2021-01-0915 Published 06 Apr 2021

Child Restraint Systems (CRS) with Minor Installation Incompatibilities in Far Side Impacts

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Citation: Mansfield, J., Kwon, H.J., and Kang, Y.S., "Child Restraint Systems (CRS) with Minor Installation Incompatibilities in Far Side Impacts," SAE Technical Paper 2021-01-0915, 2021, doi:10.4271/2021-01-0915.

Abstract

Side impacts are disproportionately injurious for children compared to other crash directions. Far side impacts allow for substantial translation and rotation of child restraint systems (CRS) because the CRS does not typically interact with any adjacent structures. The goal of this study is to determine whether minor installation incompatibilities between CRS and vehicle seats cause safety issues in far side crashes.

Four non-ideal CRS installation conditions were compared against control conditions having good fit. Two repetitions of each condition were run. The conditions tested were: 1) rear-facing (RF) CRS installed with a pool noodle to create proper recline angle, 2) RF CRS with narrow base, 3) forward-facing (FF) CRS with gap behind back near seat bight (i.e., vehicle seat angle too acute for CRS), 4) FF CRS with gap behind back near top of CRS (i.e., vehicle seat angle too obtuse for CRS). Second row captain's chairs were set up at 10° anterior of lateral. A sled pulse target of 35 kph and 24 g was used. All trials used the Q3s anthropomorphic test device (ATD) with standard instrumentation. CRS were installed using Lower Anchors and Tethers for CHildren (LATCH).

The non-ideal RF CRS conditions produced kinetic and kinematic outcomes similar to the RF control trials. All RF trials resulted in the ATD's head rolling toward the direction of impact along the CRS side wing, although upper neck moments were below injury assessment reference values (IARVs). Non-ideal FF CRS conditions also produced outcomes similar to the FF control trials. The top tether load was higher for the "vehicle seat too acute" condition, although the higher top tether loads did not correlate with higher neck forces or HIC36 values in those trials. Overall, the minor CRS/vehicle incompatibilities examined in this study do not appear to affect the performance of the CRS in the far side impact scenario.

Introduction

Side impacts were the second most frequent type of fatal collision in 2017 [1]. For children in the second row, side impacts account for similar rates of fatalities compared to frontal impacts or rollovers [2]. In regards to child restraint system (CRS) research, side impact conditions have been tested very little relative to frontal impacts despite producing a similar number of child fatalities. As the side impact crash mode gains further attention in the automotive safety research community, far-side and near-side impacts have been separately studied as individual crash conditions. While higher fatality rates have been reported for children in near-side impacts, serious injuries and fatalities have been reported for far-side impacts as well. For children less than one year old, 19% of side impact fatalities occurred with the child in the far side condition and 16% occurred with the child seated in the center position [3]. Therefore, it is important to investigate the kinematics and kinetics of far-side impact scenarios for children to better understand how CRS protect occupants in these scenarios.

Incompatibilities between CRS and vehicle seats can cause problems that may decrease the stability of the CRS in the vehicle seat. A common compatibility problem in RF CRS is the need to use a foam pool noodle or rolled towel to achieve the correct base angle. A previous study estimated this incompatibility to occur in 41.8% of RF CRS installations [4]. The study also estimated that 36.7% of rear-facing (RF) installations were not ideal when the width of CRS was compared to the width of vehicle seat [4]. For FF CRS, misalignments in the recline angles of the CRS and the vehicle seat can create gaps behind the CRS. Head restraint interference often exacerbates this problem and is estimated to occur in 33.6% of installations [4]. It is currently unclear whether these gaps decrease the stability of the CRS or affect injury metrics in a side impact.

Consumers may experience some of these problems when installing a CRS in their vehicle. Some CRS manufacturers offer guidelines regarding minor fit issues within their instruction manuals. In most cases, a tight installation can still be achieved and the effects of the problem are hypothesized to be minor. However, the consequences of these types of incompatibilities are not currently clear. This study aims to examine how CRS perform in far side impacts when their fit is not ideal within the vehicle seat. The study focuses especially on scenarios where a tight fit is possible but small gaps exist between the CRS and vehicle seat.

