EVALUATION OF RESTRAINTS EFFECTIVENESS IN SIMULATED ROLLOVER CONDITIONS

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ABSTRACT

A series of tests were conducted to determine the effectiveness of belt restraints in reducing occupant excursion in rollover crashes. A typical 3-point lap and shoulder belt configuration was tested as the baseline restraint. The baseline restraint was compared to an inflatable restraint to determine how well excursion could be reduced over current belt systems in a simulated rollover. A device called the rollover restraints tester (RRT) was used to simulate rollover conditions and to evaluate the effectiveness of restraints to prevent occupant head excursion. Vertical head excursion of a 50th percentile H-III male dummy was reduced by as much as 75 percent with the inflatable restraint.

INTRODUCTION

The lap and shoulder belt is the single most important safety device built for passenger vehicles. It is estimated that safety belts are responsible for saving over 85,000 lives from 1982 to 1996 [1]. Until the last decade, the belt system was largely unchanged. However, seat belt performance has improved recently due to the introduction of electronic and automatic locking retractors. Even greater improvements are being made with the introduction of belt pre-tensioners, load limiters and web grabbers which are improving the energy management capabilities of the restraint system. In general, these enhancements are being developed for frontal impacts and are not optimized for rollover crashes.

Most of the benefits from belt restraints are realized in frontal crashes and ejection mitigation in rollover collisions. However, the performance of restraints in rollovers also prevent impact with the vehicle's interior structure. Previous analysis of rollover crashes in NHTSA's National Automobile Sampling System [2], suggest that occupant impacts within the vehicle interior are a result of intrusion into the survival space and occupant excursion which are caused by the vehicle motion during rollover. Most restraints, by their design, do not securely hold the occupant in the seat. Consequently, we can assume that restraints that provide better coupling of the occupant with the seat, can control relative movement of the occupant with the seat thereby mitigating a large number of injuries from interior impacts.

Recently, several projects have reported investigations into effective restraint in rollovers crashes. Arndt et al [3] conducted vertical drop tests using a H-III 95th male dummy and human volunteers. It was discovered that higher lap-belt angles reduced vertical excursion when subjected to a uni-directional acceleration. Arndt et al.[4] also conducted testing to study seat belt restraint belt slack and its correlation to occupant excursion. As expected, shortening the web length reduced occupant excursion. There were also effects from spool out and seat belt anchorage location that were restraint design dependent. Another analysis was conducted by Cooper et al.[5] using a Head Excursion Test Device. It was found that the lap belt anchorage angle had a significant effect on vertical head excursion when simulating the angular roll rate in a rollover crash. It was also discovered that the anthropomorphic test device (ATD) had less vertical and lateral excursion when compared to cadavers tested in the same configuration. In 1996, NHTSA announced a program to evaluate rollover restraints in a component test fixture [6]. This device, referred to as the rollover restraint tester (RRT), was used in this study to examine seat belt restraints for the possibility of improving restraint effectiveness over current systems. Current technology used to enhance safety in frontal crashes, may be applicable to rollover collisions, since the basic restraint requirements for frontal crashes are the same for rollover crashes. The restraint should effectively couple the occupant to the vehicle/seat to control occupant motion within a vehicle during the rollover event. The objectives of the testing with the RRT were to determine:

1. The relative importance of D-ring adjustment position for improving occupant retention when exposed to rollover forces.
2. The reduction in occupant excursion during rollover with the use of an inflatable tubular torso restraint (ITTR).

TEST METHODOLOGY

Description and Operation of RRT

Real-world crash data indicated that the typical range of roll rate in a vehicle roll-over collision was 180°/sec (0.5 rev/sec) up to about 360°/sec (1.0 rev/sec), but could be as high 540 degrees/sec (1.5 rev/sec).

The rollover restraints tester (RRT) modeled a rollover condition in which the vehicle becomes airbourne at the initiation of the roll, then impacts on the roof structure after rotating approximately 180°. Pre-test photographs of the seated dummy are shown in Figures 1 and 2. Tape markers on the head were used to digitize the dummy's head movement during the simulated rollover. A reference grid behind the dummy's head was used to aid in the digitizing process.

The main features of the RRT (Figure 3) consist of 1) a support framework, 2) a counter-balanced test platform with a pivot axle, 3) a free weight and drop tower assembly, and 4) a shock tower. The support framework was rigidily attached to the

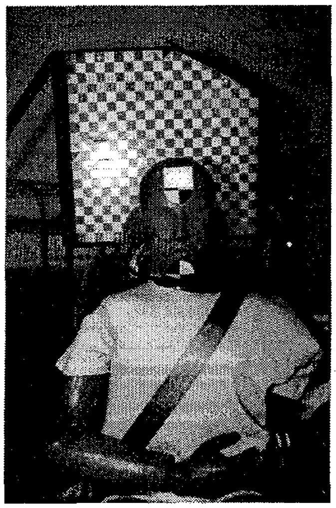

Figure 1. Dummy front view.

