THE PERFORMANCE OF TETHERED AND UNTETHERED FORWARD FACING CHILD RESTRAINTS

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ABSTRACT

Serious neck injury to children restrained in forward facing child restraint systems involved in crashes of moderate severity has been reported by several researchers in Europe and North America. No cases of similar injury have been reported in Australia for children correctly restrained in forward facing child restraints. The major difference between the forward facing restraints used in Australia and those used in Europe and North America is the universal use of a top tether strap in Australia. The rationale for this requirement of a mandatory top tether has always been that it reduces the likelihood of head contact with the vehicle interior.

This paper describes a sled test program to investigate the performance of forward facing child restraints with a variety of top tether geometries. The restraint system performance was assessed using the CRABI six month child dummy. The results of the study indicate, that as well as reducing head excursion, a top tether, with the right high mounted geometry, significantly reduces head acceleration and neck loads in frontal impacts.

SERIOUS NECK INJURY IN CHILDREN restrained in forward facing child restraints involved in frontal impacts of moderate severity has been reported by several researchers in Europe and North America, Langwieder et al (1989), Tarriere et al (1991). No cases of similar injury have been reported in Australia for children correctly restrained in forward facing child restraints. A recent study of accidents involving children as occupants conducted in Australia suggests that Australian children when correctly restrained are surviving accidents previously thought to be unsurvivable, Henderson et al (1994).

Two possible mechanisms have been proposed as the cause of the serious neck injury observed in children restrained in forward facing restraints in Europe and North America. The first suggests that a child whose torso is rigidly tied to a seat will be at risk of neck injury through neck flexion. The other involves inertial loading of the child's neck in tension by the head. The fact, that a child's head is relatively large in proportion to the rest of the body and muscles and ligaments in the neck are not fully developed, supports either theory.

A number of studies have investigated the mechanisms responsible for this type of injury in an attempt to establish a measurable threshold for neck injury in children. Most of this work has involved the reconstruction of real world accidents where children have received serious neck injury. The reconstructions have generally taken the form of laboratory crash simulations and full scale car to barrier impacts.

Planath et al (1992) used reconstruction of real world accidents together with matched tests of child dummies and animals to synthesise data to suggest values to be used as a guideline for neck protection criteria in children. The values suggested for three year old children were;

Tensile axial force (Fz)	1000N
Shear Force (Fx)	300N
Forward bending moment (My)	30Nm

A three year old Part 572 dummy with a modified neck was used in this work.

Troiselle et al (1993) used the reconstruction of accidents to investigate neck injury thresholds in children. They found that for children represented by the six month CRABI, no injury occurred under a forward shear load of Fx =950N and bending moment of My =41Nm. They did observe injury over an axial neck force of Fz =1200N. For children in the three year age group they agreed with the threshold of Fx =300N as suggested by Planath et al (1992), but for Fz and My they obtained slightly different results. The six month and three year CRABI dummies were used in this work.

Janssen et al (1993) developed a time dependant neck injury assessment curve for a 9 month old dummy from the adult Hybrid III injury assessment curves using scaling techniques. The authors suggest a maximum Fx = 800N and a slightly higher value for Fz of approximately 850N

The major difference between forward facing restraints used in Australia and those used in Europe and North America is the mandatory use of a top tether in Australia. The Australian Standard for child restraints (AS1754) requires the provision of a top tether on all child restraints (except booster cushions) sold in Australia. Originally all of the forward facing child restraints sold in Australia have had top tethers that were mounted high up on the back of the child restraint seat. Recently, there have been more overseas developed child restraints on sale in Australia. Many of the forward facing devices now on the Australian market have been imported from overseas markets and modified to meet the Australian requirements. In most cases this modification includes the addition of a top tether. There are currently no requirements covering the position of the tether mount on the child restraint, and many of these new devices on the Australian market have the tethers mounted lower on the back of the restraint than the earlier restraint systems developed in Australia.

The head is still the most frequently injured region in both restrained and unrestrained children, Henderson et al (1993), Lowne (1974), Langwieder et al (1989), and much of this injury results from contact with the vehicle interior. It is therefore necessary that head excursion (and head acceleration) be kept to a minimum. Researchers in Australia have acknowledged the benefits of a top tether in reducing head excursion, Griffith et al (1994). Until recently, no attempt had been made to quantify these benefits in terms of the biomechanical responses obtained from anthropomorphic dummies, partly because no suitable dummies have been available.

