International Journal of Crashworthiness

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tcrs20

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INTERNATIONAL JOURNAL OF CRASHWORTHINESS
https://doi.org/10.1080/13588265.2024.2371185

Evaluation of a novel head and neck restraint for harness-restrained children

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ABSTRACT

Motor Vehicle Crashes (MVCs) are a common source of neck injury and, although rare, catastrophic neck injury occurs in restrained children up to age 10 years old. Recently, a head/neck support (HNS) that cradles the head during sleep was developed. The objective of this study was to determine if the HNS improves injury criteria measured on anthropomorphic test devices (ATDs) in front facing 5-point harness child restraint systems (FFCRS). Nineteen matched pair frontal impact sled tests were conducted with ATDs representing the 12 month old, or 3 or 6 year old child in FFCRS. HNS reduced HIC36 by median 22.2%, maximum resultant head acceleration (3ms clip) by 16.2%, head excursion by 8.2%, and neck tension by 12.2%. Providing supplemental restraint directly to the head has the potential to improve injury outcomes while not adding to harm during common misuse scenarios, but further research is needed to determine if these benefits persist in real-world crashes.

ARTICLE HISTORY
Received 6 July 2023
Accepted 23 April 2024

KEYWORDS
Child restraints; neck injury; head injury; sled tests

Introduction

Children frequently fall asleep while travelling in automobiles, leading to poor-belt fit [2] and postures (Figure 1, left) that may discourage restraint use. Headovations LTD (see disclosure and funding sections below) has developed the Head Neck Support (HNS) device that supports the head during sleeping (Figure 1, right). The device is attached to the top of the child restraint system (CRS) or high-back booster using adjustable straps and has a front head 'arc' that holds the head upright during sleep. The head arc is attached *via* hook and loop fastener and a button snap, both of which can release during excessive loading by design. In its function as a sleep aid, the head arc prevents head/neck flexion by providing a posteriorly-directed force to the head.

Applying posteriorly-directed forces to the head has been shown to reduce occupant injury criteria and real-world injury. Hubbard and colleagues developed the HANS device to mitigate cranio-vertebral junction (CVJ) injury in the racing industry (Figure 2). The HANS consists of a restraint strap that is attached at one end to the helmet, and at the other end to a restraint yoke. The yoke is coupled to the torso and vehicle chassis *via* the shoulder portion of the racing harness. In this way, the inertial forces generated by the head during a crash are borne by both the neck and the HANS device. Sled testing [4] with and without the HANS showed dramatic reduction in forces in the neck, with neck tension reduced from 3.7 kN without the HANS to 1.7 kN with the HANS generation 1, and neck resultant force reduced from 4.1 kN without HANS to 2.1 kN with HANS. Head injury metrics were also reduced with the addition of the HANS; the Head Injury Criterion (HIC) went from 1681 to 746 with the HANS 1, and head acceleration went from 120 g to 74 g. These reductions in neck forces have shown great benefit in the racing industry. The racing industry endured a steady pace of CVJ injuries with catastrophic consequences since 1961. Following four deaths secondary to CVJ injuries in 9 months, then National Association for Stock Car Racing (NASCAR) implemented sweeping changes including adoption of the HANS. These changes led to a drastic reduction in CVJ injuries and deaths in NASCAR [5]. The HANS concept has also been applied to children in forward-facing harness restraints. Kapoor et al. [6] developed a finite element model of the restrained 3 year old anthropomorphic test device (ATD) in a 5 point harness child seat. Then, in a matched pair design of experiments, they added a HANS-type device to the simulations. Impacts were conducted at 0 and 45 degrees frontal and 90 degrees near side lateral with and without the HANS-type device. The authors observed a 40–75% reduction in resultant upper neck force, and a 45–60% reduction in HIC. These studies demonstrate the utility of applying direct restraint loads to the head of adults and children.

Traumatic brain and skull injuries are the most common serious injuries sustained by children in motor vehicle crashes regardless of age group or crash direction [7]. Further, motor vehicle crashes are a common source of neck injury [8] and inertial (non-contact) neck injury has been shown to occur in restrained children up to age 10 years old [9–11]. The mechanism of inertial neck injury is primarily tension in the neck [12]. While the HANS and HNS have design and function differences, both provide a

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Figure 1. Sleeping child in CRS without (left, photo credit Kid Transit [1]) and with (right) the HNS.

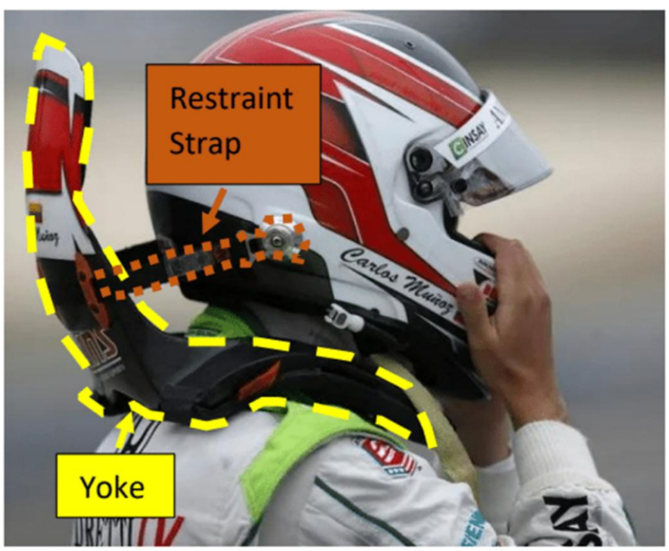

Figure 2. HANS device. Photo credit Miller [3].

posteriorly-directed restraining force to the head. Thus, there exists the possibility that the HNS could reduce neck loading in crash tests. The purpose of the study herein was to evaluate that possibility. Like the HANS and other evaluations of the effect of safety equipment [13–19], we take a matched pair approach where two otherwise identical tests (the matched pair) are conducted with one unique difference – one test in the pair has the safety intervention (the HNS) and one does not. To ensure robustness of our findings, tests were conducted across a range of plausible environment variables including six different forward-facing harness restraints, multiple ATD sizes, proper and misuse of the CRS, various attachment methods (LATCH/Tether/vehicle belt), and vehicle seat type. We hypothesised HNS reduces head and neck injury criteria in frontal sled tests with 5 point harness-restrained ATDs.

