

PERFORMANCE EVALUATION OF VARIOUS HIGH BACK BOOSTER SEATS TESTED AT 56 KPH USING A 6-YEAR-OLD HYBRID III DUMMY

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ABSTRACT

Recent increase in the use of child restraints, particularly belt-positioning booster seats, requires closer evaluation of their performance. Previous studies by Menon, et al. and Sherwood, et. al. have shown that the Hybrid III 6-year-old dummy produced unusual head-neck kinematics and neck injury measures that exceeded critical values while restrained in a high back booster seat. Both studies used similar high back booster seats for the tests but were done at different speeds and conditions. This study was undertaken to initiate a process to evaluate the performance of multiple high back booster seats by conducting a series of sled tests. These 56 kph sled tests were done using the Hybrid III 6-year-old child dummy in 4 different high back booster seats and their injury measures were compared.

Results of these tests have been summarized in this paper and provide an evidence for a differential performance among the various designs of high back booster seats compounded with the established lack of biofidelity of the Hybrid III 6-year-old dummy. Injury tolerances exceeded for the 6 year-old dummy in two of the high back booster seats for the Head Injury Criteria, in three of the seats for chest G's and in all the four seats for the Neck Injury Criteria. In two of the seats with similar design, the kinematics of the head was unusual, mainly due to the extreme hyper-flexing of the neck. This high neck injury measures obtained from the sled tests are in contrary to the field data, which show that children in belt-positioning booster seats suffered virtually no injuries to the abdomen, neck/spine/back. These test results and field data highlights the need for further research to be conducted to improve the biofidelity of the Hybrid III 6-year-old dummy neck and to understand the variation in the high back booster seat designs at higher speeds.

INTRODUCTION

Currently there are about 30 different types of belt positioning booster seats available to use for children who have outgrown child seats, but are yet not tall enough for adult seat belts [1]. The National Highway Traffic Safety Administration's (NHTSA) [2] and American Academy of Pediatrics (AAP) [3] currently recommend that children over 40 lbs and approximately between 4 and 8 years of age unless the child is 57 inches tall should be restrained using a belt positioning booster seat. Partners for Child Passenger Safety (PCPS) [4], a national data source of children in crashes, collected over a period of 5 years, provides an evidence of the increased uses of these belt positioning booster seats [5]. This data also shows that the belt-positioning booster seats provide added safety benefits over seat belts to children through age 7 years, including the reduction of injuries classically associated with improper seat belt fit in children. [6,7,8]

The study by Menon, et. al. [9] looked at the performance of the various child restraint systems by conducting sled tests with Hybrid III 3- and 6-year-old child dummies at a range of speeds. It was observed in the study that the 6-year-old dummy in the high back booster (HBB) seat at 56 kph experienced a significant neck flexion resulting in the chin and face contacting the chest of the dummy. Although this phenomenon of the dummy neck kinematics has been adequately explained by Sherwood et. al. [10] it must be noted that this extreme hyper-flexing of the Hybrid III 6-year-old dummy neck only occurred in the HBB at speeds above the standard test speed of 40 kph and not in other restraint types. Thus leading the authors to believe that the influence of the HBB design itself should not be ignored. Since there are many different high back booster seat designs that are available for use, therefore the primary purpose of this study was to conduct a series of sled tests at 56 kph with a Hybrid III 6-year-old dummy restrained in

different belt-positioning HBB designs to assess the dummy's response and to evaluate the performance of the different HBB designs. This paper documents the Hybrid III 6-year-old dummy interaction with the HBB seats.