Recently, a small number of studies have been conducted to compare the performance of tethered and untethered restraints in frontal impacts. Weber et al (1993) tested two types of forward facing child restraint systems in various configurations using the six month CRABI. The restraints were tested in both the upright and reclined position and with and without a top tether. The effect of a loosely adjusted harness was also investigated in one of the restraints. The restraints used in this test series were the Strollee and the Century 1000. Both of these restraints are forward facing, five point harness devices. The authors reported that the presence of a top tether appeared to have no beneficial effect on the neck loads produced in the restrained six month CRABI. The authors suggested that this may be partly the result of the systems not being tuned to this size of dummy.

Brun-Cassan (1993), in a report to the International Task Force on Child Restraining Systems described another test program in which the performance of tethered and untethered forward facing child restraints were compared. In this case a Britax child restraint was used in conjunction with a TNO P3/4 and a three year old CRABI. The neck forces (Fx and Fz) and the moment (My) were found to be similar in the tethered and untethered restraint when tested using the TNO P3/4. However, the neck forces were found to be lower in the tethered restraint when the three year old CRABI was used. The benefits of the top tether on limiting the head excursion of both dummies was also noted in this report.

In contrast to these results, Janssen et al (1993) reported that in their comparison of a tethered and untethered restraint, the presence of a top tether slightly increased the neck loads produced in the test dummy. In this case a TNO P3/4 was used with an unidentified child restraint system described by the authors as being a "universal forward facing seat with a four point harness".

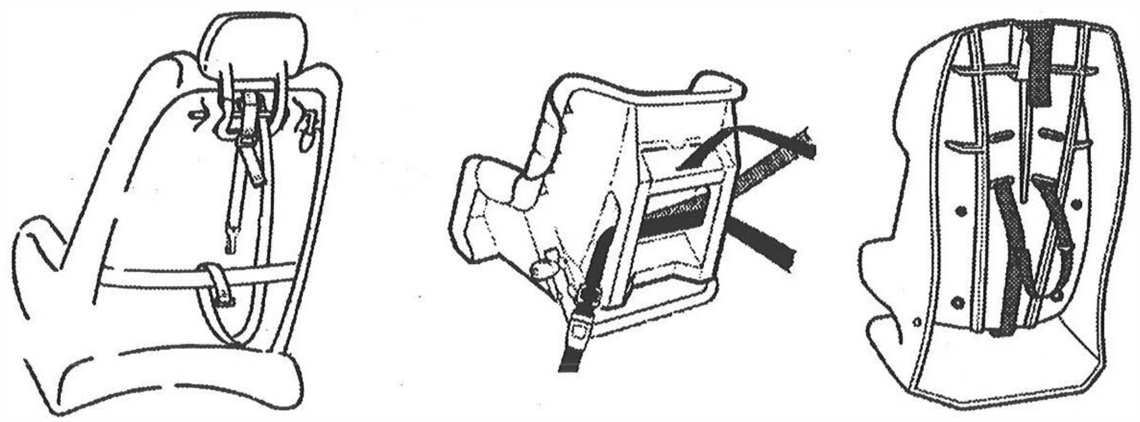
The objective of the work presented in this paper was to investigate the differences in biomechanical response of the six month CRABI dummy resulting from the use of a top tether on forward facing child restraints in frontal impact. The head and neck responses, and the effect on these responses of different tether geometries, were studied in detail.

METHODOLOGY

As described in Table 1, the performance of three different models of forward facing, six point harness, child restraint systems were evaluated in this series of tests. These were the Secure CS4, Century 1200C and Safe'N'Sound (SNS) Series III. The Secure CS4 was chosen because it is a popular restraint system both in Europe and Australia. It is fitted with a high mounted tether, but is designed for use without a tether for the European market. The Century 1200C is popular both in North America and Australia. It is fitted with a low mounted tether, but is designed for use without a tether for the US market. The third system was included for comparison purposes. The Safe'N'Sound Series III is a popular Australian system with a high mounted tether, which is designed only for use with the tether.

The tether was classified as high or low mounted according to the position of the tether mount on the restraint system with respect to the back of the test seat, see Figure 1. If the tether mount was at the same height or higher than the seat back on the test seat, then it was designated a high mounted tether. Otherwise, it was designated a low mounted tether, the implication being that

Figure 1: Diagrams of the backs of the three child restraints used in the testing



Secure CS4 Child Restraint showing the high mounted tether geometry.