Objective and Specific Aims

The objective of this study is to provide information that will allow CRS and vehicle engineers to understand the influence of the CRS fit on responses of the CRS and occupant in far-side impacts by quantifying the kinematics and kinetics of the system. The information will help engineers optimally design their products and fine-tune their installation recommendations to improve child safety. The specific aims are to compare the performance of control trials (ideal fit condition) to the following non-ideal fit conditions:

1. RF CRS installed with pool noodle to create proper recline angle
2. RF CRS with narrow base
3. FF CRS with gap behind back near seat bight (i.e., head restraint interference with top of CRS, or vehicle seat angle too acute for CRS)
4. FF CRS with gap behind back near top of CRS (i.e., vehicle seat angle too obtuse for CRS).

Methods

Vehicle Seats

Second row captain's chairs from a popular minivan were affixed to a HYGE sled. The same make and model of vehicle seat was used for all tests. Captain's chairs were selected for testing instead of bench seats because it was hypothesized that captain's chairs might allow the CRS to roll out over the edge of the seat, thus representing the worst case scenario. The seats were aligned such that the principal direction of force was 10° anterior of pure lateral (i.e., 80° from frontal). Each vehicle seat was used for two impacts but was rotated 180° between trials such that each side of the seat was impacted only once. Thus, structural damage from repeated tests was minimized.

Child Restraint Systems (CRS)

Rear-facing CRS The Evenflo Triumph LX was used for all RF trials. The CRS was replaced after each trial. All were installed using the Lower Anchors and Tethers for CHildren (LATCH) system with the lower connector strap tightened to 53 N (12 lbs) of tension. The RF CRS "control" condition (good fit) is shown in Figure 1. The CRS was installed at the manufacturer's recommended angle using the recline adjustor on the CRS.

FIGURE 1 RF CRS control condition (good fit)

The RF CRS "pool noodle" condition is shown in Figure 2. The RF CRS was installed at the manufacturer's recommended angle using a foam pool noodle (red) instead of the recline adjustor. The resulting installation angle was the same as the control trials.

The RF CRS "narrow base" condition is shown in Figure 3. The sides of the RF CRS base were trimmed by 4.25 cm on each side. The total width of the base was reduced from 38.4 cm to 29.9 cm. The installation angle was the same as the control trials.

Forward-facing CRS The Safety 1st Alpha Elite 65 was used for all FF trials. The CRS was replaced after each trial. All were installed using the LATCH system with the lower connector strap and top tether tightened to 53 N (12 lbs) of tension each. The FF CRS "control" condition (good fit) is shown in Figure 4. The recline angle of the vehicle seat was set to accommodate the FF CRS without any gaps between the surfaces.

The FF CRS "vehicle seat too acute" condition is shown in Figure 5. The recline angle of the vehicle seat was adjusted

FIGURE 2 RF CRS pool noodle condition

FIGURE 3 RF CRS narrow base condition

FIGURE 4 FF CRS control condition (good fit)

FIGURE 5 FF CRS with vehicle seat too acute

to its most upright position so that a gap existed between the bottom portion of the CRS and the seat bight (shown in pink). The horizontal distance from the back of the CRS base to the seat bight was 12.3 cm. This angle represents realistic conditions reported in a previous CRS compatibility study [4].

The FF CRS "vehicle seat too obtuse" condition is shown in Figure 6. The recline angle of the vehicle seat was adjusted rearward so that a gap existed between the top of the CRS and the seat bight (shown in pink). The horizontal distance from the top of the CRS to the post of the vehicle seat head restraint was 14.0 cm. The recline angle of the vehicle seat was slightly exaggerated to achieve this incompatibility using this equipment.

FIGURE 6 FF CRS with vehicle seat too obtuse

Sled Pulse A sled pulse target of 35 kph and 24 g was used. The target was based off the proposed FMVSS 213 side impact pulse scaled to 35 kph [5]. An exemplar sled pulse is shown in Figure 7.

Data Analysis All trials used the Q3s anthropomorphic test device (ATD) with standard instrumentation. A seat belt load cell was attached to the top tether webbing for the FF CRS trials. All signals were processed per SAE J211 guidelines [6]. CRS and ATD kinematics were recorded with high speed video at 1,000 frames per second. TEMA Motion Analysis software (v3.8, Image Systems Motion Analysis) was used to analyze these metrics, and each is reported as displacement from initial position.

