FRONTAL SLED TESTS COMPARING REAR AND FORWARD FACING CHILD RESTRAINTS WITH 1-3 YEAR OLD DUMMIES

C. P. Sherwood, J. R. Crandall
Center for Applied Biomechanics
University of Virginia
Charlottesville, Virginia, USA

ABSTRACT

Although most countries recommend transitioning children from rear facing (RF) to forward facing (FF) child restraints at one year of age, Swedish data suggests that RF restraints are more effective. The objective of this study was to compare RF and FF orientations in frontal sled tests. Four dummies (CRABI 12mo, Q1.5, Hybrid III 3yr, and Q3) were used to represent children from 1 to 3 years of age. Restraint systems tested included both 1) LATCH and 2) rigid ISOFIX with support leg designs. Rear facing restraints with support legs provided the best results for all injury measures, while RF restraints in general provided the lowest chest displacements and neck loads.

One of the maxims of designing restraint systems for vehicle occupants in frontal crashes is to increase the area over which forces are applied in a crash (Eppinger, 2002). For this reason, rear facing (RF) restraints theoretically provide superior safety performance for all occupants, children as well as adults, assuming equal injury tolerance for frontal and rear loading. While practical considerations make RF restraints unrealistic for adults and even older children, RF restraints are critical for the youngest children because of their relatively heavy heads and weak neck musculature. By simultaneously supporting the pelvis, torso, and head, RF restraints distribute crash forces over a much larger area than the harnesses in forward facing (FF) restraints, and reduce forces and moments on all joints, particularly the weak neck (Weber, 2000). For these reasons, most countries recommend that children under one year of age use RF restraints.

Based on epidemiologic studies indicating that RF restraints have the highest rates of effectiveness for children even beyond one year of age (Jakobsson et al., 2005), Sweden recommends that children remain in RF restraints up to the age of four. Based on the Swedish data as well as patterns of cervical spine injury in Canada and the US, the American Academy of Pediatrics made a recommendation that children in the US "should remain rear facing until reaching the maximum weight for the car safety seat as long as the top of the head is below the top of the seat back" (AAP, 2002). In recent years, the design of RF restraints has been modified to increase the maximum weight limits, allowing children to remain RF past the one year age recommended by traditional guidelines.

Researchers have examined the differences between RF and FF restraints (Planath et al., 1992; Kamren et al., 1993) but with younger or less advanced dummy designs. The objective of this project was to compare the performance of RF and FF child restraints for children past the conventional age of one year in a controlled laboratory environment. Different methods for attaching the restraint to the vehicle, such as ISOFIX (Turbell et al., 1993; Lowne et al., 1997) and upper tethers (Brown et al., 1995; Legault et al., 1997), have also been examined and this research has led to the design features of currently available child restraints. Since the method of attachment between the child restraint and the vehicle is a critical factor in restraint performance, multiple designs were included (Figure 1). Typical US designs use the LATCH (Lower Anchors and Tethers for Children) attachments including flexible lower webbing (RF and FF restraints) and a flexible upper tether for FF restraints. In Europe, several commercially available restraints are available which use a rigid ISOFIX attachment in combination with a support leg which extends to the vehicle floor. Each restraint design was tested in both rear and forward facing orientations.

Figure 1 – Pictures of a RF US design with flexible lower webbing (US1, left), and a RF European design with rigid ISOFIX connectors and support leg (EURO1, right).

METHODS

A total of 27 dummy/child restraint combinations were tested, as well as one repeat test for each dummy, for a total of 31 sled tests. All tests were conducted at a nominal 47.5 km/h impact speed with the acceleration pulse shown in Figure 2. The speed, maximum acceleration, and duration were similar to the U.S. FMVSS 213 (49 CFR 571.213) acceleration pulse. The tests were performed on a 2nd row captain's chair from a popular minivan. The seat pan was supported to create a durable, consistent seat system. The seat included lower LATCH/ISOFIX anchorages and the upper tether anchorage which was located on the rear of the seat base. For the restraints with support legs, the vehicle floor was simulated with a piece of 5mm thick steel covered with a piece of dense rubber and typical interior carpeting.

