PROTECTION OF CHILDREN IN CHILD RESTRAINT SYSTEMS IN OBLIQUE IMPACTS: RELATIVE MOTION OF THE CHILD AND CHILD RESTRAINT

Hans W. Hauschild
John R. Humm
Medical College of Wisconsin
United States

Kristy B. Arbogast
Matthew R. Maltese
The Children's Hospital of Philadelphia
University of Pennsylvania Perelman School of Medicine
United States

Frank A. Pintar
Narayan Yoganandan
VA Medical Center
Medical College of Wisconsin
United States

Bruce Kaufman
Children's Hospital of Wisconsin
Medical College of Wisconsin
United States

ABSTRACT

Objective. The objective was to determine the relative contribution of occupant versus child restraint system (CRS) kinematics to overall lateral head excursion for children in forward facing CRS (FFCRS) during oblique side impacts. As a secondary objective, the effect of the tether was investigated.

Methods and Data Sources. Sled tests were conducted with a FFCRS and Q3s Anthropomorphic Test Device (ATD) secured to a vehicle seat via LATCH, utilizing the center seat position. The vehicle seat and a simulated intruded door were secured to the sled at two angles (60 and 80 degrees from full frontal). Tests were conducted at 35 km/h delta-v, with and without a tether. Three-dimensional motion capture cameras captured kinematics of the ATD, FFCRS and vehicle seat. Head accelerations, neck forces and moments, and LATCH belt forces were obtained. The analysis focused on the relative contribution of the FFCRS motion versus the ATD motion with respect to the FFCRS on global lateral head excursion.

Results. The overall median lateral head excursion of the Q3s relative to the sled was 430 mm; approximately half of the excursion was the displacement of the head relative to the FFCRS (median 223 mm). Head angular motion relative to the FFCRS (median roll, pitch and yaw were -79, -55, and 34 degrees respectively) was greater than the overall angular motion of the CRS (median roll, pitch and yaw relative to the vehicle seat were -18, 5, and -17 degrees). Tether use influenced the FFCRS motion, but not the head motion within the FFCRS. Observations were similar across both test angles.

Discussion and Limitations. In order to gain a better understanding of side impact occupant protection for those restrained in FFCRS, this research examined both overall FFCRS motion as well as occupant motion within the FFCRS. Previous kinematic analyses typically examined only occupant motion relative to the vehicle frame of reference. A large proportion of the occupant's lateral head excursion was due to the head movement relative to the

FFCRS suggesting interventions that address both aspects of lateral kinematics – movement of the FFCRS as well as lateral bending/forward flexion of the occupant's torso/neck relative to the FFCRS – might result in overall injury mitigation. It was important to note that while tether use reduced FFCRS motion, it did not significantly increase the motion of the head relative to the FFCRS due to increased restraint of the FFCRS. Limitations include testing one FFCRS, one delta-v, and FFCRS attachment with a flexible LATCH system.

Conclusion. Occupant lateral head excursion and angular kinematics in oblique side impact crashes are related both to movement of the FFCRS as well as significant motion of the occupant relative to the FFCRS. This finding suggests two pathways for design intervention to mitigate overall occupant lateral excursion and potential impact with intruding structures, a common injury causation scenario for children in these crashes.

INTRODUCTION

Recent development of regulatory test procedures worldwide have been focused on evaluation of child restraint systems (CRS) in side impacts, but that work has mostly been focused on near side child occupants (Brown et al. 1997; NHTSA 2014b; Sullivan et al. 2011; Sullivan and Louden 2009). Research data suggests non-near side child occupants are being injured in side impact crashes as well (Huntley 2002; Arbogast et al. 2010; Brown et al. 2002; McCray et al. 2007; Orzechowski et al. 2003; Sherwood et al. 2003; Sullivan and Louden 2009). Injuries occurred when the child occupants contacted the vehicle interior, other CRS, their own CRS, and other occupants (Arbogast et al. 2010; Sullivan and Louden 2009; McCray et al. 2007; Charlton et al. 2007; Sherwood et al. 2003; Brown et al. 2002).

