KINEMATICS OF THE Q3S ATD IN A CHILD RESTRAINT UNDER FAR-SIDE IMPACT LOADING

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ABSTRACT

A series of sled tests was performed using the Q3S anthropomorphic test device (ATD) and the ECE R44 sled buck to study CRS and pediatric occupant kinematics in far-side impacts. Using one model of convertible child restraint system (CRS), tests were performed using a 24 km/hr, 20 g pulse to compare ATD and CRS response to lateral loading in both forward-facing (FF) and rearward-facing (RF) configurations. The effects of initial arm postures on the ATD's motion were examined. Remaining tests examined how various methods of securing the CRS to the vehicle seat affect lateral movement of the CRS and ATD. Tests were run using four tether anchorage locations for the forward-facing configuration and three tether anchorage locations for the rearward-facing configuration. In addition, the CRS was installed using different combinations of vehicle belt restraints and LATCH systems.

Arm position influences ATD kinematics, including head excursion. Placing the arms at the ATD's side, rather than angled or extended forward, reduced lateral head excursions by about 30 mm. In forward-facing tests, using the 3-point-belt with the shoulder belt anchored on the impacted side provided the greatest reduction in lateral head excursion compared to a lap-belt only condition. Using a tether in forward-facing tests also reduced maximum head excursion. In rear-facing tests, using any type of LATCH reduced head excursion compared to conventional installation with a lap belt. In a rear-facing configuration, some tether configurations reduced head excursion of the ATD. In addition to evaluating head excursion, head retention within the child restraint was also noted. The key to retaining the ATD head within the CRS is to minimize rotation of the CRS about a vertical axis. This was achieved in a forward-facing orientation through rigid LATCH lower attachments, a 3-point belt with the shoulder belt anchored on the impacted side, or a reverse belt path with a lap belt. The ATD head was not retained within the CRS in any of the rear-facing tests.

INTRODUCTION

Side impacts are a leading cause of fatalities and injuries to both pediatric and adult occupants in motor-vehicle crashes. In 1999, 32% of children ages 0-12 who died in motor-vehicle crashes were in side impacts (NHTSA 2002). CDS data from 1993-2000 indicate that 16% of nonfatal pediatric crash injuries resulted from side impacts.

Because occupants seated on the struck side of a vehicle in a side impact collision (i.e., near-side occupants) are at the highest risk of serious and fatal injuries because of direct loading by the struck door, most efforts to develop procedures for assessing side impact protection have focused on the near-side occupant. Recent efforts by the ISO/TC 22/SC 12/WG 1 to evaluate CRS performance relative to pediatric injuries in side impacts have concentrated on recreating the occupant loading conditions produced by an intruding door in side impact sled tests (Langwieder et al. 1997, Paton et al. 1998). However, while CRS design is a factor in reducing injuries to near-side pediatric occupants, a significant portion of the near-side injury problem must be addressed through changes in vehicle design rather than CRS design.

Unlike injuries and fatalities caused by door intrusion, preventing injuries from far-side impact conditions is almost exclusively an issue of restraint system design. Key elements for obtaining good CRS performance in side impact are keeping the CRS and ATD within the occupant space, retaining the

ATD's head within the CRS, and padding any CRS surface that the ATD is likely to contact. Kamren et al. (1993) noted that if head retention is a goal of improving CRS side impact performance, simulating an intruding door is less important. Procedures developed to improve impact protection for children under non-contact loading conditions are likely to be less complex than procedures for near-side occupants using a simulated intruding door. In addition, designing a CRS to prevent injury to the far-side occupant would likely have some benefit for near-side occupants, but allow separation of CRS-based improvements from vehicle-based improvements in side impact protection.

Crash studies also indicate that a substantial proportion of side impact injuries and fatalities can occur to pediatric occupants not seated directly adjacent to the impact site, and that many injuries occur without vehicle intrusion. Analysis of 1999 FARS data indicated that 45% of pediatric side impact fatalities were to center or far-side occupants (NHTSA 2002). Arbogast et al. (2000) studied 93 children aged 0 to 15 years in 55 side impacts. Crashes with no or minor intrusion produced 42% of significant injuries, including half of serious head injuries. Of the 8 seriously injured children aged 0-4, two were in far-side locations.

Australian regulatory and research testing has focused on evaluating CRS in both far-side and near-side impact conditions without an intruding door. They have examined the effect of different methods of securing the CRS to the vehicle (flexible LATCH, rigid LATCH, 3-point belt) and different tether configurations on CRS performance in side impact (Brown et al. 1995, 1997). NHTSA's preliminary CRS side impact protection research (Esselman 2004, NHTSA 2002) has focused on evaluating ATDs for side impact testing and compared flexible and rigid LATCH anchors and the performance of existing CRS models using both far-side impact conditions and near-side tests with a fixed-position simulated door.

A limitation of previous testing to examine pediatric side impact response has been the absence of pediatric ATDs developed for use in side impact testing. The testing done by ISO and in Australia has used the TNO P series of ATDs, which were designed for frontal impact conditions. NHTSA testing in support of the ANPRM on CRS side impact testing used a Hybrid III 3YO ATD, also a frontal-impact ATD. Adult side impact response corridors have been scaled and used to specify performance standards for pediatric side impact ATDs (van Ratingen et al. 1997, Irwin et al. 2002.) The first attempt to build a pediatric ATD meeting these specifications was the Q3, which was designed to meet both frontal and side impact requirements (van Ratingen et al. 1999). Initial testing with the ATD indicated that it did not meet all of the specifications, so both frontal and side impact versions of the ATD were developed. The side impact version, the Q3S, was evaluated by NHTSA with fairly good results (Esselman 2004). A few modifications have since been made to improve the neck and shoulder response, and the research program described in this paper uses this latest version of the ATD.

Another limitation of previously published studies is that most tests analyzing the effect of different methods of securing CRS to the vehicle were performed with prototype versions of LATCH anchors and attachments. Because LATCH systems are now required and widely available in the U.S. market, comparison of commercially available LATCH configurations with vehicle belt securement methods is now possible. In addition, some test configurations in the current program were selected to evaluate "misuse" conditions identified in the field for their possible advantages or disadvantages under side impact loading.

The goal of the current research program was to improve understanding of CRS kinematics under non-contact side impact loading using an ATD, the Q3S, designed specifically for this purpose. Key issues examined are the effect of initial arm placement on ATD kinematics and the effects of both primary securement and tether use on ATD and CRS kinematics under far-side impact loading.