METHODS

Four HBB seats, Century Brevera, Evenflo Express, Cosco Highback and Britax Roadster, were selected for this study. Two of the seats, Evenflo Express and Cosco Highback, had some similarities in design. A total of eight sled tests were conducted for these 4 HBB seats. These tests were conducted on a HYTE accelerator sled at Calspan Corporation, formerly known as Veridian Engineering, Buffalo NY. Two sled tests were performed for each HBB seat. All the tests were performed at an impact speed of 56 kph with the sled acceleration pulse as shown in Figure 1. The maximum acceleration was above the standard value, but the duration of pulses was similar to the FMVSS 213[11] acceleration pulse. These tests were performed with a 6-year-old dummy positioned on one side of a standard FMVSS 213 bench seat. The guidelines provided in the standard were used for conducting the tests with the exception being the test speed, which was higher than the 49 kph standard test speed. Production seatbelts were attached to the bench seat assembly in the correct anchorage locations without using the pre-tensioners or the force limiting devices. When the dummies were placed in the HBB seats, the manufacturers instructions accompanying each HBB seat were followed carefully to properly restrain the dummies with optimum belt placement. Two tests were conducted for each HBB seat design to check for the repeatability of the results.

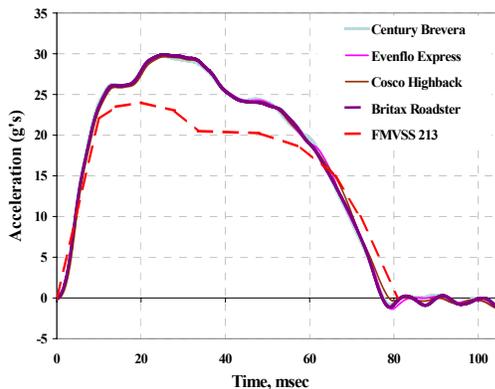


Figure 1. Sled acceleration pulse for 56 kph frontal sled tests.

The Hybrid III 6-year-old dummy was equipped with standard sensors for taking measurements, which

included the head tri-axial accelerometers, upper neck load cells, chest accelerometer, chest potentiometer, pelvis accelerometer and a shoulder belt load cell. Electronic data was sampled at 10,000 Hz and were filtered as per the Society of Automotive Engineers (SAE) recommended practice J211 [12]. Head and pelvis accelerations and upper neck loads were filtered at CFC 1000, whereas the chest accelerations were filtered at CFC 180. Chest displacement and the upper neck moments were filtered at CFC 600. Finally the shoulder belt loads were filtered at CFC 60.

Since the current FMVSS 213 consists of only a test bench without any structure to represent the vehicle interiors, the injury measures, which may be specified as compliance requirement, are non-contact in nature. In order to assess the performance of the HBB designs tested, the injury measures obtained from these tests were compared to the published injury assessment reference values (IARVs) that are shown in Table 1. The injury measures that were obtained in these sled tests were Head Injury Criteria (HIC), neck forces, neck moments, chest acceleration, chest deflection, head excursions and the knee excursion.

The N_{ij} value was calculated for the upper neck as a predictor of neck injury potential and was based on the information provided by Eppinger et al. [13]. The critical values used for calculating N_{ij} for the 6-year-old were F_{int} (tension) = 3096 N, F_{int} (Compression) = -2800 N, M_{int} (Flexion) = 93 Nm and M_{int} (extension) = -42 Nm.

Table 1. Injury Assessment Reference Values

Injury Criteria	Hybrid III 6-year-old Dummy	Source
Head Criterion (HIC _{36ms})	1000	Title 49 CFR, Part 571, FMVSS 213
Neck Criterion (N _{ij})*	1	Eppinger et al., 2000
Chest Acceleration (G)	60	Title 49 CFR, Part 571, FMVSS 213
Chest Deflection (mm)*	40	Eppinger et al., 2000
Head Excursion Without Tether (mm)	813	Title 49 CFR, Part 571, FMVSS 213
Knee Excursion (mm)	915	Title 49 CFR, Part 571, FMVSS 213

Two cameras (Kodak Ektapro high speed video cameras) were placed on either side of the bench seat to provide sufficient film coverage of the dummy motion and to record the tests at 1000 frames/sec. The head and knee excursion values reported under results were obtained from the test video with the use of visualization software. The visualization software takes care of residual parallax error in head excursion measurements and also incorporates the necessary corrections for measuring the knee excursions.