Previous work studied the protection of non-near side children in FFCRS during side impacts and examined the role of large side structures or 'side wings' designed to provide a means by which to limit lateral head excursion in oblique side impact loading. (Hauschild et al. 2015). Results demonstrated the side wings did not provide adequate head restraint as the ATD head rolled out of the FFCRS and displaced far enough to place the occupant at risk of impacting intruding side vehicle components.

Other research examined the role of the tether in controlling lateral head excursion in similar lateral oblique loading scenarios (Hauschild et al. 2016). To better assess the potential for head impact, intrusion was simulated by including a door structure on the test buck. All tests without a tether resulted in head contact with the simulated door, and two tests at near pure lateral (80 degree) impact direction with a tether also resulted in head contact. No head to door contact was observed in two tests at 60 degrees from full

frontal utilizing a tether. High speed video showed the FFCRS rotated and tipped (yawed and rolled) which caused the head to roll out of the FFCRS head side wings and make contact with the simulated intruded door.

The research described above as well as others related to child occupants in CRS has focused on the occupant motion relative to the vehicle seat fixture or vehicle used for testing (Ghati et al. 2009; Brown et al. 1997; Klinich et al. 2005; Hu et al. 2014; Hauschild et al. 2016; Sullivan and Louden 2009). In order to target strategies for improved design, it is important to understand the contributions of FFCRS motion to the overall motion of the head. Thus, the objective of this research was to quantify the relative occupant motion within the FFCRS during lateral oblique impacts compared to the FFCRS motion relative to the vehicle seat fixture for a center or far-side positioned occupant. Additionally, the role of the FFCRS tether attachment on head excursion and FFCRS roll and yaw was analyzed.

METHODS

The research methods for the current study were presented in previous research (Hauschild et al. 2016). A summary follows below.

A forward facing child restraint system (FFCRS) utilizing a Q3s ATD was secured to a reinforced production vehicle bench seat with a center LATCH for a series of nine sled tests. FFCRS were installed per the CRS manufacturer instructions and according to FMVSS 213 procedures (NHTSA, 2014a) when applicable. The FFCRS was secured to the bench seat in the center seating position using the available LATCH belt (Figure 1).

Figure 1. Vehicle seat fixture, FFCRS, and simulated door set up.

A simulated intruded door was secured on the left side of the bench seat. The static intrusion level was based on side impact New Car Assessment Program tests of small sport utility vehicles at the mid rear door crush level (163 to 296 mm, average 220mm, SD 40 mm) . Door and armrest padding on the simulated door was similar to that utilized in other testing, Dow Ethafoam (2.2 lb/cu ft density) and Armacell Oletx (4.0 lb/cu ft density) respectively (Sullivan et al. 2011, Hauschild et al. 2013). The simulated door panel surface was located 508 mm from the centerline of the center LATCH anchors.

Tests were conducted at oblique side impact angles. The vehicle bench seat was set at 80 degrees and 60 degrees from pure frontal.

Four tests were conducted at 80 degrees and five tests were conducted at 60 degrees. Test angles selected for this series were based on previous research (Arbogast et al. 2005; Hauschild et al. 2015; Maltese et al. 2007; McCray et al. 2007; Sullivan et al. 2011). The test matrix is presented in table 1.

