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Effects of head restraint (HR) interference on child restraint system (CRS) performance in frontal and far-side impacts

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ABSTRACT – Forward-facing child restraint systems (FF CRS) and high-back boosters often contact the vehicle seat head restraint (HR) when installed, creating a gap between the back surface of the CRS and the vehicle seat. The effects of HR interference on dynamic CRS performance are not well documented. The objective of this study is to quantify the effects of HR interference for FF CRS and high-back boosters in frontal and far-side impacts. Production vehicle seats with prominent, removeable HRs were attached to a sled buck. One FF CRS and two booster models were tested with the HR in place (causing interference) and with the HR removed (no interference). A variety of installation methods were examined for the FF CRS. A total of twenty-four tests were run. In frontal impacts, HR interference produced small but consistent increases in frontal head excursion and HIC36. Head excursions were more directly related to the more forward initial position rather than kinematic differences caused by HR interference. In far-side impacts, HR interference did not have consistent effects on injury metrics. Overall, these results suggest only slight benefits of removing the HR in frontal impacts specifically. Caregivers should use caution if removing a vehicle HR to ensure that the current child occupant and all future vehicle occupants have adequate head support available in case of a rear impact.

KEYWORDS – Child restraint system, CRS, booster, high-back booster, installation, head restraint, incompatible, interference

INTRODUCTION

Forward-facing child restraint systems (FF CRS) and high-back boosters are often tall enough to contact the vehicle seat head restraint (HR) when installed. This interaction can create a gap between the back surface of the CRS and the vehicle seat (i.e., "HR interference"). Previous compatibility studies estimate that HR interference occurs in roughly 33% to 50% of FF CRS installations and 28% of high-back booster installations (Hu et al. 2015, Bing et al. 2015, Bing et al. 2018). HR interference can cause the CRS to sit pitched at unintended angles during normal travel and reduce the area of contact between the back surface of the CRS and the vehicle seat back.

Manufacturers' guidelines vary on whether or not HR interference is acceptable during CRS use. Some CRS manufacturers expressly prohibit any gaps behind their products. Others prohibit the gap only in certain modes (such as booster mode), while others do not mention HR interference or provide explicit instructions about it. Similarly, some vehicle manufacturers allow the HR to be adjusted or removed during CRS installation if it improves the fit of a CRS, while others do not allow removal of the HR (Donaldson and Rose 2023). Sometimes the vehicle HR is integrated into the seat and cannot be adjusted or removed.

The effects of HR interference on dynamic CRS performance are not well documented. The regulatory bench used in Federal Motor Vehicle Safety Standards (FMVSS) No. 213 does not have a HR so interference does not occur during regulatory testing. We hypothesize that several different factors of HR interference might affect the dynamic performance of FF CRS and boosters. Gaps between the back of the CRS and the vehicle seat might introduce instability. This factor might be especially important in far-side lateral impacts by changing how the CRS interacts

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with the vehicle seat back during the lateral translation and/or rotation phases. Evidence of instability is suggested by high top tether loads in previous testing with a gap behind a FF CRS (Mansfield et al. 2021). Consequences of HR interference during near-side impacts are hypothesized to be less significant due to the close proximity of the door structure and side-curtain airbags which limit the translation and rotation of the CRS compared to far-side impacts. We further hypothesize that the initial position of the CRS caused by HR interference might create differences in excursion outcomes, especially in frontal impacts when the occupant's head is initially positioned forward of its ideal position compared to an installation without HR interference.

The long-term objective of this work is to support the safe use of CRS in realistic vehicle environments. The objective of this study is to quantify the effects of HR interference for FF CRS and high-back boosters in frontal and far-side impacts.

METHODS

Equipment

Two CRS were selected for this study: CRS 1/Booster 1 was a three-in-one restraint (capable of forward-facing harness, high-back booster, or backless booster modes) which was tested in FF harness mode (referred to as "CRS 1") and high-back booster mode (referred to as "Booster 1"). The CRS manufacturer requires the use of the recline stand for occupants less than 18.1 kg (40 lbs), so the recline stand was used for all FF harness tests with the Hybrid III 3yo or Q3s (see Table 1), which are both less than 18.1 kg. The upright position was used for all booster tests with the Hybrid III 6yo, which is greater than 18.1 kg. Booster 2 was a combination restraint (capable of forward-facing harness or high-back booster modes) which was tested in high-back booster mode only (referred to as "Booster 2"). Booster 2 did not have adjustable recline settings and was thus in its nominal upright position for all tests.

Seats from a recent model year minivan (third row, left side two-thirds seats) were attached to a sled buck using the seat manufacturer's sled template fixture. The vehicle seat fixture was oriented fully forward for the frontal impacts and then rotated 80° from frontal (i.e., 10° forward of pure lateral) for the far-side impacts. All tests were conducted in the outboard position, which was integrated into the center position (Figure 1). The vehicle seat cushion angle was 10.8° from horizontal and the seat back angle was measured from the HR post at 21.2° from vertical.

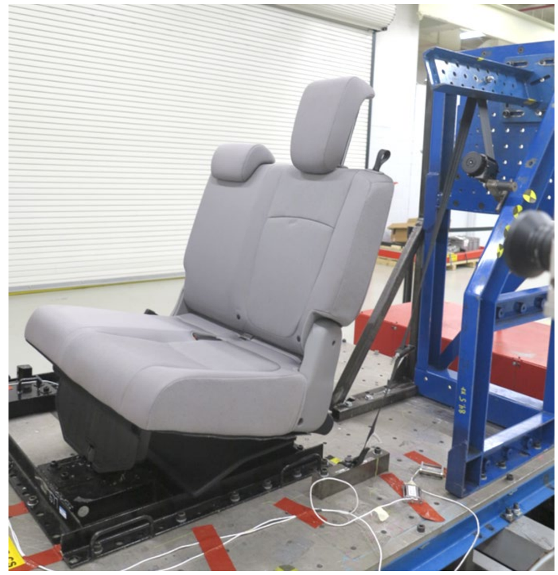

Figure 1: Third row minivan seat. All tests were conducted in the outboard position. The outboard head restraint is shown in its raised position, which was used to produce HR interference. The head restraint was removed for the No HR interference conditions.

The outboard HR was set to its raised position to produce HR interference for both CRS/booster models used in this study (Figure 1). The HR was removed to create a condition with no HR interference. The vehicle manufacturer does not allow CRS installation with the HR in the fully lowered position, so that position was not tested. The HR in the adjacent (center) position was removed for the far-side lateral tests to simplify the test environment and eliminate any potential contact between the outboard CRS/occupant and the adjacent HR. The full vehicle seat assembly (frame and cushions), seat belt, buckle, retractor, and CRS/booster were replaced after every test.

For frontal impacts, the Hybrid III 3-year-old was positioned in CRS 1 and the Hybrid III 6-year-old was positioned in Boosters 1 and 2. For far-side impacts, the Q3s was positioned in CRS 1 and the Hybrid III 6-year-old was positioned Boosters 1 and 2. CRS 1 was installed using a variety of methods (belt or lower anchors (LA), with or without top tether). Boosters were installed without the lower anchors or top tether. Twenty-four total tests were run. The full test matrix is displayed in Table 1.

Table 1: Test matrix

Test #	Head restraint	Impact direction	CRS	ATD	Installation method
1	**No HR interference** *(i.e., vehicle HR removed)*	Frontal	FF CRS 1	3yo Hybrid III	Belt, with tether
2					Belt, no tether
3					LA, with tether
4					LA, no tether
5			High-Back Booster 1	6yo Hybrid III	No LATCH
6			High-Back Booster 2		
7		Lateral (far-side)	FF CRS 1	Q3s	Belt, with tether
8					Belt, no tether
9					LA, with tether
10					LA, no tether
11			High-Back Booster 1	6yo Hybrid III	No LATCH
12			High-Back Booster 2		
13	**With HR interference** *(i.e., vehicle HR present)*	Frontal	FF CRS 1	3yo Hybrid III	Belt, with tether
14					Belt, no tether
15					LA, with tether
16					LA, no tether
17			High-Back Booster 1	6yo Hybrid III	No LATCH
18			High-Back Booster 2		
19		Lateral (far-side)	FF CRS 1	Q3s	Belt, with tether
20					Belt, no tether
21					LA, with tether
22					LA, no tether
23			High-Back Booster 1	6yo Hybrid III	No LATCH
24			High-Back Booster 2		

Test Procedures

Testing procedures from FMVSS 213 were used to guide the installation of each CRS/booster and positioning of the ATDs (NHTSA 2023). For FF harness installations, the LA or seat belt was tensioned to 53.4-66.7 N (12-15 lbs) and verified with a three-prong clip on tension gauge (Gauge Model BT3329S, Pinto Products Inc./Bosch Automotive Service Solutions, Owatonna, MN, USA). The upper end of this tension range was targeted to reduce variation. Tension values for each installation can be found in Appendix Table A1. The top tether, when used, was tensioned to 44.5-62.3 N (10-14 lbs) and verified with the three-prong tension gauge (Appendix Table A1). The ATD was positioned by aligning the ATD's posterior surface with the seating surface, holding the arms and legs forward, and pushing the torso and pelvis rearward until flush contact was made with the CRS/booster seat back. The arms and legs were settled directly downward. For harness mode, the sensor cable bundle was routed along the lateral aspect of the ATD's right thigh, underneath the pelvis portion of the harness, and off the front right edge of the CRS seating surface (Figure 2, left). The harness was tensioned to 17.8-22.2 N (4.0-5.0 lbs) and verified with the three-prong tension gauge on the spans of webbing between the main buckle and the chest clip on both the left and right sides of the harness. The retainer clip (chest clip) was positioned as per the manufacturer's instructions with the top of the clip aligned with the ATD's armpits. For booster mode, the bundle of sensor cables was positioned along the lateral aspect of the right thigh, underneath the lap belt, and off the front right edge of the booster seating surface (Figure 2, right). The lap and shoulder belt were tensioned to 20.0-22.2 N (4.5-5.0 lbs) and verified with the three-prong tension gauge. The seat belt retractor was not locked for booster tests (i.e., emergency locking mode was used).

Figure 2: Pre-test positions of the 3yo Hybrid III in FF harness CRS 1 (left) and Hybrid III 6yo in Booster 1 (right).