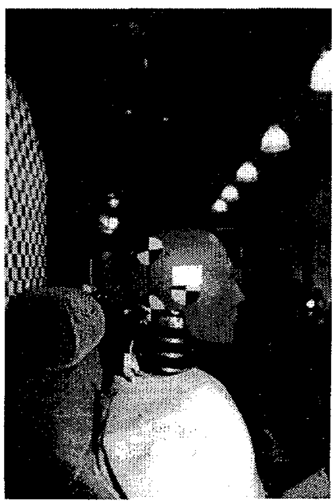

Figure 2. Dummy side view.

floor and braced to minimize any movement of the structure. The platform itself was constructed of 100 mm box beams mounted to a 50 mm axle at the pivot point. Both seat height and lateral positioning from the roll center could be adjusted as required.

The weight of the dummy and seat fixture was counter-balanced with the use of weights on the opposite wing of the platform. This design allowed the driving force of the free-weight to apply a constant acceleration pulse to the platform as it rotates 180° through the gravity field. Although the location of the center of rotation of the RRT could be somewhat different from that of an actual vehicle during rollover, this was considered a representative set-up which incorporated rollover forces and impact forces expected in a rollover collision.

Due to the relatively large lumped masses of the test components (ie. dummy, test seat, and related counter-balancing mass), the mass moment of inertia of the system was sensitive to the lateral positioning of the seat. Reducing the roll radius enhanced the velocity performance for a given drop weight, while reduction of the moment arm of the counter-balance mass significantly reduced loading stresses on the platform. For the testing reported in this paper, the seats were mounted such that the center of the seat was 610 mm from the pivot axis. This distance represented a fairly short radius of rotation typical of a compact or sub-compact vehicle.

The drop tower and free-weight system provided the motive force for the RRT (Figure 3). A cable attached to the suspended weight was routed through a system of pulleys and spooled around the large circular plate attached to the back of the platform. The radius of this circular plate provided the moment arm for the suspended weight to act upon in order to accelerate the platform. An array of 9 standard automotive piston shocks were used to catch and slow the free-weight at the end of the drop. The angular velocity (impact speed) for the RRT can be modified by varying the mass (force generating the acceleration) and/or the drop height (duration of the acceleration pulse) of the free-weight. In the current configuration, angular velocities of 180°/second up to 290°/second were generated with various combinations of drop height and drop weight.

The shock tower was used to simulate the impact of a vehicle's roof with the ground. The tower consisted of a height adjustable supporting framework housing two hydraulic shock absorbers manufactured by Enertrols Inc. The stiffness of these units were adjusted to simulate a range of roof structure

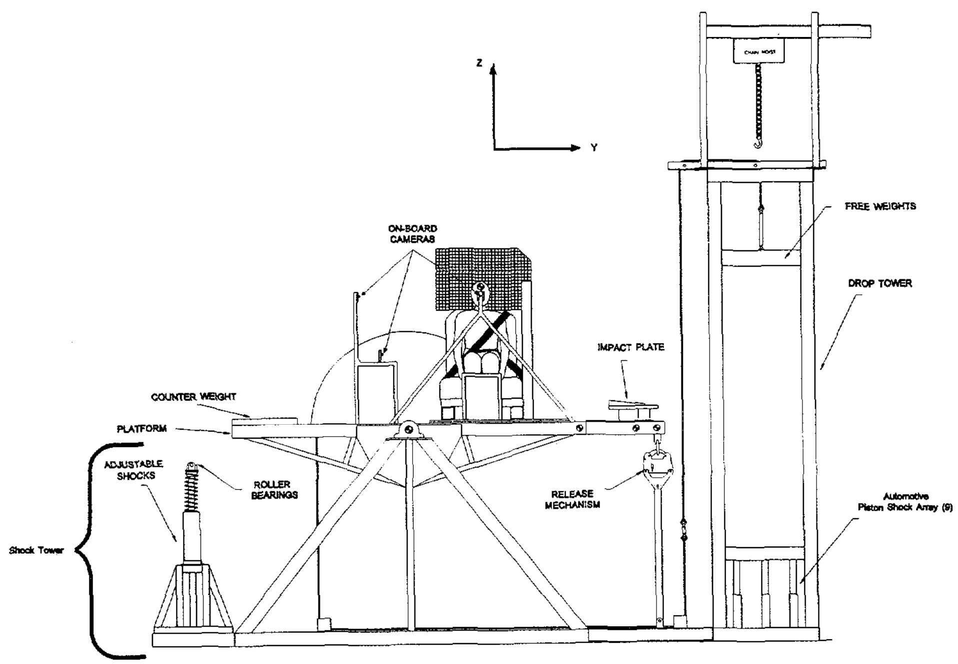

Figure 3. Schematic of RRT fixture.

force/deflection (rigidity) characteristics. The unit was capable of a maximum displacement stroke of about 254 mm in its current configuration. The height adjustment of the shock tower allowed adjustment of the angle of impact and the degree of rotation before impact. Increasing the height of the tower decreased the degree of rotation before impact occurred and modified the angle or attitude of the dummy at which that impact occurred.