Table 1.
Test matrix

Sled Test No.	Angle from Front	Int. Door	Tether	Delta v (km/h)	Peak G	Avg. G
201	60	Yes	Yes	34.8	23.0	17.7
202	60	Yes	Yes	34.9	23.4	17.6
203	60	Yes	No	34.6	23.0	17.8
204	60	Yes	No	34.6	23.1	17.8
205	60	Yes	No	34.6	23.4	17.6
206	80	Yes	Yes	34.6	23.7	17.4
207	80	Yes	Yes	34.6	23.6	17.4
208	80	Yes	No	34.6	23.8	17.5
209	80	Yes	No	34.7	23.8	17.6

The FFCRS 5 point harness was utilized to secure the Q3s ATD. CRS manufacturer instructions and FMVSS 213 procedures (NHTSA 2014a) were followed as applicable. ATD head accelerations, and upper neck loads and moments were collected according to SAE J211 recommended practices (Society of Automotive Engineers, 2014) and head injury values (HIC15) were calculated. Each test was conducted utilizing the proposed FMVSS 213 side impact pulse (NHTSA 2014a) scaled to a target 35 km/h delta-v. Pulse width remained at a maximum of 60 milliseconds (Figure 2).
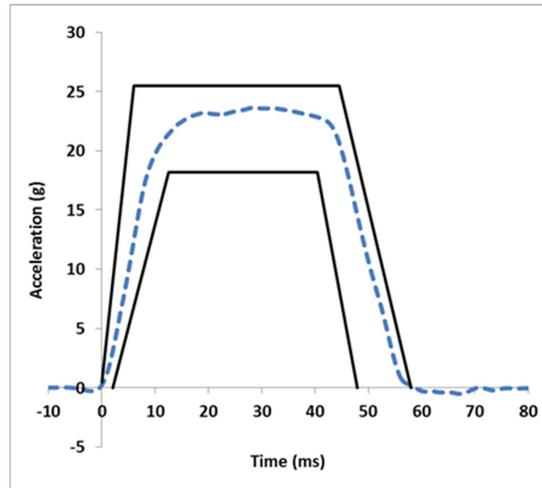
Figure 2. Sample pulse including upper and lower boundaries for proposed FMVSS 213 side impact pulse.

Three-dimensional motion capture cameras (TS40, Vicon, Denver, CO) recorded kinematics of the ATD, FFCRS and seat. The ATD, FFCRS and vehicle seat fixture had retroreflective markers secured on each in a noncollinear pattern. Ten markers were secured on each FFCRS. The ATD, FFCRS, and vehicle seat position were measured using a coordinate measuring machine (CMM) (FARO Technologies, Lake Mary, FL). Data from the CMM and 3-D motion cameras were processed to create local coordinate systems on each item of interest.

The ATD head center of gravity was calculated from the markers on the ATD head. Markers on the FFCRS were processed and utilized to create a FFCRS coordinate system to determine ATD motion with respect to the FFCRS. Head angular motion was calculated from the collected displacement data. Positive directions follow SAE conventions; positive X, Y, and Z directions are forward, right and down. To calculate FFCRS motion, the child restraint was treated as a rigid body, and the roll, pitch and yaw with respect to the vehicle seat were calculated from the retroreflective markers secured on the FFCRS. Locations of the ATD head and FFCRS were offset to their starting position for each test.

A Wilcoxon rank sum test was performed to evaluate the effect of tether use on the observed kinematics. The analysis was conducted on STATA/IC 13.1 for Mac revision 19 Dec 2014 (StataCorp, College Station, TX).

RESULTS

Overall kinematic results and discussion of the potential for head impact from this test series has been previously described (Hauschild et al, 2016). Results presented here will be limited to data examining the relative motion of the Q3s ATD within the FFCRS and the FFCRS motion relative to the vehicle seat fixture. Both the ATD and FFCRS moved toward the input pulse on the left of the Q3s. In all tests the FFCRS motion was limited by the simulated intruded door, and in 7 of 9 tests, including all tests without a tether, the ATD head contacted the simulated intruded door.

Head

The head lateral excursion relative to the FFCRS and relative to the vehicle seat fixture is presented in table 2. Head center of gravity forward, lateral and vertical excursion with respect to the FFCRS was not significantly different (p=0.07, 0.81, and 0.46) for seats restrained by the tether compared to those which were not. This finding was similar for forward and vertical head displacements with respect to the vehicle seat fixture (p =0.62 and 0.33 respectively); however the lateral head excursion with respect to the vehicle seat fixture did significantly differ with tether use (p=0.05).