Pre-test angle measurements (Appendix Table A1 and Figure A1) were collected with a digital inclinometer from two locations on each CRS: the cup holder and side ledge for CRS 1/Booster 1, and the cup holder and armrest for Booster 2. The angle of the ATD sternum and each thigh was also measured with a digital inclinometer. After positioning the ATD, the belt and LA tensions were re-checked and re-adjusted if they had drifted away from the target range. The final tensions were recorded. Matched pair, two-tailed t-tests were conducted to explore any significant differences in setup measurements between “with HR” vs. “no HR” conditions, across each set of six matched pair tests within each impact direction. Alpha level was set a priori to 0.05. All statistical analyses were conducted on JMP Pro, Version 16.0.0 (SAS Institute, Inc.).

The frontal pulse target was the FMVSS 213 frontal pulse (NHTSA 2023). The far-side pulse target was based off the FMVSS 213a side impact pulse scaled to 35 kph. This far-side pulse was selected to match previous work (Mansfield et al. 2021) which was conducted before the FMVSS 213a Final Rule was released (NHTSA 2023). The actual frontal and side sled pulses are shown in Figure 3 and summarized in Table 2. For frontal impacts, the actual accelerations were near the upper end of the FMVSS 213 limits and the velocities were slightly above FMVSS 213 upper limit. For side impacts, the actual accelerations were within the FMVSS 213a limits while the velocities were beyond the upper limit, as intended. It should be noted that the FMVSS 213a pulse was designed with respect to the side impact seat assembly (SISA) and simulated door assembly for near-side impacts (NHTSA 2023), while the current series utilized a rigidly attached seat in a far-side impact setup.

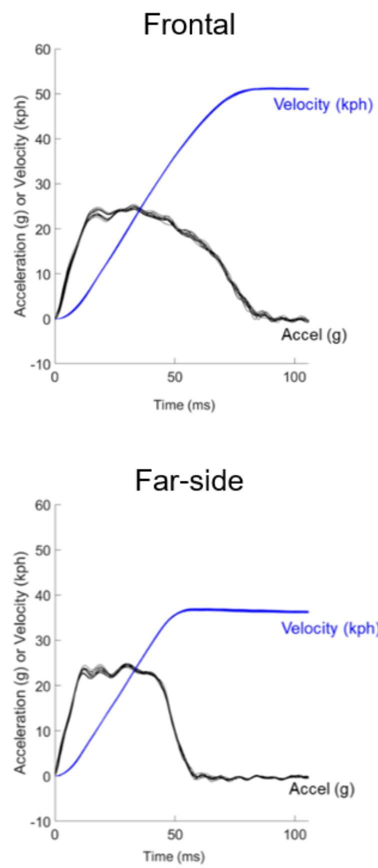

Figure 3: Sled pulses

Maximum accelerations and velocities for each pulse are summarized in Table 2 and compared to FVMSS 213 and FMVSS 213a limits.

Table 2: Actual sled pulse maximum accelerations and velocities (average ± standard deviation) compared to FMVSS 213 and FMVSS 213a limits.

	Frontal impacts		Side impacts	
	Current series, actual	**FMVSS 213 limits**	**Current series, actual**	**FMVSS 213a limits**
Acceleration (g)	24.8 ± 0.3	19.0-25.0	24.6 ± 0.2	18.5-25.5
Velocity (kph)	51.4 ± 0.9	44.8-48.0	36.8 ± 0.1	30.7-31.9

Data Collection and Data Analysis

High speed video was recorded at 1,000 fps from five camera views (left lateral, left oblique, right lateral, right oblique, and overhead). Video data were analyzed using TEMA motion tracking software (v3.8, Image Systems Motion Analysis). Each video was calibrated by scaling the coordinate system using two points of a known distance apart which was measured by hand. For frontal impacts, the diameter of a 2 inch (5.08 cm) camera target on the CRS armrest was used (Appendix Figure B1). This calibration point was slightly nearer to the camera than the points of interest which were tracked (i.e., the head CG camera target on the lateral aspect of the ATD's head, which was not visible in the initial camera frame). Therefore, some error in the magnitude of the frontal excursions might have been introduced from this out-of-plane calibration method, which is a limitation of this study. All frontal tests were calibrated using the same method so that results can be compared relative to each other within this series. For side impacts, the measured distance between the centers of two camera targets on the ATDs' forehead and chin areas were used (7.6 cm for the Hybrid III 6yo and 8.9 cm for the Q3s, Appendix Figures B2 and B3). These calibration points were within the primary plane of motion being tracked (i.e., the frontal aspect of the ATD's head). Some inaccuracy might have been introduced when the ATDs rotated out of this initial plane of motion during the impacts (i.e., nearer or farther from the camera lens).

To quantify head position and excursion in frontal impacts, a visible reference point on the sled buck near the seat bight was selected. The initial position of the CRS in the x-direction was quantified by calculating the distance between the front edge of the CRS and the sled buck reference point. The initial position of the head was determined by the distance in the x-direction between the reference point and the tip of the ATD's nose, which was the only portion of the head visible in the initial frame due to the presence of CRS/booster side wings. Matched pair, two-tailed t-tests were conducted to determine significant differences in initial CRS and nose position due to HR presence. After the event began, the head CG camera target was tracked in the x-direction with respect to the reference point on the sled buck. Head excursion in lateral impacts was quantified by tracking the location of a camera target on the forehead of the ATD from initial position through maximum lateral excursion in the YZ plane.

ATD data were collected at 20,000 Hz and processed according to SAE J-211 protocol (SAE 2022). The primary injury metrics of interest were head excursion, head displacement, HIC36, and chest resultant acceleration over 3 ms clip. Upper neck tensile force (Fz) was also recorded. Matched pair, two-tailed t-tests were conducted for each of these primary injury metrics to determine the significance of HR interference (comparing "with HR" vs. "no HR" conditions) across each of the six pairs of tests within each crash direction. Additionally, standard least squares analyses were conducted for each of the primary injury metrics using the following predictors for FF CRS tests: HR interference (with HR or no HR), installation method (belt or LA), and top tether (with top tether or no top tether). For booster tests, the following predictors were used in standard least squares analyses: HR interference (with HR or no HR), and booster model (Booster 1 or Booster 2). Frontal impacts were analyzed separately from far-side impacts. Alpha level was set a priori to 0.05. All statistical analyses were conducted on JMP Pro, Version 16.0.0 (SAS Institute, Inc.).

RESULTS

Frontal Impacts

Presence of the HR affected the pre-test angle of the CRS and boosters. The CRS/boosters installed with HR interference (orange) were significantly more reclined compared to CRS/boosters installed without HR interference (blue), shown in Figure 4 (p=0.0251, matched pair t-test). HR interference caused an additional recline of 1.6° on average for boosters and additional 1.4° on average for FF harness CRS 1.

Additional pre-test measurements are reported in Appendix Table A1. The pre-test angle at the second CRS reference point was significantly different between tests with vs. without HR (p=0.0229, matched pair t-test). There were no significant differences between ATD right or left thigh angles (p=0.2373 and p=0.3243, respectively) or ATD sternum angle (p=0.2509). Differences in CRS angles should have corresponded with differences in ATD body region angles. This lack of significance might be due to ATD positioning inconsistencies and/or small sample size. Pre-test belt tensions were exactly the same across matched pair tests (measured to the nearest 0.5 lb with the hand-held tension gauge). Top tether tensions and harness tensions were also not significantly different across matched pairs (p=0.2048 and 0.3910, respectively). These analyses indicate good consistency in installation techniques across all tests. The sample size was too small to statistically compare LA tension levels.

Camera frames from pre-test initial positions and maximum excursions are shown for exemplar conditions for CRS 1 (Figure 5) and Booster 2 (Figure 6).

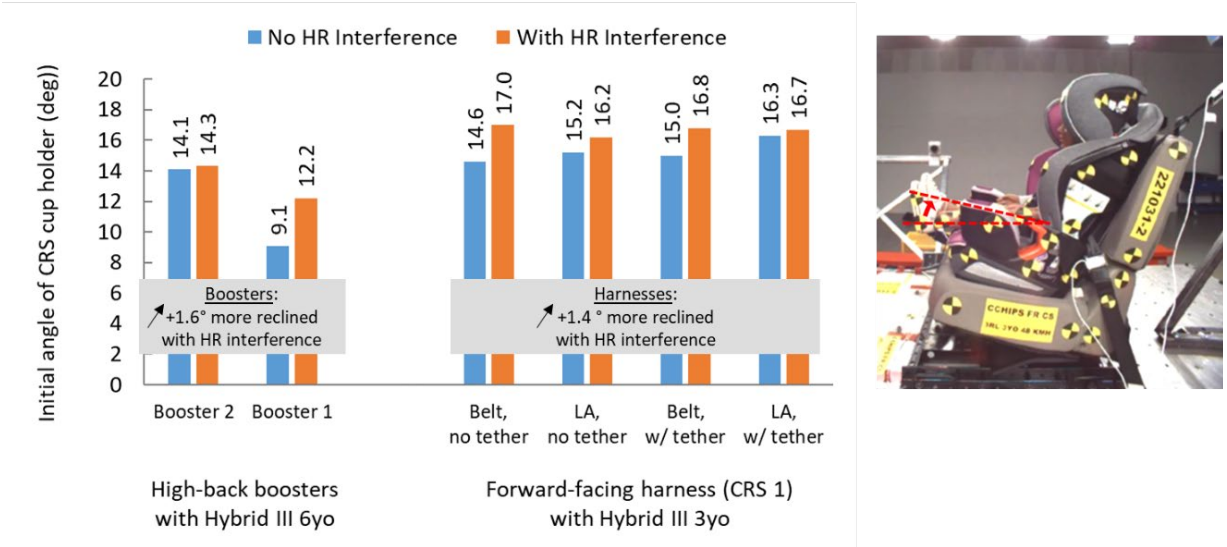

Figure 4: Initial angles of boosters and CRS for frontal impacts. The rectangular overlays summarize the average differences between No HR interference vs. With HR interference for each type of restraint.