A checkerboard of 25 mm (1 inch) squares was used as a reference grid behind the dummy's head to help track dummy vertical and lateral excursion with the on-board cameras. There were three on-board cameras tracking the Y-Z plane head movement, X-Z plane head movement, and X-Z plane pelvic movement. The video recording was then used to digitize dummy vertical and lateral excursion. The Y- and Z- axes are shown in Figure 3. The positive X-axis iss normal out of the page. A 50th percentile H-III male dummy was used for all testing.

Restraint Characteristics

Two restraint systems were examined. One off-the-shelf system and one experimental design. An off-the-shelf lap and shoulder belt incorporating inertial reel locks and an adjustable D-ring was used as the baseline system. There were no energy management enhancements. This type of restraint is currently available in most makes and models of cars. The adjustable D-ring is becoming a popular enhancement to obtain a proper fit of the shoulder belt for varying sized occupants.

The experimental restraint was the Inflatable Tubular Torso Restraint (ITTR), developed by Simula Automotive Safety Devices, Inc. This device consisted of the integration of an inflatable section into the shoulder belt portion of a conventional three-point restraint system. The ITTR augmented a standard three-point seat-belt system to allow the shoulder-belt portion to inflate during impact. This increased the diameter and decreased the length, which not only cushions and protects the occupant, but pre-tensions the seat belt. The technology on which the ITTR was based includes a low permeable liner which allowed the unit to remain inflated for at least 7 seconds, and a braided cover which provided the shape change mechanism for the unit.

TEST MATRIX

The matrix of tests conducted with the aforementioned safety belt restraints is shown in Table 1.

Table 1.
Matrix of Tests

Seat Configuration	D-Ring Position	ITTR*	Reps
Lap and Shoulder	Upper		3
Lap and Shoulder	Mid		3
Lap and Shoulder	Lower		3
Lap and Shoulder	Upper	Yes	2
Lap and Shoulder	Lower	Yes	2

*Inflatable Tubular Torso Restraint (ITTR)

TEST INSTRUMENTATION

Systron-Donner roll rate sensors were mounted at the X, Y, and Z roll axis of the RRT platform. High g accelerometers were mounted along the X, Y, and Z coordinate axis using a standard triaxial mounting block. A 24 inch string potentiometer was attached to the pivot axis of the platform. As the platform rotated, the potentiometer string spooled onto a measured radius on the axis. A computer algorithm was then used to convert this measured linear output into an angle of rotation of the platform. An array of three 50,000 pound load cells were mounted to the impact plate. The total force of the impact was determined by the summation of the three individual load cell measurements. A 14 inch linear potentiometer was mounted to the adjustable shocks so that shock compression was measured during impact. Load cells were attached to the lap and shoulder belt to measure belt loads.

Dummy instrumentation included triaxial head, chest, and pelvic accelerometers, upper neck load cell, and triaxial angular roll rate sensors in the spine of the dummy.

Static Test Procedure

Pre-test static measurements of the dummy in the upright and upside down positions were made prior to each individual dynamic rollover test run. These measurements provided information on the belt slack in the restraint. The pre-test procedure for the static upside down measurements consisted of rotating the platform slowly, with the dummy in place on the seat, until the platform impact plate was in contact with the roller bearings atop the adjustable shock absorbers. While the dummy was completely upside down in this position, measurements of the static excursion in the X, Y and Z axis were recorded. Once the pre-test static measurements were made in the upside down condition, the RRT platform was rotated back, to the pre-test upright position of the dummy for the dynamic test.

Dynamic Test Procedure

The sequence of events for a typical dynamic test will now be described. The free-falling mass, which was housed in the drop tower, then began to descend which rotated the platform. The platform accelerated to within 7- 10° of actual impact with the shock tower, then the free-falling mass impacted the shock absorber array at the bottom of the shock tower. The platform coasted at constant angular velocity until impact with the shock tower. At impact, the angular velocity dropped sharply as the platform was decelerated by the impact into the shock tower. The "stiffness" or damping of the adjustable shocks determined force/deflection characteristics of the impact. A high stiffness setting resulted in less overall deflection simulating a more rigid roof while a lower setting simulated a softer or more compliant roof. For the tests conducted in this study a somewhat softer or less rigid roof structure was simulated. Typical displacements for the adjustable shock absorbers ranged from approximately 190 to 230 mm.

