THE CUMULATIVE EFFECT OF MULTIPLE FORMS OF MINOR INCORRECT USE IN FORWARD FACING CHILD RESTRAINTS ON HEAD INJURY RISK.

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ABSTRACT

Incorrect restraint use is widespread among child passengers and increases the risk of injury in a crash. Based on previous laboratory testing, individual modes of incorrect use are often rated as serious or minor. However, in a recent population-based observational study in NSW Australia, almost one third of incorrect use was found to involve multiple minor errors. In this test series we hypothesized that the cumulative effect of multiple minor errors would result in injury protection reductions of the same order as individual, more serious forms of incorrect use.

To test this hypothesis, four relatively minor forms of incorrect use in a forward facing child restraint were tested individually and in various combinations and the relative reductions in injury protection were compared to that observed in more serious forms of incorrect use. Data from 40 frontal crash sled tests (32km/hr, 16g) using an instrumented CRABI six-month dummy were used in this analysis. Estimations of reduction in injury protection were made on the basis of relative increases in head and restraint motion as assessed using high speed digital photography. The minor errors studied were selected on their high observed frequency in the NSW population and included single and double twists or slack (25mm) in the internal harness and 25mm of slack in the lower anchorage. The serious incorrect use included positioning of the harness below the shoulder level, an incorrectly routed seat belt, 50mm of slack in the top tether, excessive slack (75mm) in the anchorage system, non-use of lower or upper anchorage and non-buckling of the belt used as the lower anchorage.

Combinations of two minor errors increased the relative motion of the dummy by up to 8% compared to when there were single errors only, with the greatest relative increase occurring when two twists were added to a moderately loose (approximately 25mm slack) internal harness of the restraint. However, much greater relative increases occurred when there were combinations of three errors (average increase of 15%, range 10-20%). Compared to when there is no incorrect use, the combination of three errors increased dummy motion in the same order of magnitude (approximately 15%) as serious forms of incorrect use such as excessive slack, partial and non-use of lower anchorages.

The results demonstrate the cumulative effect of minor incorrect use on dummy head excursion and restraint motion. Minor forms of misuse can be serious when they occur in combinations. This extends previous laboratory work demonstrating the effect of incorrect use. Based on these results, similar cumulative effects in combinations of serious errors, and in combinations of more than three errors might be expected. These findings, together with field work indicating that almost 16% of children travelling in cars have three or more errors in the way their restraint is being used, highlight the need for countermeasures to reduce the prevalence of even minor errors.

Limitations include the fact that only a single model of restraint and a standard test bench and set up was used. The absolute effect of the errors studied may vary depending on these factors.

INTRODUCTION

Appropriate and correct use of child restraint systems (CRS) reduces the risk of injury to child passengers in crashes (Du et al., 2008, Hertz, 1996, Elliott et al., 2006, Winston et al., 2000, Arbogast et al., 2004). However, the level of protection provided by CRS is reduced if restraints are not used correctly. While there has been much research into the negative effects of suboptimal CRS use (Bilston et al., 2007, Elliott et al., 2006, Lalande et al., 2003, Brown et al., 2006), this has mostly focused on single errors in restraint use. When errors occur in the real world they often occur as multiple errors (Brown et al., 2010b, Koppel and Charlton, 2009), but few studies have investigated combinations of misuse, their cumulative effects, and their association with the level of protection

afforded to the child within the restraint (Lalande et al., 2003).

It has long been acknowledged that not all errors have the same effect on restraint performance (Decina and Lococa 2005; Eby and Kostyniuk, 1999). For this reason, individual errors are often categorised as minor, moderate or severe in observational studies. Rating systems used in ease of use consumer information programs give higher priority to preventing more serious errors. It is possible that the multiple errors increase the degradation in protection previously observed with single errors. This might mean that errors observed to have only a small effect in isolation might 'add-up' to have a serious effect when they occur in combination. We hypothesize that the cumulative effect of multiple minor errors would result in injury protection reductions of the same order as more serious forms of incorrect use. To test this, we have considered the effect on protection of the most common combinations of child restraint misuse from an Australian study (Brown et al., 2010a).

METHOD

Common Errors

Data was extracted from a data set collected during an observational study of restraint misuse in NSW, Australia (Brown et al., 2010b, Brown et al., 2010a), and analysed to establish the most common forms and combinations of errors. The overall sample consisted of observations of 501 children aged 0 to 12 years using all types of restraints. Only those using forward facing restraints (N=126) were considered in this analysis.