METHODS

Overview

A series of sled tests was conducted to examine kinematics of the Q3S and CRS in forward-facing and rear-facing installations during lateral impact loading without contact with the vehicle interior. The ECE R44 buck was chosen for the study because it was easily configurable to a 90 degree impact orientation and has been used for side impact testing by others. A single model convertible CRS with a five-point harness, the Evenflo Titan V, was used in all tests; each CRS was used in one forward-facing and one rear-facing test. This CRS has a rear-facing weight limit of 13.6 kg, so the Q3S, which is just over this limit with a weight of 14.5 kg, could be used in both forward-facing and rear-facing orientations. The 24 km/hr, 20 g pulse proposed by the NHTSA for side impact testing of CRS (NHTSA 2002) was used in all tests.

Table 1 lists the ATD instrumentation used in the test series. Lateral displacements of the chest and shoulder were measured using an IRTRACC sensor, and the CRS was instrumented with six linear accelerometers mounted on a bar attached to the impacted side of the CRS. All belt loads were measured using webbing load cells. All transducer signals were filtered according to the specifications of SAE J211. Peak lateral head excursion of the leading edge of the head relative to the pre-impact head position was digitized from images collected by an overhead high-speed video camera. Containment of the ATD head within the seat was evaluated using the overhead camera view by determining if any portion of the CRS was visible beyond the head at the time of peak head excursion. Results presented in this paper are limited to maximum head excursions, head containment, and evaluation of kinematics from the videos, but the remaining data are included in a final report on the program (Klinich et al. 2005).

Table 1.
ATD instrumentation

Component	Measurement	Axes
Head	Acceleration	x, y, z
Upper Neck	Force	x, y, z
Upper Neck	Moment	x, y, z
Chest	Acceleration	x, y, z
Pelvis	Acceleration	x, y, z
Lumbar	Force	x, y, z
Lumbar	Moment	x, y, z

Effect of ATD Arm Position

Table 2 lists the test matrix used to evaluate the effect of initial arm position on ATD kinematics. These tests were performed with the CRS secured in a forward-facing orientation using a lap belt and top tether. Figure 1 illustrates the baseline arm position, as well as two other arm positions tested. In the baseline arm position, the ATD hands were placed on the tops of the thighs. In the second position, the upper arms were placed along the sides of the torso. In the third position, the arms were extended fully forward.

Table 2.
Matrix of arm position tests

Test	Arm Position
GU0405	Hands on lap
GU0407	Arms extended horizontally
GU0408	Arms at sides

Figure 1. Initial ATD positions for tests varying arm posture: baseline with hands on lap (left), arms at sides (middle), and arms extended (right).

Securing CRS Forward-Facing

Table 3 lists the tests used to evaluate how different methods of securing the CRS to the vehicle seat affect kinematics during side loading of forward-facing (FF) CRS. The baseline condition is test GU0420, with the CRS secured by a lap belt only and the belt tension adjusted to the FMVSS 213 requirement of about 50 N. Four other conditions (GU0421 through GU0501) using standard belts without tethers were also tested: higher tension lap belt (roughly double FMVSS 213 specifications), three-point belt (both passenger and driver configurations), and a reverse belt path, which is illustrated in Figure 2. The reverse belt path routes the belt around the front of the CRS on each side and around the back of the CRS. Although the particular CRS used in these tests is not specifically designed to use this type of belt routing, other CRS are available for which this routing is recommended. The reverse belt path configuration was tested because it was hypothesized that it might reduce rotation of the CRS. For the three-point belt tests, the 3PBL, or driver configuration, anchors the shoulder belt over the left shoulder of a forward-facing ATD (toward the impacted side), while the 3PBR, or passenger configuration, anchors the shoulder belt over the right side of a forward-facing ATD (toward the non-impacted side).

Table 3.
Matrix of forward-facing securement tests

Test	Main Securement	Tether Anchor
GU0419	Lap belt @ 50 N	Behind seatback
GU0420	Lap belt @ 50 N	None
GU0421	Lap belt @ 110 N	None
GU0422	3PBR	None
GU0423	3PBL	None
GU0501	Reverse lap belt	None
GU0502	Flexible LATCH through belt path	None
GU0506	Attached Flex LATCH	None
GU0504	Flex LATCH through belt path + 3PBL	None
GU0505	Lap belt @ 50 N	Roof
GU0507	Rigid LATCH	None
GU0509	Lap belt @ 50 N	Floor

GU0510	Lap belt @ 50 N	Under seat

Figure 2. Annotated photo showing reverse belt routing used in test GU0501.

Four tests were run using different types of LATCH lower attachments. Test GU0502 used the flexible attachment that was provided with the CRS, which is a length of webbing with a hook-on connector at each end that is routed through the belt path of the CRS. Test GU0504 used both a three-point belt (shoulder belt on left side) and the provided flexible LATCH attachment to secure the CRS. This condition has been identified as a common LATCH misuse installation, but was hypothesized to have possible benefits in side impact. In test GU0506, the CRS was modified by clamping short lengths of webbing with LATCH hook-on connectors to each side of the CRS, as shown in Figure 3. It was hypothesized that this configuration might reduce lateral sliding of the CRS. The webbing was attached to the CRS so it would provide the same installed belt angle as when the seat was secured with the flexible LATCH attachment routed through the belt path. Test GU0507 used rigid LATCH attachments, also illustrated in Figure 3, in which the CRS was modified by bolting rigid LATCH attachments from another CRS to each side. The rigid attachments were secured to the CRS so the orientation of the installed CRS matched that of the installation with a lap belt only.

The tether anchor locations tested are illustrated in Figure 4. The baseline location represents a tether anchor location that would typically be found in a sedan, while the roof, floor, and under seat locations represent possible tether anchor locations in minivans and SUVs. Generic tether anchor hardware was bolted in these locations to rigid structures on the sled buck.

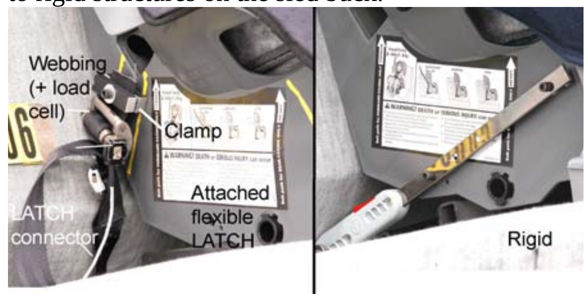

Figure 3. FF CRS modified with to have attached flexible LATCH attachments (left) and rigid LATCH attachments (right).