The event mark for this test was the initial contact of the impact plate with the roller bearings on the adjustable shocks at 180° of platform rotation. The system was configured to collect approximately two seconds of pre-event data and 0.8 seconds of post-event data to record the entire rollover event. Post-test pictures and static dummy head excursion off the seat were then measured. Video of the rollover event was captured for the head and pelvic area. These videos were digitized to obtain maximum excursion values and traces of the dummy head and pelvis in the X, Y and Z-axis.

RESTRAINT PERFORMANCE TEST RESULTS

Kinematics During Rollover Test

Dummy kinematics are dictated by the actions of gravitational and rotational forces. The dummy was initially sitting upright in a 1 g gravity field. As the platform rotates, the dummy's orientation in this gravity field also rotated with an increasingly larger force vector directed towards the center of rotation. Occupant loading or force due to gravity in the vertical (Z-axis) axis shifted from a positive 1 g to zero g's (at 90° rotation) to -1 g (at 180° rotation). As a result, the dummy moved inward (falls) toward the "interior" of the vehicle.

As angular velocity for the platform increased, the normal and tangential accelerations (rotational forces) created by the rotational motion began to increase adding force vectors to the gravitational force. The tangential acceleration for the dummy was aligned with the Z-axis of the platform and was a function of the dummy's distance from the center of rotation and the angular velocity of the platform. The normal acceleration causes a centripetal force outward from the center of rotation. As a result of this force, the dummy had a steadily increasing tendency (as angular velocity increased) to move outwards towards the "exterior" of the vehicle.

D-ring Adjustment of Baseline Restraint

The baseline lap and shoulder belt system was adjusted to three D-ring adjustment positions. The total span between the upper and lower adjustment was 95 mm. This adjustment was incorporated to determine the effect of D-ring adjustment on excursion. It was not intended as a recommendation on how much adjustment was necessary. Lap belt angle and length were held constant. Shoulder belt angle and length were changed as the D-ring was raised or lowered. Three tests were conducted for each D-ring adjustment position, for a total of nine tests.

The nine tests and their maximum roll rates, impact forces onto the adjustable shocks, and the adjustable shock deflections are shown in Table 2. Roll rate varied 3% for all nine tests. Impact force and shock deflection for the upper (952 mm) and lower (857 mm) D-ring adjustment position were within 2% of one another. Force and deflection were almost 10% different in the mid D-ring adjustment position when compared to the high and low position. As a result, the tests with the D-ring adjustment in the mid-position do not have the same impact conditions as the upper and lower D-ring adjustment position tests that could affect the comparison. Consequently, only the upper and lower D-ring adjustment positions were focused on in the analysis of the results.

X-, Y- and Z-direction head excursions for the baseline restraint is shown for all nine tests in Tables 3, 4, and 5, respectively. Static pre-test head excursion measurements, post-test and maximum dynamic head excursion are shown. Maximum dynamic head excursions were taken from digitized video, and are reported in the last column of each table. Each group of repeat tests were averaged and these averages used to make comparisons.

The post-test X- and Z-direction head excursion measurements were higher than the pre-test static excursion measurements. The dynamic loads stretched the restraints and allowed the dummy to have more post-test excursion. Post-test Y-direction head excursion was significantly less than the pre-test excursion measurement. The dynamic forces moved the dummy inboard more than the static test, but the dummy rebounded to the outboard side and came to rest at a position close to the original upright position.

The dynamic forces during the test caused the X-, Y- and Z-direction maximum head excursions to increase significantly over the static pre-test and post-test measurements. The greatest increase over the static measurement was in the X-direction. In the static rollover, gravitational forces do not act in the X-direction and most head movement was from the torso rotating back into the seat. The dynamic rollover however, caused a much higher rate of rotation of the torso back into the seat which caused the neck to bend

Table 2.
Platform Measurements for Baseline Tests with Adjustable D-ring

Test #	D-ring Position	D-ring Height above Platform (mm)	Roll Rate (deg/s)	Max. Impact Force (N)	Adjustable Shock Deflection (mm)
55	Upper	952	257	58669	238
56	Upper	952	256	58647	233
57	Upper	952	259	59443	267
Average			**257**	**58920**	**246**
48	Middle	914	260	56979	286
49	Middle	914	257	52526	278
50	Midle	914	260	50480	275
Average			**259**	**53329**	**280**
58	Lower	857	254	58358	276
59	Lower	857	258	65670	228
60	Lower	857	255	53109	265
Average			**256**	**59046**	**256**