Methods

Tests were conducted on a seating buck mounted on a HYGE accelerator sled test system (Calspan Inc Buffalo, NY). Nineteen matched pairs (38 sled tests) were conducted using a matched pair experimental design, where all test variables in each pair were held the same except that one test in the pair used the HNS and the other did not (Figure 3). Previous studies have shown a dependency of CRS performance on the vehicle seat [16], and thus the seating buck was either the current FMVSS 213b test bench [20], the retiring 213 bench [21], or a rear outboard vehicle seat and belt system from a 2015 Ford Explorer. Tether use and lower anchor type (LATCH or seatbelt) were also varied. To simulate misuse, in two tests we installed the LATCH webbing loose ('loose' defined below). Type I belt is a 2-point vehicle seatbelt and Type II belt is a 3-point vehicle seatbelt. Given the biodiversity of the human child, the make and size of the ATD was varied throughout the series by using the Hybrid III 3- or 6-year-old, Q3 or CRABI 12-month-old. Most tests were run at 30 miles per hour with a frontal (0 degree) collision; except, one pair was run with an impact angle of 30 degrees oblique, and one pair at a higher speed (34 mph). Six different make/model forward facing 5-point harness child restraint systems were tested. The FFCRS system contained multiple points for variation, including tether or no tether, LATCH or vehicle belt attachment, and vehicle seat or 213b/213 seating buck. ATDs were equipped with tri-axial head and chest accelerometers, and a six-axis upper neck load cell was available on in 24 of the 38 tests.

The laboratory test procedure described by NHTSA for compliance testing under FMVSS 213 was adapted for use in all tests [22] and the HNS was installed as per the manufacturer's instructions. For loose LATCH, the webbing was first tightened and then incrementally loosened until zero force was measured on the belt tension measurement device described in

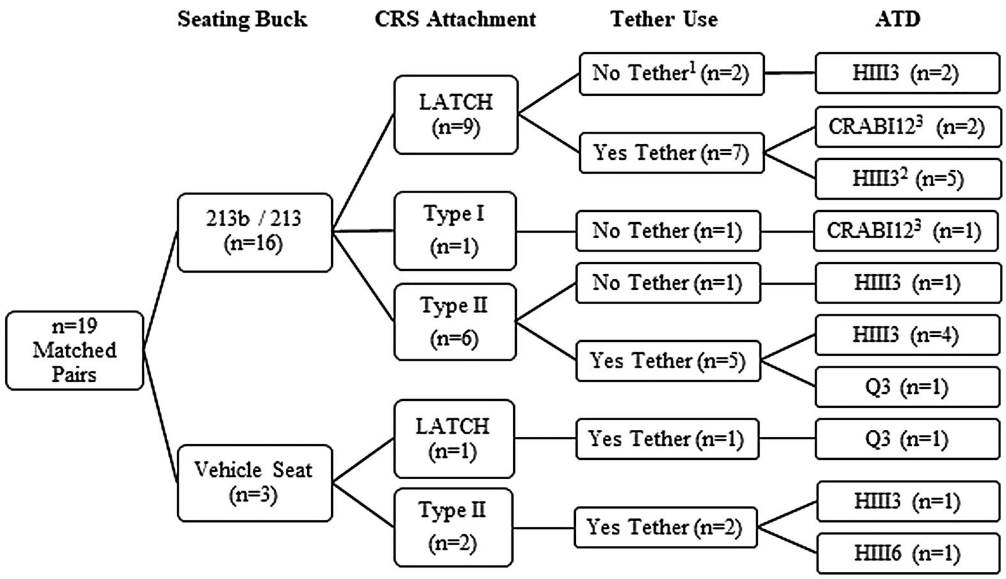

Figure 3. Matched pair sled tests with and without the HNS. All tests were frontal impact at 30 mph except when noted. All CRS were forward facing 5-point harness type, properly used except where noted. See Appendix Table A1 for full list of test conditions. *Notes.* [1]Pairs A and B (see Table A1) had LATCH webbing loose and were tested with the 213 bench. [2]Pair I speed was 34 mph and pair F angle was 30 degrees. [3]A 12 month old forward facing is not a recommended restraint practice.

the NHTSA Test FMVSS 213 Test Procedure [22]. Signal processing and sign conventions were in accordance with SAE J211 [23]. The Head Injury Criterion with a 36 ms time window (HIC36), the 3 ms clip of resultant head and chest acceleration (Head 3 ms and Chest 3 ms, respectively), were calculated. Neck tension is accepted in the biomechanics community as a mechanism for catastrophic neck injury including atlanto-occipital dislocation, and is used in regulation in the USA [5,24,25]; neck forces are monitored in European side impact regulation R129 [26]. Thus, we recorded maximum neck tension (Fz+). Maximum neck distraction force (Fr), which is the resultant of tension and shear forces, was used by the HANS developers [4] and thus we have included it herein as well. Maximum flexion (My+) and extension (My–) moments, and maximum neck injury criterion (N_{ij}) were also determined. Load cell data were truncated at 140 ms to eliminate loading generated on rebound where contact with the test fixture was possible. Head and knee excursion were measured *via* onboard high-speed videography.