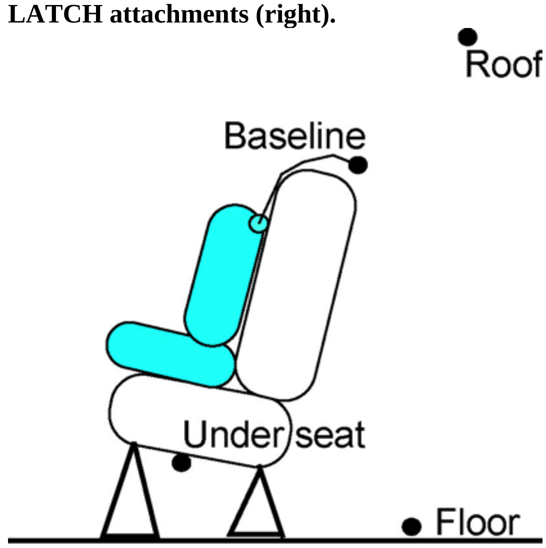

Figure 4. Illustration of four tether anchorage locations tested with a FF CRS (not to scale).

Securing CRS Rear-Facing

Table 4 lists the conditions used to evaluate methods of securing the CRS to the vehicle in the rear-facing configuration. Test GU0511 is considered the baseline test condition, using a lap belt only with the tension set at the FMVSS 213 level of about 50 N. Three other conditions that were tested in FF mode using only vehicle belts to secure the CRS were also tested in RF: higher belt tension and 3-point belt, both passenger and driver configurations. The geometry of this CRS did not allow it to be installed using a reverse belt path in the RF orientation.

The same four installations using LATCH systems that were tested in FF were also tested rear-facing. The CRS used in two tests required modifications (attached flexible LATCH attachments and rigid LATCH attachments) shown in Figure 5.

When modifying the CRS to install these LATCH attachments, the front part of the CRS was trimmed away to avoid interference when connecting the lower LATCH attachments to the lower LATCH anchorages.

Table 4.
Matrix of rear-facing securement tests

Test	Main Securement	Tether Anchor
GU0511	Lap belt @ 50 N	None
GU0512	Lap belt @ 110 N	None
GU0513	3PB Left	None
GU0514	3PB Right	None
GU0515	Flex LATCH through belt path	None
GU0516	Attached Flex LATCH	None
GU0517	Flex LATCH + 3PBL	None
GU0518	Rigid LATCH	None
GU0519	Lap belt @ 50 N	Over to baseline
GU0520	Lap belt @ 50 N	Down to floor
GU0521	Lap belt @ 50 N	Down under seat

Figure 5. RF CRS modified with attached flexible LATCH attachments (left) and rigid LATCH attachments (right).

Three tether anchorage locations were tested with RF CRS as illustrated in Figure 6, although tether use in a rear-facing configuration is not recommended for this CRS. Test GU0519 used an Australian RF tether configuration, in which the tether is routed over the top of the CRS to a tether anchorage location behind and above the vehicle seat. Test GU0520 used the Swedish RF tether configuration, in which the tether is routed down to the floor in front of the vehicle seat. Test GU0521 used a variation of the Swedish approach, routing the tether down but to a tether anchorage attached to the bottom of the vehicle seat. This type of installation has been identified as a RF misuse of tethers provided with convertible CRS for use in FF installations.

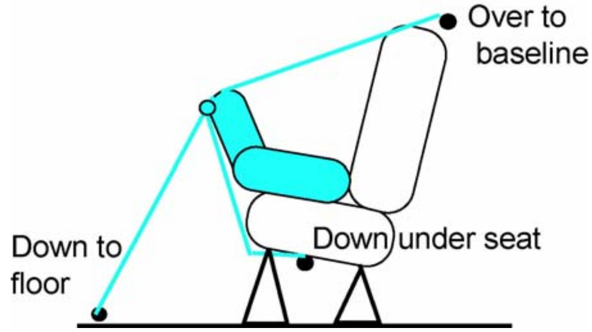

Figure 6. Three tether anchorage locations tested with RF CRS (not to scale).

RESULTS

Effect of Arm Position

Figure 7 shows the overhead high-speed video frames at the time of peak lateral head excursion for the three tests comparing initial arm placement, while the maximum head excursion values are plotted in Figure 8. The excursions for the ATD hands on lap are similar results to those with the arms extended, but placing the arms at the sides resulted in almost 30 mm less head excursion.

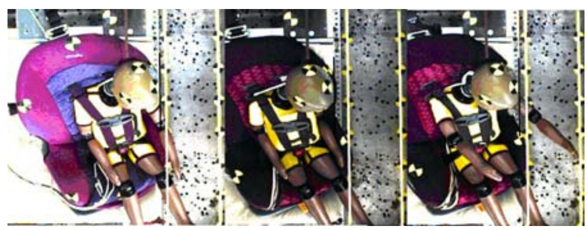

Figure 7. Peak head excursions with ATD arms initially placed on lap (left), at sides (center), and extended (right).

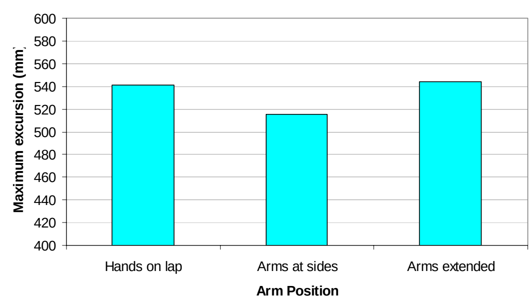

Figure 8. Maximum lateral head excursions for different initial arm positions.

Securing Forward-Facing CRS

Variations using Conventional Belts

Figure 9 illustrates the peak lateral head excursions for the five forward-facing tests that secure the CRS with conventional vehicle belts, while Figure 10 plots the magnitudes of these peak head excursions. On Figure 9 (and subsequent illustrations of FF excursion), reference lines on the sled platform have been highlighted on the photos. A black line in each photo indicates maximum lateral head excursion, while a lighter line indicates maximum CRS excursion where visible. A line across the front edge of the CRS has been highlighted in white to indicate the angle of the CRS. White reference lines have also been drawn through targets on the top of the CRS and on the top of the sled buck to assist in visualization of lateral CRS translation.

Compared to the baseline lap-belt-only condition, increasing belt tension and using a right 3-point belt decreased maximum head excursion slightly, but produced kinematics that were very similar to the baseline condition. Using the left (impacted) 3-point belt substantially reduced head excursion (by 142 mm), retained the head within the CRS, and reduced both translation and rotation of the CRS. Using a reverse belt path increased head excursion by allowing greater translation of the CRS, but contained the head and eliminated rotation of the CRS.

