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Rear-Facing Child Restraint Systems in Rear Impact Sled Tests

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Abstract

This study examines the performance of rear-facing child restraint systems (RF CRS) in moderate severity rear impact sled tests. The study also investigates the effects of RF CRS features on CRS kinematics and anthropomorphic test device (ATD) injury metrics in this scenario. Twelve tests were conducted at a moderate severity rear impact sled pulse (approximately 28.2 km/h and 18.4 g). Four models of RF CRS were tested in the rear outboard positions of a sedan seat. The CRABI 12-month-old and Hybrid III 3-year-old ATDs were instrumented with head and chest accelerometers, head angular rate sensors, six-axis upper neck load cells, and a chest linear potentiometer (3-year-old only). The effects of carry handle position, occupant size, presence of anti-rebound bar, Swedish style tethering, and lower anchor vs. seat belt installation were investigated. Data were also compared to pediatric injury assessment reference values (IARV). Head Injury Criterion (HIC15) values ranged from 9.6 to 89.2. Chest resultant accelerations (3 ms duration) ranged from 21.3 to 39.9 g. Neck loads and head contact against seat structures varied depending on the features of the CRS. The results indicate that RF CRS mitigate crash forces with a variety of methods in the moderate severity rear impacts performed in this series. This study provides experimental data to address this crash scenario, which are currently lacking in the literature. These conclusions are supported by epidemiological and field data which indicate RF CRS provide good protection for young occupants.

Introduction

Every year in the United States, motor vehicle crashes kill over 1,000 children and injure an estimated 167,000 children [1]. Child restraint systems (CRS) are effective at preventing death and reducing injury, especially rear-facing (RF) CRS [2]. In frontal and side impacts, RF CRS transfer crash forces through the child's back while keeping the head, neck, and spine aligned [3]. In a rear impact, the RF CRS typically rotates toward the rear of the vehicle, the five-point harness becomes the primary loading surface for the occupant, and the head might contact the vehicle seat back or vehicle head restraint [4].

Rear impacts tend to be less common [5] and less deadly for children than other types of crashes [6, 7]. Due to the rarity of serious injury from rear impacts, epidemiological data specifically for RF children in rear impacts are scarce. Of 3,670 children involved in crashes recorded in the Swedish Volvo accident database, only 10% were rear impact scenarios [2]. Of these rear impact crashes, no rear-facing children suffered injuries greater than 1 on the Abbreviated Injury Scale (AIS) [2]. Langwieder et al. also report no injuries over Maximum AIS (MAIS) 1 for children in RF infant seats in rear impacts, although the sample size of this study was small (42 infants total, 9 of whom were in rear impacts) [8].

Limited experimental literature addresses RF CRS in rear impacts. One study by Williams et al. investigated the response of the 6-month-old CRABI anthropomorphic test device (ATD) in RF CRS in high severity rear impact sled tests [4]. The authors report rotation of the RF CRS toward the rear of the vehicle and frequent head strikes against the vehicle seat back. The Head Injury Criterion over a 15 ms period (HIC15) ranged from 64 to 347. The authors conclude that these levels are injurious based on a HIC15 injury threshold of 85. However, this threshold was scaled from that of an adult male using a method published by Melvin [9]. More recent literature estimates the injury threshold of a 6-month-old occupant is much higher at 377 [10]. Additionally, the Williams et al. tests were run at pulses considered highly severe for rear impacts (48.2 km/h and 23.6 g) [4]. A more moderate sled pulse near 32.0 km/h is recommended for rear impact CRS testing in Regulation No. 44 by the United Nations Economic Commission for Europe (UNECE R44) [11]. This moderate speed represents a larger majority of rear impacts [5]. Previous experimental tests near the UNECE R44 pulse produce low HIC36 values (HIC calculated over a 36 ms period) for RF CRS which are free to rotate during rear impacts. For example, Manary et al. report HIC36 values of 22-29 for untethered RF CRS and 106-143 for tethered RF CRS in the CRABI 12-month-old ATD [12].

A few design features exist for controlling the kinematics of RF CRS. Swedish style tethering links the top of the RF CRS to the floor of the vehicle or front row seat structure. Anti-rebound bars can also reduce the rotation of RF CRS through interaction with the vehicle seat back. Some RF-only CRS allow the carry handle to be placed in the upright (or "carry") position during travel. The upright carry handle contacts the vehicle seat back during rearward rotation, and may help prevent the child's head from contacting the seat back or head restraint. Sled data for RF CRS with these features are scarce, especially for the rear impact condition.