Century 1200C Child Restraint showing the low mounted tether geometry

Safe'N'Sound Series III Child Restraint showing the high mounted tether geometry the tether had to follow the seat back down to the mounting point on the child restraint system.

Each model of restraint was anchored to a standard test seat by an inertia reel lap/sash (3 point) seat belt and top tether and subjected to a simulated frontal impact on a rebound sled. The severity of the impacts was as prescribed by Australian Standard AS 1754. That is, the velocity change was 49km/h with a peak deceleration of 26g. The Secure CS4 and Century 1200C were also tested in an untethered configuration under the same conditions, as these two systems are typically used in this condition outside of Australia. The SNS Series III was tested only in a tethered configuration, as is required by its design.

Table -1 Test Matrix

Test No	Child Restraint	Anchorage Details	Top Tether Geometry
941375	Century 1200C	Inertia reel lap/sash + top tether	low mounted top tether (LT)
941376	Century 1200C	Inertia reel lap/sash only	n/a (N)
941377	Century 1200C	Inertia reel lap/sash + top tether	low mounted top tether (LT)
941378	Century 1200C	Inertia reel lap/sash only	n/a (N)
941383	Century 1200C	Inertia reel lap/sash + top tether	low mounted top tether (LT)
941379	Secure CS4	Inertia reel lap/sash + top tether	high mounted top tether (HT)
941380	Secure CS4	Inertia reel lap/sash only	n/a (N)
941381	Secure CS4	Inertia reel lap/sash + top tether	high mounted top tether (HT)
941382	Secure CS4	Inertia reel lap/sash only	n/a (N)
941313	SNS Series III	Inertia reel lap/sash + top tether	high mounted top tether (HT)
941314	SNS Series III	Inertia reel lap/sash + top tether	high mounted top tether (HT)
941315	SNS Series III	Inertia reel lap/sash + top tether	high mounted top tether (HT)

All devices were anchored to the test seat in the upright position in accordance with the manufacturer's installation instructions. To ensure standardised harness adjustments between each test, measured slack was introduced into the harness system of each test. This was achieved by using a 25mm thick flexible pad which was placed behind the dummy, as the dummy was being seated in the child restraint. The harness system was adjusted as tightly as possible prior to the foam pad being removed. A new child restraint and adult seat belt system was used in each test.

The dummy used in this series of tests was the six month CRABI. The instrumentation of the CRABI allowed the measurement of: upper neck, lower neck and lumbar forces and moments; head and chest linear accelerations; angular accelerations of the head; and pelvic accelerations. Webbing force transducers were also used to measure loads in the lap and shoulder portions of the child restraint harness and in the top tether when present. Sign conventions, coordinate systems and data filter classes used in this test program were as specified in SAE J211.

Pre and post test checks of the CRABI dummy responses were carried out according to the 1994 SAE Dummy Testing Equipment Subcommittee draft calibration procedure.

Each test was filmed using two on board high speed Stalex cameras operated at 1000 frames per second. One camera was positioned to the side of the test sled and the other at 45° towards the front of the sled. Film from the side camera was used in the kinematic analysis of each test. Film from the other camera was used for observation of head motion.

RESULTS

A full listing of the results obtained from each test of this series is given in the Appendix, Table A1 which is available from the authors, on request.

The average maximum response values, measured on the 6 month CRABI dummy, are summarised in the graphs in Figure 2.

The majority of the parameters measured in the tethered and untethered Century 1200C restraint tests proved to be very similar. The measured head and restraint system excursions (Figure 3), the upper and lower neck moments (Figure 2e and 2f) and chest accelerations (Figure 2g) were higher in the untethered Century.

For the Secure restraint testing, the excursions of the head and restraint system, head acceleration (Figure 2a), HIC values (Figure 2b), upper and lower neck forces(Figure 2c and 2d) and pelvic accelerations (in the test results Appendix, Table 1) were found to be significantly higher in the untethered tests. Only the lower neck moments (Figure 2f), chest accelerations and lumbar measurements were similar.