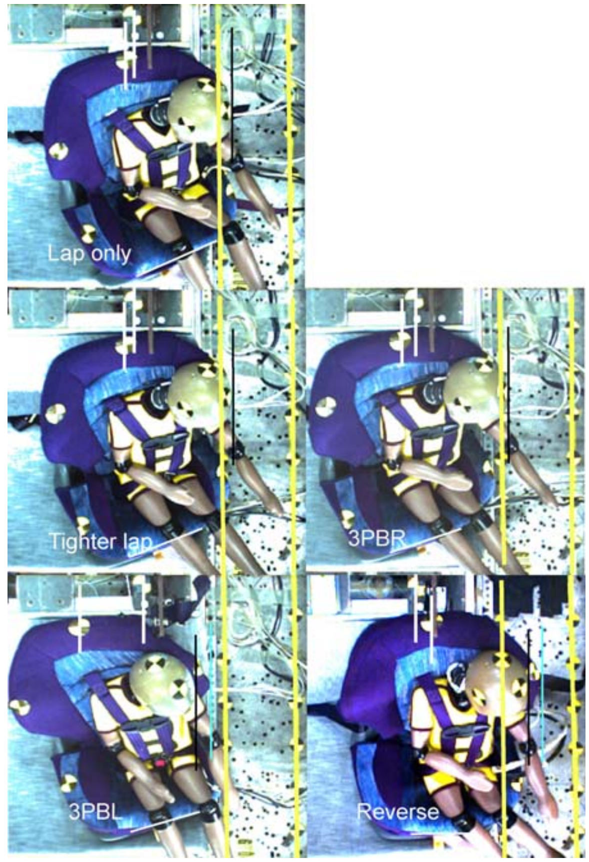

Figure 9. Peak head excursions of FF tests using lap only (top left), tighter lap belt (mid left), right 3-point-belt (mid right), left 3-point-belt (lower left), and reverse belt path (lower right).

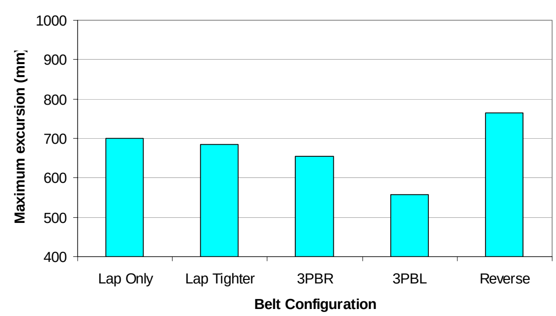

Figure 10. Maximum excursions of the head leading edge in FF tests with the CRS secured using different conventional belt configurations.

Variations using LATCH

The maximum head excursion values in the four FF tests with the CRS secured using variations of LATCH are shown in Figure 11 compared to the baseline lap-belt-only test condition. These maximum head excursions are illustrated in Figure 12. The three tests using just the LATCH system reduced head excursions slightly compared to the lap-belt-only test, but the greatest reduction in head excursion occurred when a left 3-point belt was used in addition to the flexible LATCH attachments routed through the belt path. The kinematics were similar for the two tests run with the flexible LATCH attachments (routed through the belt path or attached to the CRS), although the condition with the attached flexible LATCH appeared to have slightly less CRS rotation. Using both the left 3-point-belt and the flexible LATCH attachments routed through the belt path resulted in the smallest peak head excursion by reducing translation of the CRS back. In this test, the head was not retained. Surprisingly, using rigid LATCH attachments (without a tether) did not substantially reduce head excursion compared to baseline conditions, although it did retain the head within the CRS and eliminated rotation of the CRS. Among all forward-facing tests run, the lateral translation of the top of the CRS was the largest when the CRS was secured by rigid LATCH attachments.

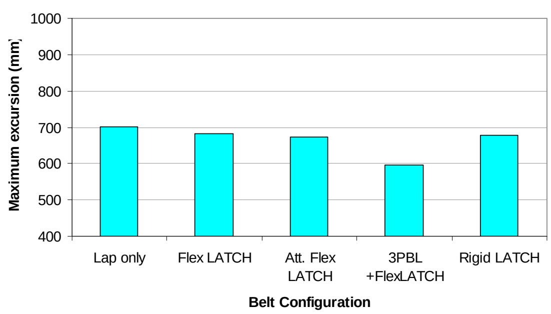

Figure 11. Maximum excursions of the head leading edge in FF tests with the CRS secured by different LATCH configurations.

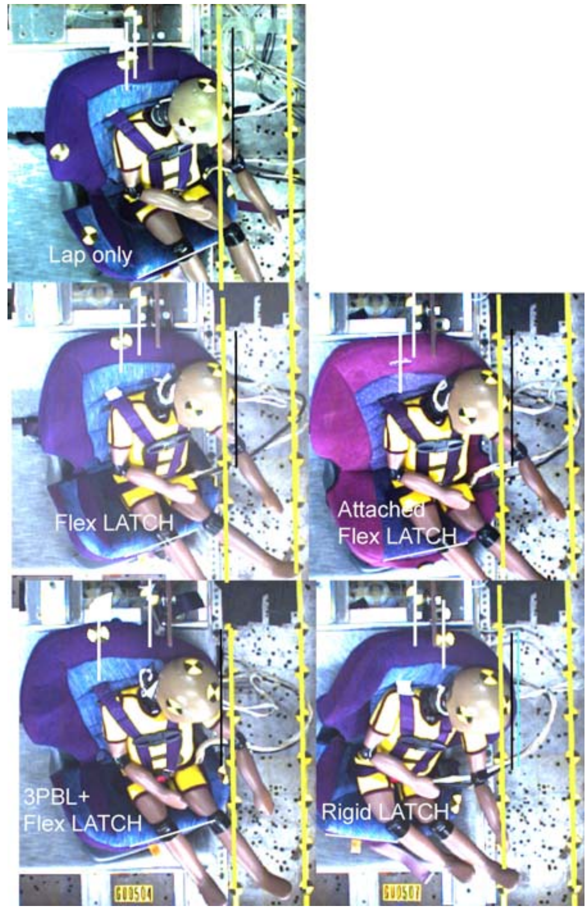

Figure 12. Peak lateral head excursions of FF tests using lap only (top left), flexible LATCH attachments through belt path (mid left), attached flexible LATCH attachments (mid right), flexible LATCH attachments through belt path plus left 3-point-belt (lower left), and rigid LATCH attachments (lower right).

Tether Effect

Figure 13 compares peak lateral head excursions measured in the four different FF tests run with the CRS secured by a tether and lap belt compared to the baseline FF condition with the CRS secured by only a lap belt. Illustrations of these peak lateral excursions are shown in Figure 14. All tests run with the top tether reduced head excursion compared to the test without. The baseline tether anchorage condition had lower head excursions than the remaining tether anchorage conditions. Of the three remaining tests run with top tethers, peak head excursions were lowest with the tether anchorage under the seat and highest with the tether anchorage mounted to the roof. The kinematics of all the tests with top tethers were similar, in that the tether reduced translation of the CRS seat back, but not necessarily rotation of the CRS. The head was not retained within the CRS in any of these tests.