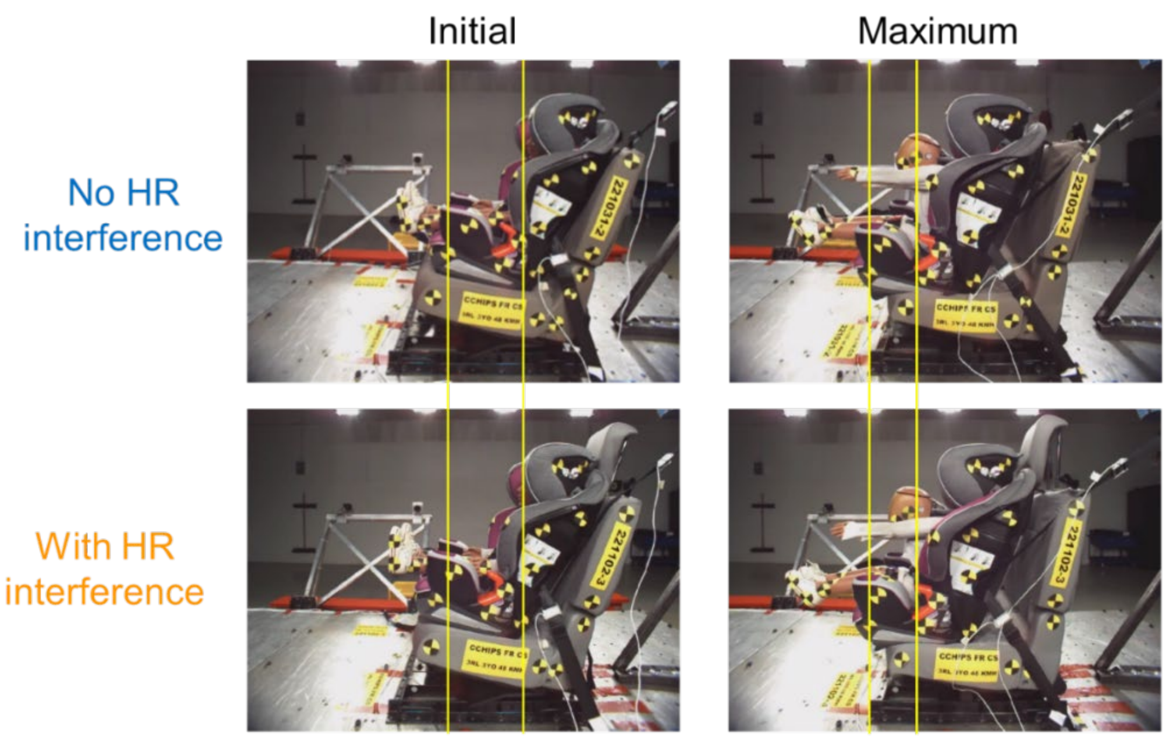

Figure 5: Initial positions and maximum excursions for FF harness CRS 1, seat belt installation, with tether, Hybrid III 3yo (Tests #1 and #13).

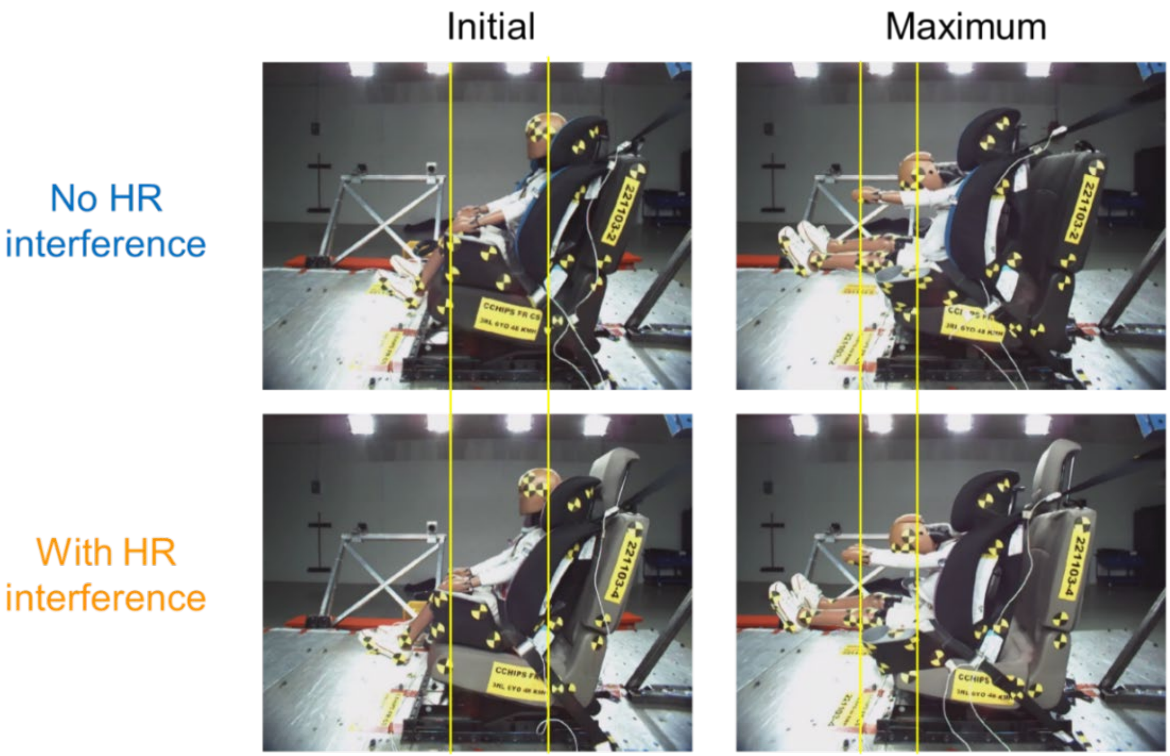

Figure 6: Initial positions and maximum excursions for Booster 2, Hybrid III 6yo (Tests #6 and #18).

TEMA software was used to measure the horizontal distance between the sled buck reference point and two pre-test points of interest: the front edge of the CRS/booster and the tip of the ATD's nose. For the frontal impacts, the front edge of the armrest of the CRS/booster was positioned further forward on the vehicle seat by an average of 4.5 cm when HR interference was present compared to tests without the HR (p=0.0002, matched pair t-test; see also Appendix Figure C1). The ATD's nose was positioned further forward on the vehicle seat by an average of 1.4 cm when HR interference was present compared to tests without the HR (p=0.0462, matched pair t-test; see also Appendix Figure C2). The front edge of the armrest was forward to a greater degree than the nose (4.5 cm vs. 1.4 cm, respectively) because the angle of the CRS/boosters were more reclined with HR. The initial nose position is denoted by the light shaded sections of the bars in Figure 7. When adding in the head displacement from initial position during the event (dark shaded bars stacked on top, Figure 7), we observe that the total head excursion (total heights of both bars) was greater with HR interference compared to without HR interference (p=0.0027, matched pair t-test). The total excursion was about 4.0 cm greater on average for boosters (13.3%) and 2.2 cm greater on average for the FF harness CRS (7.0%).

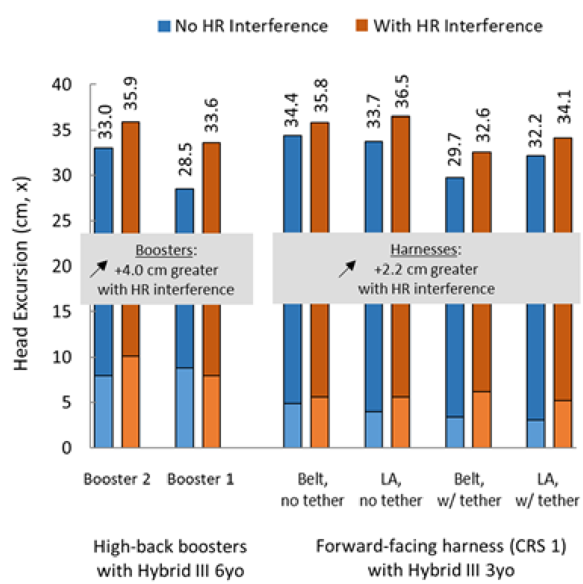

Figure 7: Total head excursion from bench reference point, displayed with head initial position (light bars) and displacement (dark bars) measured in the x-direction for frontal impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

Examining the x-displacements of the head relative to initial position shows few clear trends with respect to HR condition (Figure 8). That is, the head displaced approximately the same amount in the x-direction during the event regardless of its initial starting position or presence of HR (p=0.1939, matched pair t-test). Booster 1 was the only exception, where HR interference resulted in approximately 30% more head displacement compared to the corresponding test without HR interference. The initial position of the ATD's head/nose in the Booster 1 tests does not follow the same trend as the other pairs (Appendix Figure C2) suggesting that an ATD positioning inconsistency may have occurred during this setup.

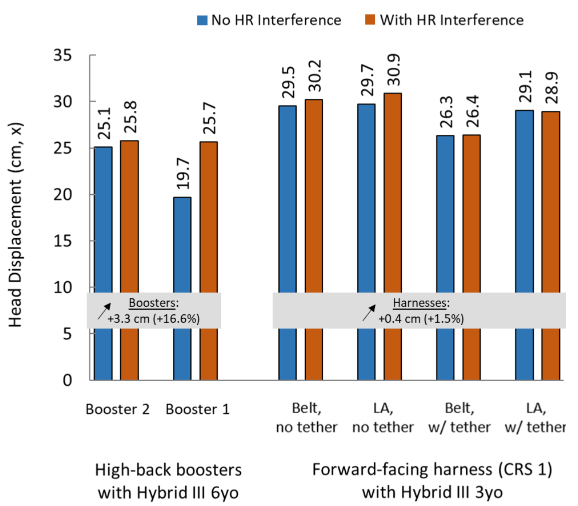

Figure 8: Head displacement in the x-direction measured from initial position for frontal impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

HIC36 is shown in Figure 9, with gray bars showing the average difference and percent difference with respect to HR presence across each type of CRS. In general, HIC36 was higher for HR interference conditions compared to no HR interference (3.2% increase for boosters and 13.1% increase for FF CRS). This difference was statistically significant across all six pairs of tests considered together (p=0.0204, matched pair t-test). All values were well below the FMVSS 213 limit of 1000. These small HIC36 magnitudes across all conditions suggest that the differences might not be clinically relevant to the pediatric population.