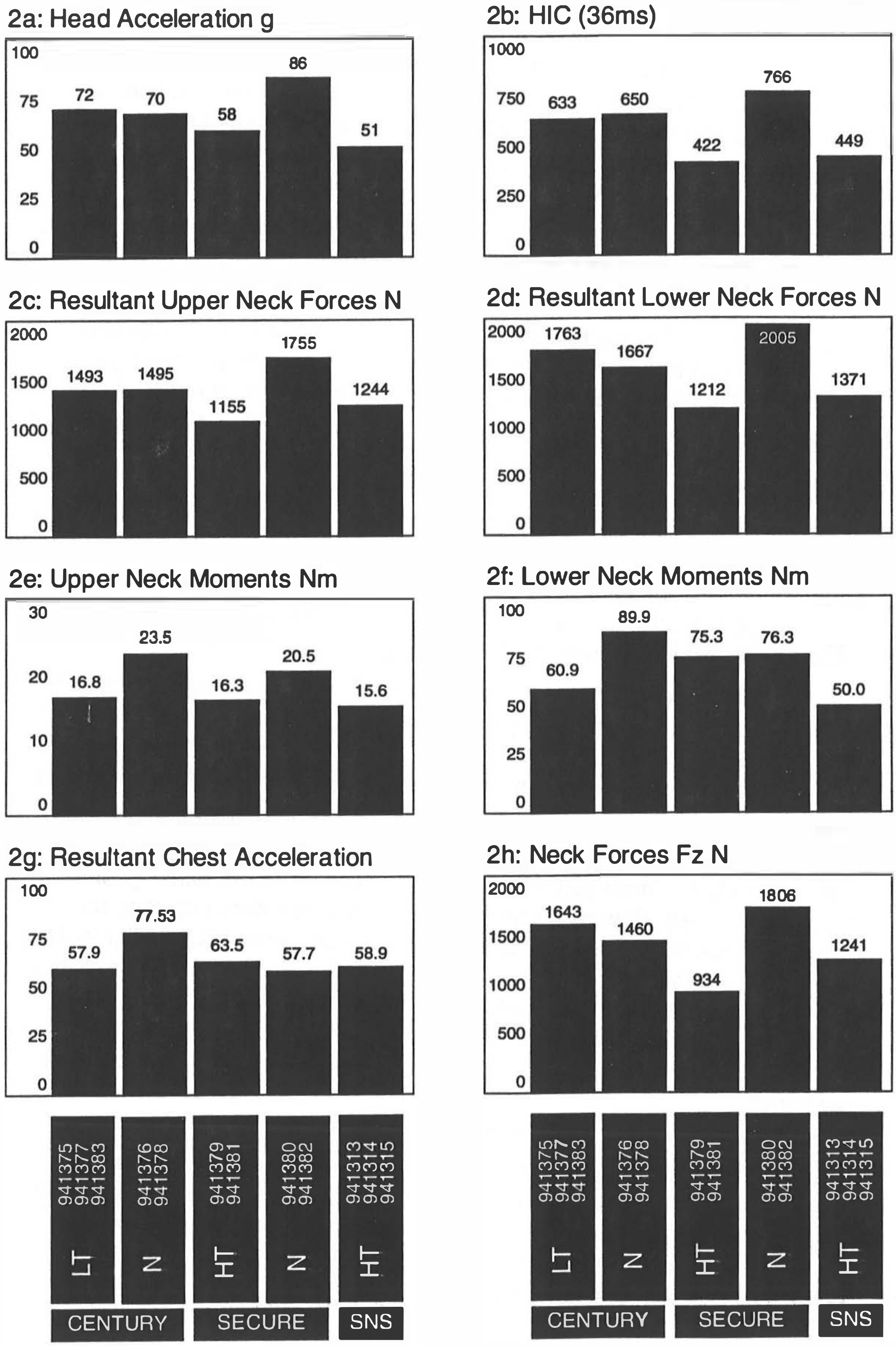
When the test results of the two restraints, the Century and Secure in the tethered configurations, were compared, the Secure with the higher mounted tether was observed to produce lower resultant head accelerations, HIC values, and upper and lower resultant neck loads. Resultant chest accelerations and lumbar spine measurements, were higher in the tethered Secure tests.

The SNS restraint tests, which were all with a high mounted tether, produced head accelerations and HIC values that were similar in magnitude to the tethered Secure tests, also with a high mounted tether, but with the resultant neck forces slightly higher for the SNS restraint. The SNS restraint tests produced the lowest upper and lower neck moments. Chest accelerations in the SNS tests were similar, if not slightly higher than in the Century, and slightly lower than the Secure. Lumbar spine loads and pelvic accelerations were not measured in the SNS restraint.