Epidemiological data show that RF CRS are safe for young infants and toddlers considering all crash types [2, 3, 13]. However, more information is needed about the performance of RF CRS in the rear impact crash mode. This study aims to define the performance of RF CRS in moderate severity rear impacts, and to investigate whether certain CRS features may mitigate or exacerbate injury risk in this scenario.

TABLE 1 Test matrix

Test	CRS	ATD	Installation description
1	Inf-A	CRABI 12MO	LA, with base, handle stowed
2	Inf-A	CRABI 12MO	LA, with base, handle upright
3	Inf -A	CRABI 12MO	Seat belt, no base, handle stowed
4	Inf -B	CRABI 12MO	LA, with base, handle stowed
5	Inf -B	CRABI 12MO	LA, with base, handle upright
6	Inf -B	CRABI 12MO	LA, with base, with anti-rebound bar
7	Conv-C	CRABI 12MO	LA, no tether
8	Conv -C	HIII 3YO	LA, no tether
9	Conv -C	HIII 3YO	LA, with Swedish tether
10	Conv -D	CRABI 12MO	LA, no tether
11	Conv -D	HIII 3YO	LA, no tether
12	Conv -D	HIII 3YO	Seat belt, no tether

Methods

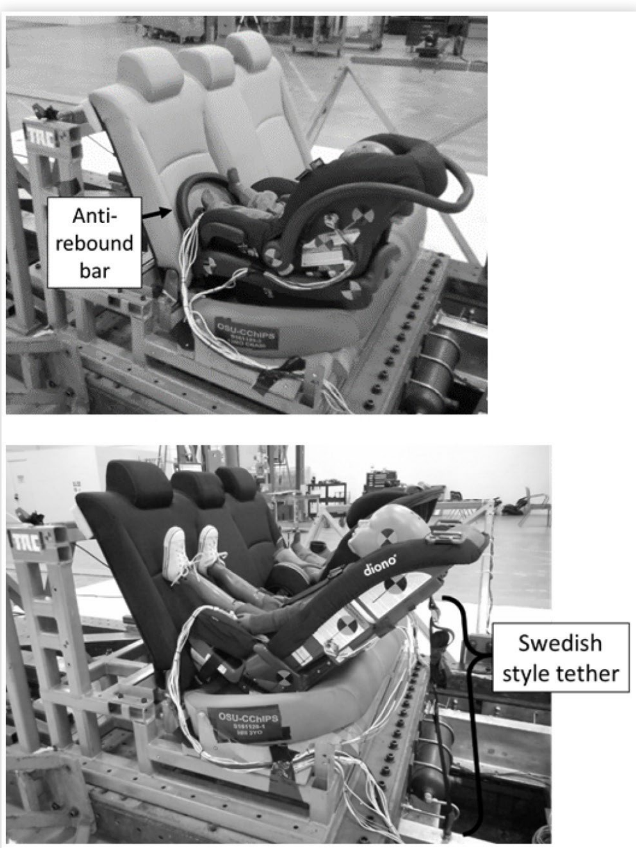
A series of twelve tests was conducted with a moderate severity rear impact sled pulse on a Hydraulic-controlled, Gas-Energized (HyGE) acceleration sled (Transportation Research Center Inc., East Liberty, Ohio). The target pulse was that described by UNECE R44 for dynamic testing of CRS in rear impacts [11]. The actual pulse was slightly below the prescribed parameters (see Figure 2). Four different models of CRS from the current US market were tested. CRS models include two infant or "RF-only" CRS: Evenflo Embrace (Inf-A) and Maxi Cosi Mico AP/Mico Max 30 (Inf-B); as well as two convertible CRS in RF mode: Diono Radian (Conv-C), and Safety 1st Continuum (Conv-D). The CRS were replaced after each impact.

The CRS were installed in the rear outboard positions of a recent model year sedan seat. Vehicle seat cushions, seat backs, and sled fixture were obtained from the manufacturer. The seat backs included integrated head restraints. The seat cushions and backs, including the head restraints, were replaced after each test. A fixed, 3-point seat belt geometry was used for tests denoted as seat belt installations (Tests #3 and #12, Table 1). A new length of seat belt webbing was used for each of these tests. All other tests used the lower anchors (LA) available on the seat fixture. No deformation of the LA was observed throughout the series. A new LA strap was used for each test.

