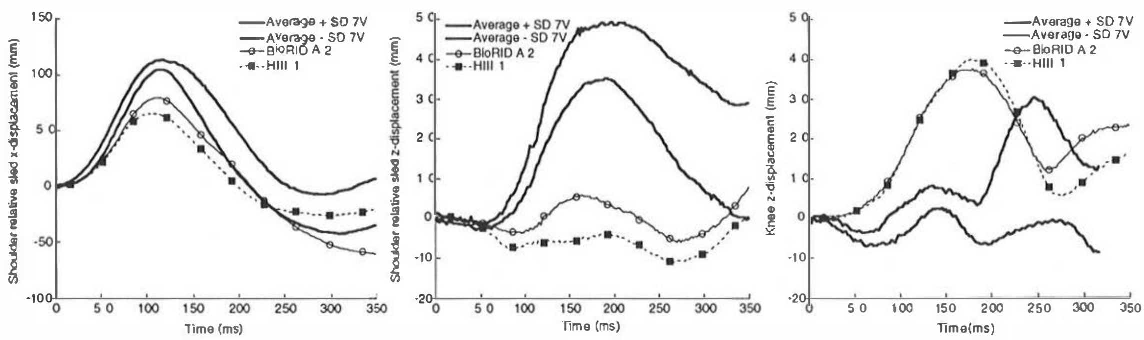

Figure 9: Linear displacement for the dummy shoulder and knee compared to volunteer response corridors (average ± standard deviation) at 7 km/h sled velocity change in sled x- and z-coordinates.

The linear accelerations for the head and T1 are shown in Figure 10. The Hybrid III head was accelerated forward more than occurred for the average volunteer between 50 ms and headrestraint contact, at about 95 ms after impact. The BioRID and the volunteer head x-acceleration however, was almost negligible prior to headrestraint contact. The Neck Injury Criterion (NIC) is also included in Figure 10 and is calculated from the relative acceleration in x-direction (Boström et al., 1996).

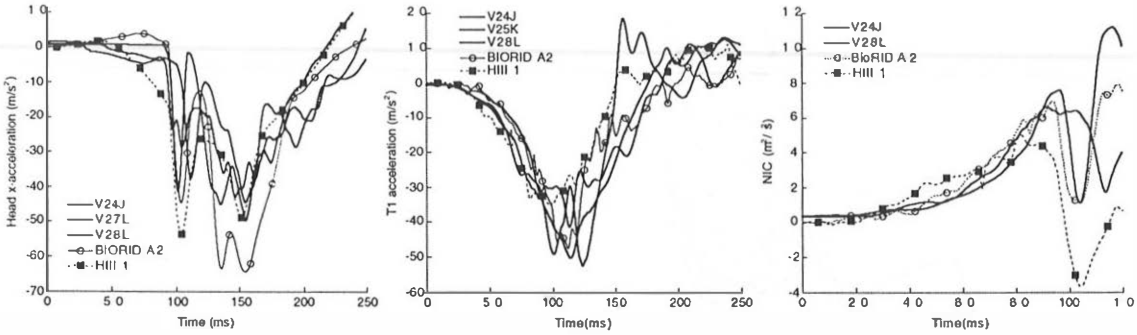

Figure 10: Linear x-acceleration in the local coordinate systems for the dummy head and T1 as well as NIC calculated by the use of the linear acceleration and velocity between the head and T1 at 7 km/h sled velocity. The data is compared to corresponding volunteer data (volunteer V6A is excluded due to insufficient head and T1 accelerometer mount, volunteer V25K is excluded due to early head to headrestraint contact and V27L is excluded due to contact at the time of impact between the T1 accelerometer mount and the seat).