INITIAL TEST SETUP

The initial test setup of the Hybrid III 6-year-old dummy in a Century Brevera HBB is shown in the Figures 2a and 2b. The vehicle belt was placed ideally over the pelvis and the chest. The belt guides provided for the shoulder belt in the HBB seat was not used because the belt path was ideally placed over the sternum without using the belt guide and this was in accordance to the manufacturer's guidelines. The seated angle of the lumbar with respect to a vertical plane was 18° and the angle of the thigh with respect to the horizontal plane was 13° . The dummy seating posture is upright.



Figure 2a. Pre-test setup of the Hybrid III 6-year-old dummy in a Century Brevera HBB



Figure 2b. Shoulder belt routing of Hybrid III 6-year-old dummy in a Century Brevera HBB

Figures 3a and 3b shows the test setup of the Hybrid III 6-year-old dummy in an Evenflo Express HBB seat. The shoulder portion of the vehicle belt was routed through the top belt guide provided in the seat for proper belt routing over the dummy's sternum. The seated angle of the lumbar with respect to a vertical plane was 32° and the angle of the thigh with respect to the horizontal plane was 16° . The dummy's initial seating posture has a slouch.

Pre-test setup of the Hybrid III 6-year-old dummy in a Cosco HBB seat is shown in the Figures 4a and 4b. The manufacturer's recommendations were used for restraining the dummy in the HBB and the vehicle shoulder belt was routed through the top portion of the belt guide for proper placement over the dummy's sternum. The seated angle of the lumbar with respect to a vertical plane was 31° and the angle of the thigh with respect to the horizontal plane was 16° . It is observed that the Hybrid III 6-year-old dummy had similar seating posture in both Evenflo Express and the Cosco Highback HBB seats.



Figure 3a. Pre-test setup of a Hybrid III 6-year-old dummy in an Evenflo HBB



Figure 3b. Shoulder belt routing of Hybrid III 6-year-old dummy in an Evenflo HBB



Figure 4a. Pre-test setup of a Hybrid III 6-year-old dummy in a Cosco HBB



Figure 5a. Pre-test setup of a Hybrid III 6-year-old dummy in a Britax Roadster HBB

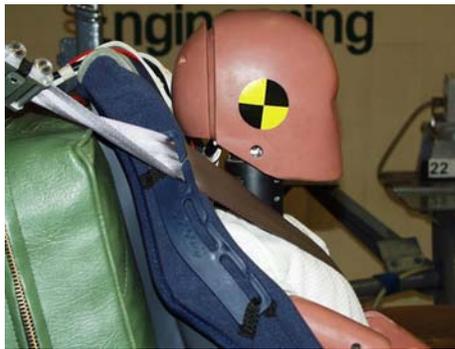


Figure 4b. Shoulder belt routing of Hybrid III 6-year-old dummy in a Cosco HBB



Figure 5b. Shoulder belt routing of Hybrid III 6-year-old dummy in a Britax Roadster HBB

The Britax Roadster HBB seat is unique in design and its back can be adjusted in height to suit the child's height. The pre-test setup of the Hybrid III 6-year-old dummy in a Britax Roadster HBB seat is shown in Figures 5a and 5b. The vehicle shoulder belt routing was done based on the guidelines provided by the seat manufacturer. The height of the HBB seat back was adjusted such that the belt guide of the seat was at the shoulder level of the dummy. From Figure 5a the seated angle of the lumbar with respect to a vertical plane was measured to be 16° and the angle of the thigh with respect to the horizontal plane was measured to be 17° indicating that the dummy seating position is upright.

OBSERVATIONS AND RESULTS

Appendix A summarizes the results obtained from the sled tests for the Hybrid III 6-year-old in these four different HBB seats. The time histories of head and chest resultant acceleration, chest deflection and the shoulder belt loads along with HIC maximum head and knee excursion and the Nij obtained from the sled tests are provided.