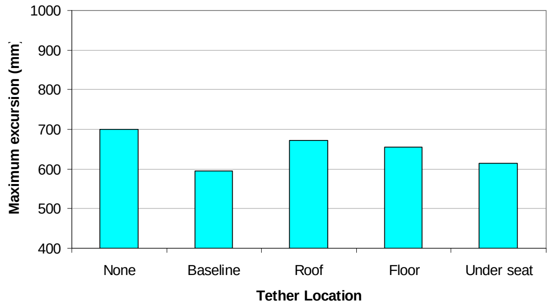

Figure 13. Maximum excursions of the head leading edge in FF tests run with different tether anchorage locations.

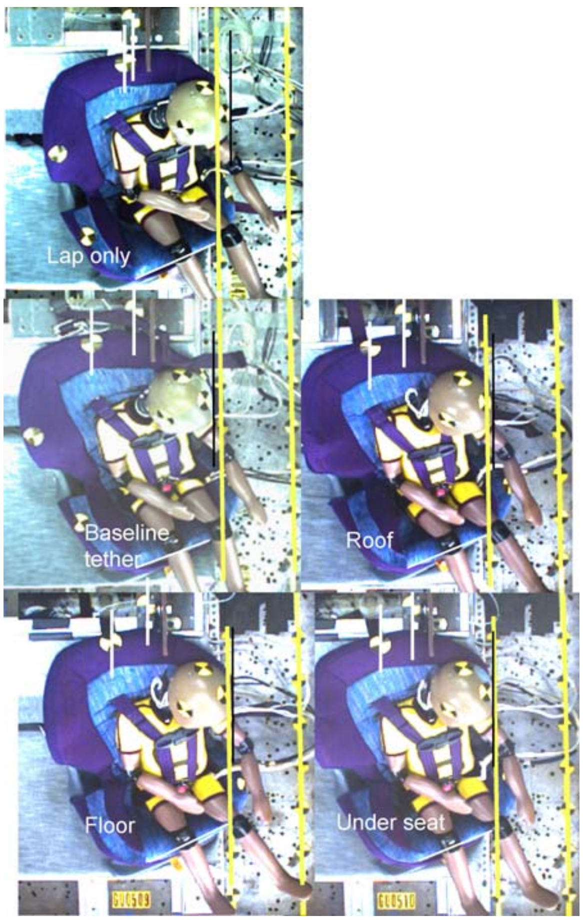

Figure 14. Peak head excursions of FF tests using no tether (top left), tether anchor behind vehicle seat back (mid left), roof tether anchor (mid right), tether anchor on floor (lower left), and tether anchor under vehicle seat (lower right).

Securing Rear-facing CRS

Variations using Conventional Belts

Figure 15 plots maximum head excursions for the four RF tests run with the CRS secured by conventional belts, while Figure 16 illustrates the overhead and front video frames at the times of maximum head excursion. On the overhead views (for this and subsequent illustrations of RF tests), the reference lines on the floor of the sled buck have been highlighted, and a black line added to indicate maximum head excursion. The angle of the CRS base has also been highlighted and a reference line relative to this angle added. On the front views, a black reference line was added to aid in visualization of CRS lateral translation, and another black line added to indicate maximum head excursion. A white reference line was drawn between two structural points on the back of the CRS to indicate the CRS angle relative to a vertical reference line. For the photo of the 3PBR test, the starting position of the CRS was shifted slightly compared to the other RF tests, so the maximum head excursion photo was shifted relative to the landmarks on the other photos to accurately compare maximum excursion.

Compared to the baseline lap-belt-only condition, using the left 3-point belt reduces head excursion by over 100 mm. As seen in the side view image, the left 3-point-belt reduces the amount that the CRS translates sideways and rolls about the vehicle longitudinal axis. The CRS also has the greatest amount of forward motion toward the front of the vehicle during this test, probably caused by pitching of the CRS about the y-axis. The motion of the ATD was different in this test as well, because the presence of the shoulder belt restricted lower extremity motion. Using a tighter lap belt reduced maximum head excursion slightly compared to the baseline lap belt only condition, while use of a right 3-point belt actually increased maximum head excursion slightly. None of the test conditions contained the head within the CRS.

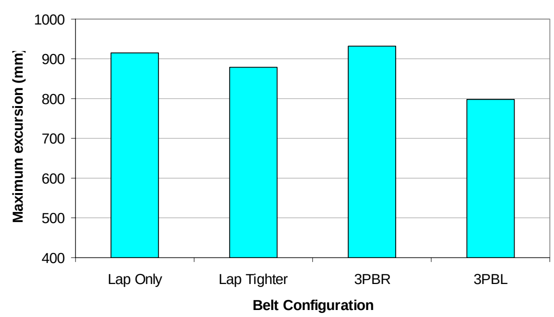

Figure 15. Maximum excursions of the head leading edge in RF tests run with the CRS secured using different conventional belt configurations.

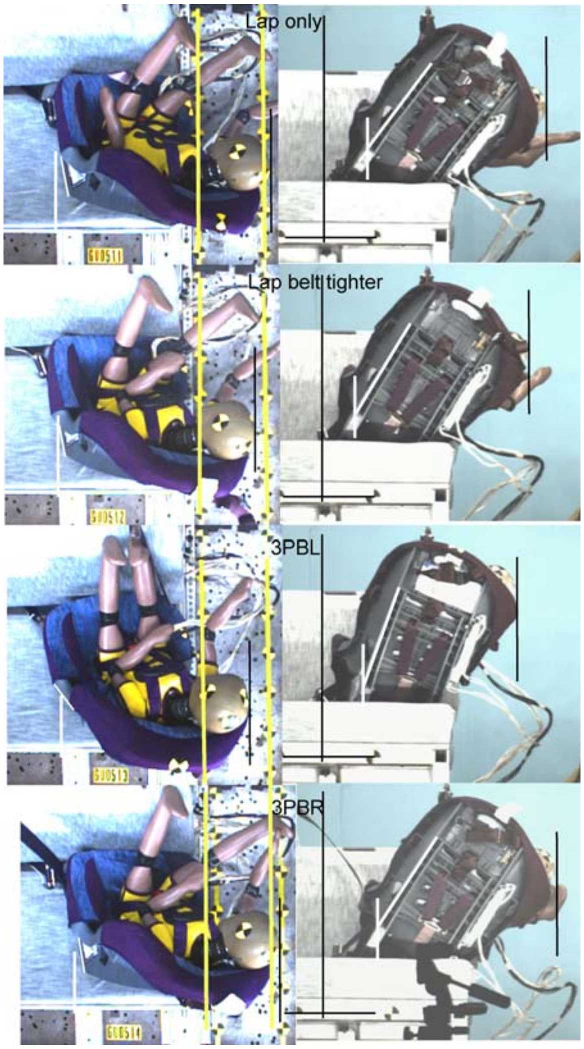

Figure 16. Top and front views of peak head excursions of RF tests using lap only (top), tighter lap belt (second from top), 3-point belt with shoulder belt on left side (third from top), and 3-point belt with shoulder belt on right side (bottom).