The lateral displacement of the FFCRS accounts for 31% of the lateral ATD head excursion for tethered FFCRS and 51% for the untethered FFCRS. Lateral excursion results are presented in table 2 below.

Table 2.
Head CG and FFCRS lateral displacements sorted by tether use.

Test	Angle	Tether	Head Impact	Max Head Lateral Disp. wrt FFCRS mm	Max Head Lateral Disp. wrt SLED mm	Max Top CRS Target Lateral Disp. wrt SLED mm	Ratio of Lateral Disp. wrt SLED CRS/ Head
201	60	Yes	No	-223	-376	-120	32%
202	60	Yes	No	-216	-382	-119	31%
206	80	Yes	Yes	-244	-418	-126	30%
207	80	Yes	Yes	-251	-431	-124	29%
203	60	No	Yes	-211	-442	-226	51%
204	60	No	Yes	-219	-426	-218	51%
205	60	No	Yes	-202	-430	-231	54%
208	80	No	Yes	-216	-445	-211	47%
209	80	No	Yes	-218	-448	-211	47%

The head roll angle relative to the FFCRS and relative to the vehicle seat fixture is presented in table 3. Head center of gravity roll, pitch and twist angles with respect to the FFCRS were not significantly different (p= 0.14, 0.90 and 0.46 respectively) for seats restrained by the tether compared to those which were not.

When the tether was utilized the FFCRS roll angle decreased and the yaw angle increased. FFCRS angular motion was significantly different depending on tether use; roll, pitch and yaw (p = 0.01, 0.02 and 0.01 respectively). The FFCRS maximum roll, pitch and yaw angles and associated timing are presented in Table 4.

Table 3.
Head CG and FFCRS roll angles sorted by tether use.

Test	Angle	Tether	Head Impact	Max Head CG Roll wrt FFCRS deg	Max Head CG Roll wrt SLED deg	Max FFCRS Roll wrt SLED deg	Ratio of Roll Angle wrt SLED CRS/ Head
201	60	Yes	No	-67	-79	-14	18%
202	60	Yes	No	-69	-80	-14	18%
206	80	Yes	Yes	-75	-89	-13	15%
207	80	Yes	Yes	-69	-79	-12	15%
203	60	No	Yes	-56	-70	-18	26%
204	60	No	Yes	-79	-94	-18	19%
205	60	No	Yes	-57	-74	-19	26%
208	80	No	Yes	-48	-69	-18	26%
209	80	No	Yes	-52	-71	-18	25%

Table 4.
FFCRS roll, pitch and yaw maximum angles sorted by tether use.

Test	Angle	Tether	Head Impact	FFCRS Roll wrt SLED Deg.	Time ms	FFCRS Pitch wrt SLED Deg	Time ms	FFCRS Yaw wrt SLED Deg	Time ms	FFCRS Angle Resultant wrt SLED deg	Time ms
201	60	Yes	No	-14	122	5	138	-20	74	24	124
202	60	Yes	No	-14	124	4	134	-21	74	24	75
206	80	Yes	Yes	-13	86	4	60	-23	67	27	67
207	80	Yes	Yes	-12	92	4	64	-24	65	27	64
203	60	No	Yes	-18	84	7	247	-12	67	22	80
204	60	No	Yes	-18	76	5	87	-13	66	22	75
205	60	No	Yes	-19	93	7	106	-13	68	22	86
208	80	No	Yes	-18	75	6	71	-16	69	25	71
209	80	No	Yes	-18	67	5	76	-17	65	25	66

Upper Neck

Upper neck tension and flexion/extension moment (Y) were not significantly different based on tether use (p= 0.81 and 0.27 respectively). Upper neck lateral bending moment (X) was significantly different based on tether use (p=0.01). Detailed upper neck results were presented in Hauschild et al. (2016).

