FACTORS INFLUENCING UPPER NECK LOADING IN REGULATORY TESTS OF CHILD RESTRAINT SYSTEMS

Costandinos Visvikis
Christoph Thurn
Thomas Müller
CYBEX GmbH
Germany

Paper Number 23-0273

ABSTRACT

Potential neck force and moment limits in UN Regulation No.129 are part of on-going regulatory discussions. Pragmatic limits for the Q0, Q1 and Q1.5dummies were proposed to regulators in 2020, based on analyses of type-approval monitoring data. However, chin-to-chest contact was acknowledged as potentially skewing the analysis and undermining the proposed limits. The aims of this study were to: 1) investigate the effect of impact direction and child restraint orientation on neck tension force and 2) quantify the effect of chin-to-chest contact on a large study sample of child restraint type-approval tests, for all Q Series dummies (Q0 to Q10).

Over 200 official type-approval tests were collected from our internal database with data extracted for neck tension force and head vertical acceleration. The head vertical acceleration multiplied by the head mass was used to calculate the neck tension force due to inertial loading from the head. This was compared with the measured neck tension force to determine the frequency of chin-to-chest contact and its likely influence on neck tension force in type-approval tests. The data were then separated for each Q-Series dummy by impact direction and child restraint orientation to identify trends for each test or installation parameter

The inertial neck tension force calculated from head vertical acceleration was lower than measured neck tension force in almost all front impacts with forward-facing child restraints and in many rear impacts with rear-facing child restraints. Differences were in the region of 30-50 percent depending on the dummy and child restraint installation parameters. This indicated the presence of chin-to-chest contact in a large proportion of the tests in the sample. Forward-facing child restraints generated highest neck loads in front impact, whereas rear-facing child restraints generated highest loads in rear-impact.

Our analysis suggests chin-to-chest contact occurs frequently in child restraint type-approval tests with substantial influence on neck measurements. This confirms that pragmatic limits derived for regulation from type-approval data are likely to be skewed upwards by this contact. Subsequent measurements in future type-approval tests are also likely to be skewed upwards and hence mitigating chin-to-chest contact may be incentivised more than limiting inertial neck loading. Although large, our sample comprised tests from one child restraint manufacturer only. A larger sample, comprising a broad range of manufacturers, is needed to validate our findings fully. Nevertheless, this study has demonstrated a robust approach for such analyses.

Child restraints are very effective in reducing the risk of serious neck injury to children in collisions. Nevertheless, a relatively large range of neck loads can be measured in type-approval, which can be influenced by dummy chin-to-chest contact, as well as child restraint installation parameters. Quantifying these influences will contribute to ongoing regulatory discussions about the use of neck force and moment limits in UN Regulation No.129.

INTRODUCTION

United Nations (UN) Regulation No. 129 specifies Q-Series dummies to assess the performance of child restraint systems in dynamic impact tests. The upper neck tension force and flexion moment must be recorded for monitoring purposes, but thresholds are not currently applied to the measurements during type-approval. However, the UN Working Party on Passive Safety (GRSP) is considering introducing neck thresholds for the Q0, Q1 and Q1.5 dummies in frontal and rear impact tests in a future amendment of UN Regulation No. 129 [1]. To that end, the European Association of Automotive Suppliers (CLEPA) proposed pragmatic thresholds to GRSP for tension force and flexion moment, developed from a large sample of international type-approval monitoring data [2-3]. This approach was authorised by GRSP because previous efforts to derive child neck injury assessment reference values from accident reconstruction were unable to generate valid neck injury risk curves [4]. Prior to that, the European Enhanced Vehicle safety Committee (EEVC) proposed thresholds scaled from Hybrid III 50th percentile male (adult) dummy regulatory thresholds, and from Hybrid III child dummy neck injury assessment reference values [5]. However, these were not adopted by UN Regulation No. 129 because a very high proportion of child restraint systems on the market would have failed to meet them, which didn't reflect real-world neck injury risk [6].

During the regulatory discussions at GRSP, it emerged that chin-to-chest contact has the potential to increase the neck tension force measured by Q-Series dummies (i.e., beyond the level it would reach under purely inertial loading from the head) [7]. This means that the pragmatic thresholds developed from type-approval monitoring data may have been skewed upwards by chin-to-chest contact and that any subsequent regulatory test measurements might be similarly skewed [8-9]. Unfortunately, the frequency of chin-to-chest contact and its effect on the proposed thesholds was impossible to quantify in the type-approval monitoring sample because the data gathering exercise in [2] was limited to the peak neck tension force and flexion moment. Other parameters that might have revealed the presence and extent of chin-to-chest contact were not collected. Nevertheless, the implication of adopting thresholds skewed by chin-to-chest contact is that preventing such contact might be incentivised by regulation as a means of reducing the dummy neck force measurements, without real consideration of the true inertial loading to the cervical spine [8-9].