DISCUSSION

Several investigators have reported limitations of the dummy, most commonly used in rear-end impacts, the Hybrid III. Therefore, our research group started to develop dummy prototypes for evaluation of seat-systems and head-restraints in rear-end impact testing. This first version, the BioRID I, is a significant step forward towards an effective tool for car seat development and evaluation. This work also emphasizes the need for more detailed data on muscle activity, initial seating posture and kinematics from volunteer tests and cadaver tests for further validation.

DUMMY DESIGN - In a human spine, the head relative to T1 kinematics are due to shearing, axial elongation and rotation between adjacent vertebra. Moffatt et al. (1979) studied the voluntary motion of the neck of a seated human in the sagittal plane and reported the typical center of rotation to be in a relatively fixed location near the center of the body of the inferior vertebra. It was concluded that, under the tested conditions, the head neck motion could be represented by a series of rigid links connected at pivot points. Ono et al. (1997) and Kaneoka et al. (1997) reported an upward shift of the instantaneous axis of rotation in the lower motion segments of the neck during staged rear-end impacts of a velocity change of 8 km/h. For simplicity, the vertebrae joints in the BioRID only allow for angular rotation and the distance between the joint centers are constant.

The differences in initial seating posture between the BioRID, Hybrid III and volunteers may have influenced the kinematics as well as the load on the seat structures in the validation and volunteer tests. Most likely, the seat design affects a person's sitting posture and this implies that two different seat designs require two different initial dummy postures. The Hybrid III back is rather straight and the construction does not allow for any changes of the initial seating posture (Figure 11). The BioRID back surface resembles a human subject seated in a soft car seat typical of an American car from the mid 80's (Schneider et al., 1983). The spine joint coordinates and the exterior design of the BioRID torso are similar to the results of Robbins (1983). In the BioRID, however, each joint segment in the lumbar and thoracic spine allows for an initial angular adjustment of ±5 and ±3 degrees per vertebra unit respectively.

The silicon rubber material used in the BioRID torso, has low creep rate, almost constant mechanical properties for a large temperature range and the aging rate of the material is low (Friberg, 1986). The degree of secondary cross linking in the silicon rubber matrix is low compared with other rubber materials (Friberg, 1986). This enables repeated dummy experiments without recovery between successive tests. The density of the silicon rubber used in the BioRID torso is 1.07 g/cm^3 and are similar to that of the human torso and abdomen density, 0.92 and 1.01 g/cm^3 respectively (Dempster, 1955).

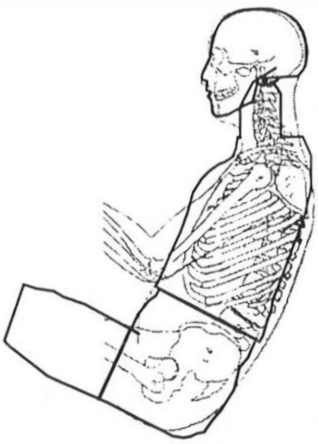

Figure 11: The sagittal plane cross cut view of the Hybrid III overlapping a schematic drawing of a human seated in a standard car seat (Schneider et al., 1983).

In the BioRID spine. polyurethane blocks were placed inbetween adjacent vertebrae to give the desired bending stiffness in the sagittal plane. The spine joint characteristics were similar in repetitive testing, also without recovery period between two following tests. This may be because the polyurethane has a low concentration of fillers. Therefore, the recovery period between two consecutive tests, recommended when a Hybrid III is being used, may be unnecessary when a BioRID is being used.

The friction coefficient between the Hybrid III flesh and the cotton dress cloth as well as between the BioRID silicon and the cotton dress cloth normally used for the crash-test dummy, was higher than the friction between the human skin and cotton clothing (Davidsson et al., 1998a). In order to simulate the friction between the skin of the subject and the test-seat surfaces, the BioRID was dressed in two layers of flexible and smooth nylon/Lycra shirt and pants in the validation study. A BioRID prototype dressed in a single cotton shirt and pants was tested for comparison. The use of double layer nylon/Lycra shirt between the torso and the seat back surface increased the T1 and H-point z-displacements about 30 % (Davidsson, 1998b).