In the extracted data, each error was assigned to a restraint component category (e.g. harness, seat belt and top tether) and designated a type of error (e.g. harness twisting and seat belt routing). The overall occurrence of each type of misuse was totalled and ranked according to the total number of cases the individual misuse was involved in. The most common errors identified are shown in Table 1.

To examine the most common combinations, the sample was further separated into the number of errors observed in each case. This ranged from two to six errors for each case. These groups were then ranked. The most common errors within each group were assessed across the sets to identify the most common combinations. These occurrences were also compared to the frequency of single errors. The top six combinations of double misuse for the forward facing data are presented in Table 2..

Table 1.
Top 10 individual forms of misuse and their frequency in forward facing restraint cases from Brown et al. (2010a).

Category	Type	Frequency of Misuse (%)
Harness	mildly twisted	50.79
Harness	slightly loose	40.48
Harness	low on shoulders	15.87
Harness	very twisted	14.29
Seat Belt	incorrectly routed	13.49
Seat Belt	loose	12.70
Harness	very loose	11.90
Seat Belt	mildly twisted	9.52
Additional	baby insert used	8.73

Table 2.
Top 6 double combinations of misuse for forward facing restraints and their frequency (Brown et al. (2010a))

Description of Type of Misuse	Cases With This Misuse	
	Total	*%*
Harness mildly twisted and slightly loose	39	30.95
Harness mildly twisted and seat belt loose	9	7.14
Harness slightly loose and seat belt loose	9	7.14
Harness mildly twisted and seat belt route incorrect	8	6.35
Harness slightly loose and too far below shoulders	8	6.35
Harness very twisted and slightly loose	8	6.35

Test Matrix

The test matrix (shown in Table 3) was designed to include the most common cases of multiple errors identified in the sampled data. These include a combination of minor and serious errors as coded by Brown et al. (2010a).

Table 3.
Test matrix

Misuse	Description of misuse		Designated Severity
	Securing (harness)	Installation	
Control (No misuse)	–	–	N/A
Single misuse	Harness mildly twisted	–	Minor
	Harness very twisted	–	Minor
	Harness slightly loose	–	Minor
	Harness low on shoulders	–	Serious
	–	Seat belt routed incorrectly	Serious
	–	Seat belt 25 mm slack	Minor
	–	Tether 50 mm slack	Serious
	–	Tether not used	Serious
	–	Seat belt not used	Serious
	–	Seat belt used, not buckled	Serious
Multiple misuse	Harness very twisted, Harness slightly loose	–	Combined Minor
	Harness mildly twisted, Harness slightly loose	–	Combined Minor
	Harness mildly twisted, Harness too far below shoulders	–	Combined Minor/Serious
	Harness very twisted, Harness too far below shoulders	–	Combined Minor/Serious
	Harness mildly twisted, Harness slightly loose, Harness too far below shoulders	–	Combined Minor/Serious
	Harness mildly twisted	Seat belt routed incorrectly	Combined Minor/Serious
	Harness mildly twisted, Harness slightly loose	Seat belt 25 mm slack	Combined Minor
	Harness mildly twisted, Harness slightly loose	Tether 50mm slack	Combined Minor/Serious
	–	Tether 75 mm slack, Seat belt 75 mm slack	Combined Serious

Table 4.
Misuse descriptions and definitions

Form of misuse	Definitions of misuse
Harness mildly twisted	1 full twist on each strap of the harness between harness tongue and collar bone region.
Harness very twisted	2 full twists on each strap of the harness (twisting did not pass through the upper shoulder slots).
Harness slightly loose	2 foam spacers to give 23.5 mm of additional slack (on top of tight harness).
Harness low on shoulders	Upper straps emerged 70 mm below the height of the dummy's shoulder using the lowest of the three harness slots, yet still passed over the top of the dummy's shoulder.
Seat belt routed incorrectly	Seat belt route passed through slots for the rearward facing mode despite the restraint operating in the upright, forward facing direction. The belt passed underneath the seat of the restraint, just rearward to the floor straps of the harness buckle.
Seat belt 25 mm slack	25mm slack was marked and taped off beneath the turning guide of the upper seat belt anchorage point.
Tether 50mm slack	50 mm slack was marked and taped off with the tether still attached to the frame.
Tether not used	Tether not attached to the anchorage clip. Only seat belt used to secure CRS.
Seat belt not used	Seat belt not extended out of holder (did not pass through CRS). Only tether used to secure CRS.
Seat belt used, not buckled	Seat belt passed through the CRS, but was unbuckled.
Tether 75 mm slack, Seat belt 75 mm slack	75 mm slack was introduced into the tether strap at the adjuster. 75 mm slack was introduced at the D-ring of the upper belt anchorage. Excess belt was pulled to rest at buckle.