The Spanish delegation to GRSP proposed a method for calculating the inertial neck force using the head vertical acceleration multiplied by the head mass above the neutral axis of the load cell [7]. This method offered the potential to derive purely inertial neck loading, free from the influence of chin-to-chest contact. Research tests confirmed the method was capable of predicting the measured neck force up to the period of chin-to-chest contact, but it could also generate unexpected results, particularly when chin-to-chest contact occured at the same time as the peak inertial loading [9-10]. Furthermore, as head vertical acceleration was not included in the initial data gathering exercise, it was also impossible to apply this method to the type-approval monitoring data in order to determine its potential effect on the pragmatic thresholds.

The frequency and influence of chin-to-chest contact in UN Regulation No. 129 tests has been highlighted with relatively small research test studies [8-10]. The full extent to which chin-to-chest contact influenced the pragmatic thresholds proposed for the regulation is unknown and is impossible to determine from the monitoring data provided by type-approval authorities. There appears to be little appetite currently from regulators to repeat the collection of type-approval monitoring data with additional parameters (either to identify chin-to-chest contact and/or to calculate purely inertial neck force). Therefore, the aims of this study were to use an internal sample of type-approval test results to: 1) investigate the effect of impact direction and child restraint orientation on neck tension force and 2) quantify the effect of chin-to-chest contact on a large study sample of child restraint type-approval tests, for all Q-Series dummies (Q0 to Q10).

METHODS

This study followed the methods used by CLEPA in [2-3] to derive pragmatic neck tension force thresholds from type-approval monitoring data. However, in our study, the source was limited to CYBEX type-approval tests. No external data were used.

Data collection

Over 200 official type-approval tests were collected from our internal test database. These comprised front and rear impact tests carried out for new type-approvals and for extensions to existing approvals. Production qualification tests, which are part of the type-approval process in UN Regulation No. 129, were excluded so as not to skew the sample with repeat tests. Research and development tests on prototype products were also excluded because they may not reflect real product performance and because most research and development tests will ultimately be repeated as an official type-approval test.

The sample was collected according to a template that included brief details of each test such as the dummy (Q0, Q1, Q1.5, Q3, Q6 or Q10), impact direction (front or rear), orientation of the child restraint (rear- or forward-facing) and its adjustment (where applicable, upright or reclined). The main test data extracted were the peak neck tension force (i.e. $+F_z$ channel) and the peak head vertical acceleration (i.e. $+a_z$). We extracted data for tests performed in our own crash test laboratory only because the correct sensor polarity was essential for the reliability of our study. This limited our sample to tests that were performed in 2019 and later (after our laboratory was installed), but it was our only means of guaranteeing that SAE J211 sign conventions had been used when the impact test was carried out. The sample included several tests with the same child restraint and dummy. This was due to the various test and set-up conditions required during the type-approval process. All such tests were included to maintain reasonable sample sizes for analysis.

Data analysis

As a first step, the data were separated for each Q-Series dummy by the impact direction and the child restraint orientation. The inertial neck force was then calculated according to the method proposed in [7] and set-out in Equation 1.

$$\textit{Inertial neck force (N) = Dummy head mass (kg) x Head vertical acceleration } (ms^{-2}) \qquad \text{(Equation 1)}$$

The inertial neck force was calculated for rear impact tests with rear-facing child restraints and front impact tests with forward-facing child restraints only. These are the only combinations of impact direction and child restraint orientation in which chin-to-chest contact can occur during the main laoding phase of the impact. The inertial neck force was not calculated for front impact tests with rear-facing child restraints because chin-to-chest contact occurs only in rebound and does not influence the overall peak neck tension force. Furthermore, as the head is in contact with the back of the child restraint from the outset, it seems likely that the calculation of the inertial neck force would not deliver a meaningful result. The intertial neck force was also not calculated for child restraints in which the child is restrained with an impact shield or in which an integrated child restraint airbag deployed. In both cases, chin-to-chest contact does not occur because the head comes into contact with the shield or with the airbag, before chin-to-chest contact can occur.