Two ATDs were used: the CRABI 12-month-old (CRABI 12MO) was tested in all four CRS models, and the Hybrid III 3-year-old (HIII 3YO) was tested in the convertible CRS models only. The ATDs were within the occupant height and weight limits of each CRS in RF mode. Each CRS was installed with the seat belt or lower anchor strap tightened to a tension between 53.5 N and 67.0 N, as prescribed by US federal testing procedures for CRS [14]. The tension was verified with a hand-held tension gauge (Burroughs Tool and Equipment, Kalamazoo, Michigan). Each CRS was tested in several different configurations. The main categories of comparison for this study are: carry handle position (upright in carry position vs. stowed behind the occupant's head), occupant size (CRABI 12MO vs. HIII 3YO), anti-rotation devices (anti-rebound bar vs. none, Swedish style tether vs. untethered), and installation method (base vs. no base, seat belt vs. lower anchors (LA)). The test matrix is shown in Table 1.

All CRS were installed according to manufacturers' instructions, with the exception of the upright carry handle position in Test 2. The upright position is typically not allowed by the manufacturer, but permission was given to test in this setting for research purposes.

FIGURE 1 Exemplar photos of sled setup for Inf-B with anti-rebound bar (Test #7; top image) and Conv-C with Swedish style tether (Test #9, bottom image).



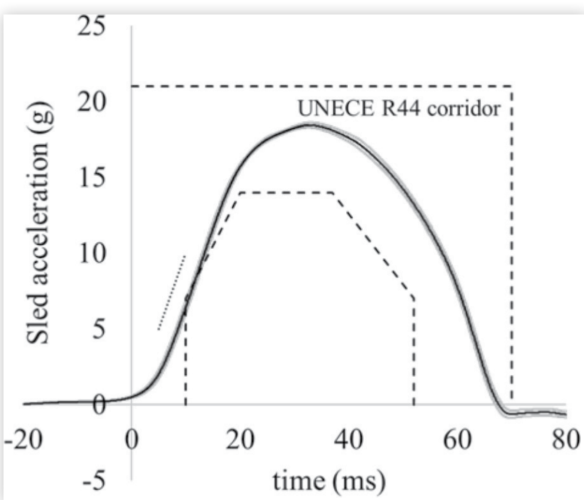
The ATDs were instrumented with head and T4 chest accelerometers (Endevco/Meggitt Sensing Systems, Irvine, CA), head angular rate sensors (Diversified Technical Systems (DTS), Seal Beach, CA), six-axis upper neck load cells (Denton, now Humanetics Innovative Solutions, Plymouth, MI), and a chest linear potentiometer in the HIII 3YO only (Servo Instrument Corporation, Baraboo, WI). All signals were processed per SAE J211 guidelines [15]. The combined axial force and moment criterion, N_{ij}, was calculated from the upper neck load cell data. Intercept values reported in Mertz et al. were used for Nij calculations [10]. CRS kinematics were recorded with high speed video at 1,000 fps. Injury metrics were compared between the different setup categories of interest and also compared to current pediatric injury assessment reference values (IARVs) from Mertz et al. and US regulatory limits [10, 16].

Results

Sled Pulse

The average sled acceleration peak was 18.4 ± 0.1g, with speeds of 28.2 ± 0.2 km/h. The average sled pulse ± one standard deviation is shown in Figure 2 with the target corridor overlaid [11]. The peak acceleration of the current series falls within the prescribed region, but the initial rise of the pulse does not meet the standard, nor does the average peak speed fall within the guidelines of 32.0 + 2 - 0 km/h. These factors limit the ability to compare these data to UNECE regulatory tests. However, comparisons can be made between trials within this series because of the high consistency of the pulse within the series.

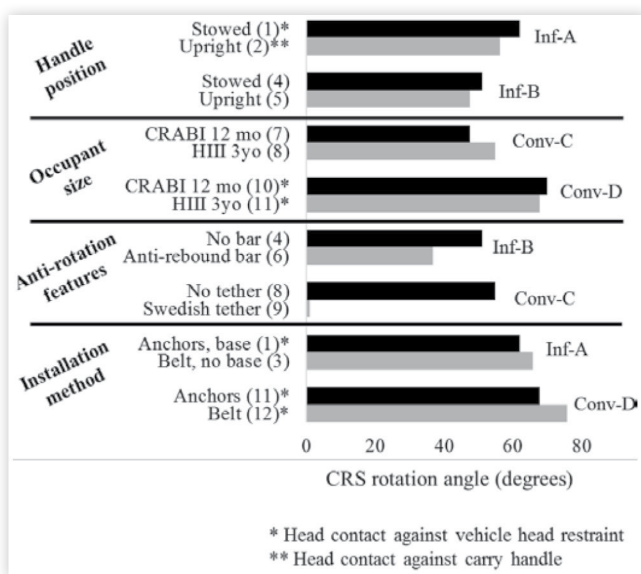
FIGURE 2 Average sled pulse (black) shown with ± one standard deviation (gray). The target UNECE R44 corridor is shown with the dashed lines [11]. Acceleration sled pulses are required to fall above the dotted line from (5 ms, 5 g) to (10 ms, 10 g). The sled pulse in the current series does not meet these requirements, although the peak acceleration is within the prescribed range.