The effect of the HNS on the following injury criteria (IC) was determined: HIC36, head and chest acceleration, N_{ij}, upper neck tension, head and knee excursion, and upper neck flexion and extension moment. The difference in IC in the pair was calculated,

$$\Delta IC = IC_{HNS} - IC_{no\ \ HNS}$$

as was the percent difference in IC,

$$P_{IC} = \frac{IC_{HNS} - IC_{no\ \ HNS}}{IC_{no\ \ HNS}} \times 100$$

Note, $\Delta IC < 0$ or $P_{IC} < 0$ indicates the HNS reduced the injury criteria and vice-versa. Wilcoxon rank sum analysis was performed to determine the probability that the null hypothesis,

$$IC_{HNS} = IC_{no\ \ HNS}$$

could be rejected. The Wilcoxon Rank-Sum test is a non-parametric statistical method used to assess two independent groups and determine if there is a significant difference between them. As a non-parametric method, it makes no assumptions about the normalcy of the underlying data, and as such it is ideally suited for small sample sizes such as the study herein. In general, it is more conservative (less likely to show significance) as compared to parametric methods such as a Student's *t*-test [27]. Statistical significance was set at $p < 0.05$. Post-hoc linear regression was used to examine the effect of test variables on ΔIC similar to the approach by Patton [17] in their assessment of rearward facing child restraints. The correlation between different ΔIC's was also examined.

Results

Mechanistically speaking, the HNS provides a passive restraint load that works in tandem with the neck to provide a ride-down effect for the head. As shown in Figure 4, the HNS engages early in the event and, together with the neck, provides a supplemental restraining force to the head. Subsequently, the hook-and-loop attachments of the HNS head arc release and thus the supplemental restraint load is removed, and the head continues its excursion restrained by the neck alone.

Exemplar neck tension force is shown in Figure 5 for a matched pair. The head arc of the HNS released in every test, and the mean release time was 51.7 ms (Standard Deviation = 6.4 ms). Sidedness of the HNS release was predominantly right side (12 tests), followed by left (3 tests) and bilateral (3 tests); in one test the rear buckle released. The HNS always released before maximum excursion.

Perhaps most interesting is the effect of the HNS on key injury criteria. HIC36, maximum resultant head acceleration (Head 3 ms), maximum head excursion, upper neck tension (Fz+) and upper neck resultant force (Fr) were always lower with the HNS than without (Appendix Table A2). The HNS

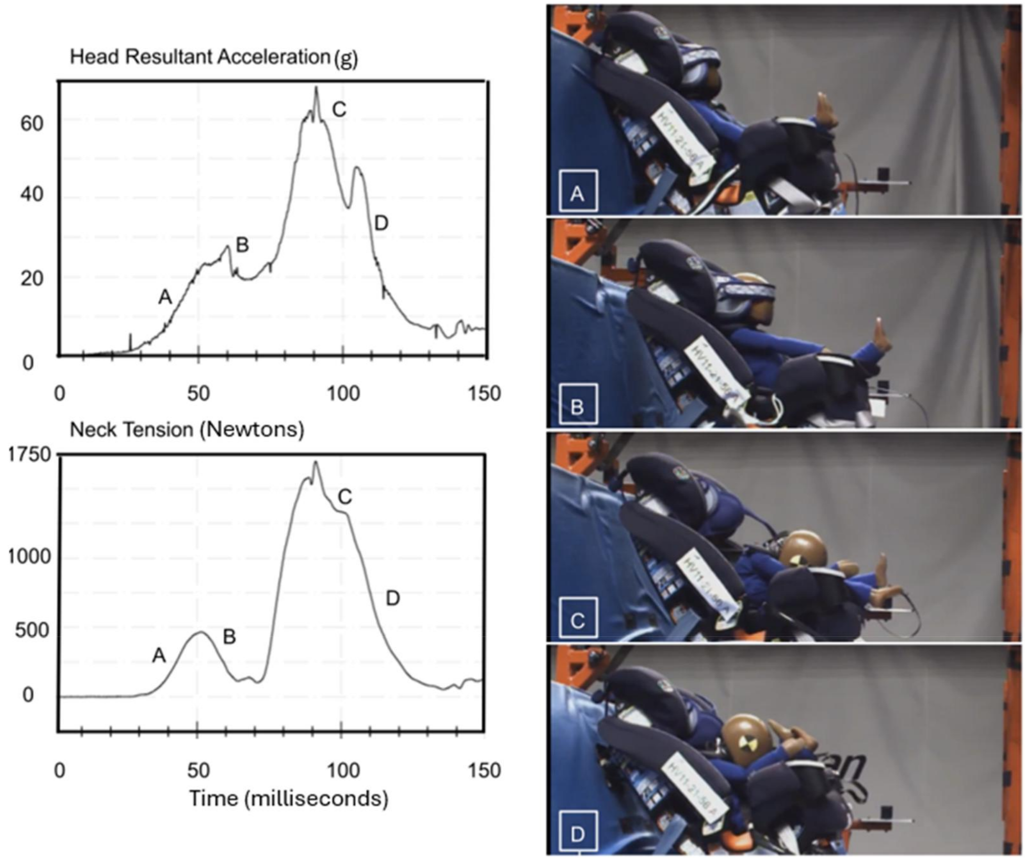

Figure 4. Frontal impact during HNS engagement and ATD forward motion.