The percentage change from the measured neck tension force to the calculated inertial neck tension force was calculated for each applicable test. This was used to determine the presence of chin-to-chest contact and to estimate the level of neck force that might have been measured, if the contact had not occurred or had been mitigated. Substantial chin-to-chest contact was assumed to have occurred when the percentage change in the neck force was 10 percent or greater. This was a somewhat arbitrary figure chosen to ensure the level of difference was greater than that expected through normal test-to-test repeatibility. To validate this approach, a selection of representative time histories were analysed to verify the presence, or not, of chin-to-chest contact for a given level of percentage change. In each case, the external head contact force was calculated and plotted with the neck force (measured and calculated inertial). The external head contact force was determined using the procedure specified in SAE J2052 [11]. The procedure uses the head mass (above the neutral axis of the load cell), the head acceleration components (a_x, a_y, a_z) and the neck force components (F_x, F_y, F_z) in a root sum square calculation. A contact is assumbed to have occurred when the external head contact force level has reached 500 N.

Worst-case combinations of impact direction and child restraint orientation from which to derive pragmatic thresholds were identified in [2] for each Q-Series dummy. No further separation by child restraint adjustment was made after an initial scan of the data revealed very low sample sizes for some combinations of dummy, impact direction and child restraint adjustment.Two statistical analyses were carried out on the results from these worst-case combinations: 95^{th} percentile and the mean plus two standard deviations (“Mean +2SD”). We identified the same worst-case combinations and performed the same statistical analysis, in order to compare our sample with the larger study and to investigate how reduced data that avoided the influence of chin-to-chest contact might have influenced the pragmatic proposals.

RESULTS

Sample characteristics

Our study sample comprised around 20 child restraint systems and 210 type-approval tests with Q-Series dummies (Table 1). In UN Regulation No. 129, the stature range of the child restraint determines which dummies must be used in the dynamic tests. For a given dummy, impact direction and orientation, each child restraint is typically tested several times to cover different seat and/or support leg adjustments (where applicable). After the data were separated by impact direction and child restraint orientation, each sub-sample ranged from 7 tests (Q10, front impact, forward-facing) to 32 tests (Q0, rear impact, rear-facing). Tests with the Q6 were removed from the sample to avoid the specific model of child restraint being identified.

Table 1.
Child restraint system (CRS) type-approval sample characteristics

Test dummy	Impact direction	CRS orientation	Number of CRS	Number of tests
Q0	Front	Rear-facing	13	27
	Rear	Rear-facing	12	33
Q1	Front	Rear-facing	4	9
	Rear	Rear-facing	5	9
Q1.5	Front	Rear-facing	9	23
		Forward-facing	5	16
	Rear	Rear-facing	10	20
Q3	Front	Rear-facing	7	17
		Forward-facing	10	30
	Rear	Rear-facing	7	19
Q6	Front	Forward-facing	0	0
Q10	Front	Forward-facing	3	7
Total			**≈20***	**210**

*All child restraints cover more than one dummy/impact direction/orientation

Effect of test and child restraint parameters on neck tension force

The peak neck tension force measured by the upper neck load cell tended to increase with dummy size for any given impact direction and child restraint orientation (Figure1). A large spread in the neck tension force values was observed in most combinations of conditions and was substantial in the front impact tests with forward-facing child restraints. Although there were overlaps, the highest neck tension force tended to be measured in rear impact tests for both the Q0 and the Q1 dummies. The highest tension force was measured in front impact with forward-facing child restraints for the Q1.5, Q3 and Q10 dummies. These 'worst-case' combinations of impact direction and child restraint orientation for each dummy reflect those used in the development of pragmatic neck thresholds in [2].

The inertial neck tension force (calculated from the head vertical acceleration) followed similar overall trends to the measured force (Figure 2). However, there were some important differences. Firstly, the spread in the values reduced markedly for the forward-facing child restraints. This meant that the upper value, and the mean were also reduced greatly. More moderate effects were observed in the rear impact tests (i.e. with rear-facing CRS). Nevertheless, the spread in the values with the Q0 was visibly reduced. The inertial force was not calculated for the rear-facing child restraints in front impact, but the unchanged measurements were included on the chart for comparison with the other conditions. Despite these differences, the worst-case combinations of impact direction and child restraint orientation remained the same. In five tests with the Q0 (rear-facing in rear impact), the calculated neck force increased markedly compared with the measured force (typically around 25%). It was unclear why this happened and until measurement errors could be ruled out these tests were excluded from subsequent analyses of the difference between the measured and the calculated force.