Variations using LATCH

The maximum head excursions of four RF tests run with different types of LATCH securement are compared to the test run with the CRS secured by lap belt only in Figure 17. Overhead and front views at the time of maximum head excursion are illustrated in Figure 18. All of the RF LATCH conditions reduced maximum head excursion by reducing translation of the CRS, which is most clearly visible on the front views by comparing the amount of vehicle seatback cushion visible between the CRS and a black reference line. Results for the two tests run with flexible LATCH attachments were similar, while adding a left 3-point belt to the flexible LATCH led to further reductions in maximum head excursion. Using rigid LATCH attachments to install the CRS resulted in the greatest reduction in maximum head excursion. None of these tests contained the head within the CRS based on analysis of the overhead views, although the front views indicate that using attached flexible LATCH, flexible LATCH plus left 3-point-belt, and rigid LATCH attachments came close to doing so.

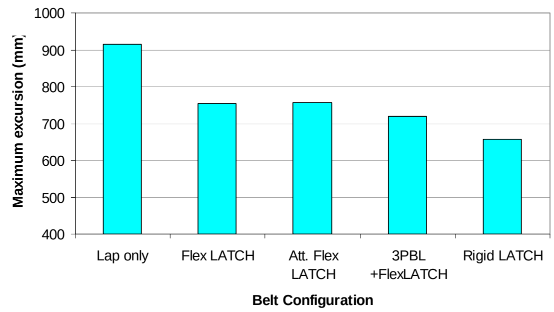

Figure 17. Maximum excursions of the head leading edge in RF tests run with different LATCH configurations compared to lap only condition.

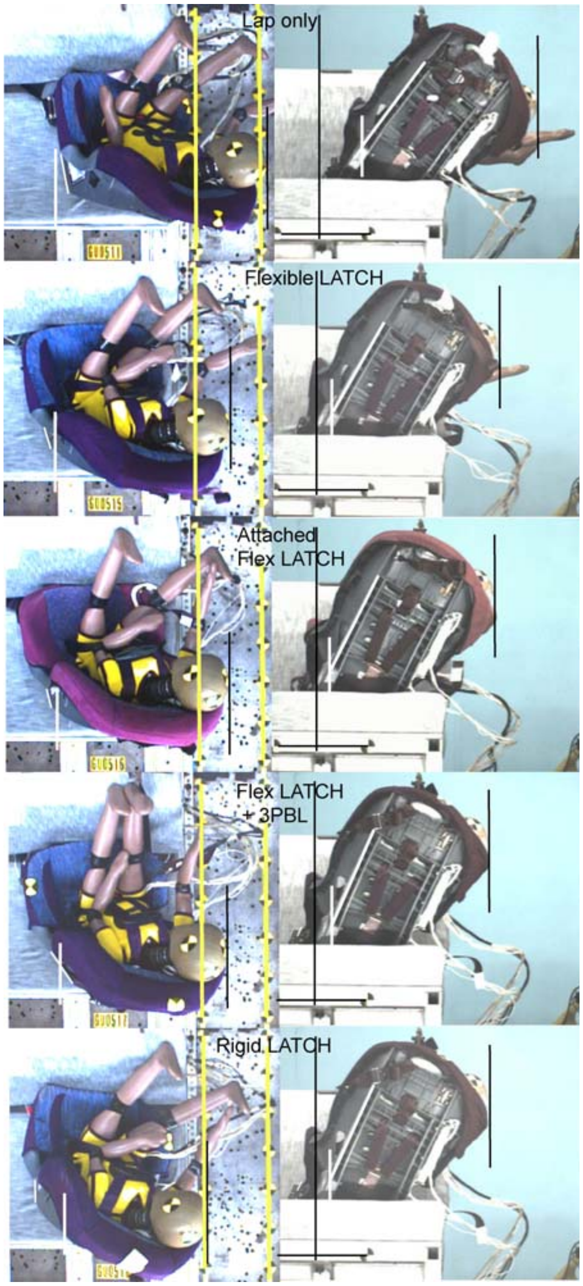

Figure 18. Top and front views of peak head excursions of RF tests using lap only (top), flexible LATCH attachments routed through the belt path (second from top), attached flex LATCH attachments (third from top), flex LATCH attachments through the belt path plus 3-point belt with shoulder belt on left side (fourth from top), and rigid LATCH attachments (bottom).

<u>Tether Effect</u>

The peak head excursions for the RF tests run with a tether are shown in Figure 19 and illustrated in Figure 20. For the test with the tether anchored down to the floor, the starting position of the CRS was shifted slightly compared to the other RF tests, so the maximum head excursion photo was shifted relative to the landmarks on the other photos to accurately compare maximum excursion. Routing the tether over the CRS to an anchorage above the back of the vehicle seat reduces head excursion by reducing lateral translation of the CRS, reducing roll of the CRS about the longiduinal axis, and keeping the seat more upright (reduces translation toward the front of the vehicle). When the tether is anchored down to the floor, it increases head excursion by increasing the roll of the CRS about the longitudinal axis and the pitch of the CRS about the y-axis, although it reduces yaw of the CRS about the z-axis. Anchoring the tether down under the seat reduces head excursion by reducing yaw about the z-axis, roll about the x-axis, and lateral translation, although it increases pitch of the CRS about the y-axis, which places the top back of the CRS closer to the front of the vehicle. The ATD head was not retained within the seat for any of these tests, but anchoring the tether over the top to behind the vehicle seatback came closest to doing so.

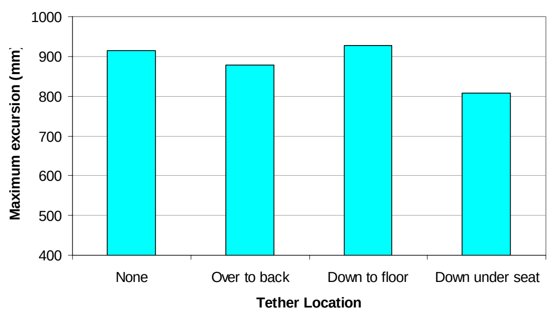

Figure 19. Maximum excursions of the head leading edge in RF tests run with different tether anchorage locations compared to lap only condition.