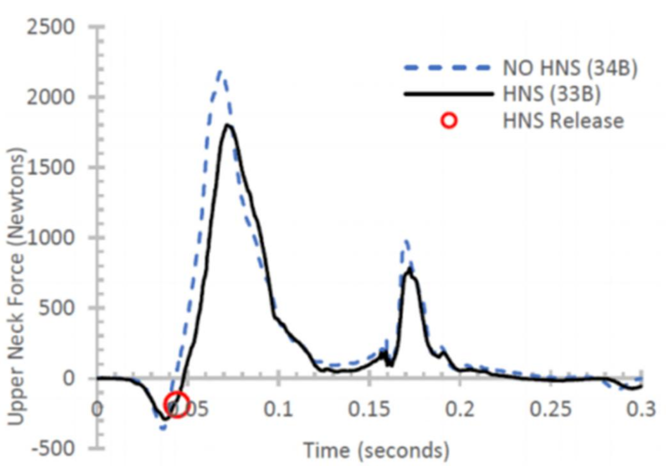

Figure 5. Upper neck axial force (Fz) of matched pair tests with and without the HNS. Red circle indicates time of HNS release.

reduced HIC36 by a median 22.2% ($p = 0.0001$), Head 3 ms by 16.2% ($p = 0.0001$), head excursion by 8.2% ($p = 0.0001$), Nij by 11.2% ($p = 0.0033$), and neck tension by 12.2% ($p = 0.0033$). In all but three pairs, the N_{ij} mode, which refers to the presence of axial tension or compression and flexion or extension moment, was tension-extension both with and without the HNS (Appendix Table A2). Tension-extension N_{ij} criterion, indicates that the neck of the ATD was experiencing loads that simultaneously pulled the head up away from the torso and bent the neck backwards. For the remainder of the pairs, in two pairs the N_{ij} mode was tension-flexion, and in one pair the mode was tension-flexion without the HNS and tension-extension with the HNS. Flexion moment (ΔMy+) was marginally significant ($p = 0.05$), and extension moment was non-significant ($p = 0.9645$). Chest acceleration (Chest 3 ms) increased by 6.2% ($p < 0.01$). The HNS did not change knee excursion (0.7%, $p = 0.3237$).

Linear regression on attachment method and vehicle seating surface showed no statistically significant findings for all head injury criteria, N_{ij} and neck forces (Table 2). Flexion moment (My+) showed statistical significance on tether, belt and vehicle seat ($p = 0.000$–0.034); however, the physical importance of these differences is tempered by the fact that HNS had only a marginally significant ($p = 0.05$, Table 1) effect on flexion moment. For Chest 3 ms, there was a statistically significant increase ($p = 0.019$) on the presence of a belt instead of LATCH (Table 2); however, the magnitude of this effect was relatively small as a change from LATCH to belt attachment yielded a 1.3 g increase in Chest 3 ms.

There was high correlation between ΔFz + and ΔFr, (Table A4, $r = 0.968$, $p = 0.000$) indicating that neck tension is the dominant component in resultant neck force. Similarly, ΔN_{ij}max and ΔFr were correlated ($r = 0.694$, $p = 0.018$) as was ΔN_{ij}max and ΔFz were correlated ($r = 0.769$, $p = 0.006$). Interestingly, there was a non-significant negative correlation between neck tension (ΔFz+) and head acceleration (ΔHead 3 ms) ($r = -0.547$, $p = 0.082$). This indicates that when the HNS is more effective in mitigating neck tension, it is less effective in mitigating head acceleration, though it is important to note that this finding did not achieve statistical significance.

Discussion

This is the first publication of a commercially available head-neck support for children that engages the head directly and provides an alternative load path that mitigates the inertial forces applied to the neck by the head. Here, we show in the laboratory environment that providing supplemental restraint directly to the head has the potential to improve injury outcomes, but further research is needed to determine if these benefits persist in the real-world.

The concept of applying an alternative load path to mitigate neck forces in a restrained occupant is not novel, and as mentioned earlier has seen application in automobile racing in the form of the HANS device [5,28,29]. While the effectiveness of the HANS in reducing head acceleration and neck loads exceeds considerably what we present for the HNS herein, the HNS reductions of HIC 36 (22%) and Neck Tension (12%) are noteworthy. In addition, we observed a statistically significant increase in chest acceleration of 2.5 g or 6.2% with the addition of the HNS. All chest accelerations were below the 60 g limit in FMVSS 213 and the injury thresholds set forth in Mertz et al [25]. Thus, we are not concerned with this increase in chest acceleration. The results above are consistent with our preliminary results in farside impact testing where we observed 31.7% decrease in neck tension, 33.5% decrease in HIC 15, 15% decrease in head acceleration, and a 2.5% decrease in chest acceleration with the HNS [30].

In addition to HANS and HNS devices, other devices providing supplemental loading to the head have been shown to mitigate neck loading in other restraint types. That is, the rear-impact head restraint (head rest) reduces neck forces [31] in rear impacts, and in side impact restraint of the head laterally *via* window netting has been shown to mitigate neck loads in racing [32]. Though the directionality of these systems are all different, the application of Newton's 2nd law *via* a free body diagram reveals that the HANS, HNS, rear-impact head restraint and lateral impact window netting all act similarly to modulate neck loads and head acceleration *via* application of an external restraining force to the head.