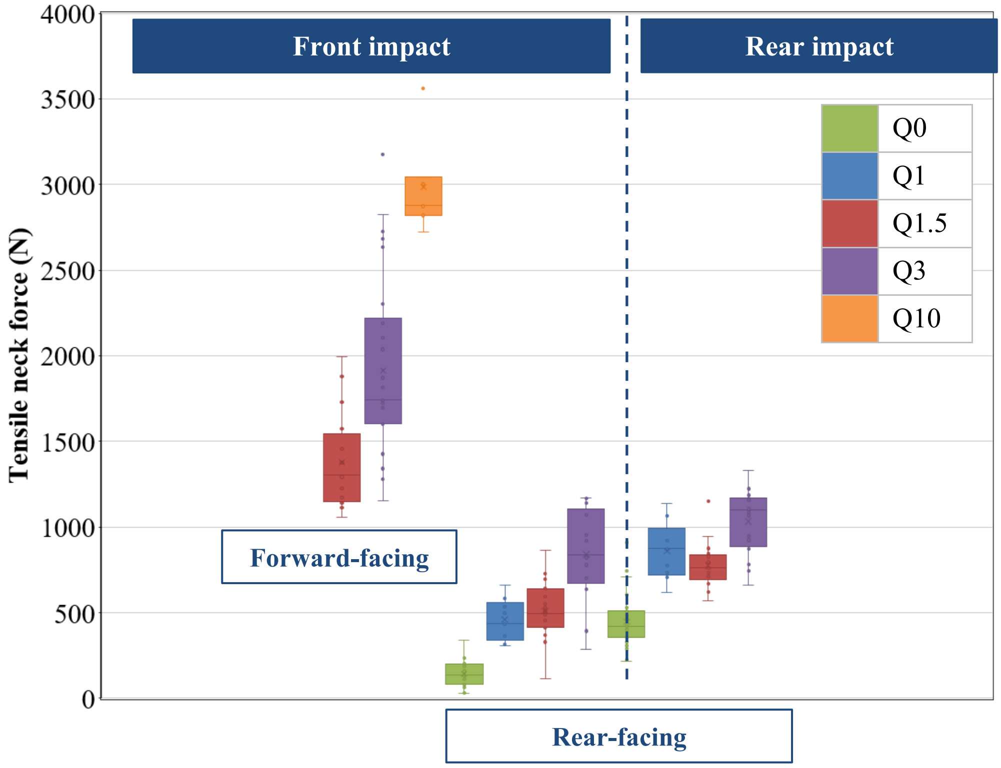


Figure 1. Peak measured neck tension force by impact direction and child restraint orientation