Rotation of CRS

Figure 3 shows the change in angle between each CRS's initial position and its maximum angle of rotation toward the rear of the vehicle (counter-clockwise as depicted in Figure 1). The most dramatic reduction in CRS rotation occurred with the Swedish tether installation. The tethered CRS rotated only 0.9°, compared to a control test without the tether which rotated 55.0°. Neither of these tests resulted in head contact at the sled pulse used. The presence of an anti-rebound bar also reduced CRS rotation compared to a similar test without the anti-rebound bar. Neither of these tests resulted in head contact at the sled pulse used. Upright carry handles on the infant CRSs resulted in slightly less rotation compared to similar tests with stowed handles, although the difference was less pronounced than the tether or anti-rebound bars. In Inf-A, head contact occurred when the handle was both stowed (contact against vehicle head restraint) and when the handle was upright (head contact against the underside of the handle). Head contact did not occur for either handle position for Inf-B. Seat belt installations exhibited slightly more rotation than lower anchor installations. Occupant size did not show a consistent effect on CRS rotation: the larger HIII 3YO produced more rotation than the CRABI 12MO in Conv-C, but less rotation than the CRABI 12MO in Conv-D. Neither ATD experienced head contact in Conv-C, but the heads of both ATDs contacted the vehicle seat back in Conv-D. Statistical significance of kinematic differences could not be calculated due to the sample size of one per condition.

FIGURE 3 The difference between the initial angle of each CRS and its angle of peak rotation is plotted. Test numbers are displayed in parenthesis on the x-axis and correspond to the setup conditions in the test matrix in Table 1. The twelve tests are sorted and displayed according to category, with tests 1, 4, 8, and 11 appearing multiple times as controls for two different categories of interest. The Swedish tether allowed only 0.9° of rearward rotation.



Head Y Angular Velocity

The head Y angular velocities are plotted in Figure 4. The most drastic difference in angular velocity was exhibited by Inf-A installed with the base using lower anchors (1254°/s) vs. without the base using a seat belt (3086°/s). Using a Swedish style tether also dramatically increased head Y angular velocity. The anti-rebound bar did not appear to increase head Y angular velocity as much as the tether. Conv-D exhibited higher head Y angular velocities for the HIII 3YO compared to the CRABI 12MO, but this effect was not nearly as great for the same pair of occupants in Conv-C. Carry handle position had minimal effects on head Y angular velocity.

Head Injury Criterion (HIC)

HIC15 values are shown in Figure 5. The maximum HIC15 values across all tests were 89.2 for the CRABI 12MO and 50.8 for the HIII 3YO. In all cases with head contact, the peak HIC15 occurred during the rotational phase before head contact. The highest HIC15 value of 89.2 resulted from the installation of Inf-A using a seat belt without the base. The Swedish style tether resulted in a HIC15 value of 50.8 compared to a similar control test without the tether which produced a HIC15 of 17.0. HIC36 values are reported in Table A1 in the appendix.

Neck Combined Axial Force and Moment (N_{ij})

Data from key channels of the upper neck load cells are reported in Table A2 in the appendix. The peak values for each N_{ij} (compression-flexion (CF), compression-extension (CE), tension-flexion (TF), and tension-extension (TE)) are shown in Table 2.

FIGURE 4 The peak head Y angular velocity for each test is plotted next to similar tests in each category.