The HNS reduced neck tension by a statistically significant median of 12.2%. For comparison, other interventions have shown similar reductions in neck injury metrics. Bohman et al. [14] evaluated the effect of pretensioners and load limiters on the 6 year old ATD in backless boosters; the pretensioner and load limiter reduced neck loading by 11–16%. Similarly, Patton et al. [17] demonstrated in a single matched pair a 23% reduction in neck tensile forces with the addition of a load leg to a rear-facing infant seat. For comparison, in the study herein 27% was the largest reduction in neck tension observed (Table 1). The compelling aspect of the comparison between the HNS and the load leg or load limiters is the cost of the intervention. Pretensioners are pyrotechnically driven electro-mechanical devices that must be integrated into the vehicle structure and require a sophisticated sensing system to detect a crash and fire the pretensioner. Similarly, integration of a load leg into a CRS requires retooling of shell mould and engineering of the leg deployment/storage mechanism. All of these costs are in contrast to the HNS, which is a 'soft goods' design that can be integrated into the fabric elements of the CRS.

It should also be noted that there is variability in all test procedures even when running matched pair tests that are exact repeats of one another. Termed 'repeatability' in the regulatory parlance, government standards for crash testing are not enforceable unless the test-to-test variance of repeatability tests (measured by the coefficient of variation) is below a subjective maximum and declared as acceptable in the final regulation. Prior studies of the proposed FMVSS

Table 1. Median, minimum, and maximum difference (ΔIC) and percent difference (P_{IC}) in injury criteria between paired tests, with *p* value from Wilcoxon rank sum and number of samples (*N*).

ΔIC P_{IC}	*N*	Median	Min	Max	*p*
HIC 36	19	**−112.10**	−308.90	−4.90	**0.0001**
		−22.2%	−54.2%	−1.2%	
Head 3 ms	19	**−9.30**	−16.80	−1.00	**0.0001**
		−16.2%	−23.2%	−2.2%	
N_{ij}	11	**−0.14**	−0.22	0.00	**0.0033**
		−11.2%	−19.2%	0.2%	
Fz+	11	**−266.20**	−490.80	−124.00	**0.0033**
		−12.2%	−27.2%	−6.2%	
Fr	11	**−251.50**	−412.70	−110.60	**0.0033**
		−12.2%	−22.2%	−6.2%	
My+	12*	**−0.50**	−3.00	1.30	**0.05**
		−12.2%	−60.2%	13.2%	
My-	11	0.00	−6.00	2.80	0.9645
		0.2%	−25.2%	67.2%	
Chest 3 ms	19	**2.50**	−3.90	4.90	**0.01**
		6.2%	−8.2%	12.2%	
Head Excursion	19	**−28**	−59	−1	**0.0001**
		−8.2%	−13.70%	−0.40%	
Knee Excursion	19	1	−8	23	0.3237
		0.7%	−4.96%	16.9%	

*N = 11 for % difference because Moment was 0 in the no HNS test.
Injury criteria evaluated are head injury criterion at 36 ms (HIC 36), head acceleration 3 ms (head 3 ms), neck injury criterion (N_{ij}), upper neck tension (Fz+), upper neck resultant force (Fr), flexion moment (My+), extension moment (My−), chest acceleration 3 ms clip (chest 3 ms), and knee and head excursion. Bold values indicate p<0.05.

Table 2. Linear regression results showing effect of tether attachment, belt attachment, and seating buck on effectiveness of HNS across multiple injury criteria.

	Tether			Belt			vehicle seat		
	$p>\|t\|$	[95% conf. interval]		$p>\|t\|$	[95% conf. interval]		$p>\|t\|$	[95% conf. interval]	
ΔHIC 36	0.964	−48.3	50.5	0.080	−75.0	4.8	0.887	−52.2	59.8
ΔHead 3 ms	0.860	−2.8	3.3	0.236	−3.9	1.0	0.266	−5.3	1.6
ΔN_{ij}	0.159	−0.02	0.11	0.196	−0.02	0.09	0.461	−0.10	0.05
ΔFz+	0.375	−57.8	135.1	0.100	−17.0	154.1	0.766	−121.7	93.6
ΔFr	0.473	−59.6	116.0	0.125	−20.4	135.4	0.641	−118.2	77.9
ΔMy+	**0.034**	**−0.8**	**0.0**	**0.000**	**−1.2**	**−0.6**	**0.001**	**0.6**	**1.4**
ΔChest 3 ms	0.581	−1.0	1.7	**0.026**	**0.2**	**2.3**	0.128	−2.7	0.4
ΔHead Excur.	0.759	−8.02	10.8	0.288	−11.5	3.7	0.990	−10.6	10.7
ΔKnee Excur.	0.669	−4.7	7.04	0.945	−4.9	4.6	0.915	−7.0	6.3

Bold values indicate p<0.05.

213 bench used herein found the coefficient of variation in repeatability to be between 3.5% and 10% for HIC 36 and 1.1% to 9.0% for chest displacement [33]. Thus, the difference between a single matched-pair is certainly contaminated with random test-to-test variability. However, on the assumption that any repeatability limitations are random (i.e. equally likely to increase or decrease the injury criteria with the HNS), the resulting error caused by repeatability should cancel to zero as more tests are conducted.

This research is subject to certain limitations. First, the testing has been conducted with ATDs and, although accepted for use in regulations worldwide, the ATDs are subject to certain limitations especially with regard to neck injury. In particular, when compared with post-mortem human subjects there is some evidence that the 6 year old ATD overestimates neck injury potential [34] in belt-restrained frontal impacts. Even with this limitation, neck loads measured on the ATDs have utility in comparative studies where the forces and moments are compared to a control group [14,35], and paediatric ATD neck forces and moments are used in regulations with set limits [24] and for monitoring [26,p.129]. Second, the results presented herein are for frontal crash tests and thus the findings cannot be extended to other crash directions. The HNS has been crash tested in other impact directions, and those results will be the subject of future publications.