Table 3.
Baseline Restraint X-axis Head Excursion

Test #	D-ring Position	Static Test (mm)	Dynamic Test (mm)	
			Post-Test	Maximum
55	Upper	64	57	133
56	Upper	67	73	148
57	Upper	60	73	153
Average		**64**	**68**	**145**
48	Mid	57	67	182
49	Mid	57	57	160
50	Mid	60	67	170
Average		**58**	**64**	**171**
58	Lower	57	98	223
59	Lower	64	83	155
60	Lower	60	102	175
Average		**60**	**94**	**184**

Table 4.
Baseline Restraint Y-axis Head Excursion

Test #	D-ring Position	Static Test (mm)	Dynamic Test (mm)	
			Post-Test	Maximum
55	Upper	117	19	182
56	Upper	124	35	187
57	Upper	127	48	203
Average		**123**	**34**	**191**
48	Mid	102	32	188
49	Mid	114	19	190
50	Mid	108	16	181
Average		**108**	**22**	**186**
58	Lower	98	57	203
59	Lower	105	32	236
60	Lower	127	64	226
Average		**110**	**51**	**222**

Table 5.
Baseline Restraint Z-axis Head Excursion

Test #	D-ring Position	Static Test (mm)	Dynamic Test (mm)	
			Post-Test	Maximum
55	Upper	51	143	146
56	Upper	48	133	131
57	Upper	51	98	119
Average		**50**	**125**	**132**
48	Mid	60	130	120
49	Mid	57	127	130
50	Mid	44	130	123
Average		**54**	**129**	**124**
58	Lower	76	140	154
59	Lower	64	127	147
60	Lower	57	114	130
Average		**66**	**127**	**144**

and increase head X-direction movement. Z-direction motion was also much higher in the dynamic test. In this case, dummy loading against the restraints was increased dynamically which allowed the dummy to come off the seat much more than in the static rollover.

D-ring adjustment position had a significant effect on the pre-test occupant excursions. The pre-test Z-direction static excursion increased 24% from the upper to lower D-ring adjustment position.

However, the post-test head excursion was similar for each D-ring adjustment position. Maximum dynamic Z-direction head excursions were within 20 mm for all three D-ring adjustment positions.

The X-, Y- and Z- direction maximum dynamic head excursion increased from the upper to lower D-ring adjustment position (when excluding the mid-position measurements). It appeared there was some adverse consequences to wearing the belt at its lowest position for the 50th percentile male dummy. The lower D-ring adjustment position allowed the shoulder belt to slide off the shoulder more easily during the rollover test. This resulted in the belt going from the top of the shoulder to in front of the shoulder and allowed the upper torso to push down on the shoulder restraint and rotate forward and side-to-side. When the restraint is in the upper position, it fits the 50th percentile shoulder better and stays over the shoulder, improving the restraint during the rollover. This result was counter-intuitive to the expected result. It was expected that the shorter belt length in the lower anchorage position would have less slack and result in less excursion. Additional testing with different sized dummies could verify the correlation between occupant size, D-ring adjustment position, and resulting occupant excursion.

Dynamic Comparison of Restraints Effectiveness

Using the same roll rate and adjustable shock stiffness, a series of tests with the ITTR were conducted at the upper and lower D-ring adjustment positions. Two tests were conducted for each test condition. The results of vertical head excursion from the dynamic tests with the ITTR are shown in Table 6, along with a comparison to the baseline results at the same D-ring adjustment positions. When the ITTR was inflated, the dummy was pushed into the seat 19 mm. Since the excursion measurements were made after the ITTR was inflated, the total excursion measured and recorded in Table 6 is 19mm more than the net vertical excursion from the nominal seating position.

The ITTR substantially reduced vertical excursion when compared to the baseline 3-point restraint. In the upper D-ring adjustment position, the vertical excursion was reduced from 132 mm to 32 mm on average. Similarly, when the D-ring was set to its lowest adjustment position, the vertical excursion was reduced from 144 mm to 53 mm on average. Vertical excursion was higher for both belt systems when the D-ring anchorage was in the lower position, particularly with the ITTR. Although, this was attributed to the belt fitting the shoulder of the 50th percentile male dummy better in the upper D-ring adjustment position, it may not be the reason for the same trend in the ITTR. The design of this experimental unit was such that the tension in the shoulder belt would be higher in the upper D-ring adjustment position. This resulted in a reduction in excursion. Consequently, a better shoulder belt fit was probably a contributing factor to reduced occupant excursion, but it most probably was not the only factor.

The tighter coupling of the occupant to the seat from the ITTR did not result in large increases in neck loads. Neck tension forces went down when comparing the ITTR to the 3-point baseline restraint, and were well below the 3300 N threshold for neck axial tension currently used in FMVSS No. 208. There was an increase in the neck shear load caused by the increased head acceleration when the torso was restricted during impact of the RRT platform. But, the shear loads were very small in comparison to possible injury thresholds.