Relevant injury metrics are reported in the manuscript: Head Injury Criterion (HIC36), chest resultant acceleration, upper neck tension, lateral bending, and torsion, and top tether tension. Metrics were compared across installation conditions and also compared to current pediatric injury assessment reference values (IARVs) from Mertz et al. [7] and US regulatory limits in FMVSS 213 [8]. Peak values from additional sensor channels can be found in the Appendix.

Test Matrix Each condition was tested twice to establish the repeatability of the setup.

FIGURE 7 An exemplar sled pulse

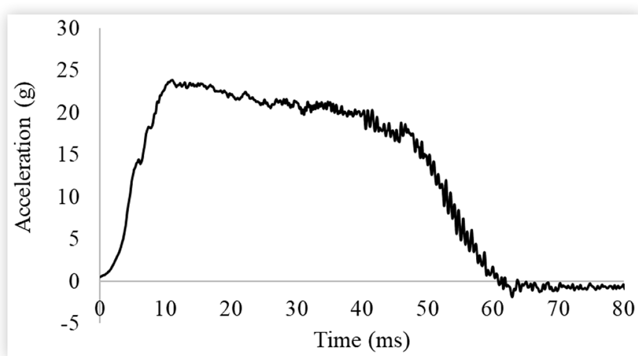


TABLE 1 Test matrix

Test #	CRS	Installation Condition
1	RF - Triumph	Control: Good fit
2	RF - Triumph	Control: Good fit
3	RF - Triumph	Pool noodle for recline angle
4	RF - Triumph	Pool noodle for recline angle
5	RF - Triumph	Narrow base
6	RF - Triumph	Narrow base
7	FF - Alpha Elite 65	Control: Good fit
8	FF - Alpha Elite 65	Control: Good fit
9	FF - Alpha Elite 65	Vehicle seat too acute
10	FF - Alpha Elite 65	Vehicle seat too acute
11	FF - Alpha Elite 65	Vehicle seat too obtuse
12	FF - Alpha Elite 65	Vehicle seat too obtuse

Results

RF CRS

The camera target in the upper left corner of each RF CRS was tracked using TEMA Motion Analysis software (Figure 8). The installations with the pool noodle translated slightly further laterally and downward compared to the control or narrow base conditions. The narrow base conditions translated the least amount laterally or downward. The bases of all RF CRS translated partially off the side edge of the vehicle seat. Additional photos of CRS translation are in Appendix A.

In all RF CRS installation conditions, the Q3s's head rolled on the side wing of the CRS. Figure 9 shows an overhead view of a control installation near the point of maximum excursion. The face of the Q3s is looking down at the ground as the neck is in torsion and lateral bending.

HIC36 values are slightly higher for the narrow base condition compared to other conditions, although they are below the FMVSS 213 limit of 1000 for all trials [8]. Chest resultant accelerations (over a 3 ms clip) were similar across all RF CRS installation conditions and all values were below the IARV of 92 g [7]. Upper neck lateral bending moments (Mx) were higher in the narrow base condition than the control condition. Upper neck torsion moments (Mz) did not show clear trends across conditions. The neck metrics exhibited poorer repeatability than the head and chest metrics in the RF CRS. The individual neck bending moments and torsion moments were below their respective IARVs (32 Nm and 21 Nm, respectively [7]). The compound effect of these two loading directions together is not well understood for children. Tabulated data from these channels can be found in Appendix B.

Lateral chest and shoulder deflections were slightly higher for the pool noodle condition, although differences were small and all deflection values were below the IARVs [7]. These data are included in Appendix C.

FIGURE 8 The traces show the movement of the upper left camera target on the back of the RF CRS. The CRS in the narrow base condition translated less laterally and downward than the control or pool noodle conditions