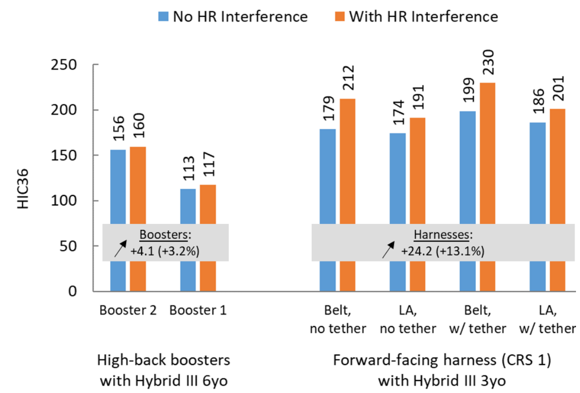

Figure 9: HIC36 for frontal impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

Chest resultant acceleration over a 3 ms clip showed small increases for some conditions with HR interference compared to no HR interference (increase of 3.3% for boosters and 6.2% for FF CRS), although some pairs were similar in magnitude (Figure 10). This difference was not statistically significant across all six pairs of tests considered together (p=0.1161, matched pair t-test). Some of the booster values were at or near the FMVSS 213 limit of 60 g, perhaps influenced by the pulse velocity being slightly above FMVSS 213 limits.

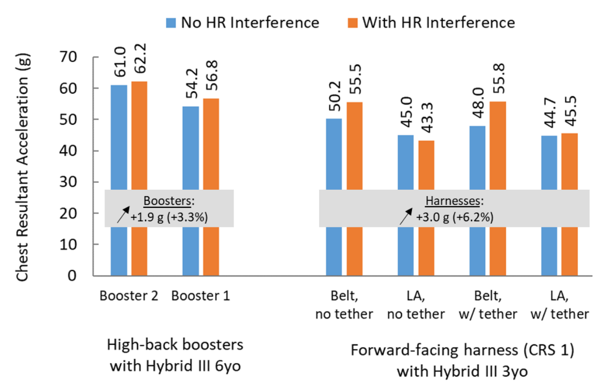

Figure 10: Chest resultant acceleration over a 3 ms clip for frontal impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

Upper neck tension (Fz) is reported in the Appendix Figure D1. Due to unknowns regarding the biofidelity of this body region for pediatric ATDs and corresponding injury thresholds, no further analyses were conducted on the neck tension values.

The maximum top tether load was examined for tests using the tether (Figure 11). There were no clear patterns with respect to HR interference, with the seat belt installations having a higher tether load with HR interference and the LA installations having higher tether load without HR interference. Overall, top tether loads were higher for the seat belt installations compared to LA.

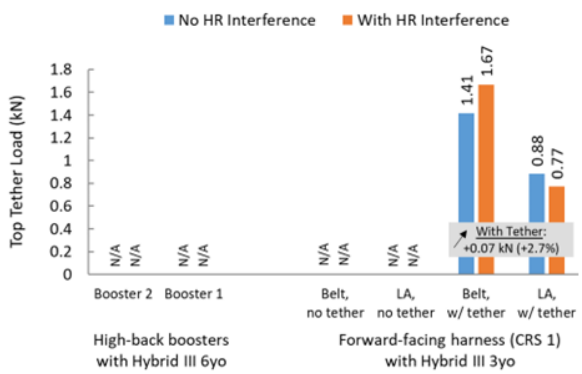

Figure 11: Maximum top tether load (kN) for frontal impacts. The rectangular overlay summarizes the average difference and percent difference between No HR interference vs. With HR interference.

A standard least squares analysis was conducted for the four pairs of FF CRS frontal impact tests to investigate the influence of HR interference, installation method, and top tether (Table 3).

HR interference was found to be a significant predictor for head excursion and HIC36. These results reflect the outcomes of the matched pair t-tests reported above. Installation method was a significant predictor for HIC36 and chest resultant acceleration. Seat belt installations resulted in higher injury metrics compared to LA installations in these comparisons. Top tether was a significant predictor for head excursion, head displacement, and HIC36. Presence of the top tether reduced head excursion and head displacement but slightly increased HIC36.

A separate standard least squares analysis was conducted for the booster tests to examine the effects of booster model (Booster 1 or Booster 2) and HR presence (with HR or no HR). The small sample size (n=4 tests) means these tests have limited utility. Booster model was a significant predictor for HIC36, but none of the other predictors were significant with respect to injury metrics. The results are tabulated in Appendix Table E1.

Far-Side Impacts

Similar to the frontal impact series, the initial angle of the CRS/boosters installed with HR interference (orange bars, Figure 12) were significantly more reclined than CRS/boosters installed without HR interference (blue bars; p=0.0002, matched pair t-test). HR interference caused an additional recline of 2.7° on average for boosters (32.0%) and additional 2.7° in FF harness CRS (18.2%).

Table 3: Standard least squares analysis for FF CRS frontal impact tests, with mean (standard deviation) for each group of tests.

	HR interference			Installation method			Top tether		
		Mean (st.dev)	*p-value*		*Mean (st.dev)*	*p-value*		*Mean (st.dev)*	*p-value*
Head excursion, x (cm)	With HR	34.7 (1.8)	**0.0175**	Belt	33.1 (2.6)	0.1558	With tether	32.1 (1.8)	**0.0067**
	No HR	32.5 (2.1)		LA	34.1 (1.8)		No tether	35.1 (1.3)	
Head displacement, x (cm)	With HR	29.1 (2.0)	0.509	Belt	28.1 (2.0)	0.0636	With tether	27.7 (1.5)	**0.0162**
	No HR	28.7 (1.6)		LA	29.7 (0.9)		No tether	30.1 (0.6)	
HIC36	With HR	208.5 (16.5)	**0.0063**	Belt	204.8 (21.6)	**0.0224**	With tether	203.9 (18.4)	**0.0323**
	No HR	184.4 (10.8)		LA	188.1 (11.2)		No tether	189.0 (17.2)	
Chest resultant acceleration (g)	With HR	50.0 (6.6)	0.189	Belt	52.4 (3.9)	**0.0160**	With tether	48.5 (5.0)	0.9996
	No HR	47.0 (2.6)		LA	44.6 (0.9)		No tether	48.5 (5.5)	

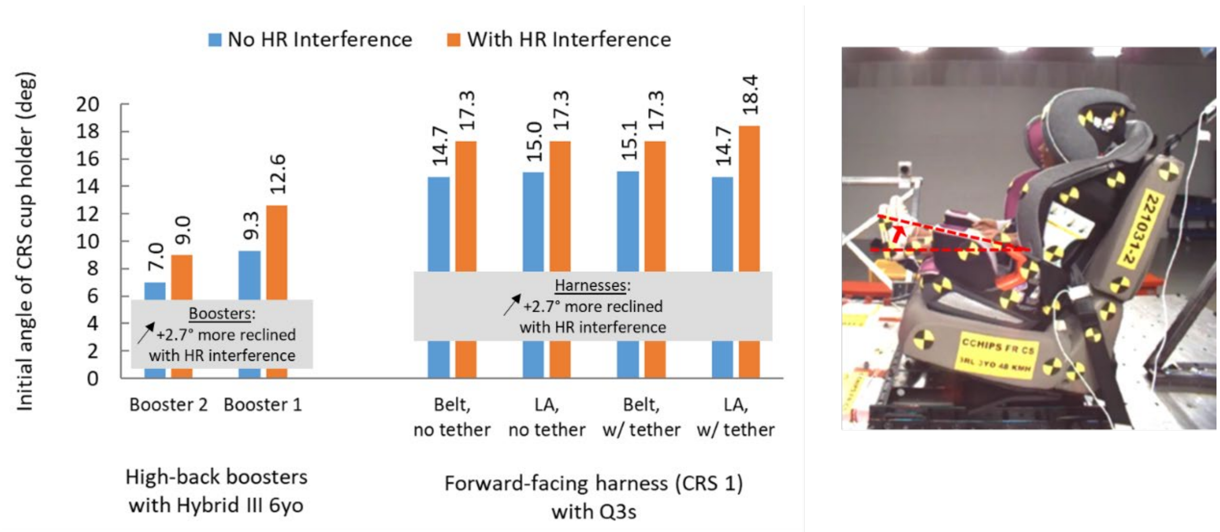

Figure 12: Initial angles of boosters and CRS for far-side impacts. The rectangular overlays summarize the average differences between No HR interference vs. With HR interference for each type of restraint.

Additional pre-test measurements are reported in Appendix Table A1. The pre-test angle at the second CRS/booster reference point was also significantly different between tests with vs. without HR (p=0.0004, matched pair t-test). ATD right and left thigh angles were significantly different with respect to HR interference (p=0.0232 and p=0.0003, respectively). Sternum angle was not significantly different (p=0.1323). This lack of expected significance might be due to minor ATD positioning inconsistencies and/or small sample size. Pre-test belt tensions, top tether tensions, and harness tensions were not significantly different across matched pairs (p=0.3910, p=0.7952, and 0.6376, respectively), indicating good consistency in installation techniques across all tests. The sample size was too small to compare LA tension levels. Initial positions of the front edge of the CRS and the ATD nose could not be calculated using TEMA because the far-side impact setup lacked a camera view positioned laterally to the ATDs.

Camera frames from pre-test initial positions and maximum excursions are shown for exemplar conditions for CRS 1 (Figure 13) and Booster 2 (Figure 14). The shoulder belt slipped off the left shoulder for all booster tests in the far-side impact direction.