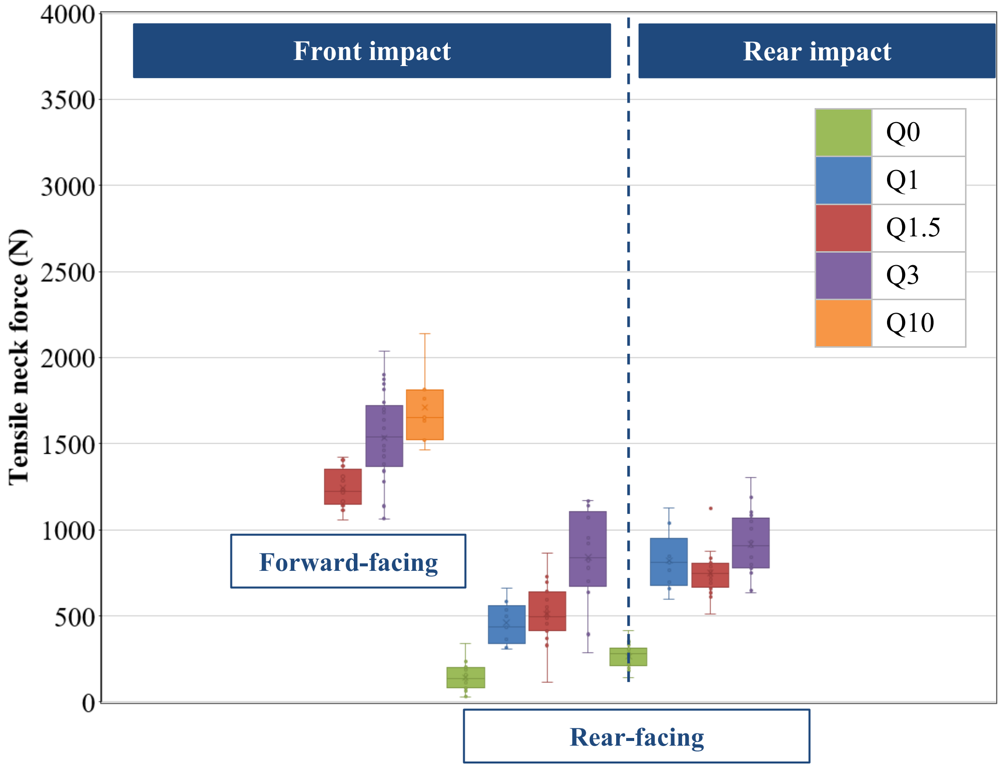


Figure 2. Peak calculated inertial neck tension force by impact direction and child restraint orientation

Effect of chin-to-chest contact on neck tension force

The percentage change from the measured neck tension force to the calculated neck tension force varied across each combination of impact direction and child restraint orientation (Table 2). The percentage change also varied to some extent within each combination. This suggests that chin-to-chest contact was more frequent in some combinations of impact direction and child restraint orientation than others, but that individual cases could occur in almost all combinations. For example, the greatest average percentage change was observed with the Q0 dummy in rear impact tests and the Q10 dummy in front impact tests, albeit with a very small Q10 sample. In the case of the Q0, 85% of tests displayed evidence of chin-to-chest contact (as defined by a percentage change of 10% or greater).

Relatively large differences were also observed with the Q1.5 and Q3 in forward-facing child restraints, which displayed average percentage changes of 18% and 26%. Although these average changes did not reach the level of those observed with the Q0, substantial proportions of each sample were affected, with 57% and 90% of applicable tests in each condition being affected by chin-to-chest contact. In contrast, the Q1 and Q1.5 (in rear impact) seemed least influenced by chin-to-chest contact and the Q1 in particular seeming to be unaffected in any of the tests, although the sample was small.

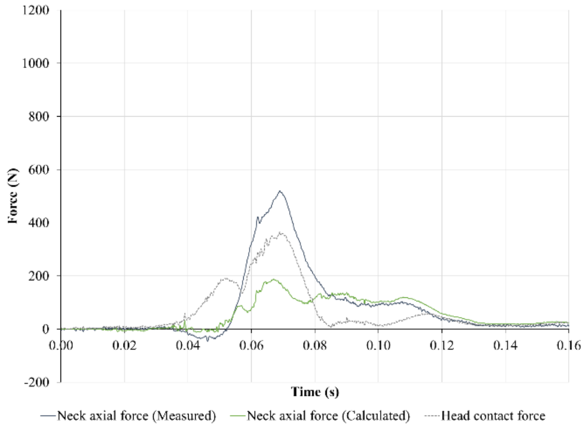
Table 2.
Percentage change in peak neck tension force from measured value to calculated value

Test dummy	**Impact direction**	**CRS orientation**	**No. of tests**	**% change in neck tension (measured to calculated)**		**Proportion with chin-to-chest contact**
				Average	**Range**	
Q0	Rear	RF	28	-44%	-64% to -29%	85%
Q1	Rear	RF	9	-4%	-9% to -1%	0%
Q1.5	Front	FF	7	-18%	-30% to -4%	57%
	Rear	RF	20	-3%	-33% to 0%	10%
Q3	Front	FF	20	-26%	-40% to -1%	90%
		FF – Integral	*15*	*-23%*	*-34% to -1 %*	*87%*
		FF – Boosters	*5*	*-32%*	*-40% to -27%*	*100%*
	Rear	RF	19	-11%	-29% to -2%	50%
Q10	Front	FF	7	-43%	-52% to -39%	100%