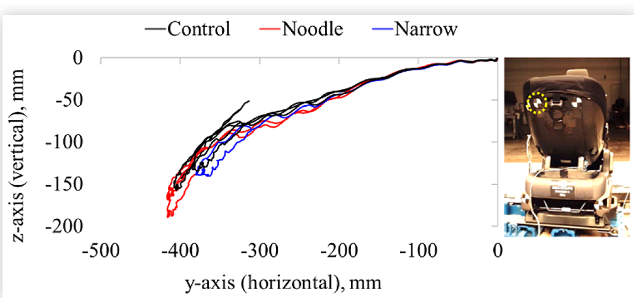
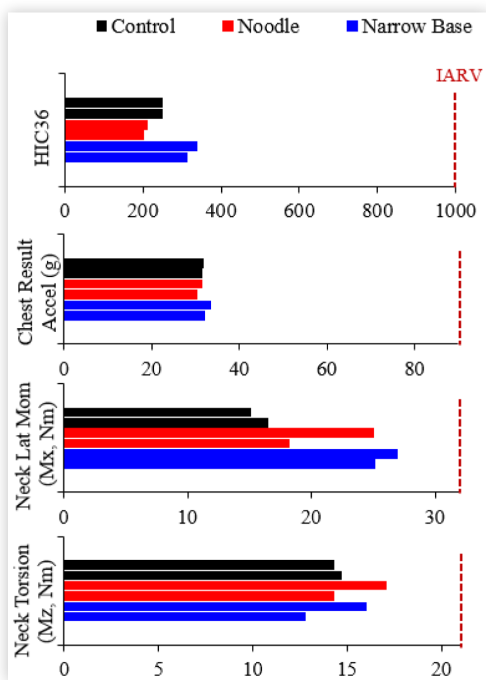


FIGURE 9 In all RF CRS conditions, the head of the Q3s rolled along the side wing and a torsional moment was produced on the neck. The image above shows an overhead view of a control installation

FIGURE 10 Injury metrics for each RF CRS installation condition are compared



FF CRS

The camera target on the ATD's face in each FF CRS was tracked using TEMA Motion Analysis software (Figure 11). The installations with the vehicle seat angle too obtuse produced the least amount of lateral and downward head excursion. The front corner of each FF CRS translated partially off the side edge of the vehicle seat (Figure 12). Additional photos of CRS and ATD translation are in Appendix A.

HIC36 values for FF CRS were highest for the control condition and lowest for the "vehicle seat angle too acute" condition (Figure 13). All HIC36 values were below the FMVSS 213 limit of 1000 [8]. Chest resultant acceleration was below the IARV of 92 g [7] for all trials. Neck tension (+Fz) did not show clear differences across installation conditions. Upper neck lateral bending moment (Mx) was slightly lower in the "vehicle seat too acute" condition compared to the other two conditions. The top tether load was noticeably greater for the "vehicle seat too acute" condition (973 N) compared to the "vehicle seat too obtuse" condition (364 N) and the control trials (408 N). The higher top tether loads in the "acute" condition did not appear to correlate with higher injury metrics in the ATD's head, neck, or chest. Tabulated data from these channels can be found in Appendix D.

FIGURE 11 The traces show the movement of the camera target on the ATD's face in FF CRS. The CRS in the "vehicle seat too obtuse" condition translated less laterally and downward than the control or acute conditions

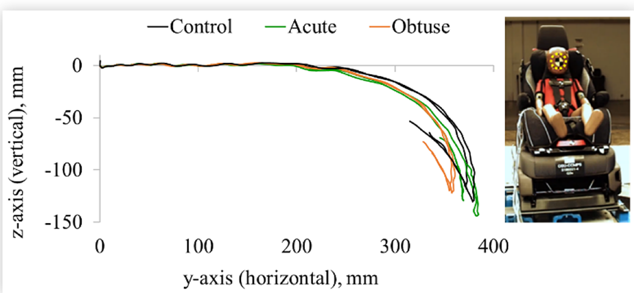
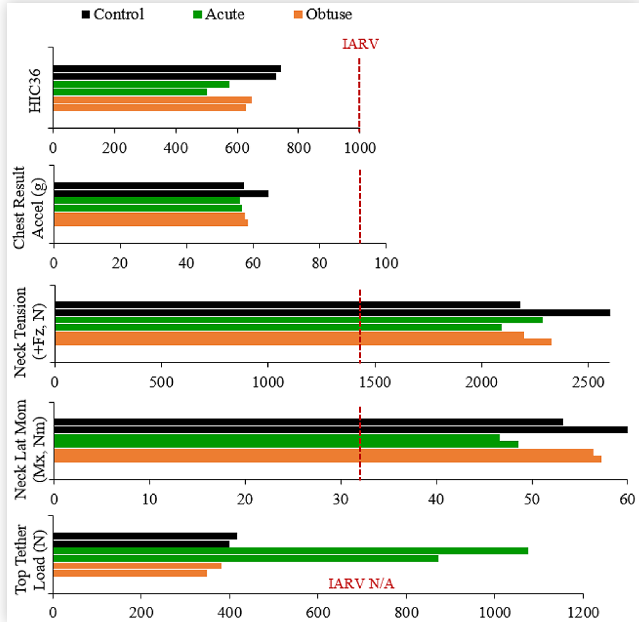