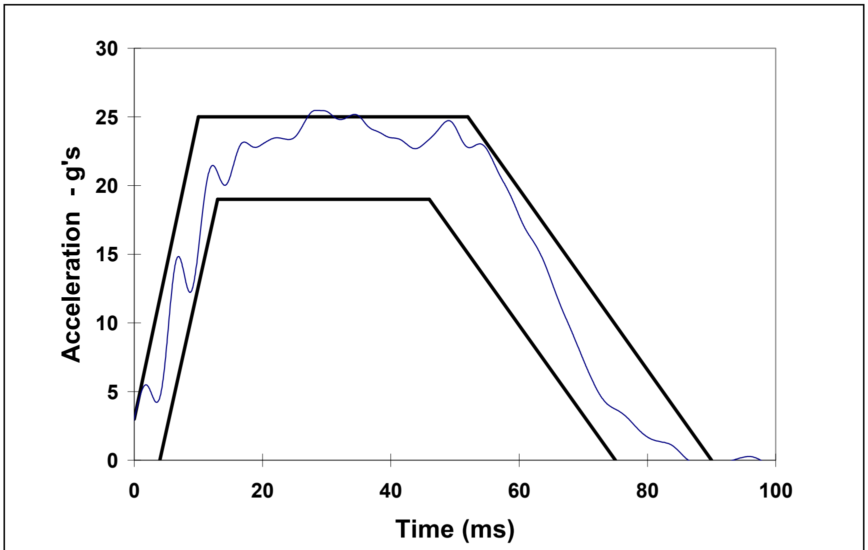

Figure 2 – Sled pulse and U.S. FMVSS 213 corridors

Four different test dummies were used in the sled tests to capture a range of dummy sizes and designs: CRABI 12 month, Q1.5 (representing an 18 month child), Hybrid III 3 year (H3), and Q3 (representing a 3 year old child). The dummies were instrumented with triaxial accelerometer arrays at the head, chest, and pelvis; load cells at the upper neck (UN), lower neck (LN, except Q1.5), and lumbar spine; chest displacement sensors (Q1.5 and H3 only). Electronic data were sampled at 10,000 Hz and were filtered per Society of Automotive Engineers (SAE) Recommended Practice J211. The tests were recorded at 1000 frames/sec with side and overhead digital video cameras. Two-dimensional kinematic analysis was performed using Motion Analysis Video Viewer (Concurrent Processing, Inc.).

Table 1 – Test matrix

	Child Restraint	CRABI	Q1.5	H3	Q3
Rear Facing	US1	X	X		
	US2	X	X		
	Euro1	X	X	X	X
	Euro2	X	X	X	X
Forward Facing	US1	X	No Data	X	X
	US3	X	X	X	X
	Euro1	X	X	X	X
	Euro3	X	X	X	X

The test matrix for all restraint conditions tested is shown in Table 1. Restraints were chosen based on consumer popularity and in order to include both convertible and FF only models. The US1 and EURO1 restraints (Figure 1) were convertible seats, and were tested in each orientation. The US2 restraint (Figure 3) was a convertible restraint and was tested rear facing. The US3 restraint was a combination seat that could be used as a FF restraint or as a booster seat, and was tested forward facing. The EURO2 was a rear facing only restraint, while the EURO3 could only be used forward facing. No US style RF restraints were tested with the 3YO dummies because the only RF restraints with higher weight limits led to unrealistic seating postures due to the height of the dummies.

Figure 3 – Pre-test photos of restraints: US2 (top left), US3 (top right), EURO2 (bottom left), EURO3 (bottom right).

Each restraint was installed by a certified child passenger safety technician according to the restraint owner's manual. Both of the RF US designs used a lower tether (to vehicle floor) to allow for better control of the restraint angle and to prevent rebound, although the user's manual for one of the restraints did not specify that the upper tether could be used in this way. These tethers, however, have been shown to have only minor effects on kinematics and injury measures in frontal crashes (Sherwood et al., 2005). The RF Euro designs had an adjustment mechanism built into the child restraints. All restraints were positioned with a thorax angle of 58 (±5) degrees, with respect to vertical. The dummy was then positioned according to US FMVSS 213 guidelines, with the exception of the internal harness tension. To match typical real-world installations, the internal harness had no slack, but was not under tension (Decina and Knoebel, 1997).