VALIDATION TEST - In Figure 6 and 7, the BioRID, Hybrid III and volunteer T1 x-displacement and T1 angular displacement are compared. Even though the volunteers were asked to relax prior to impact, they may have been somewhat tensed at the time of impact resulting in the volunteers possible resistance to head and torso motion. Only healthy, young and rather athletic test subjects were permitted to participate in the volunteer study. Had an older and less athletic subject been exposed to the same impact as in the volunteer test, the maximum angular and linear x-displacement of the T1 may have been larger. A dummy torso for rear-end impact testing should be representative for the whole population of car occupants and should, therefore, at least not be stiffer than the BioRID torso in extension, which is the case for the Hybrid III torso.

Figure 8 shows the dummy and volunteer x-displacement of the seat panels in the same impact situation. The Hybrid III shows less upper-thorax panel displacement and more lower-thorax and abdomen panel displacement than do the volunteers and the BioRID. This indicates that the Hybrid III, unlike the BioRID, does not load the seat structures properly. This may be due to the back curvature, torso stiffness and mass distribution of the Hybrid III.

After 200 ms, the seat panels were unloaded in all tests (Figure 8). Initially, the dummies displaced the upper and lower thorax panel about 10 mm less than did the volunteers. This indicates that initial volunteer seating posture was different than that of the Hybrid III and the BioRID. The upper part of the volunteers' backs were leaning somewhat more rearward and the necks were slightly more protracted for the dummies. Had the dummies been better supported by the upper part of the seat in the validation test, the dummies' T1 and head x-displacement would probably have been somewhat smaller than in this study (Figure 6).

The head relative to T1 angular displacements are depicted in Figure 7. The head relative T1 angle for the BioRID resemble the volunteer data but was unfortunately not within the volunteer corridor in the rear phase. The head relative Tl angle for the BioRID is highly dependent on the muscle substitute characteristics. In the most recently developed BioRID version, the wire housing stiffness and the friction between the muscle substitute wire and wire housing were higher than in the previous version of the BioRID. In the previous version, the BioRID head relative T1 angle was closer to that of the volunteer average. The muscle substitutes in BioRID A, B and C will be replaced.

The Hybrid III neck yielded a larger head relative to T1 rearward angle than did the volunteer and the BioRID neck. The head and T1 x- and angular displacements for the dummies and volunteers, in the same tests, are shown in Figure 6 and 7. The Hybrid III peak head and Tl x-displacements were lower than the volunteer and BioRID displacements. This resulted in a lower contact force between the head and head rest in the Hybrid III tests compared to the volunteer and BioRID tests. The peak head rearward rotation in the BioRID and volunteer experiments were, therefore, prevented by the headrestraint to a larger extent than in the Hybrid III tests. This may explain the higher peak rearward angular displacement of the Hybrid III head. The data also show that the rearward angular displacement of the Hybrid III head relative to Tl started 40 ms before it did for the volunteers and the BioRID. The data demonstrate that the Hybrid III thoracic spine was too stiff in sagittal bending and that the Hybrid III resistance to neck s-shape motion was too high.

In volunteer tests, McConnell et al. (1993), Davidsson et al. (1998a) and Ono et al. (1996) found that during the acceleration phase of a rear-end impact, when the occupants body was pressed against the seat-back, the spinal curvature straightened. This in turn caused an upward motion of the T1 and head. In a comparative study by Scott et al. (1993), the upper torso of the Hybrid III was less prone to move up along the seat-back than were those in the volunteer study. In this validation study, however, the H-point z-displacement shows that both dummies and volunteers were almost equally prone to ramp up along the seat-back (Figure 6). However, the Hybrid III's T1 moves downward (Figure 6) while the BioRID's T1 mainly moves slightly upward for the first 160 ms. The BioRID T1 trajectory resembles that of the volunteers and the result indicates that a dummy for rear-end impacts most likely should incorporate a flexible spine. This is also indicated in the change of distance between the H-point and the Tl plot in Figure 6.