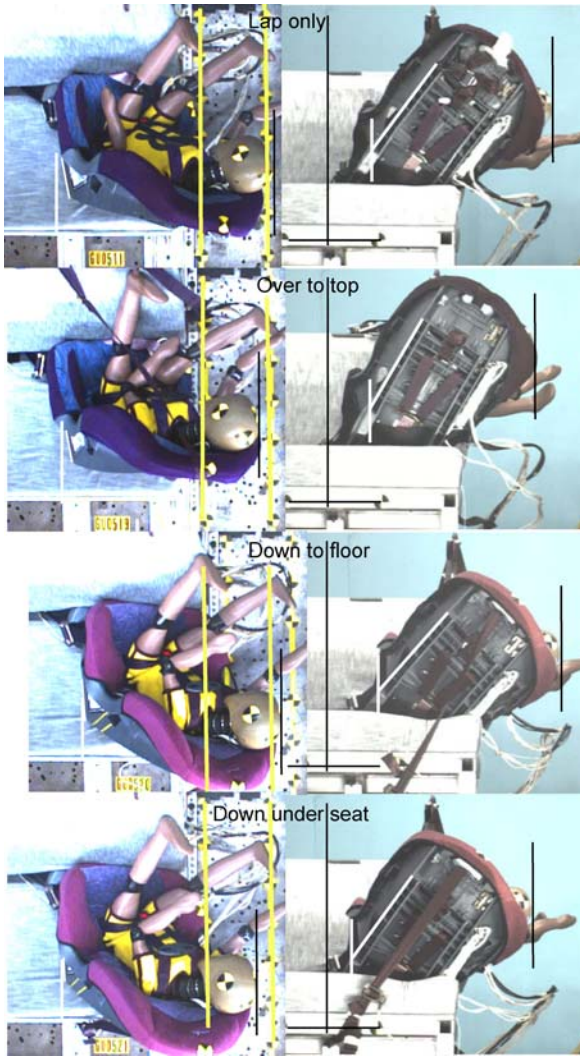

Figure 20. Top and front views of peak head excursions of RF tests using lap only (top), tether anchored over to behind the vehicle seat (second from top), tether anchored down to floor (third from top) and tether anchored down under seat (bottom).

DISCUSSION

Effect of Arm Position

Arm position was studied in this test program because other users had reported variation in chest displacement and acceleration when arm position was varied under direct contact loading (Tylko 2004). For these less severe loading conditions, chest readings did not vary substantially, but kinematics were affected. Moving the arms from the baseline hands-on-lap position to the arms at the side reduced head excursion by as much as changing from lap belt only to flexible LATCH attachment. In addition, the head was retained when the arms were at the sides but not in the baseline condition.

The Q3S is the only side impact ATD ever designed with complete arm components. None of the adult side impact ATDs incorporate a forearm component, and often the upper arm component is coupled to the torso to improve response repeatability. Because the arm position will affect kinematics, it should be specified when developing a procedure for evaluating CRS in side impacts.

Securing CRS Forward-Facing

The most interesting finding in these lateral FF tests was that the most effective means of reducing lateral head excursion was securing the CRS with a three-point belt that had the shoulder belt anchored on the left (impacted) side. Prior research evaluating securement techniques under lateral loading has usually compared response of proposed LATCH systems (flexible or rigid) and tether recommendations to the baseline securement used in the regulations of the country (lap belt only in U.S, 3-point belt in Australia). Prior comparison of responses between lap only and three-point-belt has not been reported.

This finding has implications for recommendations about securing FF CRS in the United States. Currently, best recommended practice is to secure CRS with LATCH when possible because it theoretically makes CRS installation easier than when using conventional vehicle belts. In addition, securing CRS with both LATCH and conventional belts is considered misuse. The results of this test series, though preliminary, indicate that use of a 3-point-belt to secure a FF CRS may provide some protection in side impact, even more than adding a tether, and might provide some benefit when used together with LATCH.

Eliminating rotation of the CRS around the vertical axis seems to be the key factor to retaining the head within the CRS. The only three tests that retained the head used securement conditions that substantially reduced rotation of the CRS: rigid LATCH attachments, left (impact side) 3-point-belt, and reverse belt path. While prior research has indicated that making side wings on CRS bigger might be required to retain the head, these tests indicate that controlling rotation of the CRS through different securement methods may also be an effective means of improving head retention.

Using a tether in FF tests reduced head and CRS excursion compared to lap belt only tests, but did not eliminate CRS rotation or retain the ATD head. These findings agree with results of Brown et al. (1995, 1997). The shortest tether length provided the greatest reduction in head excursion among tether conditions.

Using rigid LATCH attachments, without a tether, reduced head excursion compared to a lap belt only test. However, it was not the best performing securement condition among the forward-facing tests. A possible reason is that the CRS was not equipped with rigid LATCH attachments, and that the modifications that were made to add rigid LATCH attachments to this CRS were not optimal for securing an ATD of this weight, having bent about 15 degrees during the test. In addition, most of the motion of the CRS secured by rigid LATCH attachments occurred at the top back of the CRS, which would be reduced by using a tether.

One of the FF securement conditions used with conventional belts of a reverse belt path had high head excursions because of large translations of the CRS, even though it did eliminate rotation of the CRS and contain the head. The CRS used was not designed to use this belt routing and was probably the reason for the large translations. It is possible that redesigning the CRS to allow use of a reverse belt path for either a conventional belt or flexible LATCH attachment may be an effective means of controlling CRS and ATD kinematics in side impact.

Using two variations of flexible LATCH attachments (routed through the belt path or webbing attached to either side of the CRS) did not lead to substantially different kinematics. However, the short length of webbing used in the attached flexible LATCH test caused interference with the belt load cell, so the belt could not be tightened to FMVSS 213 levels prior to the test and may contribute to the unexpected similarity in performance. Using the attached flexible LATCH attachments did reduce rotation of the CRS somewhat compared to using the flexible LATCH routed through the belt path.

The results presented here evaluating securement of FF CRS under lateral loading differ in some ways from the results of Australian testing. In their tests, rigid LATCH attachments (without a tether) had superior results, and flexible LATCH attachments, with and without tether, worked better than the 3-point-belt securement. Results may differ because they used a P3/4 ATD in their evaluations, and their test involved contact with a simulated door, which may disguise differences in kinematics. They noted that the location on the CRS where the tether is attached is higher on Australian CRS than North American CRS and may affect evaluation of its lateral response.

Securing Rear-facing CRS

In the rear-facing tests, using rigid LATCH attachments provided the greatest reduction in head excursion (over 250 mm) compared to the baseline test in which the CRS was secured by only a lap belt. This substantial reduction might have been even larger if the rigid LATCH attachments had been optimized for this seat and size of ATD, as they were bent about 15 degrees post-test. However, all of the tests that used LATCH attachments had lower head excursions than the tests that did not, possibly because the LATCH anchors are more closely spaced than lap belt anchors. This appears to have reduced the lateral translation of the CRS. Using the flexible LATCH attachments together with the left 3-point belt led to additional reductions in head excursion. The Australian securement testing of RF CRS (1997, 1995) also found that rigid LATCH had the best response, but had better results in securing the CRS with a 3-point-belt than with flexible LATCH and tether.