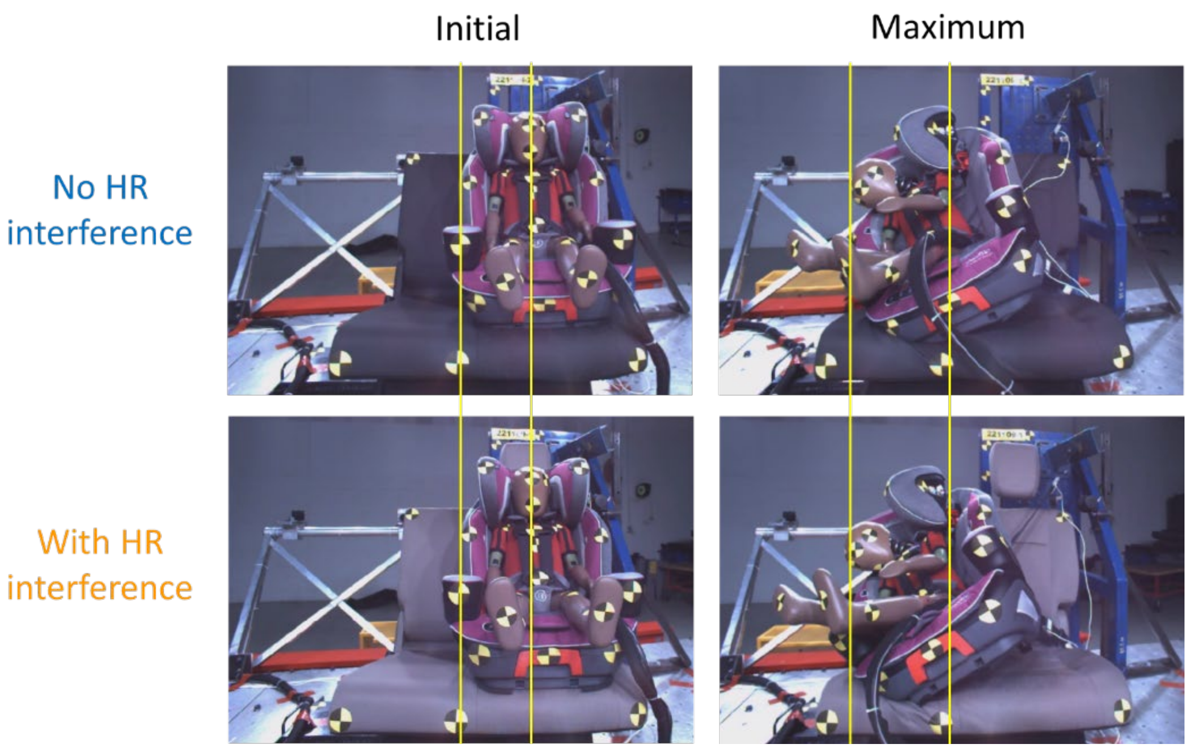

Figure 13: Initial positions and maximum excursions for FF harness CRS 1, seat belt installation, no tether, with Q3s (Tests #8 and #20).

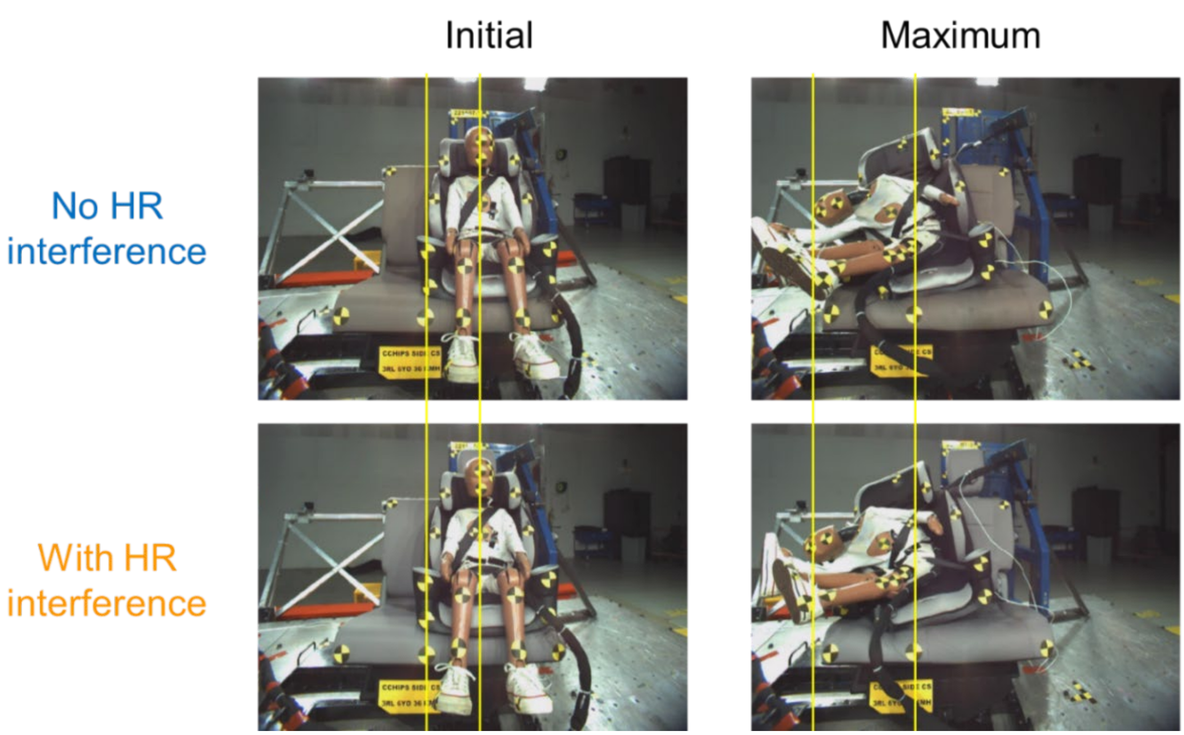

Figure 14: Initial positions and maximum excursions for Booster 2, Hybrid III 6yo (Tests #12 and #24).

Lateral head displacements from initial position were slightly increased when HR interference was present for the boosters (increase of 3.9 cm or 5.8%) and for FF harness installations without a top tether (increase of 3.4 cm or 6.5%) (Figure 15). However, when the top tether was used, HR interference resulted in less lateral head displacement compared to installations with HR interference (decrease of 3.6 cm or 6.8%). Differences in lateral head displacement were not significant with respect to HR interference across all six pairs of tests together (p=0.4694, matched pair t-test).

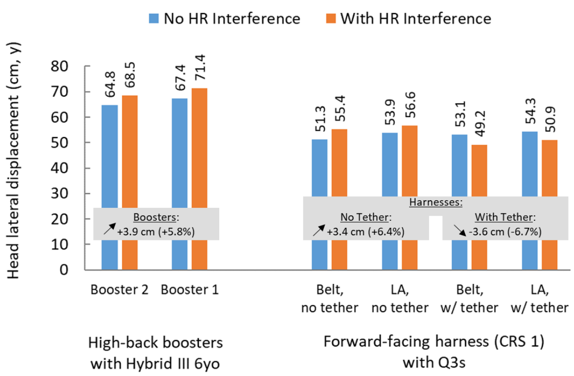

Figure 15: Lateral head displacement from initial position for far-side impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

HIC36 for high back boosters was similar between HR and non-HR conditions (Figure 16). For FF harness seats, the top tether seemed to have played a role: for installations without the top tether, HR interference resulted in higher HIC36 values (increase of 25.8 or 17.2%). For installations with the top tether, HR interference resulted in lower HIC36 values (decrease of 50.3 or 28.5%). HIC36 was well below the FMVSS 213 limit (1000) in all tests. In addition, variations were not significantly different with respect to HR interference across all six pairs of tests together (p=0.6395, matched pair t-test).

Chest resultant acceleration over a 3 ms clip was similar across conditions for high back boosters (Figure 17). When CRS 1 was installed with the top tether, HR interference resulted in higher chest resultant accelerations compared to no HR interference (increase of 8.1 g or 15.2%). Overall, differences in chest resultant acceleration were not significant with respect to HR interference across all six pairs of tests together (p=0.2138, matched pair t-test).

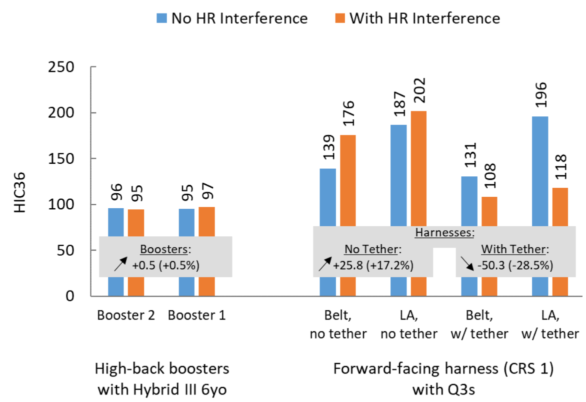

Figure 16: HIC36 for far-side impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

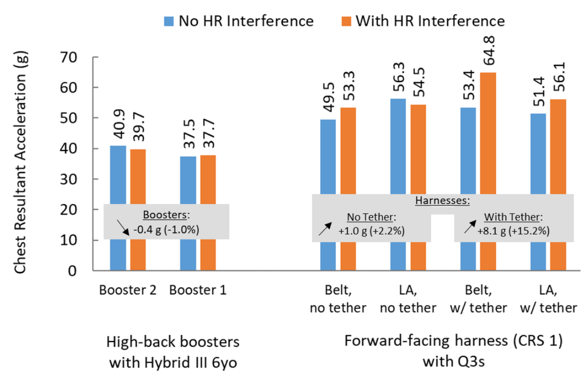

Figure 17: Chest resultant acceleration over 3 ms clip for far-side impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

Upper neck tension (Fz) is reported in Appendix Figure D2. No further analyses were conducted on this metric.

The maximum top tether load was examined for tests using the tether (Figure 18). HR interference resulted in higher top tether loads (increase of 0.23 kN or 123%). The difference was much larger in the LA tests compared to the seat belt tests.

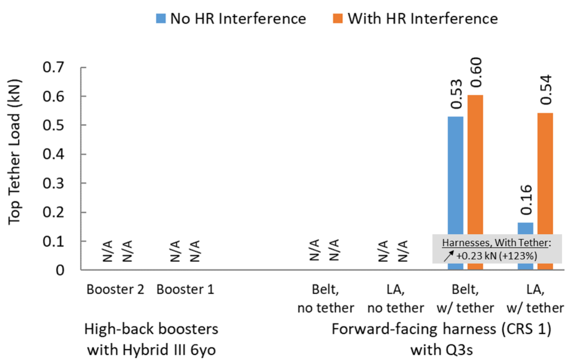

Figure 18: Maximum top tether load (kN) for far-side impacts. The rectangular overlay summarizes the average difference and percent difference between No HR interference vs. With HR interference.

A standard least squares analysis was conducted for all FF CRS far-side impact tests to investigate the influence of HR interference, installation method, and top tether (Table 4). None of the predictors were found to be significant for any of the injury metrics examined here. These outcomes match the results of the matched pair t-tests reported above which examined the role of HR presence. Top tether presence was not significantly related to injury metric outcomes, perhaps because its influence varied throughout different test conditions. The small sample size might have affected these outcomes.