RESULTS

One restraint condition was tested twice for each dummy to gauge the repeatability of the sled tests. Each set of tests was very repeatable, with an average difference of 7.1% for HIC15, chest 3ms clip, and upper neck tension values.

The primary kinematic assessment for the tests was maximum forward excursion (Tables 2-5). For the FF restraints the forward most point on the dummy's head was measured, while the forward most point on the child restraint was measured for RF restraints. Assessing the excursions in this manner identifies the point (either on the dummy or the restraint) that would make first contact with a forward vehicle structure. The values were measured from the LATCH bars, which are 102mm forward of the U. S. FMVSS 213 Z-point origin. The FMVSS 213 excursion limit (with tether) in this LATCH coordinate system represented a value of 618 mm. For the RF restraints, the EURO2 seat had the greatest forward excursion, although this was due to its farthest forward installed position. The EURO1 restraint had the lowest forward excursion amounts.

The FF restraints all had forward excursion values of the head less than the U. S. FMVSS 213 limit of 618 mm. Comparing the excursions for the 3 year old dummies, the US1 design had the lowest levels of excursion (469 mm), while the EURO3 had the highest levels (551 mm). The differences between the restraints were largely due to the varying initial positions of the dummies. The EURO1 design had a very rigid support leg system with virtually no deflection, while the EURO2 and EURO3 designs had legs which deformed and allowed greater rotations of the restraints, particularly in the EURO3 test with the H3 dummy.

A selection of peak injury measures including HIC15, Chest 3ms clip, Chest Displacement, Upper Neck Fz (+tension), and Lower Neck My (bending moment, +flexion) are presented in Tables 2-5.

Table 2 – Maximum data values for RF US restraints

		RF US1				RF US2			
	Units	CRABI	Q1.5	H3	Q3	CRABI	Q1.5	H3	Q3
HIC15		426.5	450.3			736.7	845.6		
Chest 3ms	G's	49.6	47.3			56.1	57.5		
Chest disp	mm		7.9				9.3		
UN Fz	N	797.1	811.0			981.4	1289.8		
LN My	Nm	20.6				4.0			
Fwd excurs	mm	852	837			853	872		

Table 3 – Maximum data values for RF EURO restraints

		RF EURO1				RF EURO2			
	Units	CRABI	Q1.5	H3	Q3	CRABI	Q1.5	H3	Q3
HIC15		270.4	415.2	363.0	212.7	415.3	443.0	282.6	239.2
Chest 3ms	G's	51.2	46.6	39.6	39.5	46.9	47.5	38.4	36.0
Chest disp	mm		4.5	6.6			5.1	7.6	
UN Fz	N	614.7	783.9	1952.2	893.5	1005.9	771.3	1336.2	967.3
LN My	Nm	6.4		0.0	0.0	2.0		0.0	0.0
Fwd excurs	mm	747	789	838	797	868	878	899	899

Table 4 – Maximum data values for FF US restraints

		FF US1				FF US3			
	Units	CRABI	Q1.5	H3	Q3	CRABI	Q1.5	H3	Q3
HIC15		474.2		660.9	1010.0	413.9	589.3	375.9	576.4
Chest 3ms	G's	47.5		60.3	62.4	56.0	56.6	54.1	51.0
Chest disp	mm			30.9			23.0	19.0	
UN Fz	N	2316.3		2759.5	4068.4	2020.3	2086.1	1676.7	2443.9
LN My	Nm	60.1		203.4*	120.5*	54.6		99.1	113.2
Fwd excurs	mm	367		496	441	469	558	538	532

Table 5 – Maximum data values for FF EURO restraints

		FF EURO1				FF EURO3			
	Units	CRABI	Q1.5	H3	Q3	CRABI	Q1.5	H3	Q3
HIC15		451.8	539.5	537.9	541.6	504.9	948.9	320.3	575.3
Chest 3ms	G's	57.2	46.4	52.6	43.1	45.5	43.9	40.9	41.2
Chest disp	mm		17.2	14.4			25.0	22.1	
UN Fz	N	1854.1	1601.2	1861.8	2056.2	1810.9	2400.5	1434.0	2098.0
LN My	Nm	60.1*		113.1	109.0	60.2*		113.4	111.3
Fwd excurs	mm	367	441	532	471	404	453	601	500