Traces of X, Y, and Z-direction excursions for baseline and ITTR tests in the upper and lower D-ring adjustment position are shown in Figures 4 through 9. Figures 4 through 6 are traces of the results with the baseline restraint and ITTR in the upper D-ring adjustment position. Figures 7 through 9 are the corresponding plots to the tests with the lower D-ring adjustment position. Each graph shows all the tests conducted at that condition. As indicated by the overlay of the tests on the graphs, the dummy motion was highly repeatable for the conditions tested.

In the upper D-ring adjustment position, head X-direction excursion began about 0.6 seconds before the peak excursion with the baseline restraint (Figure 4). However, the ITTR restricted motion until impact with the shock tower. The ITTR also limited motion in the X-direction to approximately 80 mm, compared to 130 mm for the baseline restraint. Y-direction head motion represented the dummy moving side-to-side. The initial motion in the baseline restraint was negative

Table 6.
Baseline and ITTR Z-axis Head Excursion and Neck Loads

ITTR Results				
Test #	D-ring Position	Maximum Dynamic Vertical Excursion (mm)	Maximum Neck Tension (N)	Maximum Neck Shear [x-force] (N)
51	Upper	37	1810	572
52	Upper	27	1724	534
Average		**32**	**1767**	**553**
53	Lower	42	1888	588
54	Lower	64	1834	536
Average		**53**	**1861**	**562**
Baseline Results (Averages)				
55,56,57	Upper	132	2147	434
58,59,60	Lower	144	2144	407

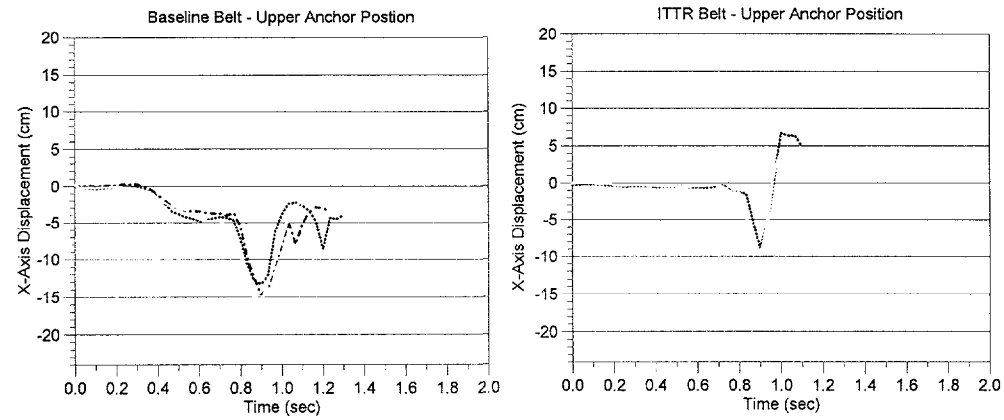

Figure 4. X-axis excursion in upper d-ring adjustment position.

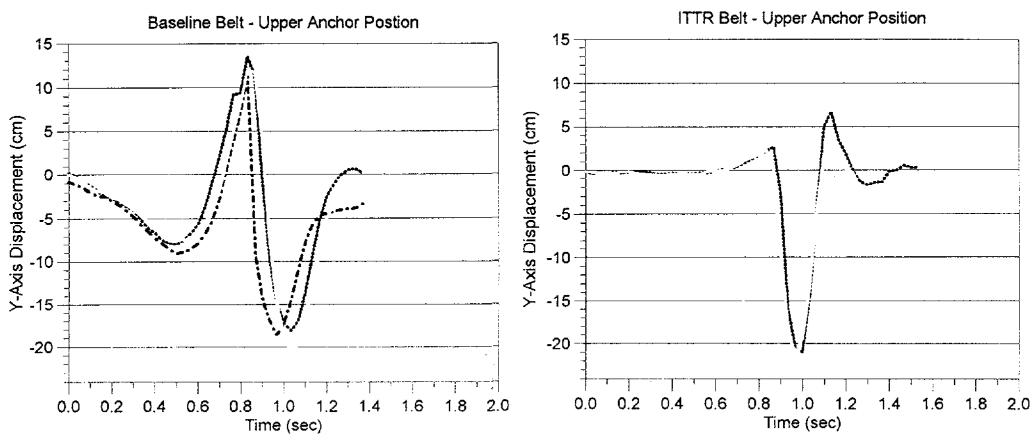

Figure 5. Y-axis excursion in upper d-ring adjustment position.