The Appendix also contains a summary of the excursion of five points, the top and bottom of the child restraint and the top of the head, fingertips and ankle of the dummy in each test, Table A2. Table A2 is also available from the authors', on request.

The use of a top tether with the Secure and Century limited the maximum excursion of both the restraint and the dummy head. The tethered Secure allowed the least amount of excursion. Excursion measurements for the SNS

Figure 2: Average Maximum Six Month CRABI Dummy Responses Values



device are not available.

DISCUSSION

RESULTANT AND AXIAL NECK LOADS The results obtained in this series of tests show that the use of a high mounted tether consistently reduced the resultant neck loads produced in the upper and lower neck of the six month CRABI in frontal impacts by 30 - 40%, see Figure 2(c) and (d).

The Century tests, with a low mounted tether, did not have the same reduced neck loads as the restraint systems with high mounted tethers, ie the Secure and SNS . When upper and lower resultant loads were averaged, as was done by Weber et al (1993), a similar pattern was maintained.

Loads produced in the Fz direction of the dummy neck, ie. the axial loads, exhibit the same pattern observed in the resultant neck loads, see Figure 2 (c), (d) and (h). That is, the restraint systems with high mounted tethers had significantly reduced axial loads in both the upper and lower neck transducers of the six month CRABI. However, in the Century tests with low mounted tethers, there was no reduction in the axial loads.

Weber et al (1993) found that the use of a top tether with the Strollee and the Century 1000 forward facing restraints had no real effect on the neck loads produced. The Century 1000 is very similar to the Century 1200 in design, and the testing reported here confirmed these results. Weber's results may be explained by the low mounted tether geometry of this system.

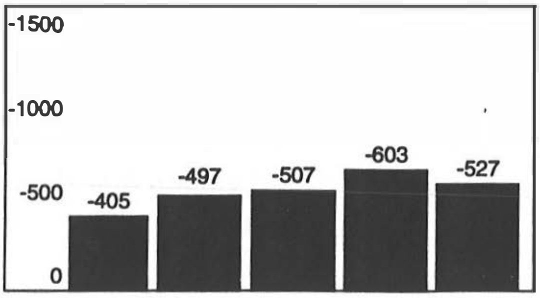
A tether mounted some distance below the top of the back of a child restraint appears to provide not much improvement in supplementary anchorage. In other words, a child restraint using a low mounted tether, performs in a very similar manner to that same device anchored by a three point seat belt only.

Brun-Cassan (1993) observed a slight decrease in resultant and Fz neck loads in a tethered Britax Freeway, a forward facing 5 point child restraint system, using the three year old CRABI. The details of the tether geometry were not reported. However, using a TNO P3/4 in the same system, she observed a slight increase in these loads. This last result was similar to that obtained by Janssen et al (1993), using a similar dummy. The increase and decrease were approximately within the range of $\pm$ 17% of the untethered values. This type of variation between tethered and untethered loads is similar to that observed in the Century system with the low mounted tether during this test series.

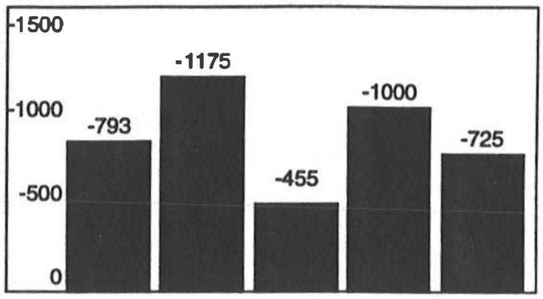
NECK SHEAR FORCES AND FORWARD BENDING MOMENT From the results of this test series, it appears that the presence of a top tether and its geometry does not have a major influence on the shear loads, Fx, and forward bending moments, My, of the six month CRABI dummy neck, Figure 3. It is possible that other restraint and anchorage features such as seat belt geometry, seat belt routing and child restraint harness geometry may have more of an influence on these values. This should be further explored.