Test Set Up

Each test was performed twice in the Impact Injuries Research Laboratory at Neuroscience Research Australia on a purpose built rebound crash sled propelled by bungee cords. Peak sled acceleration averaged 16.2g, simulating a frontal impact with approximately 32 km/hr change of velocity. Video footage for each test was captured by a Phantom high speed digital video camera (v4.1, Vision Research, Wayne, NJ). Data was acquired via a 10-channel signal conditioner at 10kHz according to SAE J211/1 standards through tri-axial head acceleration and upper neck forces and moments transducers on a CRABI six month old dummy. This dummy represents a 50th percentile six month old weighing 7.8 kg with a sitting height of 439mm and was clothed in appropriate apparel and fitted with photographic targets for head excursion measurement.
A single model convertible rearward facing/ forward facing CRS was used in the test series. For the correct use case, the dummy was secured to the restraint and the restraint installed as per the manufacturer's directions. As required in testing to AS 1754, a 23 mm polystyrene foam spacer was used to standardise harness fit. The errors tested are described fully in Table 4. The multiple forms of misuse were the combination of the single errors.

Data and Video Processing

Sensor output data was filtered in accordance with SAE J211/1. Resultant neck forces (Fx and Fz presented) and moments (My presented), and head accelerations were calculated and plotted. The head injury criteria (HIC15) and peak resultant head acceleration (PRHA) for each test case were also calculated.

Phantom software was used to manually digitize data points from the markers on the sled (reference) and centre of gravity (c of g) of dummy head, and top and bottom of the restraint. A template was used to estimate the location of the head c of g when the c of g marker was obscured from view by the dummy's arm. Dummy excursion in the x-direction was calculated, using a custom designed program. Maximum head excursion and restraint rotation was computed.

Results from each individual pair of duplicated tests were averaged, and the averaged value used in the analysis.

Data Analysis

The cumulative effects of the errors were evaluated in two ways. First the percentage change from the baseline (correct use) was calculated for each test scenario (single errors and combined errors). i.e. we calculated the average percentage change for each variable in each test case (i.e. average of two repetitions) compared to the correct use case. The percentage changes from the correct use case for combinations of errors were compared to the worst individual error among the combination. For example, we calculated the increase in head excursion over the correct use case for each tested single error and each tested combination. We then compared the percentage change in head excursion when there was a slightly loose harness, a slightly twisted harness, **and** the shoulder straps were in a slot too far below the shoulders with the highest percentage change in head excursion for each of those individual errors tested separately – i.e. with slightly loose harness.

An 'expected' cumulative effect was then calculated, and compared to the measured effect of the combination of errors. To calculate the 'expected' cumulative effect, the percentage change in each of the individual errors was summed. E.g. for the example in the previous paragraph, we added up the % increase in head excursion for each of the test cases (Expected % = % increase for slightly loose harness + % increase for a slightly twisted harness +% increase when the shoulder straps were in a slot too far below the shoulders). This was compared to the measured % increase in head excursion for the combination test.

This was done for forward head excursion, HIC15, PRHA, Fx, Fz and My for each combination case.

RESULTS

A summary of the percentage change in the performance measures obtained in each test scenario are presented in Appendix 1.

Head Excursion

Head excursion ranged from 186 mm to 347 mm. The scenario with an incorrectly routed seat belt (only) produced the least amount of forward head excursion. The triple misuse combination with this error was the next best scenario. Both these cases resulted in less forward head excursion than the baseline case with no misuse.

Apart from the incorrect belt route case, most of the individual errors resulted in additional head excursion of 2% to 6.5%. The exception was when the harness was too far below the shoulders, where there was an increase of 12.6% in forward head excursion. Higher values were observed with combinations of errors, ranging from 9.1% to

22.3%. The worst case was the combined triple harness misuse (harness mildly twisted + harness slightly loose + harness too far below shoulders).

Figure 1 compares the percentage change in forward head excursion in the individual and combined errors, demonstrating that the cumulative effect of multiple minor errors is of the same order as some of the more serious individual errors.