DISCUSSION

In order to improve performance of FFCRS in lateral oblique crashes, this research examined the occupant motion with respect to the FFCRS as well as the overall FFCRS motion. Previous research studies examining this crash direction have only examined the child ATD motion with respect to the seat fixture (Ghati et al. 2009; Brown et al. 1997; Klinich et al. 2005; Hu et al. 2014; Hauschild et al. 2016; Sullivan and Louden 2009). This study is an extension of previous research examining the influence of the tether and the possibility for head impact during oblique side impacts (Hauschild et al. 2016).

Previous studies examining head excursion in oblique side impact testing found excursion levels which could potentially expose the center positioned child occupant to intruding vehicle components or a far-side child occupant to impacts with adjacent occupants (Arbogast et al. 2010, Ghati et al. 2009; Hauschild et al. 2015; Sherwood et al. 2003).

This study highlighted that the displacement of the FFCRS is a factor in the peak lateral head excursion values. One-third to one-half of the overall lateral head excursion is derived from the motion of the FFCRS itself demonstrating the importance of controlling the FFCRS motion for limited occupant excursion. When considering angular motion, the contribution of the FFCRS motion was less, representing only 15 0 25% of the overall head roll angle.

This study also examined the influence of the FFCRS tether on these relationships. The head CG lateral excursions with respect to the vehicle seat fixture were significantly lower when the tether was utilized (median 400 mm with tether and 442 mm without tether). The tether is primarily designed to control forward excursion of the FFCRS in frontal crashes; these data demonstrate that it is also effective in controlling lateral motion in side impacts. In contrast the head CG lateral excursions with respect to the FFCRS trended slightly higher when the tether was utilized (median 234 mm with tether and 216 without the tether). This is likely due to the lateral restraining force the tether provides to the FFCRS such that the head's response to the crash energy requires it to move farther relative to the child restraint. The FFCRS displacement contributed approximately 50% of lateral excursion when the tether was not utilized; whereas when the tether was used that ratio was smaller (approximately 30%).

When the tether was utilized, the FFCRS had increased yaw and decreased roll with respect to the

vehicle seat fixture, which corresponded to less lateral displacement at the top of the FFCRS and less overall lateral head displacement. The roll angles and lateral displacements were limited by the interaction with the simulated intruded door and may have been higher if the tests had been conducted without the simulated door or if the FFCRS was placed in a far-side seat position where interaction with the door is less likely. Tests with higher FFCRS roll angles and lateral head excursions trended to higher HIC values due to the intruded door contact (Hauschild et al. 2016).

The kinematic observations are summarized in Figure 3 below displaying the FFCRS motion. The figure demonstrates the additional lateral movement of the upper portion of the untethered FFCRS (dotted lines) which leads to greater ATD lateral head excursions.

The figure also shows the untethered (dotted lines) FFCRS has more lateral travel and rebound past its starting position. This may lead to injury for a far side occupant who impacts the adjacent vehicle side structure on rebound. The study by Brown et al. (1997) also indicated that the far side occupant could potentially have injuries on rebound.

The FFCRS motion also influences upper neck moments. The lower roll angles and higher yaw angles of the tethered FFCRS had higher upper neck lateral bending moments which directly correlate to lateral head displacements within the FFCRS ($r^2 = -0.89$). In contrast, there was not a relationship between neck moments and lateral head excursion with respect to the vehicle seat fixture. As the FFCRS is held in place by the tether the occupant tends to roll out more relative to the FFCRS thereby increasing the lateral bending neck moment.