Figure 3: Comparison of the average maximum shear force Fx, and forward bending moments, My

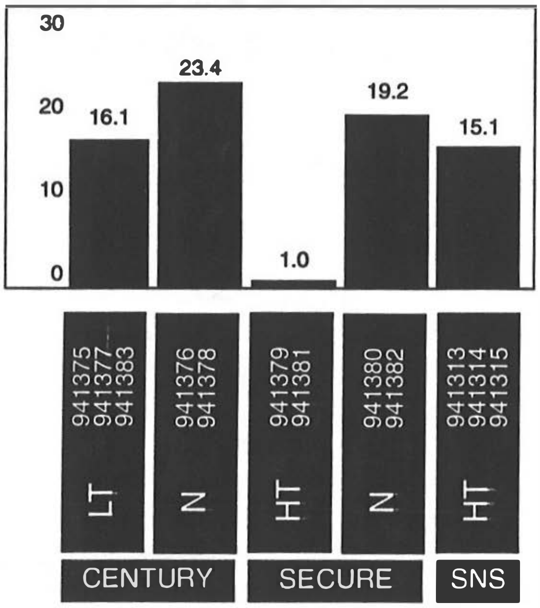
3a: Average Maximum Upper Dummy Neck Forward Shear Force, Fx (N)



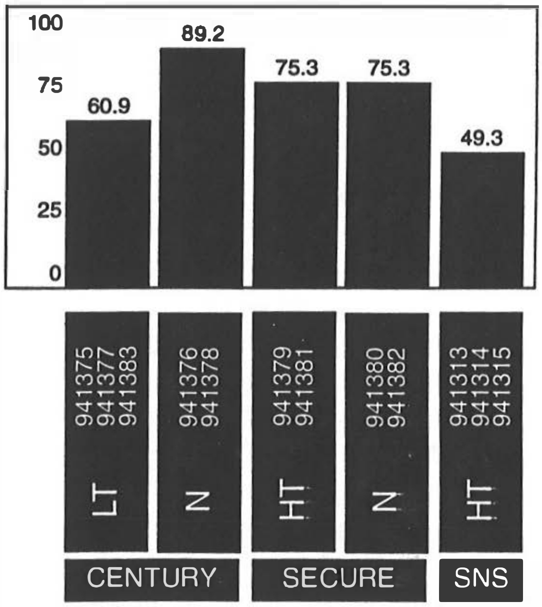
3b: Average Maximum Lower Dummy Neck Forward Shear Force, Fx (N)



3c: Average Maximum Upper Dummy Neck Forward Moment, My (Nm)



3d: Average Maximum Lower Dummy Neck Forward Moment, My (Nm)



EFFECT OF TETHER TYPE ON RESTRAINT SYSTEM MOTION The kinematic analysis of the high speed film showed the effects on the motion of the child restraint systems by the different geometries of the tethers used. Figure 4 shows the differences in motion between the untethered Secure, tethered Century (with a low mounted tether) and tethered Secure (with a high mounted tether). The beneficial effect of the top tether is clearly illustrated. The untethered Secure, Figure 4a, demonstrated a marked amount of rotation as well as forward translation during the test. The Century's low mounted tether, Figure 4b, reduced the forward translation but still allowed significant rotation. The test of the Secure, with the high mounted tether shows almost no rotation, just translation, Figure 4c. This variation in restraint motion may be an indication of the mechanism by which the high mounted tether is more effective.

This justifies further investigation of its effect on the mechanism of neck injury in the child occupant.

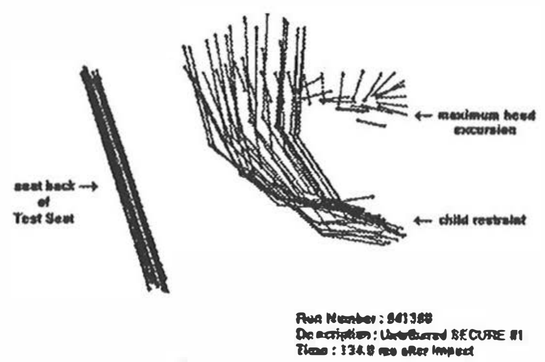
COMPARISON OF RESULTS WITH EXISTING BIOMECHANICAL DATA

Troiselle et al (1993), using the six month CRABI in their reconstruction of real world accidents, found no injury occurring under a neck shear force of less than Fx =950N and a forward bending moment of less than My =41Nm.