As shown in Figure 2, multiple minor errors combined to increase forward excursion beyond that observed when the individual errors occurred in isolation. This was not the case when the serious errors were combined with minor errors. As shown in Figure 3, these increases were generally greater than would have been expected by simply summing the changes in observed forward excursion for each individual error, relative to the correct use case.

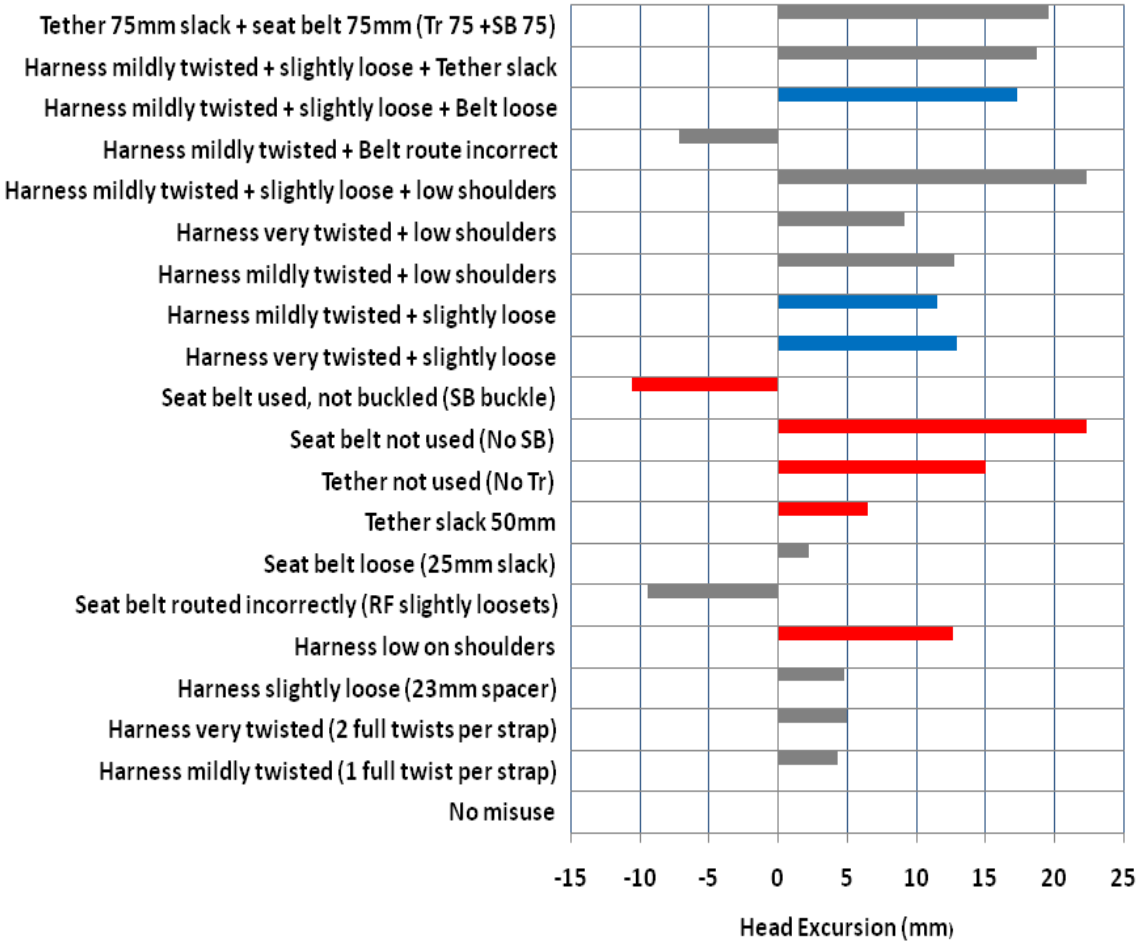

Figure 1. The increased percentage of forward head excursion for individual errors and combination errors. Red bars denote serious individual errors. Blue bars denote multiple minor error combinations.

Head Acceleration (PHRA), HIC, Neck Loads

PRHA ranged from 25 to 41g. Incorrect belt routing also resulted in the lowest PHRA and as with head excursion, PHRA was lower than that in the baseline test. Among the other individual errors, those that added slack into the system (harness slightly loose, seat belt 25mm slack, tether 50mm slack) also reduced the PRHA, and the other individual errors had little effect on PRHA.