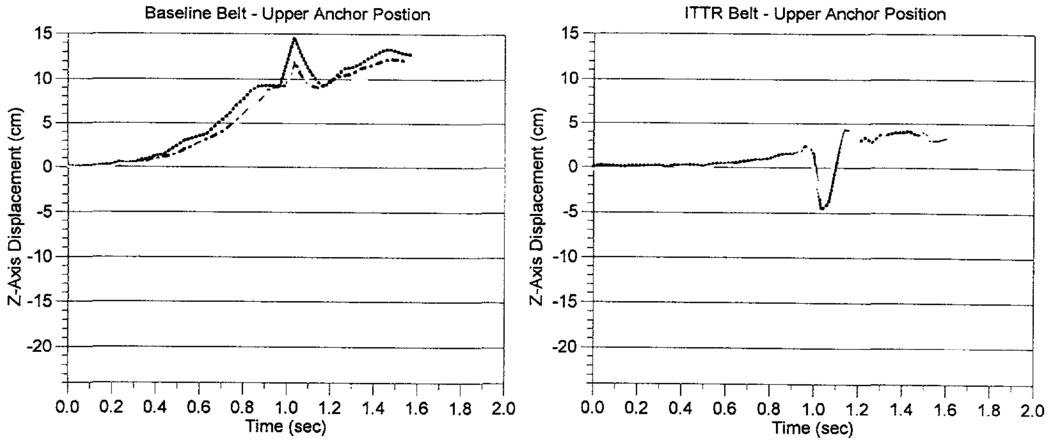

Figure 6. Z-axis excursion in upper d-ring adjustment position.

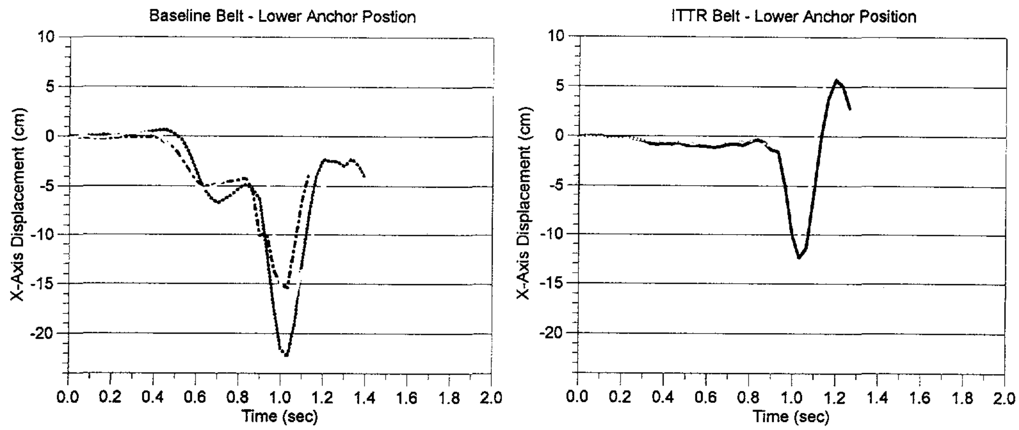

Figure 7. X-axis excursion in lower d-ring adjustment position.

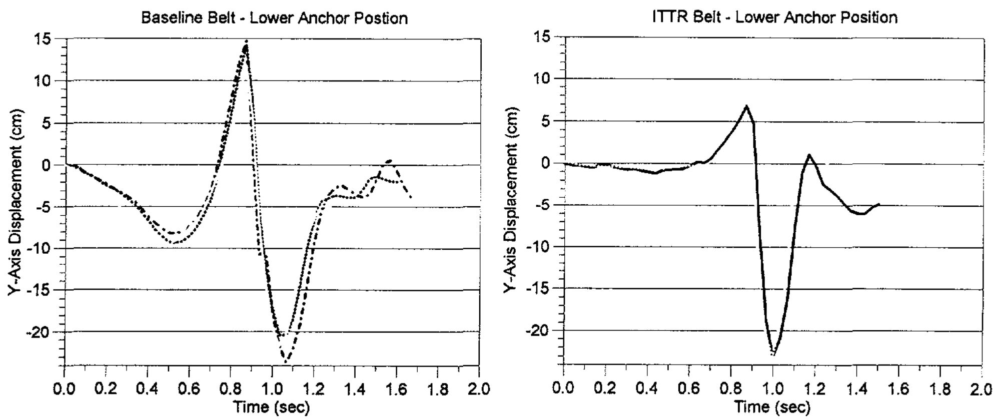

Figure 8. Y-axis excursion in lower d-ring adjustment position.