The resultant head accelerations were measured with the help of a triaxial accelerometer mounted on the center of gravity of the dummy head. The time history of the head acceleration of the Hybrid III 6-year-old in the different HBB seats is shown in Figure 6. The head acceleration measured from the Evenflo Express and the Cosco Highback HBB seats were almost identical.

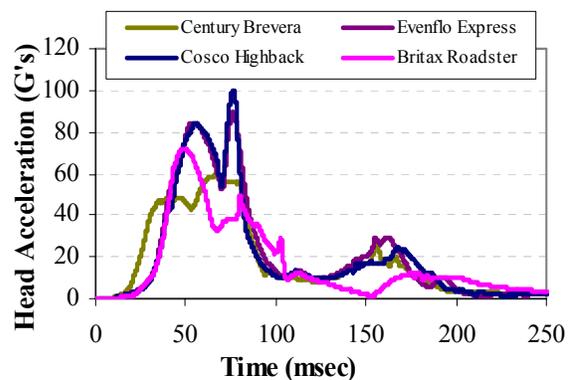


Figure 6. Resultant head acceleration with respect to time of a Hybrid III 6-year-old dummy

Head Injury Criteria (HIC), the predictor of head injury is calculated using the resultant head acceleration and the threshold limit of 1000 is considered as injurious. The HIC values are shown in Figure 7. The Evenflo Express and Cosco Highback HBB seated Hybrid III 6-year-old dummy experienced HIC values greater than 1000 whereas the Britax Roadster HBB seated dummy had the least.

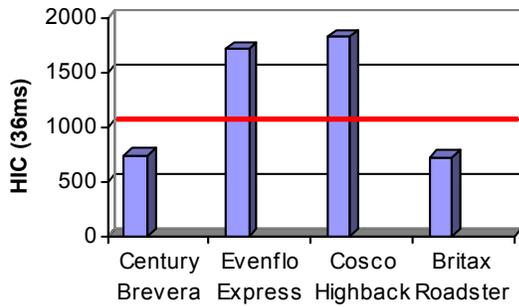


Figure 7. HIC (36ms) for the Hybrid III 6-year-old dummy

The resultant chest acceleration measured over a 3ms clip is shown in Figure 8. Of all the 4 types of HBB seats, the Century Brevera restrained Hybrid III 6-year-old dummy experienced the lowest chest accelerations.

Chest deflections of the Hybrid III 6-year-old dummy measured with respect to time is shown in Figure 9. The Century Brevera and the Britax Roadster restrained dummy experienced the highest chest deflections and their values exceeded the threshold limit of 40 mm. The other two HBB seats produced lower chest deflection measures.

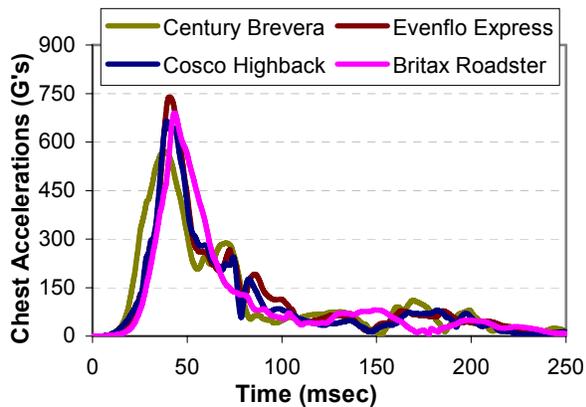


Figure 8. Resultant chest acceleration of a Hybrid III 6-year-old dummy

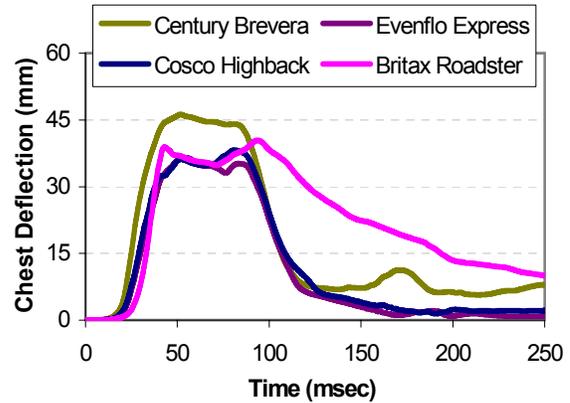


Figure 9. Chest deflections of a Hybrid III 6-year-old dummy in different HBB designs

The head and knee excursions for the 6-year-old dummy in all the different HBB seats were lower than their corresponding threshold limit and are shown in the Figures 10 and 11 respectively.