A separate standard least squares analysis was conducted for the booster tests to examine the effects of booster model (Booster 1 or Booster 2) and HR presence (with HR or no HR). The small sample size (n=4 tests) means these tests have limited utility. Booster model and HR presence were significant predictors for lateral head displacement, but none of the other predictors were significant with respect to any injury metrics. The results are tabulated in Appendix Table E2.

DISCUSSION

Overall, the presence of the HR affected head excursion and HIC36 in frontal impacts. HR presence had a less consistent effect on far-side impacts. All outcome metrics are summarized in Table 5, with respect to the relative increase (orange) or decrease (green) in each metric when HR interference was present compared to no HR interference (baseline).

Table 4: Standard least squares analysis for FF CRS far-side impact tests, with mean (standard deviation) for each group of tests.

	HR interference			Installation method			Top tether		
		Mean (st.dev)	*p-value*		*Mean (st.dev)*	*p-value*		*Mean (st.dev)*	*p-value*
Head displacement, y (cm)	With HR	53.0 (3.5)	0.9478	Belt	52.3 (2.6)	0.3917	With tether	51.9 (2.3)	0.2477
	No HR	53.2 (1.3)		LA	54.0 (2.3)		No tether	54.3 (2.3)	
HIC36	With HR	150.8 (45.1)	0.6026	Belt	138.4 (28.0)	0.1634	With tether	138.2 (39.6)	0.1598
	No HR	163.1 (33.0)		LA	175.5 (38.9)		No tether	175.7 (26.6)	
Chest resultant acceleration (g)	With HR	57.2 (5.2)	0.2415	Belt	55.3 (6.6)	0.8381	With tether	56.4 (5.9)	0.4094
	No HR	52.6 (2.9)		LA	54.6 (2.3)		No tether	53.4 (2.8)	

Table 5: Change in each metric when HR interference was present compared to no HR interference as the baseline condition

Frontal Impacts	Boosters	FF CRS 1 (all installations)	
Head excursion (x-direction)*	+ 4.0 cm (+13.3%)	+ 2.2 cm (+7.0%)	
Head displacement (x-direction)	+ 3.3 cm (16.6%)	+0.4 cm (+1.5%)	
HIC36*	+ 4.1 (+3.2%)	+ 24.2 (+13.1%)	
Chest resultant acceleration	+ 1.9 g (+3.3%)	+ 3.0 g (+6.2%)	
Top tether load	N/A	N/A	+0.07 kN (+2.7%)

Far-Side Impacts	Boosters	FF CRS 1, no tether	FF CRS 1, with tether
Head displacement (y-direction)	+ 3.9 cm (+5.8%)	+ 3.4 cm (+6.5%)	- 3.6 cm (-6.8%)
HIC36	+ 0.5 (+0.5%)	+ 25.8 (+17.2%)	- 50.3 (-28.5%)
Chest resultant acceleration	- 0.4 g (-1.0%)	+ 1.0 g (+2.2%)	+ 8.1 g (+15.2%)
Top tether load	N/A	N/A	+0.23 kN (+123%)

Legend	
>10% increase	dark orange
5 to 10% increase	light orange
< 5% change	grey
5 to 10% decrease	light green
>10% decrease	dark green
* p<0.05 across all six pairs combined	

For frontal impacts, there was a small but relatively consistent increase in head excursion and HIC36 when the HR was present vs. not present. Differences in HIC36 were small in magnitude and were all quite far below the FMVSS 213 limit of 1000. The increased head excursion in the x-direction (with respect to the test bench) appeared to be caused by the more forward initial position of the installations with HR-interference rather than dynamic differences during the crash event. This is evident through the similar measures of head displacement with respect to its initial position across all conditions (Figure 8). Outcomes in chest resultant acceleration were not significant with respect to HR condition in matched pair t-tests or the standard least squares analysis (Table 3).

Outcomes for far-side impacts had fewer clear trends with respect to HR interference. Head lateral displacement and HIC 36 trended higher for CRS 1 with HR interference when the top tether was not used. When the top tether was used, both head metrics trended lower for tests with HR interference. Chest resultant acceleration was non-significantly increased with HR interference for FF CRS with tether, but was not affected strongly by HR interference for boosters and FF CRS with no top tether. None of the explored predictors (HR interference, installation method, or presence of top tether) were significant with respect to injury outcomes in far-side impacts (Table 4). These results suggest that the simultaneous lateral translation and rotation of the CRS in far-side impacts is affected by many factors which are not easy to separate during analyses.

The top tether loads in this study varied with respect to impact direction and installation method. Trends with respect to HR interference are less clear, although both sets of far-side impacts resulted in higher tether loads when HR interference was present. This outcome agrees with previous testing where high top tether loads were observed when a similar gap was created behind a FF CRS due to the recline angle of the vehicle seat being too acute to achieve a flush installation of the FF CRS against the seat back (Mansfield et al. 2021). We hypothesize that the tether managed more of the crash energy in these cases because less of the CRS frame itself is able to interact directly with the vehicle seat back due to the gap. However, difficulties in setting the pre-test tension of the top tether to a consistent level might have influenced the results of the current series. Pre-test tether tensions ranged from 44.5-62.3 N (10-14 lbs; Appendix Table A1). Matched pair t-tests of pre-test tensions indicated no significant difference across pairs; however, further study is needed to elucidate the role of the top tether in these conditions.

Though not a primary focus of this study, it can be observed that the top tether was effective in reducing forward head excursion (3.0 cm on average; p=0.0067) and head displacement from initial position (2.4 cm on average; p=0.0162) in the frontal series compared to corresponding tests without the top tether (Table 3). The top tether also reduced head excursion in two of the far-side impact conditions: 6.2 cm (seat belt with HR), and 5.7 cm (LA with HR) (calculated from Figure 15). The other two far-side impact conditions resulted in slightly higher lateral head excursions with the top tether: increases of 0.4 cm (LA, no HR) and 1.8 cm (seat belt, no HR) (calculated from Figure 15). The standard least squares analysis did not reveal significant differences for these tests with respect to top tether presence.

For the booster tests in frontal impacts, there were no significant differences in head excursion or displacement with respect to HR condition or booster model (Appendix Table E1). In far-side impacts, HR interference and booster model were significant factors for lateral head displacement (Appendix Table E2). Head excursion/displacement metrics are critical for the pediatric population because the most common injury for children in crashes is head injury due to head strikes against surfaces in the vehicle (Arbogast et al. 2009, Arbogast and Durbin 2013). Thus, reducing head excursion should remain a top priority for pediatric injury prevention.

Given the lack of biomechanical data on which to develop pediatric injury thresholds, we must rely on field performance of CRS to confirm laboratory findings. CRS designed to meet the excursion, HIC36, and chest resultant acceleration requirements of FVMSS 213 are very effective. The current evaluation of how these measures vary with HR should be considered alongside field injury risks. HIC36 was consistently below the FMVSS 213 limit of 1000, indicating low risk of injury regardless of HR condition. We did not observe any head strikes in this test series, although the test setup did not contain any front row seat structures or adjacent passengers/cargo. Chest resultant accelerations were near or slightly beyond the FMVSS 213 limit of 60 g for boosters in frontal impacts and CRS 1 in far-side impacts. Chest injuries in children are reported less often than head, extremity, or abdominal injuries, but they do still occur in the field at moderate rates (Arbogast and Durbin 2013).

It is important to recognize that removing the HR from a vehicle seat to improve CRS fit might have detrimental consequences in crash scenarios other than those studied here. In a severe rear impact crash, it is unclear whether the CRS shell itself can provide enough posterior head support to appropriately restrain a child's head. CRS are manufactured from a variety of different materials, some with more rigid and supportive frames than others. Keeping the vehicle HR behind the CRS head support might be important to prevent injuries to children in rear impacts. Also, if an HR is removed, caregivers might lose the HR or neglect to replace it when the child transitions out of the CRS or booster. This would create a seating position in the vehicle with no HR support for adolescent or adult occupants. Therefore, an appropriate best-practice recommendation might be to use a CRS which can physically accommodate the vehicle HR in its usual or raised position without pushing the child occupant's head forward. CRS with a contoured back surface might be better at accommodating vehicle HRs compared to CRS which have a tall, flat back surface with no contours or flexibility to accommodate vehicle HRs. Future CRS designs should consider the wide variety of HR shapes and sizes in the modern vehicle fleet and make efforts to accommodate vehicle HRs without requiring their removal.

The shoulder of the 6-year-old Hybrid III slipped out of the shoulder belt in all far-side impacts with boosters. Shoulder belt slip-off has been reported in dynamic driving maneuver studies with child volunteers, especially for booster-seated children with short statures (Baker et al. 2018). Belt slip-off with poor head and torso containment has also been reported in other studies of ATD booster occupants in far-side impacts (Tylko et al. 2015, Thorbole et al. 2020, Visvikis et al. 2021, Mansfield 2023). Data suggest that installing the booster with LATCH or ISOFIX along with the use of a seat belt pretensioner might reduce booster occupants' head excursions in far-side impacts (Tylko et al. 2015, Thorbole et al. 2019). However, the presence of robust side wings does not appear to affect lateral head excursions for booster occupants (Mansfield 2023).

This study includes several limitations. It is important to note that the test setups with HR interference also had the CRS initially more reclined and positioned further forward on the vehicle seat cushion compared to tests without HR interference. It cannot be determined from this series if the differences in kinematics and kinetics were due to the HR interference in general, or whether one or both of these pre-test position factors (angle and fore/aft position on the seat cushion) were the primary cause for differences in outcomes. Since HR interference might produce different initial positions for different vehicles or different CRS models, these results might not apply to all cases of HR interference.

Additional limitations include dynamically testing only two CRS models and one vehicle seat. The underlying structure of the vehicle seat might be different from others in the modern vehicle fleet. Geometric and structural differences across CRS and booster designs can also affect the dynamic response. The amount of HR interference and size of the gap behind the CRS in this setup were relatively small and might not represent the full range of severity possible in the field. Other vehicles with different CRS might create larger gaps or more severe instability. Head excursions in this study were calculated from camera views that were calibrated according to known distances near the center of the field of view. The known distances for the far-side tests were within the plane of motion being examined (front aspect of the ATD's face). The known distance for the frontal impacts was located on the armrest of the CRS, which is slightly closer to the camera than the lateral aspect of the ATD's head which was being tracked. This practice might result in inaccuracies due to out-of-plane calibration. The calculated excursions could not be validated directly. However, the calibration methods were consistent within each crash direction in this study, so the results are comparable within this series. No repeated test conditions were run in this series, so the repeatability of the test setup cannot be quantified. Lastly, the Hybrid III 6 year old is has not been validated for side impact scenarios, but no other side-impact ATD was available for this particular occupant size.