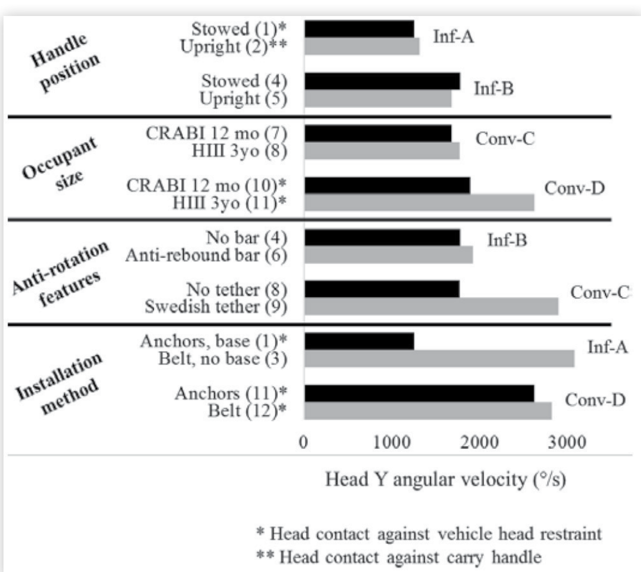
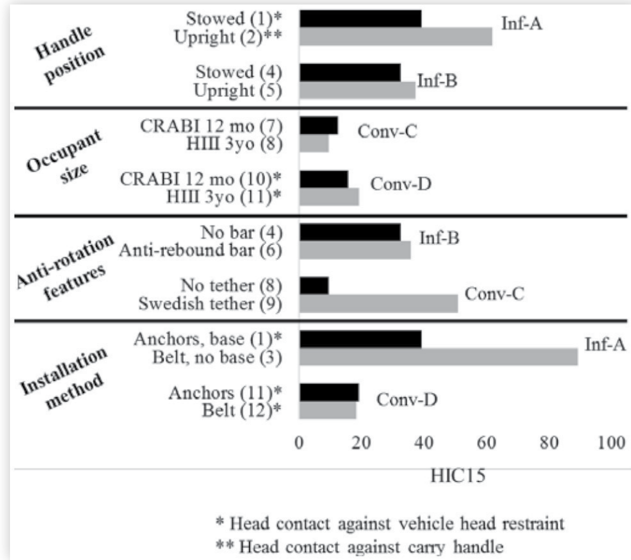


FIGURE 5 HIC15 for each test is plotted next to similar tests in each category.



The HIII 3YO in Conv-D (tests 11 and 12) returned some of the highest overall N_{ij} values, which occurred in the compression-flexion condition during head contact against the head restraint. The CRABI 12MO in the same CRS experienced smaller compression-flexion loading during head contact, possibly because of its lesser mass and more glancing manner of head contact at the end of its rotational arc. In Inf-A, the peak N_{ij} occurred in tension-extension during the rotational phase, although the N_{CF} during head contact was similar in magnitude for the stowed carry handle condition. The tethered test resulted in higher N_{ij} values in all conditions, especially N_{TE}, compared to a similar untethered test. The tethered test also returned higher neck loads in pure tension, compression, extension, flexion, and shear compared to the untethered test (Table A2). The anti-rebound bar produced higher N_{CE} values than the test without the anti-rebound bar, which did not experience the N_{CE} condition at all. Pure neck forces (tension, compression, and shear) were slightly higher in the test with the anti-rebound bar, but neck moments (flexion and extension) were lower (Table A2).

Thorax

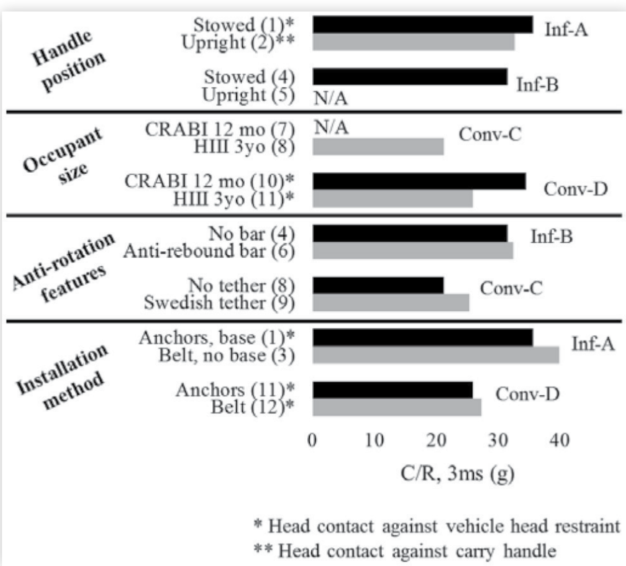
The peak chest resultant acceleration over a 3ms duration (C/R) are summarized in Figure 6. The x-axis chest accelerometer malfunctioned during tests 5 and 7, so those data were omitted. The C/R ranged from 31.6 to 39.9 g for the CRABI 12MO. The C/R for the HIII 3YO ranged from 21.3 to 27.3 g across all tests. C/R values are shown in Figure A1 in the appendix. Comparisons of C/R across CRS configurations show no remarkable patterns. Chest deflection for the HIII 3YO ranged from 2.0 to 4.8 mm across all tests (see Appendix Table A1). The greatest chest deflection occurred in the Swedish tether test (4.8 mm; Test 9).

TABLE 2 The maximum neck combined axial force and moment (Nij) values are displayed for each pair of tests in each category. The peak value across all four loading conditions is shaded in gray.