FIGURE 12 In all FF CRS conditions, the head of the Q3s translated past the CRS side wing. The image above shows the excursion of a control installation

FIGURE 13 Injury metrics for each FF CRS installation condition are compared



Lateral chest and shoulder deflections did not trend with installation condition. All deflection values were below the IARVs [7]. These data are included in Appendix E.

Discussion

Overall, only small differences were observed between the control conditions (i.e., good fit) compared to the non-ideal fit conditions examined here. The results indicate that these minor fit issues are not expected to cause significant detriments to safety in the far side impact scenario examined. As always, the instructions of both the CRS manufacturer and the vehicle manufacturer should always be followed to ensure the safest possible use of a CRS.

For the RF conditions, the narrow base condition showed slightly less movement and higher injury metrics, although the magnitude of these differences is likely not significant. All HIC36 values were low for RF CRS (Figure 10) because abrupt head strikes did not occur; the head simply rolled along the side wing of the CRS. All values were below the FMVSS 213 limit of 1000. HIC36 was highest for the narrow base conditions, followed by the control conditions, and were lowest for the pool noodle conditions. This pattern roughly correlates to the translation of each CRS. CRS installations which allowed for more lateral or downward movement resulted in lower HIC36 values because the Q3s had a longer period of time to decelerate more slowly.

For the FF conditions, the "acute vehicle seat" condition resulted in higher top tether loads compared to the control condition (973 vs. 409 N, respectively). This result may have been caused by relatively little of the back of the CRS interacting with the vehicle seat back during the crash event. The higher tether loads do not show any corresponding increase in upper neck loads. The acute seat condition also had the lowest HIC36 values and similar chest resultant accelerations compared to other FF conditions. Thus, the higher forces on the top tether do not appear to be a detriment for the child occupant in the far side impact scenario examined here. These results indicate that the top tether plays an important role when the fit of the CRS is not ideal.

Although not a primary goal of the study, the results suggest that the RF CRS protects the child occupant more effectively than the FF CRS in this far side impact condition. The RF CRS produced lower HIC36 values, chest resultant accelerations, and neck loads across all conditions compared to the FF CRS conditions. Thus, this work supports the American Academy of Pediatrics' guidelines to keep children RF for as long as possible.

Future work may be warranted to investigate the rolling of the head on the side wing in the RF condition. Specifically, one might examine whether different side wing designs could prevent these kinematics or whether the biofidelity of the Q3s neck is appropriate to evaluate these outcomes.

Limitations

This study is limited by small sample size. Only one RF CRS and one FF CRS model were tested. Different CRS may react differently to installation conditions, especially those with different base geometries or additional features such as load legs, RF tethers, ISOFIX, etc. The Q3s is the most biofidelic side impact ATD available for children, although it has not been well validated in far side impact conditions. A convertible RF CRS was chosen for this study because it easily accommodates the size of the Q3s ATD. No RF infant CRS with smaller occupants were tested because smaller biofidelic side impact ATDs are not available. It is unclear whether a RF infant CRS with a smaller occupant would be more or less sensitive to the installation conditions examined here. Additionally, only one vehicle seat model was included in this study. Vehicle seats with different underlying structures may affect the performance of the CRS. Manufacturers' instructions should always be followed regarding any minor incompatibilities between the CRS and vehicle.

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Acknowledgments

The authors would like to acknowledge the National Science Foundation (NSF) Center for Child Injury Prevention Studies at the Children's Hospital of Philadelphia (CHOP) and the Ohio State University (OSU) for sponsoring this study and its Industry Advisory Board (IAB) members for their support, valuable input and advice. The views presented are those of the authors and not necessarily the views of CHOP, OSU, the NSF, or the IAB members. Special thank you to Transportation Research Center, Inc.