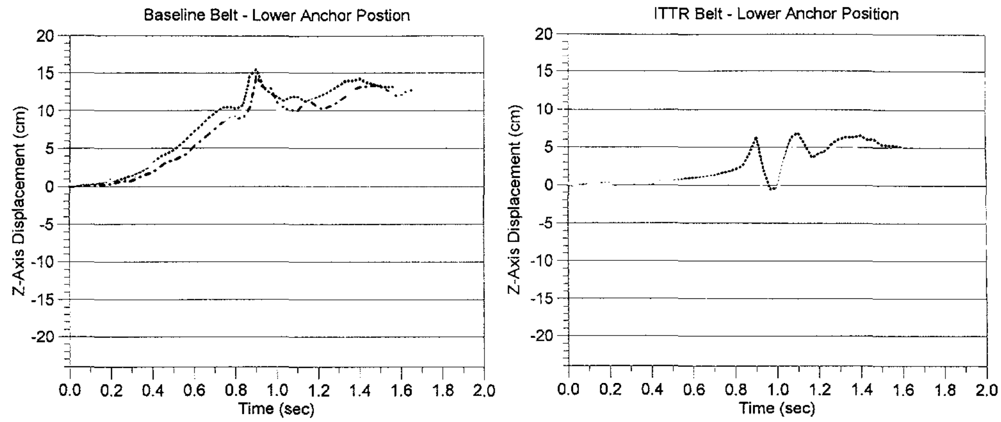

Figure 9. Z-axis excursion in lower d-ring adjustment position.

which means the dummy moved inboard as the platform rotated (Figure 5). As the platform rotated beyond 90° of rotation, the rotational forces began pulling the dummy outboard and a sharp peak occurred (0.9 seconds). At the same time, the platform impacted the shock tower and the platform decelerated. The dummy momentum continued in the same path and moved to the inboard side against the restraint. The ITTR again effectively restricted motion up to the impact with the shock tower at 180° of rotation. However, the maximum inboard motion was as severe as the baseline restraint after impact with the shock tower.

Vertical head excursion was measured in the Z-direction and results are shown in Figure 6 for the lower D-ring adjustment position. Maximum excursion was greatly reduced (as shown in Table 6) using the ITTR. When looking at the excursion trace (Figure 6) a sudden dip in vertical excursion after the initial peak is shown. This was attributable to the side-to-side motion which effectively reduced the vertical head excursion.

Head excursion in the lower D-ring adjustment position were qualitatively similar to those in the upper D-ring adjustment position. The baseline restraint and ITTR had lower excursion numbers in the upper D-ring adjustment position for all three directions. As discussed with the tabular data, this change in excursion is attributable to the shoulder belt height and angle change as the anchorage is raised or lowered. The angle on the shoulder and height on the shoulder determine how well it holds the upper torso in position. In this case, the upper or mid D-ring adjustment position was most effective in preventing head excursion.

SUMMARY AND CONCLUSIONS

A test program was conducted to determine the effectiveness of D-ring adjustment and an improved restraining device on preventing occupant excursion in a rollover crash. A typical 3-point lap and shoulder belt system and an inflatable tubular torso restraint (ITTR) were tested in a rollover restraints tester (RRT). Each restraint was placed on a 50th percentile male dummy and testing conducted at a single roll rate with varying D-ring adjustment positions. Each test simulated what was approximately a 260° per second rollover with the roof impacting the ground after 180° of roll. Occupant excursion and dummy injury measurements were recorded. Two or three tests were conducted under each condition. The following conclusions were drawn from this study:

1. 1The maximum dynamic vertical head excursion was almost three times the static dummy vertical excursion measurements made with the dummy upside down in the restraint.

2. The fit of the shoulder belt (D-ring adjustment position) on the 50th percentile male appeared to affect occupant excursion in dynamic testing. Raising the D-ring decreased the dummy head X-, Y- and Z-direction excursion in both restraints.

3. The ITTR effectively restrained the Z-direction (vertical) and X-direction excursion of the dummy. A reduction of approximately 60 to 75 percent was realized when compared to the baseline 3-point restraint. Y-direction excursion was not reduced from the baseline results.

Consequently, in this limited series of tests, it appears that occupant excursion can be reduced in rollover crashes with appropriate countermeasures, such as the ITTR. Reduced excursion would help prevent partial ejection and impact with vehicle interior components. The potential of holding the occupant upright in the seat while the roof collapses into the survival space, may be a negative consequence of such a system. However, it is expected that improved roof crush resistence would also be an integral part of the rollover crashworthiness of a vehicle, in conjunction with an improved restraint system.

FUTURE WORK

Additional testing is planned to address questions raised in this study. Testing with the 5th percentile female and 95th percentile male would aid in determining the role that the D-ring adjustment has in improving occupant restraint. It appears that D-ring adjustment could be an important factor in determining the effectiveness of restraints in preventing excursion in rollovers. Additional testing is also planned to examine a stiffer impact to determine how sensitive occupant motion is to roof stiffness.

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