		Test Description (Test Number)	Peak N_{CF}	Peak N_{CE}	Peak N_{TF}	Peak N_{TE}
Handle position	Inf-A	Stowed (1)*	0.52	0	0.43	0.60
		Upright (2)**	0.47	0	0.31	0.88
	Inf-B	Stowed (4)	0.48	0	0.24	0.68
		Upright (5)	0.51	0	0.24	0.63
Occupant size	Conv-C	CRABI 12mo (7)	0.34	0.14	0.23	0.19
		HIII 3yo (8)	0.20	0.22	0.22	0.17
	Conv-D	CRABI 12mo (10)*	0.21	0.31	0.34	0.31
		HIII 3yo (11)*	0.96	0.22	0.27	0.74
Anti-rotation devices	Inf-B	No bar (4)	0.48	0	0.24	0.68
		Anti-rebound bar (6)	0.48	0.53	0.29	0.58
	Conv-C	No tether (8)	0.20	0.22	0.22	0.17
		Swedish tether (9)	0.22	0.35	0.45	0.60
Installation method	Inf-A	Anchors, with base (1)*	0.52	0	0.43	0.60
		Belt, no base (3)	0.20	0.36	0.42	0.70
	Conv-D	Anchors (11)*	0.96	0.22	0.27	0.74
		Belt (12)*	0.84	0.30	0.29	0.69

* Head contact against vehicle head restraint
** Head contact against carry handle

FIGURE 6 The peak chest resultant acceleration over a 3 ms duration (C/R) for each test is plotted next to similar tests in each category.



Discussion

Comparison of CRS features

Upright carry handles had a relatively minor effect in reducing the rotation of the two infant CRS models tested. The slight reduction in rotation resulted in small increases in HIC15 and neck tension, although other neck channels and N_{ij} calculations did not show clear trends. Head contact occurred for both carry handle positions in Inf-A, and for neither carry handle position in Inf-B. This suggests that other design factors within each CRS affect head contact outcomes more than carry handle positions for these specific CRS models at the sled pulse utilized.

The anti-rebound bar reduced CRS rotation more than the upright carry handle in Inf-B. However, head contact did not occur in any of the Inf-B tests, so it cannot be determined if the reduction in CRS rotation was truly beneficial in reducing the risk of head contact at this sled pulse. The anti-rebound bar had minimal effects on head rotation, HIC15, and chest resultant acceleration. The anti-rebound bar slightly increased neck tension, compression, and shear values, but its presence slightly decreased neck extension and flexion moments. From these limited data, it appears that the anti-rebound bar was effective in reducing CRS rotation without substantially increasing any of the examined injury metrics. These results should be further confirmed with a larger variety of CRS models, vehicle seats, sled pulses, and more repetitions to determine statistical significance.

The Swedish style tether prevented virtually all rotation of the CRS. However, this abrupt restriction of rotation of the harnessed thorax resulted in greater head rotation rate, HIC15, neck tension, neck extension moment, neck shear, and peak N_{ij} (N_{TE}) compared to a similar non-tethered test. The tethered test also slightly increased C/R, neck compression, neck flexion moment, and N_{CF}, N_{CE}, and N_{TF} values. Ultimately, however, all injury metrics were below the IARVs reported in Mertz et al. for both the tethered and untethered tests [10]. These results agree with similar tethered and untethered tests performed by Manary et al. [12]. However, neck injuries are not a common problem for RF occupants, even in regions where Swedish style tethering is common [2]. Similarly, children in the US and other countries which do not typically tether RF CRS are also rarely injured in RF CRS [3, 13]. Thus, while RF tethers do not appear to directly cause injuries, they might not be necessary for adequate protection of the occupant in rear impacts. The Swedish style tether may be more effective at reducing injury metrics in other types of impacts [17]. The tether can also help control the installation recline angle of RF CRS for small infants [17].

The larger HIII 3YO occupant fared similarly to the smaller CRABI 12MO in Conv-C, where head contact did not occur for either occupant at this sled pulse. In Conv-D, head contact occurred for both ATDs. With head contact, the neck loads and N_{ij} of the HIII 3YO were substantially larger than those of the CRABI 12MO. The HIII 3YO's head contacted the vehicle head restraint earlier than the CRABI 12MO due to its larger profile. The HIII 3YO also has a larger torso mass which loaded the neck more severely than the CRABI 12MO's smaller torso mass. These results suggest that reducing RF CRS rotation may be more vital for larger, older children, who may suffer more serious consequences from head contact with the vehicle head restraint or seat back.