CONCLUSIONS

In frontal impacts, HR interference produced small increases in frontal head excursion and HIC36. Head excursion was more directly related to the more fore initial position of the CRS and occupant rather than kinematic differences caused by HR interference. Trends with respect to HR interference were consistent in both tethered and non-tethered FF CRS installations in frontal impacts and the top tether was effective in reducing both head excursion and head displacement. In far-side impacts, HR interference had less consistent effects on injury metrics. Overall, these results suggest only slight benefits of removing the HR in frontal impacts specifically. Caregivers should use caution when removing a vehicle HR to ensure that the current child occupant and future vehicle occupants have adequate head support available in case of a rear impact.

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APPENDIX A: PRE-TEST MEASUREMENTS

Table A1: Pre-test setup measurements are presented with tests listed in chronological order (with corresponding matrix test number included)

Frontal Impacts:

Chronological order	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Test # in matrix (Table 1)	**1**	**2**	**3**	**4**	**13**	**14**	**15**	**16**	**6**	**5**	**18**	**17**
ATD	HIII 3yo	HIII 3yo	HIII 3yo	HIII 3yo	HIII 3yo	HIII 3yo	HIII 3yo	HIII 3yo	HIII 6yo	HIII 6yo	HIII 6yo	HIII 6yo
CRS	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	Booster 2	Booster 1	Booster 2	Booster 1
HR interference	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Installation method*	Belt + TT	Belt	LA + TT	LA	Belt + TT	Belt	LA + TT	LA	None	None	None	None
CRS recline setting	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	N/A	Upright	N/A	Upright
LA tension, N (lbs)	N/A	N/A	66.7 (15)	62.3 (14)	N/A	N/A	62.3 (14)	62.3 (14)	N/A	N/A	N/A	N/A
Belt tension, N (lbs)	62.3 (14)	66.7 (15)	N/A	N/A	62.3 (14)	66.7 (15)	N/A	N/A	22.2 (5)	20.0 (4.5)	22.2 (5)	20.0 (4.5)
Top tether tension, N (lbs)	53.4 (12)	N/A	62.3 (14)	N/A	48.9 (11)	N/A	53.4 (12)	N/A	N/A	N/A	N/A	N/A
Harness tension, N (lbs)	17.8 (4)	22.2 (5)	17.8 (4)	17.8 (4)	17.8 (4)	17.8 (4)	17.8 (4)	17.8 (4)	N/A	N/A	N/A	N/A
CRS angle, at cupholder, deg	15.0	14.6	16.3	15.2	16.8	17.0	16.7	16.2	14.1	9.1	14.3	12.2
CRS angle, ref pt 2, deg**	24.0	23.2	25.2	24.6	26.7	26.2	25.2	26.2	N/A	18.0	N/A	20.9
ATD thigh angle, right, deg	8.0	7.6	9.8	9.0	9.0	N/A	9.0	9.0	19.8	13.6	21.0	16.2
ATD thigh angle, left, deg	7.4	6.7	9.8	9.0	9.0	N/A	9.0	9.0	19.0	11.0	19.0	15.4
ATD sternum angle, deg	30.3	28.9	28.8	28.9	29.9	30.6	29.6	29.4	20.2	12.0	20.2	22.3

Lateral (far-side) Impacts:

Chronological order	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Test # in matrix (Table 1)	**12**	**11**	**24**	**23**	**7**	**8**	**9**	**10**	**19**	**20**	**21**	**22**
ATD	HIII 6yo	HIII 6yo	HIII 6yo	HIII 6yo	Q3s	Q3s	Q3s	Q3s	Q3s	Q3s	Q3s	Q3s
CRS	Booster 2	Booster 1	Booster 2	Booster 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1	CRS 1
HR interference	No	No	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes
Installation method*	None	None	None	None	Belt + TT	Belt	LA + TT	LA	Belt + TT	Belt	LA + TT	LA
CRS recline setting	N/A	Upright	N/A	Upright	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand	Recline stand
LA tension, N (lbs)	N/A	N/A	N/A	N/A	N/A	N/A	66.7 (15)	66.7 (15)	N/A	N/A	62.3 (14)	62.3 (14)
Belt tension, N (lbs)	22.2 (5)	22.2 (5)	22.2 (5)	22.2 (5)	57.8 (13)	62.3 (14)	N/A	N/A	57.8 (13)	57.8 (13)	N/A	N/A
Top tether tension, N (lbs)	N/A	N/A	N/A	N/A	53.4 (12)	N/A	44.5 (10)	N/A	44.5 (10)	N/A	48.9 (11)	N/A
Harness tension, N (lbs)	N/A	N/A	N/A	N/A	20.0 (4.5)	20.0 (4.5)	17.8 (4)	17.8 (4)	17.8 (4)	20.0 (4.5)	20.0 (4.5)	20.0 (4.5)
CRS angle, at cupholder, deg	7.0	9.3	9.0	12.6	15.1	14.7	14.7	15.0	17.3	17.3	18.4	17.3
CRS angle, ref pt 2, deg**	13.0	16.6	14.9	20.6	23.0	22.9	23.7	24.0	26.0	26.7	26.7	26.0
ATD thigh angle, right, deg	18.5	12.8	19.0	18.0	9.9	8.7	8.3	9.3	10.1	12.0	11.8	11.7
ATD thigh angle, left, deg	16.2	14.0	18.0	16.0	9.4	9.0	9.6	8.3	11.5	11.4	12.3	11.9
ATD sternum angle, deg	19.3	12.6	20.2	21.9	33.9	32.7	32.3	32.1	34.0	33.5	34.3	34.0

* Belt = lap and shoulder belt; LA = lower anchors; TT = top tether
** Side ledge (CRS 1/Booster 1) or armrest (Booster 2) (deg)

Figure A1: Locations of pre-test angle measurements. The left thigh cannot be seen in this camera view, but was measured on the top aspect of the thigh in the same manner as the right thigh.

APPENDIX B: TEMA MOTION TRACKING CALIBRATION

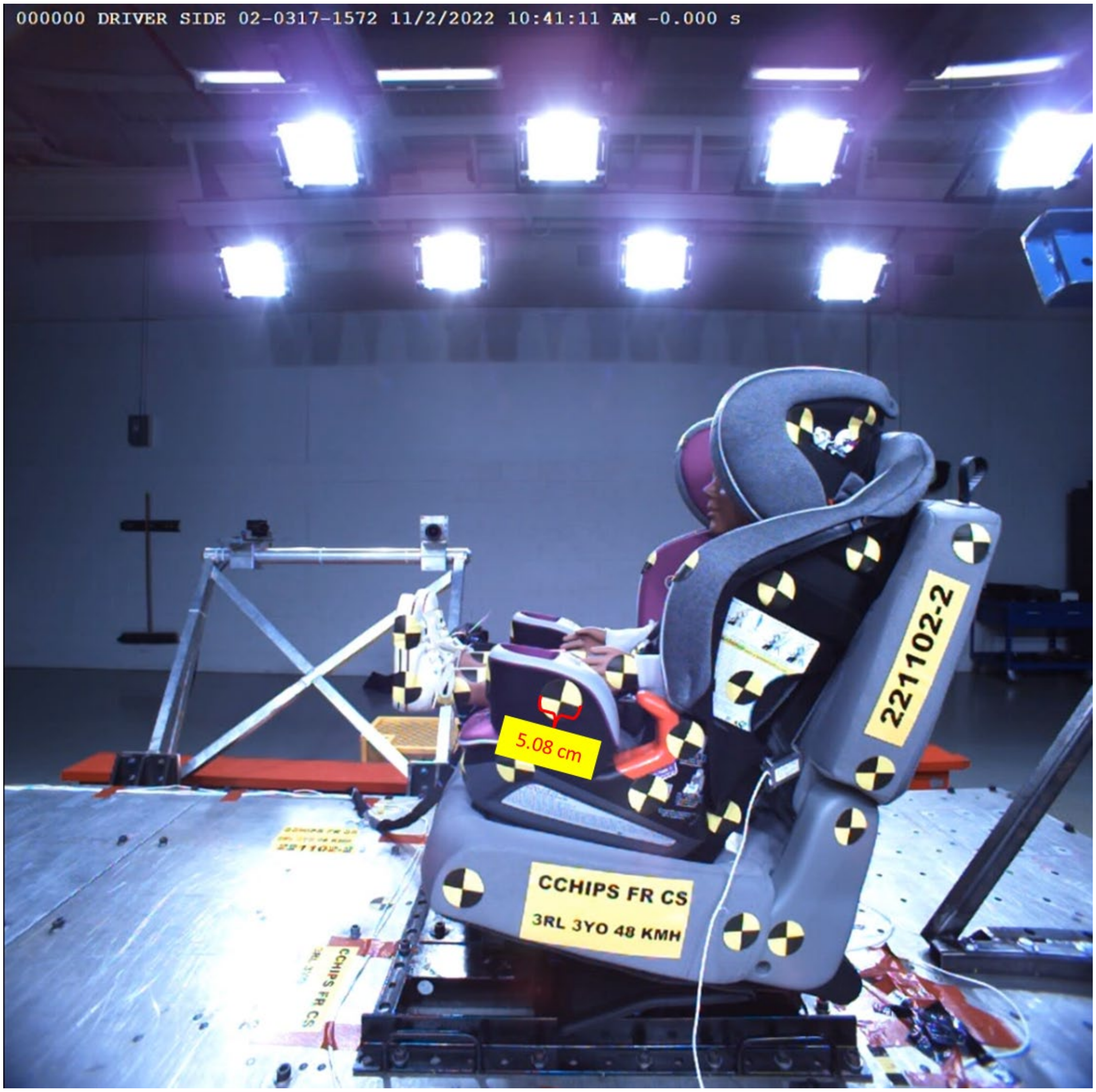

Figure B1: The 2 inch (5.08 cm) camera target on the side of the CRS arm was used to calibrate the lateral-view videos for each frontal impact.

Figure B2: The measured distance between the camera targets on the Hybrid III 6yo's forehead and chin (7.6 cm) was used to calibrate the frontal-view videos for each far-side impact with the Hybrid III 6yo. These camera targets were not moved or removed across all tests with the Hybrid III 6yo.