Note: * denotes a value exceeding the measurement capability of the load cell

Figure 4 presents the injury measure data averaged for each restraint condition (RF US, RF EURO, FF US, FF EURO). To normalize the data for the different dummy sizes, the percentage of the Injury Assessment Reference Value (%IARV) was calculated for each injury measure by dividing the peak value by each dummy's IARV, shown in Table 6 (Eppinger et al., 2000). The IARVs for the Q1.5 were determined by using the same scaling techniques employed for the other dummy sizes (Melvin, 1995; Mertz et al., 1997). The use of IARVs for comparison in these study were used to normalize data across dummies of multiple ages rather than provide an indication of the injury potential since the National Highway Traffic Safety Administration (NHTSA) has decided against including the IARVs in the U. S. FMVSS 213 standard due to concerns about dummy biofidelity (Code of Federal Regulations).

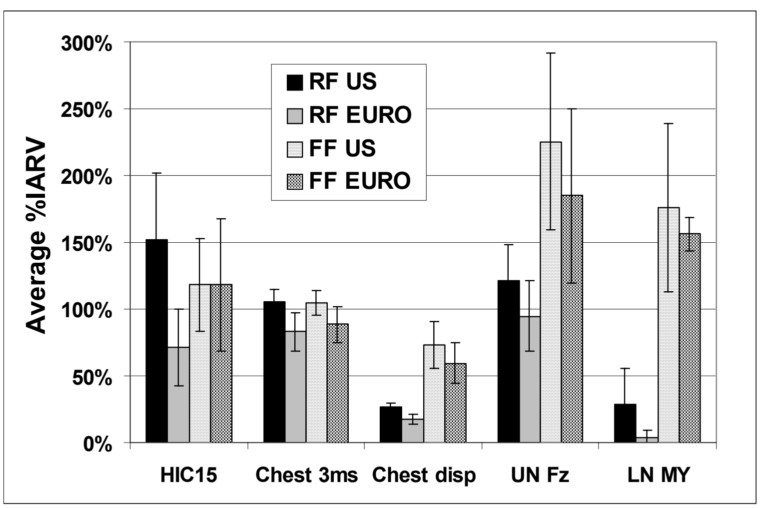

Figure 4 – Graph of averaged percentage of IARV values.

Table 6 – Injury Assessment Reference Values

Injury Measure	CRABI	Q1.5	H3/Q3
HIC15	390	420	570
Chest 3ms clip (g's)	50	50	55
Chest Displacement (mm)	30	32	34
Upper Neck Tension (N)	780	820	1430
Lower Neck Flex Moment (Nm)	43	45	68

To test the null hypothesis that there were no differences among the four restraint types, two-sided t-tests were performed to compare the data in Figure 4, at a significance level of $\alpha=0.05$. The results are presented in Table 7.

Table 7 – T-test values comparing differences among restraint types

		HIC15	Chest 3ms	Chest disp	UN Fz	LN My
RF US	RF EURO	**0.005**	**0.021**	**0.042**	0.401	**0.047**
RF US	FF US	0.221	0.956	**0.039**	**0.001**	**0.006**
RF US	FF EURO	0.298	0.053	**0.047**	**0.009**	**0.000**
RF EURO	FF US	**0.013**	**0.004**	**0.001**	**0.000**	**0.000**
RF EURO	FF EURO	**0.036**	0.424	**0.002**	**0.003**	**0.000**
FF US	FF EURO	0.998	**0.018**	0.334	0.258	0.470

The RF EURO restraints resulted in the lowest risk of injury for all injury measures, and the differences were statistically significant for all but 2 comparisons. While questions remain about the relevance of some of the IARV for injury prediction, all RF EURO results were below the IARV. The RF US restraints had the highest normalized HIC15 value (152%) and Chest 3ms clip value (105%), although these measures were only significantly different between the RF US and RF EURO restraints. For all other injury measures, however, the RF US restraints had values similar to the RF EURO with both restraint types exhibiting much lower, and significantly different, values than either of the FF restraint types.

The relative difference between the two FF restraint types (0% – 11%) was much less than the difference between the RF designs (21% – 89%). The FF EURO restraints had normalized injury values that were lower than or equal to the FF US restraints, although only the chest 3ms clip value had statistically significant differences.