Conclusion

Providing supplemental restraint directly to the head through the HNS reduces head and neck injury criteria in paediatric-aged crash test dummies restrained in 5-point harness in frontal impacts, and further research is needed to determine if these benefits persist in the real-world with real children.

Disclosure statement

Some of the authors are the developers of the HNS. Mr. Cohen Gazit has an equity interest in Headovations LTD.

Funding

This research was financially supported by Headovations LTD (Tel Aviv).

Data availability statement

The complete dataset used in the analysis is available in the Appendix or by contacting the authors.

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Appendix

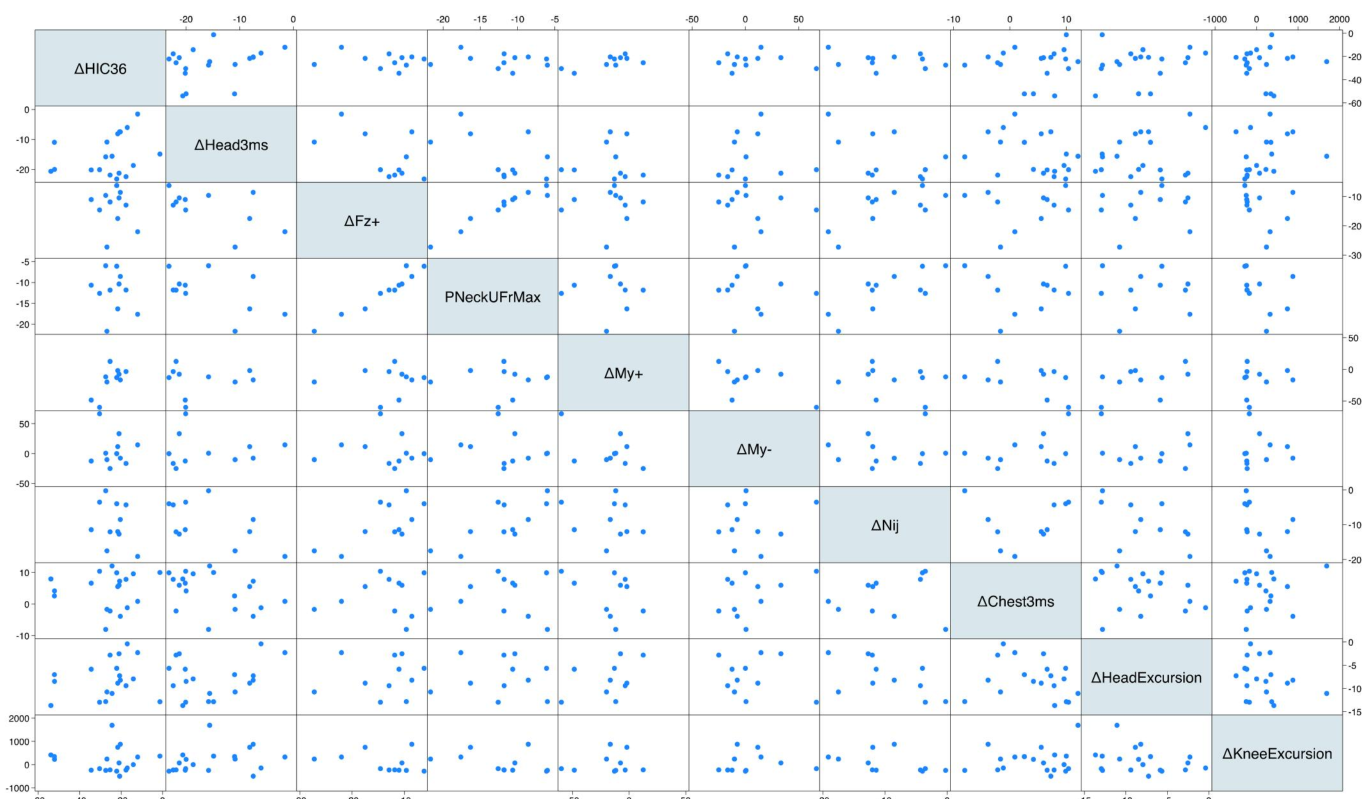

Figure A1. ΔIC correlation matrix.

Table A1. Matched pair sled tests.

Pair	Seating buck	Attachment: Lower anchor	Attachment: Tether	ATD	Angle Degrees	Speed mph
A	213	LATCH*	N	HIII3	0	29.8
B	213	LATCH*	N	HIII3	0	29.8
C	213n	LATCH	Y	CRABI12	0	29.8
D	213n	LATCH	Y	CRABI12	0	29.9
E	213n	LATCH	Y	HIII3	0	28.8
F	213n	LATCH	Y	HIII3	30	29.5
G	213n	LATCH	Y	HIII3	0	29.8
H	213n	LATCH	Y	HIII3	0	29.9
I	213n	LATCH	Y	HIII3	0	34.0
J	213n	Type I	N	CRABI12	0	29.9
K	213n	Type II	N	HIII3	0	29.7
L	213n	Type II	Y	HIII3	0	29.8
M	213n	Type II	Y	HIII3	0	29.8
N	213n	Type II	Y	HIII3	0	29.8
O	213n	Type II	Y	HIII3	0	29.8
P	213n	Type II	Y	Q3	0	29.4
Q	Vehicle	LATCH	Y	Q3	0	29.4
R	Vehicle	Type II	Y	HIII3	0	29.2
S	Vehicle	Type II	Y	HIII6	0	29.2

*LATCH webbing was intentionally loose in this pair.
Each row represents two sled tests, one conducted with the HNS and one conducted without the HNS.