The outcomes of a seat belt vs. lower anchor installation of convertible Conv-D were similar. However, the installation of infant Inf-A with and without the base produced substantial differences in response. When installed with the base, Inf-A rotated in an arc about its fulcrum point near the seat bight. The infant seat installed without the base did not have a well-defined fulcrum about which the CRS could rotate. The seat translated linearly toward the rear of the vehicle until its interference against the vehicle seat back slowed its translation. Then, the head of the ATD pulled away from the seat and appeared to pull it into its rotational phase. These CRS kinematics resulted in a high head Y angular velocity and high HIC15. Despite different head kinematics, the neck loads and N_{ij} values were similar with and without the base at this sled pulse.

The Swedish tether greatly altered the CRS kinematics and ATD injury metrics. The upright carry handles and anti-rebound bar had less obvious effects. However, all the CRS in this study were properly and tightly installed. RF CRS which are not tightly installed may be free to rotate more quickly and result in more forceful head contact against the vehicle seat back or other structures of the vehicle interior. In these cases, anti-rotation features may provide more valuable protection to the occupant by reducing excessive CRS rotation and preventing potentially injurious head contact. A properly tensioned five-point harness also plays an important role in controlling head excursion. A loose harness may increase the risk of head contact against vehicle seat structures. Misuse of a Swedish style tether, such as a loose attachment or attachment to an improper anchor point, may also affect its performance. High CRS misuse rates in the field warrant further study of the role of these features under a variety of misuse conditions.

Comparison to IARVs

Of all twelve tests conducted at the moderate sled pulse, none resulted in injury criteria exceeding those defined in Mertz et al. or Federal Motor Vehicle Safety Standard (FMVSS) No. 213 [10, 16]. HIC15 values ranged from 9.6 to 89.2, which are low compared to HIC15 IARVs of 389 and 568 for the CRABI 12MO and HIII 3YO, respectively [10]. HIC36 values were also low (see appendix Table A1), and were similar to those reported in previous work using a similar sled pulse and UNECE R44 test bench [12]. Williams et al. investigated a more severe rear impact pulse and report HIC15 values from 64 to 347 [4]. As expected, the higher sled pulse appears to produce greater risk of injury. Williams et al. report higher HIC15 values for tests with head contact against the vehicle seat back [4], but it is unclear whether the peak HIC15 values occurred during head contact or the preceding rotational phase. In the current study, HIC15 peaked during the rotational phase of the CRS.

In the current study, the C/R ranged from 31.6 to 39.9 g for the CRABI 12MO, which is below the IARV of 87 g, and also below the FMVSS 213 limit of 60 g [10, 16]. Similarly, the C/R for the HIII 3YO ranged from 21.3 to 27.3 g, which is below the IARV of 92 g and the FMVSS 213 limit of 60 g [10, 16]. The maximum recorded chest deflection of 4.8 mm is below the IARV of 28 mm [10]. Additionally, the N_{ij} values were all below 1. A threshold of 1 is considered a 5% risk of injury [10]. Comparisons to IARVs should be considered with respect to the moderate sled pulse used, as higher sled pulses are expected to produce higher injury metrics.

Limitations

There are several important limitations in this study. RF CRS responses were examined in only one type of vehicle seat. Head restraints in the rear row of the modern vehicle fleet exhibit a large variety of shapes, sizes, and rigidity. FMVSS 202a has recently been expanded to require that all rear seating positions with outboard head restraints be compliant to a number of static and dynamic testing standards as of September 2011 [18]. As a result, manufacturers have developed several new and innovative head restraint designs over the last several years. In addition to meeting the standards which protect adult and forward-facing occupants, manufacturers should also consider how RF occupants may be affected by head restraint design decisions. Additionally, this study included only four CRS models, which does not fully encompass the large variety of products on the market. Only one test was conducted per condition, so statistical significance of observed differences in outcomes could not be calculated, and the repeatability of the setup could not be evaluated. The rise of the sled pulse used in this study was slightly outside of the target UNECE R44 corridor, and this may have mitigated the severity of the injury metrics recorded. Valid comparisons of kinematics and kinetics can be made across test conditions within this series, but comparison to other literature must be conducted with caution. Other limitations include the lack of accurate tools for pediatric injury data analyses. It is unclear whether the biofidelity of the pediatric ATDs is sufficient to provide realistic injury metrics. Additionally, pediatric IARVs have been determined mostly from scaling practices, with very few supporting cadaveric studies [10]. This is especially true for neck injury criteria.

Summary/Conclusions

- Head contact against seat structures was influenced by CRS design.
- The Swedish style tether reduced CRS rotation but increased neck loads. The anti-rebound bar reduced CRS rotation without substantial increase in other injury metrics.
- For the moderate severity rear impacts performed, HIC15, chest resultant acceleration, and neck loads (including N_{ij}) were all below IARVs in Mertz et al. and federal testing thresholds in FMVSS 213 [10, 16].