In most cases, the combined errors reduced PHRA compared to the individual components, but resulted in greater PHRA than would have been expected from summing the errors in PHRA from the component individual errors (see Figure 4 and Figure 5). This was particularly the case in the triple combinations of errors.

HIC 15 followed a similar pattern to that seen with PRHA and was lower among the individual errors than in the correct use case. Notably, HIC 15 increased by more than 20% in the triple combinations of errors compared to the individual error components (Figure 6). The triple combination of errors also resulted in 10% greater HIC values than would have been expected from summing the components (Figure 7). However, all HIC 15 values were low (<150) in these tests.

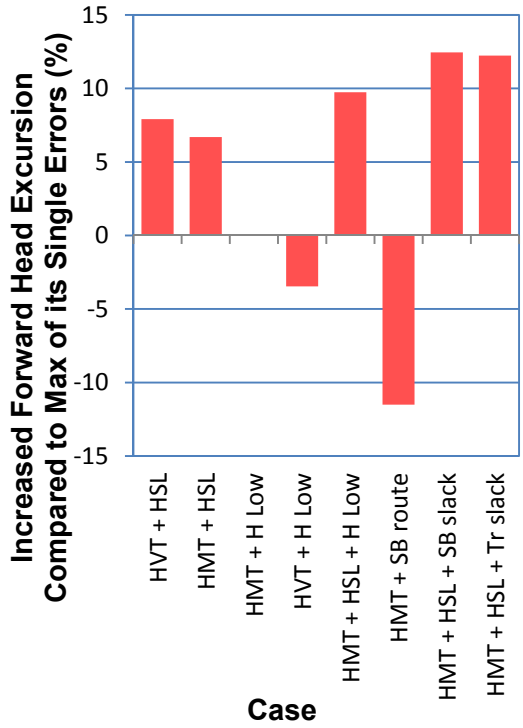

Figure 2. The increased percentage of forward head excursion for combination cases compared to the maximum value of its single errors.

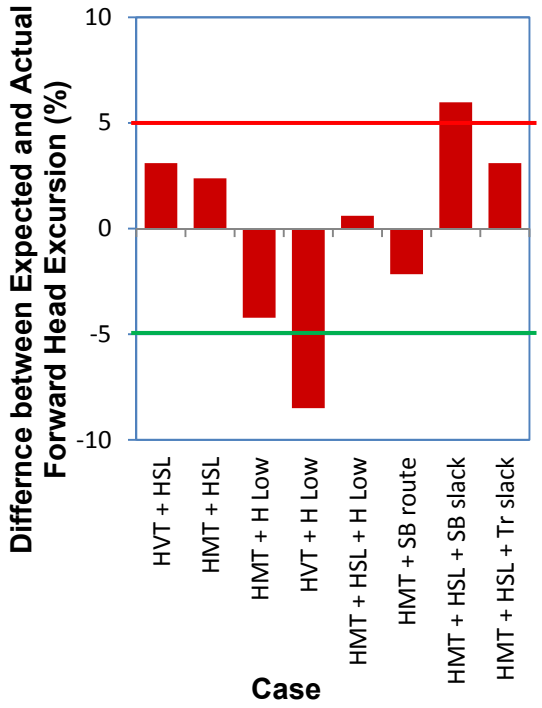

Figure 3. The difference between the recorded maximum forward head excursion and the expected value. Red line indicates 5% above the expected value; green line indicates 5% below the expected value.

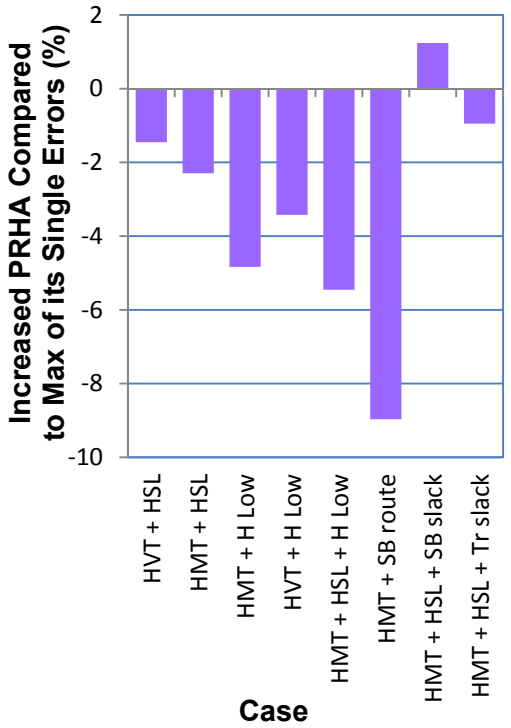

Figure 4. The increased percentage of PRHA for combination cases compared to the maximum value of its single errors.