Table A2. Test data.

Pair	Test #	HNS	HIC36	Excursion: Head mm	Excursion: Knee mm	3ms Clip: Head g	3ms Clip: Chest g	N_{ij}: Max	N_{ij}: Mode	Neck: Fz+ N	Neck: Fr N	Neck: My+ Nm	Neck: My− Nm	Arc release: Side	Arc release: time ms
A	057A	No	418	549	379	54	48	**1.17**	TE	1803	1903	3	−15		
	058A	Yes	305	490	388	48	47	0.96	TE	1312	1491	2	−13	Rear	67
B	057B	No	507	484	215	64	47	0.93	TE	1975	2116	0	−4		
	058B	Yes	446	473	222	63	47	0.75	TE	1540	1744	0	−5	Both	72
C	060B	No	388	262	136	56	43	n/a	n/a	n/a	n/a	n/a	n/a		
	060A	Yes	322	261	134	53	42	n/a	n/a	n/a	n/a	n/a	n/a	Both	42
D	059B	No	352	228	116	43	43	n/a	n/a	n/a	n/a	n/a	n/a		
	059A	Yes	168	212	120	38	44	n/a	n/a	n/a	n/a	n/a	n/a	Left	54
E	040B	No	429	318	140	77	40	**1.06**	TE	2229	2295	7	−9		
	039B	Yes	339	310	141	61	43	0.93	TE	1995	2057	6	−12	Right	51
F	022A	No	471	273	120	59	49	**1.20**	TE	1706	1843	8	**−16**		
	021A	Yes	342	238	117	50	45	**1.19**	TE	1542	1732	7	**−16**	Right	52
G	061B	No	382	288	137	58	37	n/a	n/a	n/a	n/a	n/a	n/a		
	061A	Yes	377	251	142	49	41	n/a	n/a	n/a	n/a	n/a	n/a	Left	59
H	062B	No	313	290	136	58	40	n/a	n/a	n/a	n/a	n/a	n/a		
	062A	Yes	269	267	136	47	43	n/a	n/a	n/a	n/a	n/a	n/a	Right	42
I	034B	No	571	339	188	68	45	**1.61**	TE	2184	2334	5	−21		
	033B	Yes	447	309	202	62	48	**1.42**	TE	1801	1953	5	**−23**	Right	48
J	056B	No	786	479	337	74	55	**1.92**	TE	1912	1927	3	−16		
	056A	Yes	515	451	329	59	58	**1.70**	TE	1701	1721	2	−14	Right	58
K	042B	No	474	336	141	72	36	0.93	TF	1987	2016	10	−10		
	041B	Yes	369	317	137	55	40	0.89	TF	1863	1892	9	−10	Right	54
L	064B	No	379	248	141	50	41	n/a	n/a	n/a	n/a	n/a	n/a		
	064A	Yes	301	230	134	46	44	n/a	n/a	n/a	n/a	n/a	n/a	Right	42

Table A2 (cont.) Test data. Refer to Table A1 for test conditions.

				Excursion		3ms Clip		N_{ij}		Neck				Arc release	
Pair	Test #	HNS –	HIC36 –	Head mm	Knee mm	Head g	Chest g	Max –	Mode –	Fz+ N	Fr N	My+ Nm	My− Nm	Side	time ms
M	065B	No	392	253	136	57	41	n/a	n/a	n/a	n/a	n/a	n/a		
	065A	Yes	297	225	159	48	46	n/a	n/a	n/a	n/a	n/a	n/a	Right	43
N	066B	No	593	331	133	58	43	n/a	n/a	n/a	n/a	n/a	n/a		
	066A	Yes	284	303	136	46	45	n/a	n/a	n/a	n/a	n/a	n/a	Both	56
O	067B	No	524	344	144	51	42	n/a	n/a	n/a	n/a	n/a	n/a		
	067A	Yes	242	297	150	41	45	n/a	n/a	n/a	n/a	n/a	n/a	Right	55
P	038B	No	470	301	171	67	41	0.91	TF	2115	2172	5	−9		
	037B	Yes	327	262	168	53	46	0.88	TE	1806	1898	2	−15	Left	54
Q	018B	No	714	391	221	75	41	**1.29**	TF	**2661**	2671	10	−10		
	017B	Yes	533	380	216	58	40	**1.13**	TF	**2345**	2355	12	−8	Right	59
R	020B	No	549	366	217	94	44	**1.51**	TE	1722	1898	3	−21		
	019B	Yes	437	336	236	87	42	**1.38**	TE	1574	1736	3	−19	Right	55
S	024B	No	704	447	258	75	54	**1.05**	TE	2059	2130	9	−17		
	023B	Yes	580	405	252	58	58	1.00	TE	1793	1878	8	−14	Right	60

Refer to Table A1 for test conditions. Cell values in bold text indicate exceedance of IARVs proposed in FMVSS 213 [20] for HIC, chest and excursion, and Mertz et al. [25] for head acceleration and neck tension and moment.

Table A3. Linear regression results for the effect of tether or no tether, LATCH or belt attachment, and vehicle seat or 213n/213 seating buck on ΔIC.