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Definitions/Abbreviations

AIS - Abbreviated Injury Scale

ATD - Anthropomorphic Test Device

CE - Compression Extension

CF - Compression Flexion

C/R - Chest Resultant (acceleration)

CRABI 12MO - CRABI (Child Restraint Air Bag Interaction) 12-Month-Old

CRS - Child Restraint System
FMVSS - Federal Motor Vehicle Safety Standard
HIC - Head Injury Criterion
HIII 3YO - Hybrid III 3-year-old
HyGE - Hydraulic-controlled, Gas-Energized
IARV - Injury Assessment Reference Value
LA - Lower Anchors
MAIS - Maximum Abbreviated Injury Scale
N_{ij} - Neck Combined Axial Force and Moment
NHTSA - National Highway Traffic Safety Administration
RF - Rear Facing
UNECE - United Nations Economic Commission for Europe

Appendix

TABLE A1 All kinematic data and injury metrics

Test	CRS	ATD	Installation description	Head contact?	CRS rotation (degrees)	Head Y angular velocity (degrees/s)	HIC15	HIC36	Chest resultant acceleration,3 ms duration (C/R) (g)	Chest deflection X (mm)
1	CRS-A	CRABI 12MO	LA, with base, carry handle stowed	Vehicle head restraint	62.0	1254	39.2	39.3	35.7	N/A
2	CRS-A	CRABI 12MO	LA, with base, carry handle upright	Carry handle	56.3	1316	61.9	61.9	32.8	N/A
3	CRS-A	CRABI 12MO	Seat belt, no base, carry handle stowed	None	65.8	3086	89.2	133.5	39.9	N/A
4	CRS-B	CRABI 12MO	LA, with base, carry handle stowed	None	51.2	1783	32.7	32.7	31.6	N/A
5	CRS-B	CRABI 12MO	LA, with base, carry handle upright	None	47.5	1685	37.3	37.9	NA	N/A
6	CRS-B	CRABI 12MO	LA, with base, with anti-rebound bar	None	36.7	1925	35.7	37.3	32.5	N/A
7	CRS-C	CRABI 12MO	LA, no tether	None	47.6	1686	12.6	14.6	NA	N/A
8	CRS-C	HIII 3YO	LA, no tether	None	55.0	1771	9.6	17.2	21.3	2.0
9	CRS-C	HIII 3YO	LA, with Swedish tether	None	0.9	2901	50.9	108.2	25.4	4.8
10	CRS-D	CRABI 12MO	LA, no tether	Vehicle head restraint	70.0	1896	15.7	19.6	34.5	N/A
11	CRS-D	HIII 3YO	LA, no tether	Vehicle head restraint	67.8	2624	19.1	26.6	25.9	3.1
12	CRS-D	HIII 3YO	Seat belt, no tether	Vehicle head restraint	75.8	2821	18.3	25.5	27.3	2.3

TABLE A2 Relevant metrics from the upper neck load cells

Test	CRS	ATD	Installation description	Shear, +Fx (N)	Shear, -Fx (N)	Tension, +Fz (N)	Compression, -Fz (N)	Extension moment, -My (Nm)	Flexion moment, +My (Nm)
1	CRS-A	CRABI 12MO	LA, with base, carry handle stowed	87	-153	743	-637	-7.5	8.2
2	CRS-A	CRABI 12MO	LA, with base, carry handle upright	68	-245	954	-545	-7.6	7.9
3	CRS-A	CRABI 12MO	Seat belt, no base, carry handle stowed	3	-287	737	-300	-8.4	6.4
4	CRS-B	CRABI 12MO	LA, with base, carry handle stowed	82	-166	422	-695	-8.7	9.6
5	CRS-B	CRABI 12MO	LA, with base, carry handle upright	76	-170	565	-724	-6.2	9.9
6	CRS-B	CRABI 12MO	LA, with base, with anti-rebound bar	145	-196	470	-741	-6.2	6.8
7	CRS-C	CRABI 12MO	LA, no tether	18	-187	329	-442	-2.7	4.4
8	CRS-C	HIII 3YO	LA, no tether	23	-149	403	-374	-4.0	8.6
9	CRS-C	HIII 3YO	LA, with Swedish tether	31	-643	1036	-435	-10.9	9.2
10	CRS-D	CRABI 12MO	LA, no tether	255	-124	397	-363	-3.2	9.6
11	CRS-D	HIII 3YO	LA, no tether	70	-316	605	-912	-14.1	35.8
12	CRS-D	HIII 3YO	Seat belt, no tether	137	-315	542	-877	-14.0	30.2

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