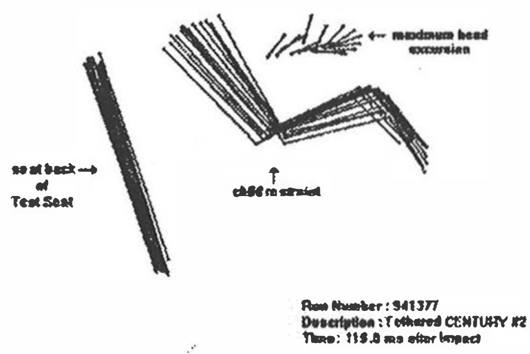
The neck shear force results obtained in this current series show that all of the systems, tethered or untethered met this criteria for the upper neck, figure 3. For the lower neck, only one of the high mounted tethered systems (SNS) and the system with a low mounted tether (Century) produced values below 950N. The forward neck bending moments obtained from the upper neck transducer from all of the devices, tethered and untethered were below 41Nm, while none of the lower neck values were below this value. On examination of the average upper and lower neck moments, only one restraint, the SNS, which has a high mounted top tether, produced average maximum forward bending moments below 41Nm.

The neck axial force injury threshold, for Fz, indicated by Troiselle et al

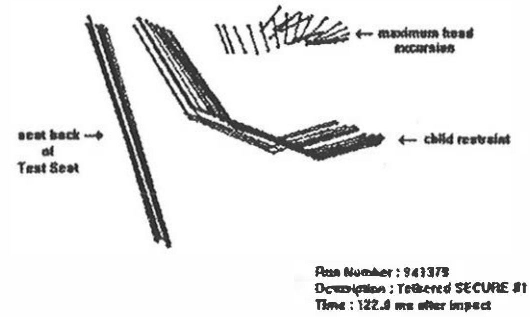
Figure 4: Comparison of the motion of the child restraint systems during a test:



4a: Secure CS4 - Untethered



4b: Century 1000C - Low Mounted Tether



4c: Secure CS4 - High Mounted Tether

(1993) was 1200N. Only the devices using a high mounted tether, the Secure and the SNS Series III, came close to meeting this criteria, Figure 2h.

The other work reviewed, that by Planath et al (1992) and Janssen et al (1993), was not conducted with the six month CRABI dummy. Therefore it is not appropriate to draw any comparisons with the values reported by these researchers and those obtained in this series of tests. However, Planath et al (1993) proposed Fx = 300N, Fz =1000N and My =30Nm from work conducted with representative three year old dummies. Based on the results obtained here these values seem a little low to be realistically achievable with forward facing restraints.

THE BENEFICIAL EFFECTS OF A TOP TETHER ON HEAD PROTECTION

The head is still the most frequently injured region in restrained and unrestrained children (Henderson et al, 1994, Lowne, 1974, Langwieder, et al, 1989), and much of this injury results from contact with the vehicle interior. To maximise the protection offered by a child restraint system it is necessary that head excursion (and head acceleration) be kept to a minimum.

A top tether, regardless of its effect on the neck loads produced in the CRABI dummy, has a beneficial effect on limiting the forward excursion of the child restraint and the dummy's head. This is illustrated clearly in the test results and Figure 5. Brun-Cassan (1993) also noted the advantageous effect of a top tether on limiting excursion in her comparison of tethered and untethered devices.

Not surprisingly, the high mounted top tethers also reduce head acceleration in a similar manner to their reduction of resultant neck loads and axial neck

Figure 5a: Average Maximum Forward Excursion of the Child Restraint Top (mm)