ΔHIC36	Coefficient	Std. err.	t	$p>\|t\|$	[95% conf. interval]	
Tether	1.065684	23.17771	0.05	0.964	−48.33643	50.46779
Belt	−35.11182	18.70921	−1.88	0.080	−74.98956	4.765927
Vehicle Seat	3.790454	26.27444	0.14	0.887	−52.21219	59.7931
_cons	−132.3189	30.75028	−4.30	0.001	−197.8615	−66.77619
ΔHead 3ms	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	.2562122	1.431888	0.18	0.860	−2.795785	3.30821
Belt	−1.425455	1.155831	−1.23	0.236	−3.889049	1.03814
Vehicle Seat	−1.876969	1.6232	−1.16	0.266	−5.336739	1.5828
_cons	−11.27076	1.899712	−5.93	0.000	−15.3199	−7.221617
ΔN_{ij}	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	.0428836	.0272166	1.58	0.159	−0.0214733	.1072405
Belt	.0345345	.0241429	1.43	0.196	−0.0225543	.0916233
Vehicle Seat	−0.023681	.0303791	−0.78	0.461	−0.0955162	.0481541
_cons	−0.1400474	.0289463	−4.84	0.002	−0.2084945	−0.0716003
ΔFz+	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	38.64181	40.78943	0.95	0.375	−57.80986	135.0935
Belt	68.56724	36.18289	1.90	0.100	−16.99171	154.1262
Vehicle Seat	−14.09052	45.52914	−0.31	0.766	−121.7498	93.5688
_cons	−290.6737	43.38176	−6.70	0.000	−393.2553	−188.0921
ΔFr	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	28.19957	37.148	0.76	0.473	−59.6415	116.0406
Belt	57.49828	32.95271	1.74	0.125	−20.42251	135.4191
Vehicle Seat	−20.17845	41.46459	−0.49	0.641	−118.2266	77.86972
_cons	−270.5539	39.50891	−6.85	0.000	−363.9776	−177.1301
ΔMy+	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	−0.4155172	.1576149	−2.64	0.034	−0.7882172	−0.0428173
Belt	−0.912069	.1398147	−6.52	0.000	−1.242678	−0.5814597
Vehicle Seat	1.025862	.1759297	5.83	0.001	.6098545	1.44187
_cons	−0.1396552	.167632	−0.83	0.432	−0.5360418	.2567314
ΔChest3ms	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	.3548485	.6294056	0.56	0.581	−0.9866979	1.696395
Belt	1.258182	.5080609	2.48	0.026	.1752757	2.341088
Vehicle Seat	−1.147879	.7134995	−1.61	0.128	−2.668667	.3729093
_cons	.9069696	.8350439	1.09	0.295	−0.8728843	2.686824

Table A3 (cont). Linear regression results for the effect of tether or no tether, LATCH or belt attachment, and vehicle seat or 213n/213 seating buck on ΔIC.

ΔHeadExcursion	Coefficient	Std. err.	t	$p>\|t\|$	[95% conf. interval]	
Tether	1.381061	4.412215	0.31	0.759	−8.023353	10.78547
Belt	−3.927273	3.561573	−1.10	0.288	−11.51858	3.664039
VehicleSeat	.0651515	5.001724	0.01	0.990	−10.59577	10.72607
_cons	−27.80379	5.853766	−4.75	0.000	−40.28079	−15.32678
ΔKneeExcursion	**Coefficient**	**Std. err.**	t	$p>\|t\|$	**[95% conf. interval]**	
Tether	1.195455	2.743961	0.44	0.669	−4.65316	7.044069
Belt	−0.1545455	2.214945	−0.07	0.945	−4.87559	4.566499
VehicleSea2	−0.3363636	3.110577	−0.11	0.915	−6.966402	6.293674
_cons	1.859091	3.640463	0.51	0.617	−5.900372	9.618554

Table A4. Pairwise correlations of ΔIC.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) ΔHIC36	1.000									
(2) ΔHead3ms	0.275	1.000								
	(0.254)									
(3) ΔNeckUFzMax	−0.159	−0.579	1.000							
	(0.641)	(0.062)								
(4) ΔNeckUFrMax	−0.170	−0.530	**0.968***	1.000						
	(0.618)	(0.094)	**(0.000)**							
(5) ΔNeckUMyMax	0.708*	0.063	0.074	0.029	1.000					
	(0.022)	(0.864)	(0.839)	(0.936)						
(6) ΔNeckUMyMin	−0.055	0.014	−0.062	−0.047	−0.544	1.000				
	(0.873)	(0.968)	(0.855)	(0.891)	(0.104)					
(7) ΔN_{ij}max	−0.287	−0.548	**0.694***	**0.769***	−0.164	0.131	1.000			
	(0.393)	(0.081)	**(0.018)**	**(0.006)**	(0.650)	(0.700)				
(8) ΔChest3ms	0.052	−0.404	0.130	0.007	−0.374	0.434	0.127	1.000		
	(0.832)	(0.086)	(0.704)	(0.984)	(0.286)	(0.182)	(0.710)			
(9) ΔHeadExcursion	0.211	0.235	0.109	−0.007	0.425	−0.204	−0.566	−0.243	1.000	
	(0.385)	(0.334)	(0.750)	(0.983)	(0.221)	(0.547)	(0.069)	(0.316)		
(10) ΔKneeExcursion	−0.044	0.271	−0.312	−0.375	0.168	0.028	−0.446	0.132	−0.268	1.000
	(0.858)	(0.262)	(0.350)	(0.255)	(0.643)	(0.934)	(0.169)	(0.590)	(0.267)	

***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.
Pearson's r shown with p-value in parentheses.