Definitions/Abbreviations

ATD - Anthropomorphic test device

CRS - Child restraint system

FF - Forward-facing

FMVSS - Federal Motor Vehicle Safety Standard

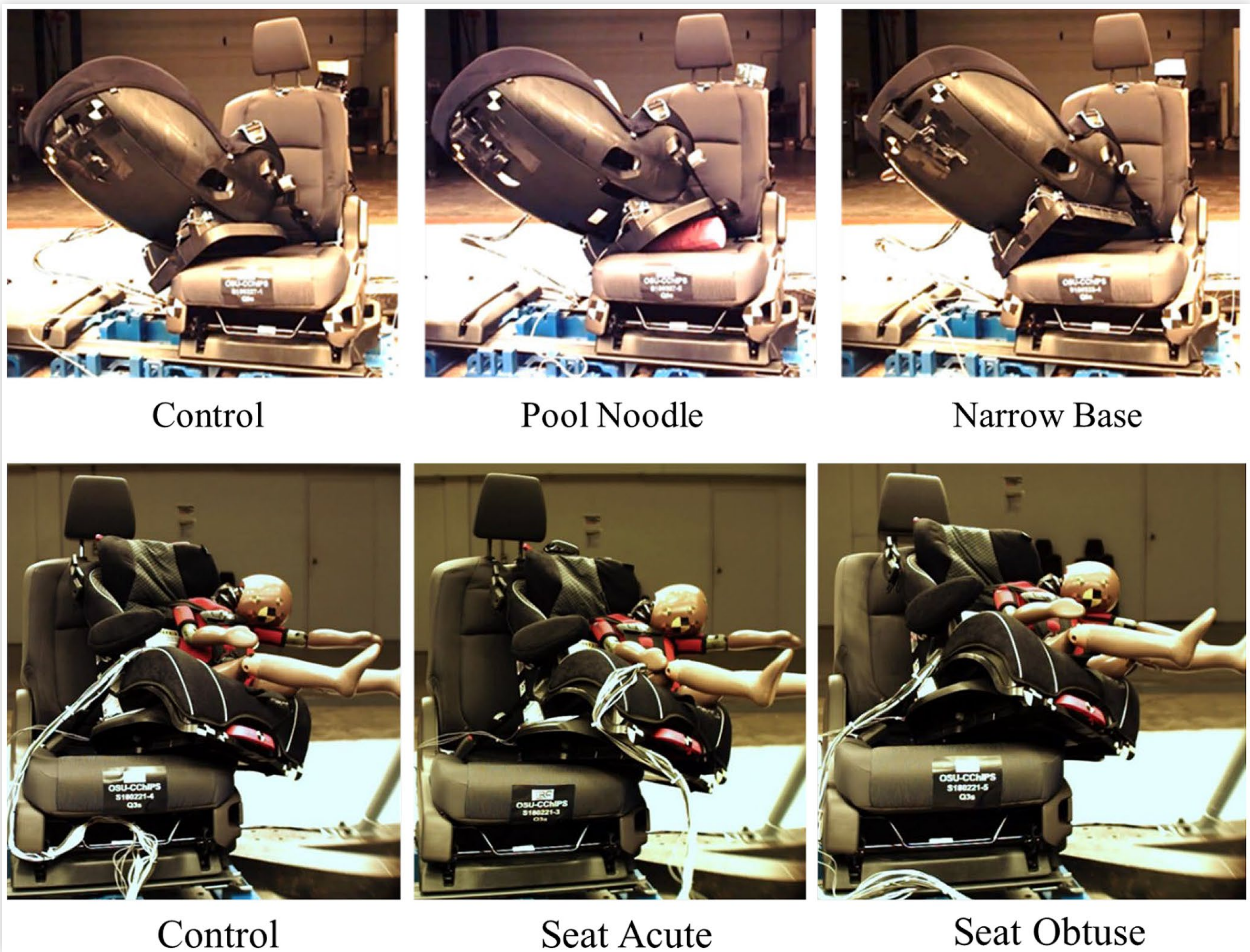
HIC - Head injury criterion

IARV - Injury assessment reference value

LATCH - Lower anchors and tethers for children

RF - Rear-facing

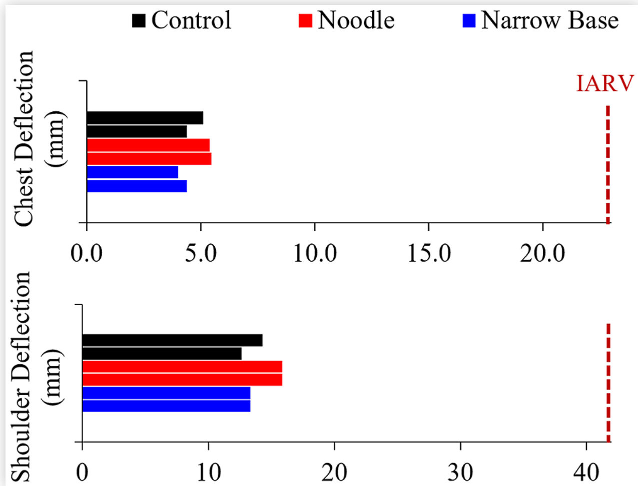
Appendix A: Excursion Photos



Appendix B: Data Table, RF CRS

	IARV	Control 1	Control 2	Noodle 1	Noodle 2	Narrow 1	Narrow 2
HIC36	1000	249	252	212	202	340	314
Chest Result Accel (g)	60.0	31.9	31.7	31.5	30.4	33.5	32.3
Neck Lat Moment, -Mx (Nm)	32.0	15.2	16.5	25.0	18.2	27.0	25.2
Neck Torsion, +Mz (Nm)	21.0	14.3	14.7	17.1	14.3	16.0	12.8

Appendix C: Deflections, RF CRS

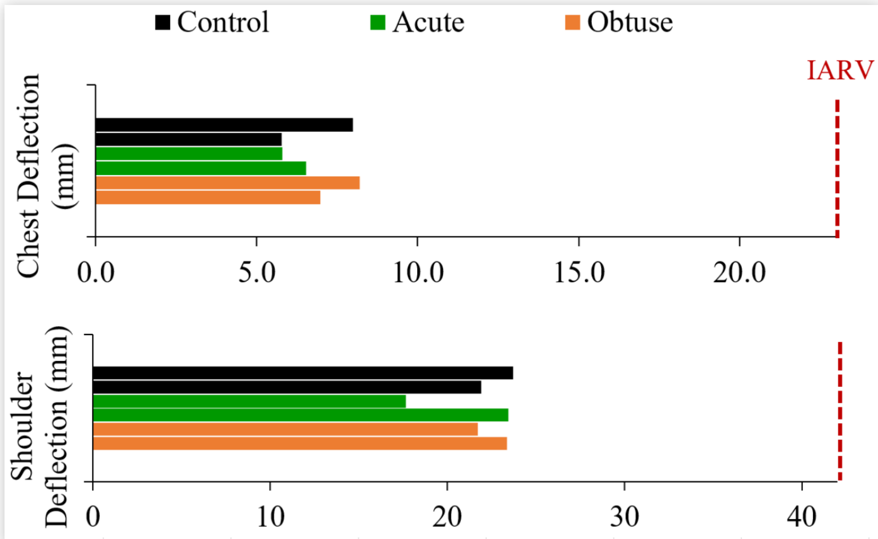


	IARV	Control 1	Control 2	Acute 1	Acute 2	Obtuse 1	Obtuse 2
Chest Deflection (mm)	23.0	5.1	4.4	5.4	5.5	4.0	4.4
Shoulder Deflection (mm)	42.0	14.3	12.6	15.9	15.9	13.3	13.3

Appendix D: Data Table, FF CRS

	IARV	Control 1	Control 2	Acute 1	Acute 2	Obtuse 1	Obtuse 2
HIC36	1000	744	728	573	502	648	627
Chest Result Accel (g)	60.0	57.3	64.6	56.1	56.8	57.4	58.5
Neck Tension, +Fz (N)	1430	2181	2600	2285	2092	2198	2329
Neck Lateral Moment, +Mx (Nm)	32.0	53.3	60.3	46.7	48.6	56.4	57.2
Top Tether Force (N)	N/A	418	399	1075	872	380	348

Appendix E: Deflections, FF CRS



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	IARV	Control 1	Control 2	Acute 1	Acute 2	Obtuse 1	Obtuse 2
Chest Deflection (mm)	23.0	8.0	5.8	5.8	6.5	8.2	7.0
Shoulder Deflection (mm)	42.0	23.7	21.9	17.7	23.5	21.7	23.4

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ISSN 0148-7191