Figure B3: The measured distance between the camera targets on the Q3s's forehead and chin (8.9 cm) was used to calibrate the frontal-view videos for each far-side impact with the Q3s. These camera targets were not moved or removed across all tests with the Q3s.

APPENDIX C: INITIAL POSITIONS OF FRONTAL IMPACT TESTS

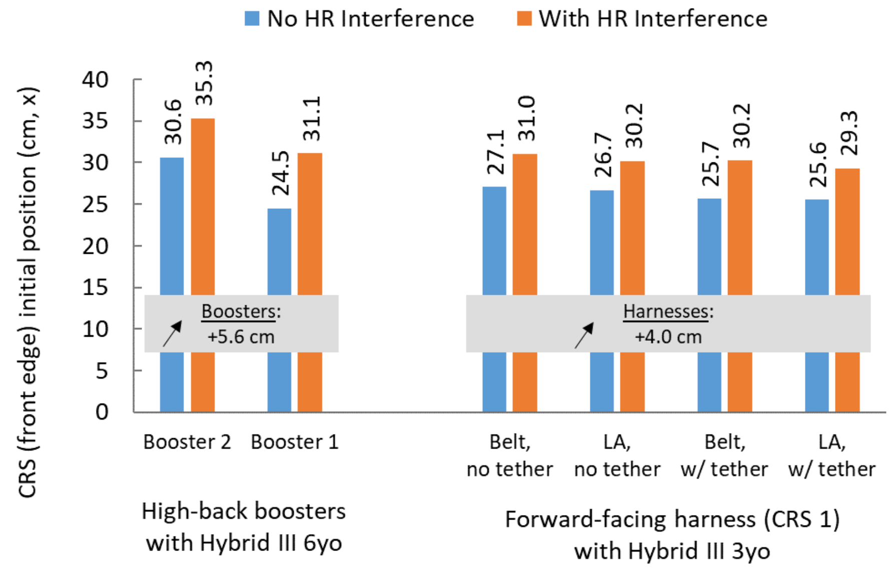

Figure C1: Initial position of the front edge of the CRS armrest with respect to the reference point on the sled buck in the x-direction. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint. Across both types of restraint, tests with HR interference were positioned an average of 4.5 cm further forward on the seat.

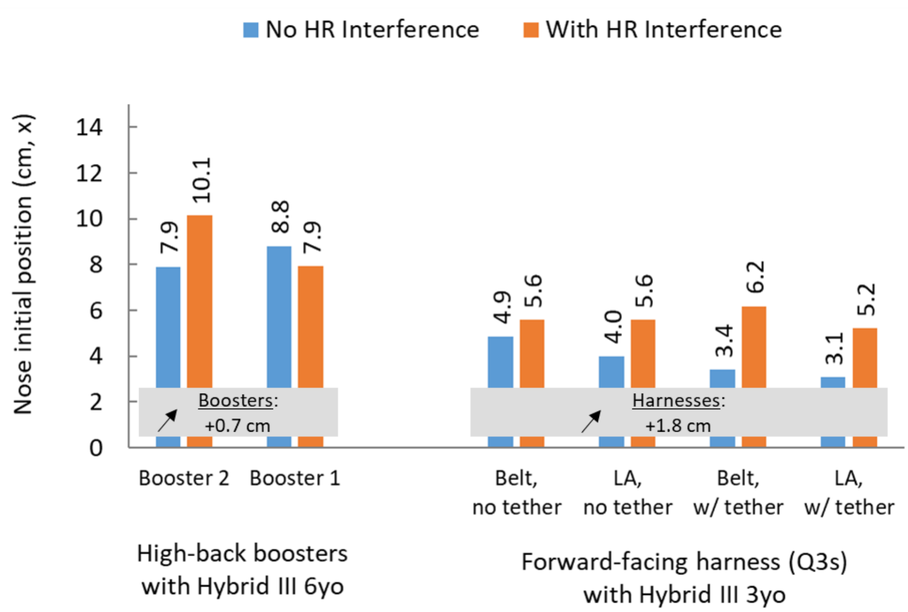

Figure C2: Initial position of the ATD's nose with respect to the reference point on the sled buck in the x-direction. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint. Across both types of restraint, tests with HR interference were positioned an average of 1.4 cm further forward on the seat.

APPENDIX D: UPPER NECK TENSIONS

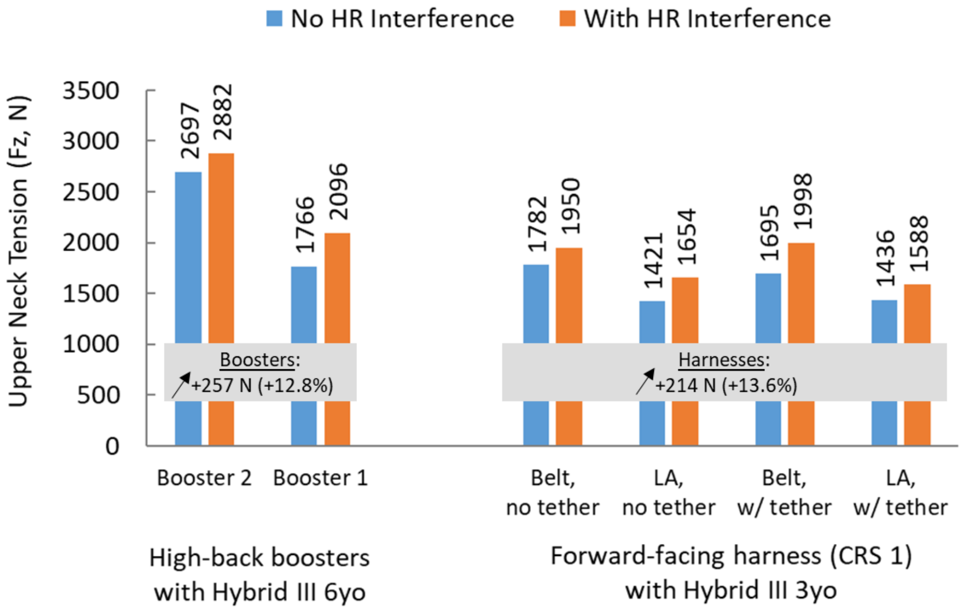

Figure D1: Upper neck tension (Fz) for frontal impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

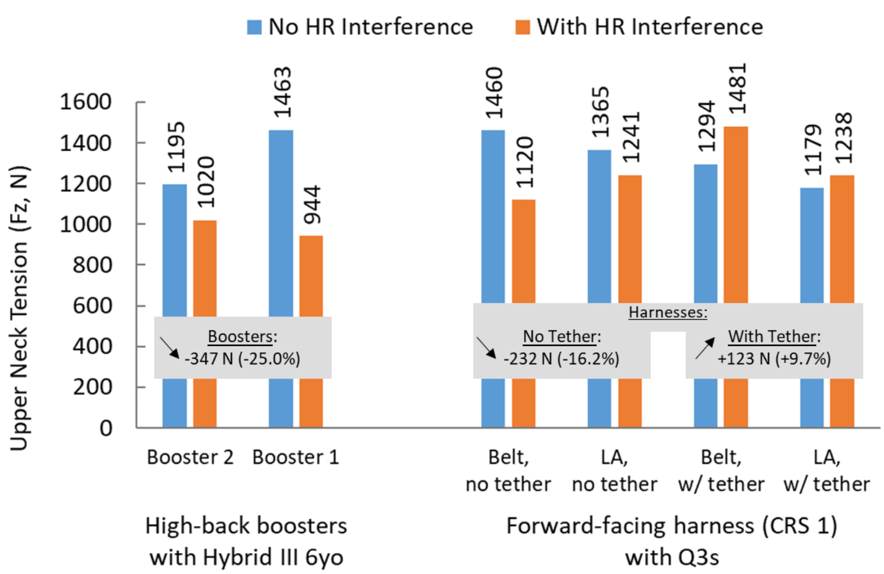

Figure D2: Upper neck tension (Fz) for far-side impacts. The rectangular overlays summarize the average differences and percent differences between No HR interference vs. With HR interference for each type of restraint.

APPENDIX E: STANDARD LEAST SQUARES ANALYSES FOR BOOSTER TESTS

Table E1: Standard least squares analysis for booster frontal impact tests, with mean (standard deviation) for each group of tests. Low sample size (n=4) is a limitation of this analysis.

`	HR interference			Booster model		
		Mean (st.dev)	*p-value*		*Mean (st.dev)*	*p-value*
Head excursion, x (cm)	With HR	34.7 (1.6)	*0.1704*	Booster 1	31.0 (3.6)	*0.1977*
	No HR	30.7 (3.2)		Booster 2	34.4 (2.1)	
Head displacement, x (cm)	With HR	25.7 (0.1)	*0.4271*	Booster 1	22.7 (4.2)	*0.4855*
	No HR	22.4 (3.8)		Booster 2	25.4 (0.5)	
HIC36	With HR	138.5 (29.8)	*0.1044*	Booster 1	115.1 (3.4)	***0.0101***
	No HR	134.4 (30.7)		Booster 2	157.8 (2.4)	
Chest resultant acceleration (g)	With HR	59.5 (3.8)	*0.2392*	Booster 1	55.5 (1.8)	*0.0760*
	No HR	57.6 (4.9)		Booster 2	61.6 (0.8)	

Table E2: Standard least squares analysis for booster far-side impact tests, with mean (standard deviation) for each group of tests. Low sample size (n=4) is a limitation of this analysis.

	HR interference			Booster model		
		Mean (st.dev)	*p-value*		*Mean (st.dev)*	*p-value*
Head displacement, y (cm)	With HR	70.0 (2.0)	***0.0201***	Booster 1	69.4 (2.8)	***0.0284***
	No HR	66.1 (1.8)		Booster 2	66.7 (2.6)	
HIC36	With HR	96.0 (1.6)	*0.7933*	Booster 1	96.2 (1.3)	*0.6414*
	No HR	95.5 (0.4)		Booster 2	95.3 (0.7)	
Chest resultant acceleration (g)	With HR	38.7 (1.4)	*0.6323*	Booster 1	37.6 (0.2)	*0.1586*
	No HR	39.2 (2.4)		Booster 2	40.3 (0.8)	