The best RF restraints (RF EURO) clearly outperformed the best FF restraints (FF EURO) when comparing injury measures. There were statistically significant differences at all injury measures except chest 3ms clip. The RF EURO restraints resulted in a reduction in normalized injury measures ranging from 6% – 98%, with an average reduction of 53%.

DISCUSSION

The RF EURO restraints provided the lowest injury risk for all injury measures. One of the RF Euro designs also had the lowest amount of forward excursion, suggesting that these types of systems can accommodate larger children without requiring greater space than current RF designs. These seats also had some of the lowest variations in data, illustrating that eliminating the vehicle seat cushion as a factor can provide a more repeatable and predictable environment. While RF US restraints generally had some of the higher head and chest accelerations, one of the RF US designs had substantially lower values than the other design. This likely illustrates the variability inherent in systems dependent on the vehicle seat cushion. Chest displacement, upper neck tension, and lower neck flexion moments, however, were all substantially lower with both RF restraint types, compared to the FF restraints.

FF EURO designs resulted in lower or equal injury risk across all injury measures when compared to FF US designs, although the differences were not generally statistically significant. The amount of forward head excursion varied significantly among different restraints, and was predominantly determined by the initial position of the dummy's head relative to the vehicle which was greatest in the FF EURO designs.

A critical factor in child restraint performance is the presence of misuse in these restraint systems. The relative rates of misuse in different restraint systems is difficult to quantify, except in field studies after the restraints are available to the public. It should be noted, however, that the two restraint designs (US, EURO) had substantially different installation procedures. The EURO designs had rigid ISOFIX connectors and support legs, and thus did not require any webbing components which needed to be tensioned. The subjective assessment of the authors was that the EURO designs were easier to install. If the EURO designs were to be shown to result in less frequent misuse, their safety benefits would be magnified even further.

Current child dummies do not provide the means to measure abdominal loading. The US1 restraint had thigh straps which were routed much higher than any of the other designs, actually crossing the abdomen rather than across the tops of the thighs. This design defies the accepted practice of positioning harnesses such that the strongest portions of the body (i.e., pelvis rather than abdomen) are loaded. Despite the lack of abdominal instrumentation, it is clearly inadvisable to design restraints in such a way that may improve performance in certain body regions with injury assessment measures at the expense of other regions not currently instrumented in test dummies.

The current U. S. FMVSS 213 standard does not allow child restraints to be tested with support legs that contact the vehicle floor. Restraints with support legs can only be certified for use in the US if they can pass the 213 standard without the leg, but most restraint designs include the leg as an integral component, and thus the current regulation in effect precludes these designs from being used in the US. The superior performance of the RF EURO designs, combined with the real world benefit inherent with keeping children in rear facing restraints to older ages suggests that the NHTSA consider modifying the standard to allow these types of restraints.

LIMITATIONS

These tests were only performed in the pure frontal crash mode at the regulatory crash conditions (i.e., nominally 48 km/h). Furthermore, this testing was performed on one vehicle seat which had been rigidized for testing purposes. Other vehicle seats may result in different results, particularly in RF restraint systems in which the vehicle cushion is a critical component of performance.

Head acceleration measurements in RF restraints are likely significantly affected by the initial position of the head with respect to child restraint back. Since children are often not seated in the standard testing position, a more robust testing technique would incorporate dummies with adjustable neck designs. As is already available in some adult dummy designs, an adjustable lower neck bracket allows the neck angle, and thus the fore-aft position of the head, to be controlled. The neck could be adjusted for consistent initial positions and would also allow for the dummies to be tested with an initial gap between the head and the child restraint to measure the ability of the restraints to protect the head when not in ideal positions.

All dummy designs suffer from a lack of biofidelity. Several high neck flexion moments were measured in the FF restraints, and it is likely that these values overestimate the true bending moments due to the rigidity of the dummy thoracic spine (Sherwood et al., 2003).

CONCLUSIONS

For multiple dummy ages and designs, RF restraints using rigid ISOFIX connectors and support legs provided the lowest injury measures at the head, chest, and neck. This data provides additional evidence that RF restraints can provide the greatest safety potential for children past 1 year of age. The NHTSA should consider modifying current compliance standards to allow these types of restraint designs to be used in the US.

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