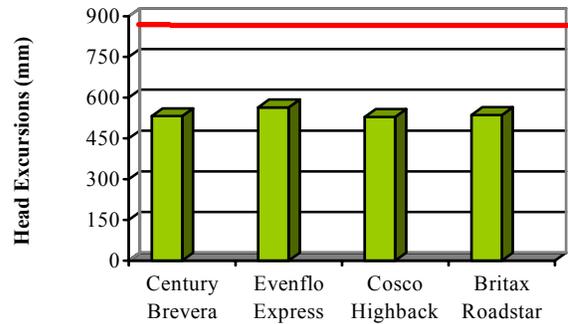


Figure 10. Head excursion of a Hybrid III 6-year-old dummy in different HBB designs

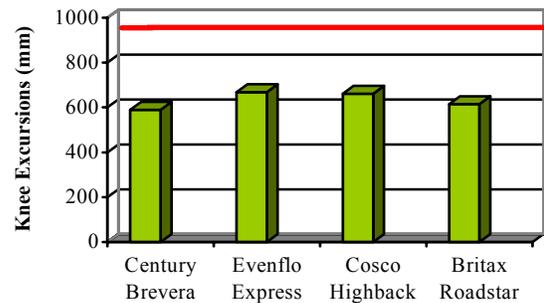


Figure 11. Knee excursion of a Hybrid III 6-year-old dummy in different HBB designs

The neck injury measure N_{ij} calculated based on the reading obtained from the neck load cell is shown in Figure 12. The N_{ij} values exceeded the threshold limit of 1 for all the HBB seats. The failure of the

neck can be observed mainly due to the higher tension values (both in flexion and extension). The Hybrid III 6-year-old dummy's neck experienced relatively low forces in compression.

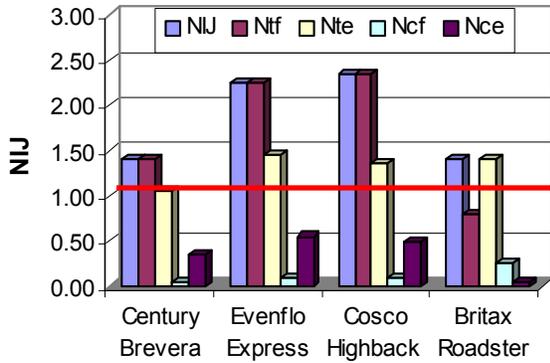


Figure 12. Neck injury measures of a Hybrid III 6-year-old dummy in different HBB designs

The shoulder belt loads experienced by the Hybrid III 6-year-old dummy during the sled tests is shown in Figure 13. It can be noted from the graph that the load distributions were almost identical in all HBB seats.

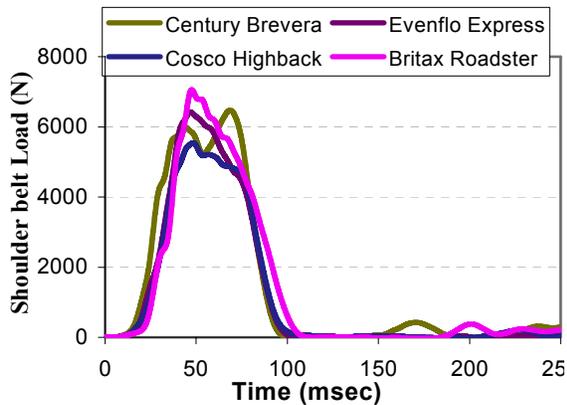


Figure 13. Shoulder belt loading of a Hybrid III 6-year-old dummy in different HBB designs