Although there currently is no criteria for neck lateral bending moments (X) specifically for the Q3s ATD, values are approaching or in some case exceeding the recommended IARV for a 3 year old in lateral bending (32 Nm) (Mertz et al. 2003). Neck flexion/extension moments (Y) were slightly higher with tether use but did not exceed the recommended maximum IARV (21 Nm) (Mertz et al. 2003). The results suggest other pathways related to vehicle and FFCRS interaction to control the head and neck motion may be required to reduce neck tension and moments.
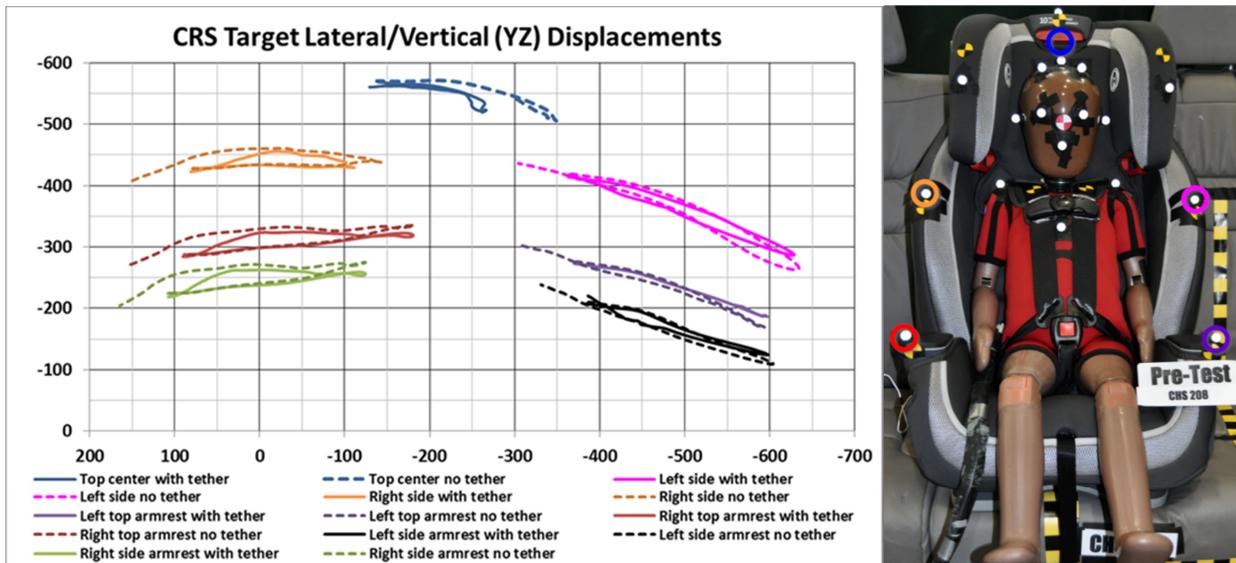

Figure 3. Exemplar 2-dimensional displacement of the targets on the FFCRS from the 80 degree tests, demonstrating FFCRS motion in lateral and vertical planes (solid lines – tether use; dashed line – non-tether use). Select marker locations are circled in image on right.

Limitations

Limitations of this study include the testing of one FFCRS, one input pulse, one delta-v, and a single vehicle seat fixture. The FFCRS was a common child restraint and had no distinguishing design features which suggest its response would be different from others. The FFCRS was attached using the available single LATCH belt and tether webbing system. It is likely that the results would be different for other lower attachment methods; this should be the focus of future exploration. A stock production bench seat from a small SUV type vehicle was used for testing. Other seat types may have an effect on occupant response.

CONCLUSION AND RECOMMENDATIONS

This research found the occupant lateral displacement and angular kinematics are related to the motion of the FFCRS in oblique side impact crashes. A substantial proportion of the occupant's lateral head excursion was due to the FFCRS movement relative to the vehicle seat fixture. This result varied by tether use such that 50% of the overall lateral head excursion was due to FFCRS motion in untethered FFCRS while only 30% of the overall lateral head excursion was due to the FFCRS motion when tethered. It was noted that while tether use reduced FFCRS motion, it did not significantly increase the motion of the head relative to the FFCRS due to increased restraint of the FFCRS. Interventions that address both aspects of lateral kinematics – movement of the FFCRS as well as lateral bending/forward flexion of the occupant's torso/neck relative to the FFCRS – might mitigate overall lateral excursion and potential impact with intruding structures, a common injury causation scenario for children in these crashes.

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