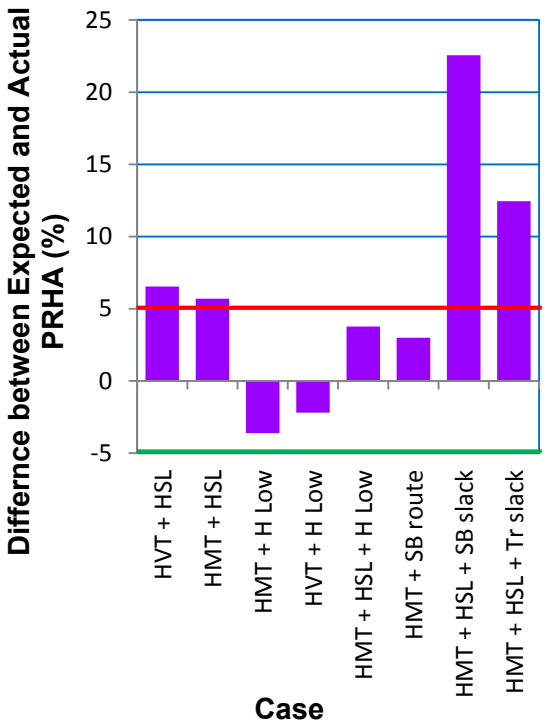

Figure 5. The difference between the recorded PRHA and the expected value. Red line indicates 5% above the expected value; green line indicates 5% below the expected value.

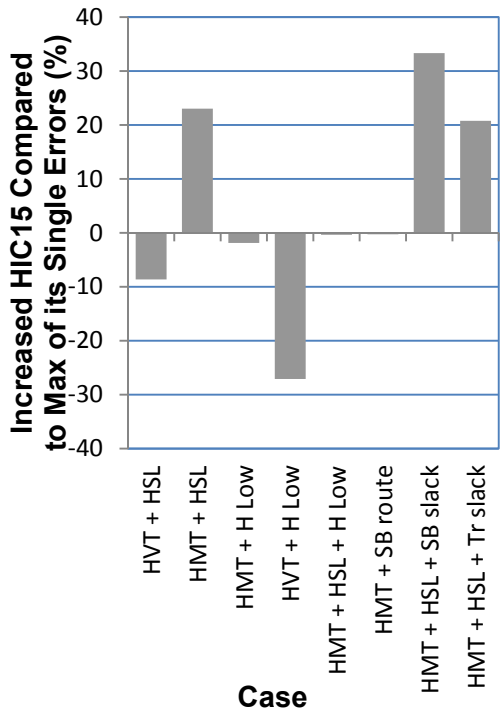

Figure 6. The percentage increase in HIC 15 for combinations compared to the maximum change among the constituent single misuse cases.

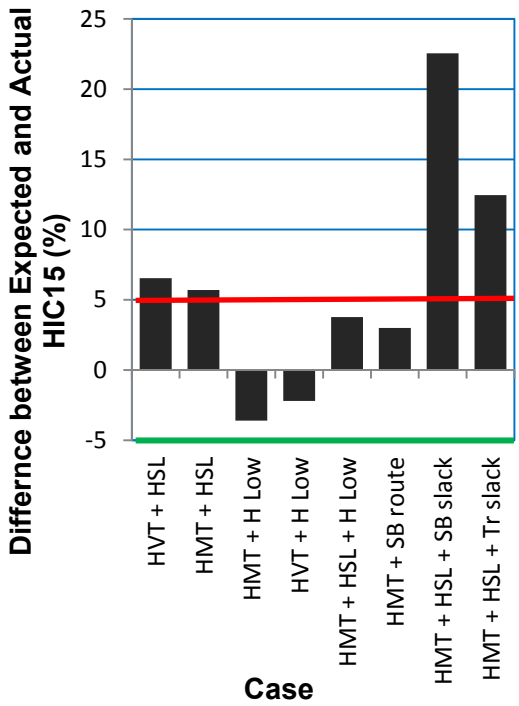

Figure 7. The difference between the recorded HIC 15 and the expected value. Red line indicates 5% above the expected value; green line indicates 5% below the expected value

Changes in Neck Fx, Fz and My relative to baseline are presented in Appendix 1. The effect of both the individual and combinations of errors was less clear in the neck responses measured in the dummy. Neck loads were all relatively low (Fx <0.64kN, Fz<0.75kN) My ranged between 0.05 and 9.5kNm.