Two RF tether anchorage locations reduced maximum head excursion, although they achieved this by different means. The tether anchored over the top of the CRS to behind the vehicle seat reduced head excursion by reducing pitch of the CRS about the y-axis and roll about the x-axis. The tether anchored underneath the vehicle seat increased pitch of the CRS about the y-axis, but reduced head excursion by eliminating yaw about the z-axis and reducing y-translation. A possible advantage of the over-the-top tether anchorage position is that it would be more likely to prevent contact of the CRS with the vehicle seat in front of it.

An interesting finding of this study of RF CRS kinematics under lateral loading was the pattern of ATD and CRS kinematics. Pioneering testing of CRS in the 1960's indicated that a RF CRS would swing toward the door about a vertical axis under lateral loading (Weber 2005). However, with today's CRS and securement methods, it appears that a greater amount of motion occurs from the CRS rotating about the fore-aft axis towards the impact side. Figure 21 plots the angle of the CRS back relative to vertical against peak head excursion, with a linear fit through all points except for the 3PBL test. Translation of the head seems to be largely affected by how much the CRS tips toward the door rather than rotates toward the door. This may partly result from the choice of the CRS used in testing or from the CRS approaching the edge of the R44 seat, but should be investigated further when analyzing motion of RF CRS in side impact.

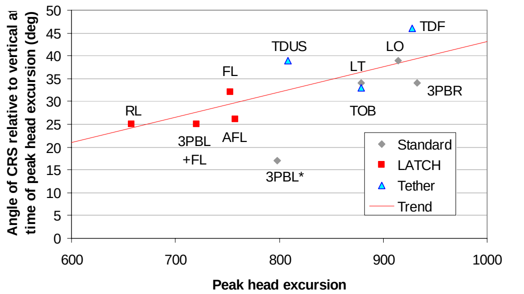

Figure 21. Angle of the CRS back relative to vertical at time of peak head excursion vs. peak head excursion. * not included in trendline.

Comparing FF and RF Tests

Figure 22 compares the maximum head excursions for the FF and RF tests run under each securement condition. The RF head excursions with a single CRS range from 657 to 933 mm with a mean value of 821 mm, while the FF head excursions range from 558 to 764 mm with a mean value of 656 mm. The mean FF head excursion is essentially the same as the best RF head excursion, while the worst FF head excursion is over 50 mm less than the mean RF head excursion. The only condition where the RF test had a lower head excursion than the FF test was when rigid LATCH attachments were used. All of the RF excursions in this program are greater than the excursion limit of 622 mm proposed by NHTSA for a 3-year-old ATD.

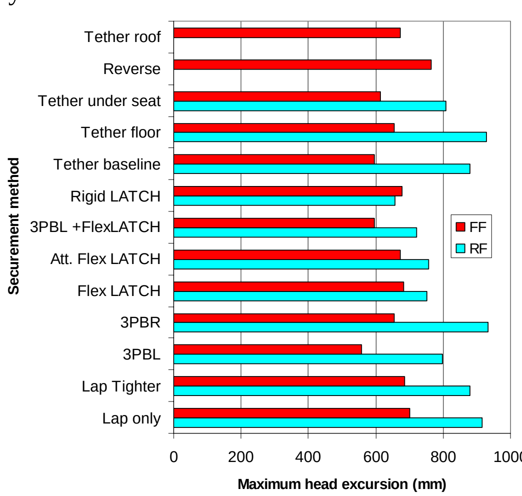

Figure 22. Comparison of RF and FF head excursions under the same securement conditions.

Analysis of the kinematics of these tests indicates FF and RF CRS have different degrees of freedom under lateral loading. FF CRS primarily have translation of the top and bottom of the CRS seatback and rotation of the CRS about a vertical axis. RF CRS translate laterally and rotate relative to all three axes, which affects the amount of forward and lateral motion of the CRS seatback and ATD head.

A concern when evaluating CRS under side impact conditions is how to fairly test forward-facing and rear-facing CRS using the same test procedure. The ISO/TC 22/SC 12/WG 1 has proposed testing FF seats in a vehicle front seat configuration, and RF seats in the rear vehicle seat configuration, so both conditions would represent worst case scenarios of intrusion at the B-pillar. This approach presents challenges in the United States, where best practice recommends seating children in the rear seat, and a test procedure that appears to evaluate CRS in the front seat would contradict this best practice. In testing to support their ANPRM, NHTSA evaluated both FF and RF seats under non-contact and non-intruding door conditions and proposed a single head excursion limit for all types of CRS. However, because RF seats almost always have higher head excursions than FF seats, these criteria would suggest that FF CRS are safer than RF seats in side impacts. This implication is inconsistent with results from crash investigation studies, in which children seriously injured in rear-facing CRS are quite rare. The unintended consequences of making RF CRS appear less protective than FF CRS in side impact, contrary to field data, should be seriously considered when developing a side impact procedure for evaluating CRS.

Study Limitations

This study provided a thorough examination of factors that affect kinematics in non-contact side impact of an ATD secured in a CRS. The main limitations are that only one test in each configuration was tested, only one model of CRS was used in the program, and only one size of ATD was used. Also, testing was conducted using a laboratory bench seat that simulates a vehicle seat. Actual rear vehicle seats have contouring, bolsters, and support structures that might significantly alter CRS and ATD kinematics. Additional tests to examine repeatability and confirm trends in this initial test matrix are planned, and other CRS models will be evaluated.

CONCLUSIONS

- Arm placement of the Q3S affects kinematics and should be considered and specified when developing a CRS side impact test procedure.

- Head retention in FF CRS was associated with reduced CRS rotation about the vertical axis. Rotation was reduced compared to baseline lap only conditions by securing the CRS with a 3-point belt on the impacted side, rigid LATCH attachments, and a reverse belt path.

- Using a tether with FF CRS limits translation but does not affect rotation of the CRS about a vertical axis nor result in head retention within the CRS. The test with the shortest distance to the tether anchorage had lower peak head excursions than the other tether anchor locations tested.

- Relative to baseline conditions with CRS secured by only lap belts, rigid LATCH attachments were more effective in the rear-facing configuration than the forward-facing configuration at reducing ATD head excursion, rigid LATCH attachments still exhibited good performance in the forward-facing test.

- Rear-facing CRS secured with any type of LATCH attachments had lower peak head excursions than those secured with any variation of conventional belts.

- Head excursion in rear-facing tests is primarily caused by rotation of the CRS about the fore-aft axis, not the vertical axis.

- None of the tests in the rear-facing configuration retained the head within the CRS, but the Australian tether configuration came closest to doing so.

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