In the volunteer study (Davidsson et al., 1998a) a number of volunteers appeared to move their knees downward (Figure 9). This knee motion was not reproduced by any of the two dummies.

Svensson et al. (1992) reported translation motion without angular displacement for the head center of gravity relative T1 in the validation of the RID-neck. It was concluded that a larger head lag was possible if the RID-neck design was supplemented with anterior and posterior muscle elements. A later validation study by Geigl et al. (1995) indicated that the head lag is too small with the RID-neck in rear-end impacts. Therefore, the BioRID neck was fitted with posterior and anterior muscle substitutes connecting the occipital interface and the T1. The design is similar to that of the next generation frontal impact dummy (Eppinger et al., 1994). In the human, the neck muscle loads are transferred between all of the head and neck skeletal structures as well as the torso (Cailliet, 1981). In the BioRID, however, the muscle substitute loads are transferred between the head and the Tl vertebra only. In the development of the BioRID, the thoracic and lumbar spine stiffness was tuned to replicate the volunteer T1 angular and x-displacements. In a BioRID prototype, the influence of the thoracic spine stiffness on Tl z-displacement was evaluated. It was concluded that a less stiff thoracic spine resulted in increased straightening of the kyphosis and upward motion of T1 but also a larger T1 angular displacement than desired. In a future modification of the BioRID design, an improved interface between the T1 vertebra and the upper part of the rubber torso will be included as well as a reduction of the thoracic spine stiffness. Another solution taken into consideration will be to extend the neck muscle substitutes to also include parts of the thoracic spine.

The Hybrid III thoracic spine is rigid and, as shown in Figure 8, results in extensive x-displacement of the lower thorax and abdomen seat panels. In any seat-back test, the dummy performance is determined by the load transferred from the seat to the dummy. In case the dummy thoracic spine is rigid, as in the Hybrid III, seat backs with distributed stiffness may result in dummy performances similar to that of a seat back with an unevenly distributed stiffness. The articulated spine of the BioRID will probably resolve the influence of seat back stiffness distribution on the occupant response to a higher degree than does the Hybrid III.

The BioRID was developed to replicate the human motion in a rear-end collision and to enable the prediction of risk of injury to an occupant. However, the exact relation between head-neck motion and the risk of sustaining a neck injury has not yet been fully established. Boström et al (1996; 1997) have developed a neck injury criterion, NIC, for rear-end impacts. The NIC value is calculated as the weighted sum of the linear relative acceleration between the head and T1 and the square of the relative velocity between the head and T1 at the moment the head starts to rotate. i. e. when the cervical spine has reached its maximum s-shape/retraction. On the basis of those findings, the dummy T1 and head velocity and acceleration are of significant interest in a dummy test. The head and T1 acceleration and NIC as a function of time are depicted in Figure 10. The BioRID shows values closer to the volunteer values in comparison with the Hybrid III.

CONCLUSION

A new dummy prototype, BioRID, for rear-end collision testing at low velocity changes has been developed. It has a new human like flexible spine, a soft torso and a new pelvis. The neck is fitted with posterior and anterior muscle substitutes. The dummy allows motions in the sagittal plane. The design has proven to be repeatable and reproducible.

The new dummy has been validated against volunteer tests (Davidsson et al. 1998a). The BioRID's T1 and head rearward and angular displacements are close to that of the average volunteer while the Hybrid III's displacements are much smaller than those of the average volunteer. Neither the BioRID nor the Hybrid III were able to mimic the volunteer T1 and head upward motion. The BioRID will be further adjusted to better fit these data.

Preliminary sled-tests have shown that the BioRID functions well and it appears to be a significant step forward towards an effective tool for car-seat development.

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