DISCUSSION

This study demonstrates that multiple or combined minor errors in the use of a forward facing restraint can increase the amount of forward excursion to the level seen with serious errors. It also demonstrates that head excursion and other measures of head injury potential increase substantially when there are triple combinations of errors compared to when there are single or double errors. Surprisingly, one of the errors studied here was an exception and actually improved the performance of the restraint. This was when the seat belt was incorrectly routed through the rearward facing slots whilst the CRS was used in forward facing mode. The results likely reflect the advantages of a lower anchorage that encircles the base of the restraint, minimising the restraint's upward rotation. This result may be specific to this model of restraint. There are a number of ways that seat belt routing might be achieved incorrectly in different restraints, and as, Lalande et. al. (2003) and Lesire (2007) found, this type of error may negatively affect restraint performance in other configurations. Forward head excursion was also reduced when the seat belt buckle was not engaged but review of this test revealed vertical head excursion had increased by more than 500% indicating a definitive degradation in protection.

Our results support previous research demonstrating that the misuse of child restraints decreases the protection offered to the child (Lalande et al., 2003, Hummel et al., 1997). Additionally, it provides new information regarding the threat of injury to occupants as a result of multiple errors in restraint installation and use. This material can be conveyed to road safety advocates, child restraint manufacturers and related industry bodies, standards committees, government authorities, and most critically, the end users of restraint systems. There needs to be continual development to improve the design of restraints to make them easier to properly fit to the vehicle, and to secure the child within the restraint, and harder to be used erroneously. Restraints might also provide feedback to users when misused. While regulatory bodies and consumer test programs may focus on improving restraint design such that the system is harder to misuse, there is still an imperative need to educate the end users. Parents, guardians and carers need to be made aware of the

dangers and risks associated with incorrect use, and the importance of correct use of child restraints. Particular emphasis should be placed on informing users of the risks involved with combinations of the more common minor errors.

The greatest degradation of safety resulted from the combination of a slightly loose harness with mild twisting and having the harness straps positioned too far below the shoulders. This was followed by the seat belt slack combination, then the tether slack combination. Moreover, in these two latter cases, there was a cumulative effect of misuse when compared to that expected by summing its constituent errors. The highest head and neck injury criteria were observed in cases involving loose installation belts. This shows that installation slack substantially reduce the effectiveness of a child restraint.

However, installation errors do not always lead to an increased injury risk, as the incorrect seat belt route in this particular instance provided additional protection to the occupant when compared to the correct set up. In this case, it was also observed that smaller amounts of restraint rotation due to the belt route were seen to significantly decrease the amount of forward head excursion. This provided substantially better protection than the correct restraint configuration. Therefore, restraints should be designed to limit upwards rotation. If seat belts are used in the new design, the route should pass around or through the base of the restraint. A design limitation exists in many of the systems currently available in that the seat belt passes through slots at the back of the restraint, which are often high above the seat bight, which appears to allow significant upward restraint rotation. Further testing could be conducted to establish the contribution of restraint rotation to the risk of child injury. In this test series, the incorrect seat belt route was only tested in combination with a mildly twisted harness. It can be surmised that this form of installation misuse might offset potentially harmful other forms of misuse in combinations. This should be investigated to ascertain whether limiting rotation of a child restraint has a beneficial effect on child safety in crashes, and if so, the extent of protection offered.

Currently, categories for assigning the severity of an error are usually based on single misuse scenarios. The results of this study suggest that this may not adequately reflect the potential consequences in the real world, as we found that a combination of 'minor' errors led to amounts of head excursion normally recorded in serious isolated errors. As studies in the area of multiple misuse continue, researchers may need to consider whether these current ratings are sufficient, and whether a more comprehensive way of assigning severity ratings should be developed.

This study only examined cases of single and combination misuse for a forward facing restraint system in the frontal direction. Further work may be warranted to explore the consequences of multiple errors in other impact directions and/or different types of restraint systems (e.g. infant restraints, booster seats). Furthermore, this test series was modelled on a six month old child, which is at the younger limit for graduating to the forward facing mode. Analysis using the three year old dummy in the same restraint mode may yield additional information and provide a more comprehensive picture of the effect of multiple forms of misuse in forward facing restraints.