The HBB seats were examined post-test for damage. The Century Brevera was the only HBB seat with no visible damage to the seat structure. The visual inspection of the other three HBB seats revealed structural damage to all of them especially at the point of seat belt loading which varied from stress marks to breakage. The damage to the seats are shown in Figures 14a, 14b and 14c. The Evenflo Express had plastic deformation of the fins, the Cosco HBB seat broke at the lower belt guide and the Britax Roadster split at the seam.



Figure 14a. Post-test structural damage (stress marks and bending of material) of the Evenflo Express HBB seat



Figure 14b. Post-test structural damage of the Cosco Highback HBB seat



Figure 14c. Post-test structural damage of the Britax Roadster HBB seat

DISCUSSION

This study was undertaken to evaluate the performance of different high back booster seats by conducting a series of sled tests. These 56 kph sled tests were done using the Hybrid III 6-year-old child dummy in four different HBB seats and their injury

measures were compared. These tests demonstrated that there is a difference in performance among the different designs of HBB seats compounded with the established lack of biofidelity of the Hybrid III 6-year-old dummy. Injury tolerances exceeded for the Hybrid III 6-year-old dummy in two of the HBB seats for the HIC, in three of the HBB seats for chest G's and in all the four HBB seats for the N_{ij} .

In two of the HBB seats, the Evenflo Express and the Cosco Highback, which were similar design, the kinematics of the head was unusual, mainly due to the extreme hyper-flexing of the neck causing the forehead to contact the chest. This phenomenon may be attributed to the stiff spine of the Hybrid III 6-year-old dummy as demonstrated by Sherwood et. al. [10]. A sequence of the sled tests with all the four HBB seats is provided in Appendix B, for comparison. Although the hyper-flexion of the Hybrid III 6-year-old dummy neck was also observed in the other two HBB seats (Century Brevera and Britax Roadster), the extent of the flexion was not as high and the forehead of the dummy did not make contact with its chest. This calls attention to the hypothesis by the authors that the design of HBB seat has an effect on the performance of the Hybrid III 6-year-old dummy.

This high neck injury measures obtained for all the HBB seats from the sled tests are in contrary to the field data, which show that children in belt-positioning booster seats suffered no injuries to the abdomen, neck/spine/back [8]. These test results and field data highlights the need for further research to be conducted to improve the biofidelity of the Hybrid III 6-year-old dummy neck and to understand the variation in the high back booster seat designs at higher speeds.

The kinematics of the tests show that the lap belt moved up on the pelvis of the Hybrid III 6-year-old dummy restrained in the Evenflo Express and the Cosco Highback HBB seats. Due to the lack of the abdominal measuring capability in the dummy any unwarranted forces on the Hybrid III 6-year-old dummy was not captured. This reiterates the need for the development for an abdominal measuring capability in the dummy.

Chest loading is directly dependent on the belt routing over the sternum. During these sled tests the shoulder belt slipped away from the sternum, when the Hybrid III 6-year-old dummy was restrained in the Evenflo Express and the Cosco Highback HBB seats thus giving lower chest deflection measures in

these tests. Whereas the Century Brevera and the Britax roadster restrained dummy experienced higher chest deflections because of the proper routing of the shoulder belt and the correct loading of the sternum during the test. Therefore it is safe to assume that the design of the HBB seat induced belt slippage.

CONCLUSIONS

Overall the Hybrid III 6-year-old dummy responded differently while being restrained in the Evenflo Express and the Cosco Highback HBB seats when compared to the Century Brevera and the Britax Roadster HBB seats. The dummy had higher head accelerations, chest accelerations, knee excursions and higher neck tension loading in the Evenflo Express and Cosco Highback HBB seats. The higher head accelerations, chest accelerations and neck tension loads highlight the differential performance of the HBB seats due to their designs.