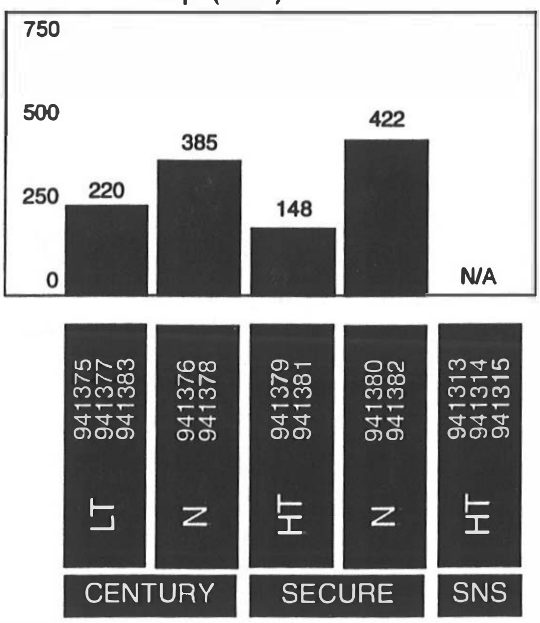
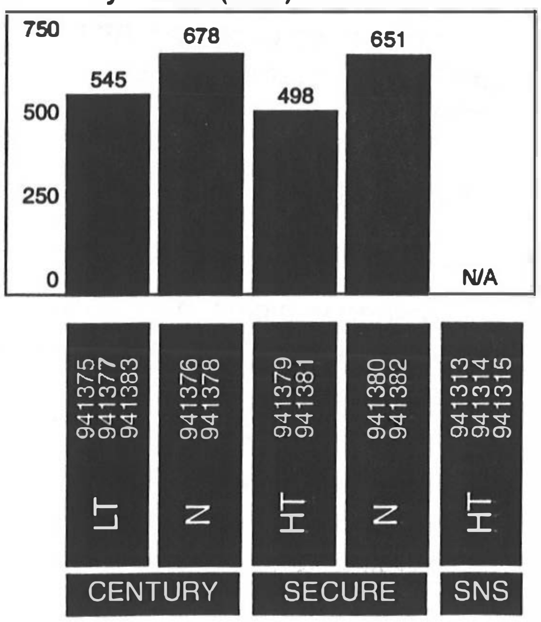


Figure 5b: Average Maximum Forward Excursion of the Top of the Dummy Head (mm)



loads, Figure 2a, c, d and h. This suggests that the way in which the high mounted tether affects the neck loads produced in the CRABI dummy may be linked to head acceleration.

THE RELEVANCE OF THE RESULTS OBTAINED TO IMPROVED PROTECTION FOR CHILD OCCUPANTS. The results obtained in this series of tests show the characteristics of top tether straps that can provide substantial improvement in protection of child occupants in frontal impacts.

The more obvious benefit is that head excursion can be limited by the use of a top tether anchorage.

Resultant neck loads, axial neck loads and head accelerations can be reduced significantly by using top tethers that are mounted high up on the back of the child restraint. The use of a low mounted top tether has no measurable beneficial effect on these parameters, with the tethered and untethered configurations producing very similar results. Both the tethered and untethered configurations of the Century 1200C, the system with the low mounted tether, produced somewhat lower resultant neck loads, axial neck loads and head accelerations than the untethered Secure. However, it appears likely that the performance of the Century 1200C could be improved by raising the tether mount position.

The possibility that other anchorage and child restraint parameters may influence forward shear loading, Fx, and bending moment, My, appears worthwhile exploring by some means, such as mathematical simulation, which will allow further variation of the restraint system design parameters.

Because the CRABI dummy can monitor a wider variety of biomechanical test responses, an opportunity exists to gain further information about the tolerance of children to injury by reconstructing real crashes. Reconstructions are currently being carried out internationally with the encouragement of the International Task Force on Child Restraint Systems. In this regard, it is important to reconstruct non injury cases as well as those where injury was known to have occurred. An indepth study of car crashes in which occupants are injured is currently being conducted by the Roads and Traffic Authority of NSW. This is one possible source of such cases.

CONCLUSIONS

1 The head is the most frequently injured body region of child occupants of crashed vehicles, and much of this injury is caused by impact with the vehicle interior, Henderson et al (1994). The use of a top tether on a child restraint system limits head excursion. On this basis alone, it is worth while encouraging its use internationally.

2. The use of a high mounted top tether with a forward facing child restraint system can significantly reduce the resultant neck forces, which are dominated by the axial neck force (Fz), and the resultant head acceleration produced in the six month CRABI dummy in frontal impacts.

3. It is possible that the reduction in dummy neck forces brought about by high mounted top tethers, is a factor in the absence of serious neck injury to children restrained in forward facing child restraints in Australia.
4. Significant improvement in the protection of child occupants in frontal impacts can be made by addressing the method of anchorage of child restraints to the vehicle.
5. A much better understanding of the tolerance of children to impact injury is required to be able to fully realise the improvements possible in the protection of child occupants. With the improved dummies now available, an appropriate method is to reconstruct field accidents with known injury outcomes, both injurious and non injurious, and compare the injury information to the dummy responses.

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