Limitations

There are some limitations in the methods used that should be kept in mind when reviewing the results. The dummy used was assumed to be a good surrogate for a real child. While the CRABI was designed to accurately represent the anthropometry and impact response of a child, the torso is rigid and cannot deform as an infant's would. This is likely to have affected the response of the dummy, particularly during the multiple harness errors where the stiff torso and spine may have led to a lower likelihood of escape from the harness and less forward torso rotation. The tests were also conducted at relatively low velocities (30-35 km/hr), and since these results may not be directly extrapolated to higher velocities, the results presented may be an underestimation of the worst cases. Finally, this study only used one type of child restraint (albeit one of the most common), so the results may not be representative of all other restraints.

CONCLUSION

This study has examined the effects of common single and combination errors in the use of a forward facing child restraint system. The results demonstrate that combinations of errors increase the likelihood of injury for the occupant when compared with cases which only involve one error. Specifically, combinations of errors assigned a minor severity ranking increased the amount of head excursion to an extent usually only seen in a single serious error.

The results also demonstrated that the number of errors in a combination is a critical factor for determining the likely degradation in protection, with the worst cases all involving three errors. Additionally, these cases resulted in the greatest

relative increase in injury risk compared to the increased risk of its constituent errors.

One error that involved using a different belt path in forming the lower anchorage improved the performance of the restraint tested. Limiting restraint rotation appears to significantly decrease the amount of forwards head excursion.

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Appendix 1.

Relative percentages of the critical values of head excursion, PRHA, HIC15, Fx, Fz, My and restraint rotation compared to the baseline for each case.. (–) indicates no data collected. * indicates tests compared to baseline 2

Misuse Description	Max Forward Excursion	PRHA	HIC15	Fx	Fz	My	Max Δ Angle
	(mm)	(g)		(kN)	(kN)	(kNm)	(deg)
No misuse	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Harness mildly twisted (HMT)	4.3	-0.6	-19.2	-5.5	-10.9	87.6	-12.0
Harness very twisted (HVT)	5.0	0.3	-13.3	-8.5	-10.0	-4.0	-4.9
Harness slightly loose (HSL)	4.8	-8.0	-12.3	-7.8	-9.5	11.4	-4.9
Harness too far below shoulders (H Low)	12.6	-1.2	-6.5	-10.6	-7.5	195.9	0.5
Seat belt routed incorrectly (SB route)	-9.4	-12.0	-22.6	-0.2	-24.9	205.3	-91.3
Seat belt 25 mm slack (SB slack)	2.2	-13.3	-27.9	0.2	-10.5	-6.4	10.7
Tether 50mm slack (Tr slack)	6.5	-5.4	-9.2	1.1	-2.5	-24.7	-18.1
Tether not used (No Tr)*	15.0	-4.2	2.4	36.1	21.0	-22.0	-
Seat belt not used (No SB)*	22.3	-	-	-	-	-	-
Seat belt used, not buckled (SB buckle)*	-10.6	-16.0	-9.1	-74.4	-73.4	-55.1	-
Harness very twisted + Harness slightly loose (HVT + HSL)	12.9	-1.2	-20.9	-4.9	-12.8	191.2	-4.1
Harness mildly twisted + Harness slightly loose (HMT + HSL)	11.5	-2.9	10.8	-10.8	-5.5	97.0	2.5
Harness mildly twisted + Harness too far below shoulders (HMT + H Low)	12.7	-5.4	-8.4	-13.4	6.0	100.6	3.3
Harness very twisted + Harness too far below shoulders (HVT + Hz Low)	9.1	-3.2	-33.6	-5.4	-20.2	96.0	3.1
Harness mildly twisted + Harness slightly loose + Harness too far below shoulders (HMT + HSL + H Low)	22.3	-6.0	-6.9	-19.7	-5.5	183.2	3.2
Harness mildly twisted + Seat belt route incorrect (HMT + SB route)	-7.2	-9.6	-19.5	0.2	-21.6	100.3	-91.4
Harness mildly twisted + Harness slightly loose + Seat belt slack (HMT + HSL + SB slack)	17.3	0.7	21.0	-0.3	1.7	96.2	16.8
Harness mildly twisted + Harness slightly loose + Tether slack (HMT + HSL + Tr slack)	.7	-1.5	11.6	-0.8	2.4	104.5	16.7
Tether 75 mm slack + Seat belt 75 mm slack (Tr 75 + SB 75)*	19.6	0	87.2	36.1	78.9	11.8	-