These tests confirm:

- a) the differential performance of the HBB seats,
- b) the need for a more biofidelic Hybrid III 6-year-old dummy, and
- c) highlights the divergence between laboratory test performance of the dummy in the HBB seats with the data from the field.

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APPENDIX A

Test results for Hybrid III 6-year-old dummy at 56 kph in different high back booster seats

Sled Velocity (kph)	Restraint Used	Test No.	HEAD		NECK				CHEST		KNEE		
			Max Res. Accel. (G)	HIC-36	Excursion (mm)	Tension (N)	Compression (N)	Flexion (N-m)	Extension (N-m)	Nij		Max Res. Accel. (3MS) (G)	Deflection (mm)
	IARV			1000	813	3096	2800	93	42	1.0	60	40	915
56	Century Brevera	21050	64	802	523	3526	35	33	23	1.6	56	46	594
		21051	60	690	541	2765	100	31	23	1.2	60	48	584
	Evenflo Express	21052	90	1674	566	5230	81	44	24	2.3	73	36	673
		21053	90	1748	561	4907	71	52	34	2.2	75	38	663
	Cosco Highback	21054	101	1815	526	5267	72	43	28	2.3	68	38	658
		21055	113	1829	531	5774	99	38	24	2.4	63	38	663
	Britax Roadster	21056	70	693	533	2150	32	28	26	1.3	67	41	602
21057		75	758	538	2234	126	38	33	1.3	66	43	625	

APPENDIX B

Test sequence of the Hybrid III 6-year-old dummy at 56 kph in different high back booster seats

Century Brevera



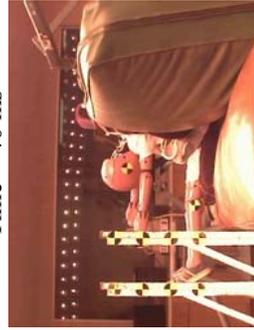
Time = 0 ms



Time = 20 ms



Time = 40 ms



Time = 60 ms

Evenflo Express



Time = 0 ms



Time = 20 ms



Time = 40 ms



Time = 60 ms

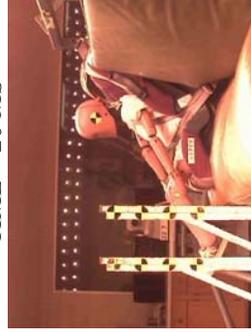
Cosco Highback



Time = 0 ms



TIME = 20 MS



TIME = 40 MS



Time = 60 ms

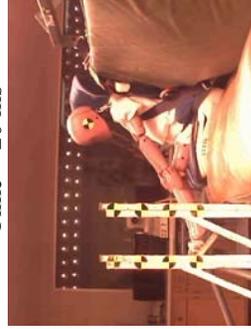
Britax Roadster



Time = 0 ms



Time = 20 ms



Time = 40 ms



Time = 60 ms

Century Brevera



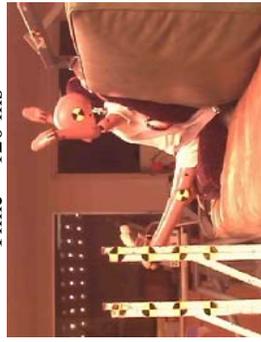
Time = 80 ms



Time = 100 ms



Time = 120 ms



Time = 135 ms

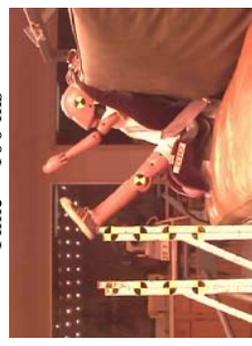
Evenflo Express



Time = 80 ms



Time = 100 ms



Time = 120 ms



Time = 135 ms

Cosco Highback



Time = 80 ms



TIME = 100 MS



TIME = 120 MS



Time = 135 ms

Britax Roadster



Time = 80 ms



Time = 100 ms



Time = 120 ms



Time = 135 ms