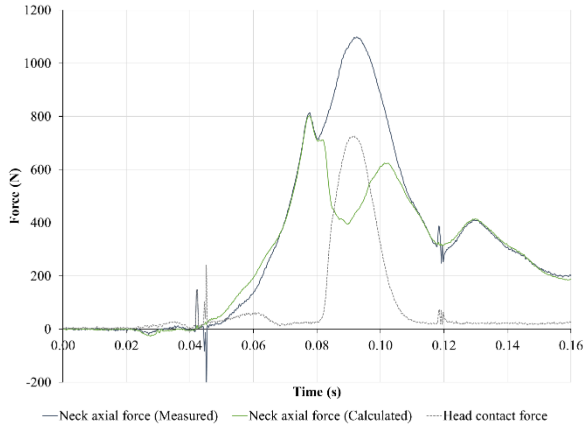
* RF: rear-facing; FF: forward-facing

A clear chin-to-chest interaction can be distinguished in representative time history plots in which the calculated force exceeded the measured force by a large margin (Figure 3). Two different responses are illustrated in the examples below. The Q3 (rear impact, rear-facing), Q1.5 (front impact, forward-facing) and Q10 (front impact, forward-facing) showed an initial, purely inertial, peak prior to chin-to-chest contact, followed by a second, much larger peak during the period of contact. The onset of this second peak corresponded with the time of engagement between the chin and chest, identified from the external head contact force. The second tensile peak, due to chin-to-chest contact, was the overall peak value. In each case, the calculated inertial neck force followed the measured force very closely up to the point of chin-to-chest contact at which point it diverged from the measured force over the period of contact. In some examples (i.e., the Q1.5 and Q3 in Figure 3), the inertial force fell away very rapidly.

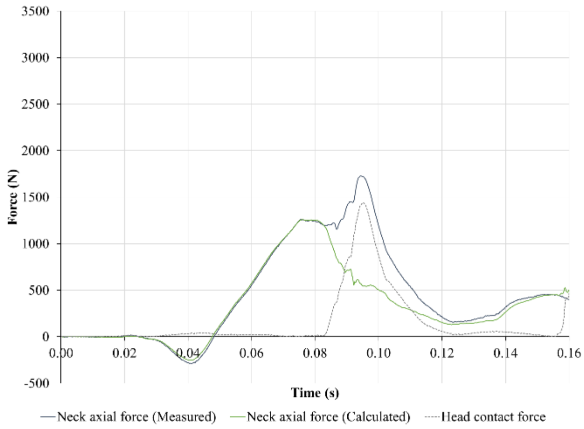
The Q0 dummy (rear impact, rear-facing) displayed different behaviour. As shown in the example (Figure 3, top left), the calculated force diverged from the measured force earlier than the other examples, over the period of peak neck force. This behaviour was typical of the Q0 tests. The external head contact force did not reach the 500 N threshold specified in SAE J2502, however, the threshold was likely developed for adult dummies in mind. The external head force reached around 400 N with the Q0 and suggests some degree of contact occurred.



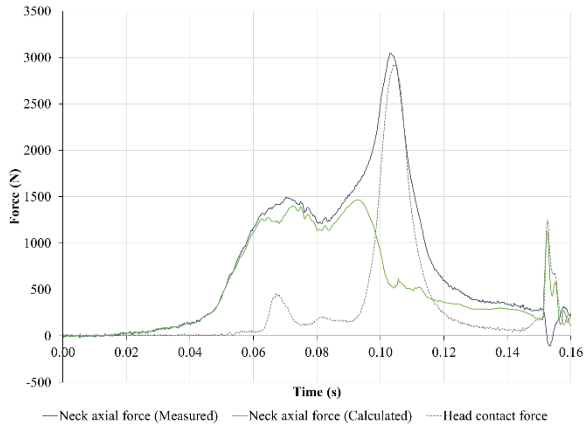
Q0: Rear impact, rear-facing
Percentage change: 64%



Q3: Rear impact, rear-facing
Percentage change: 27%



Q1.5: Front impact, forward-facing
Percentage change: 29%

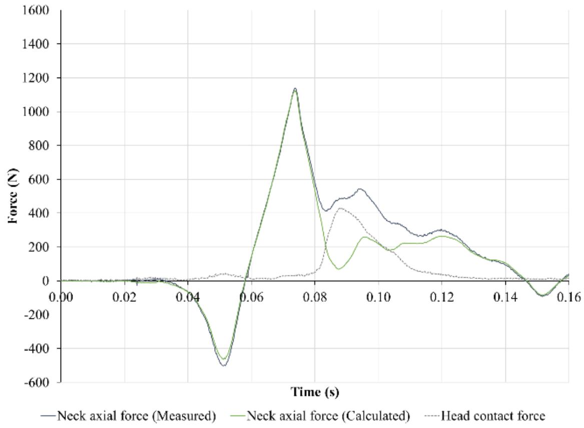


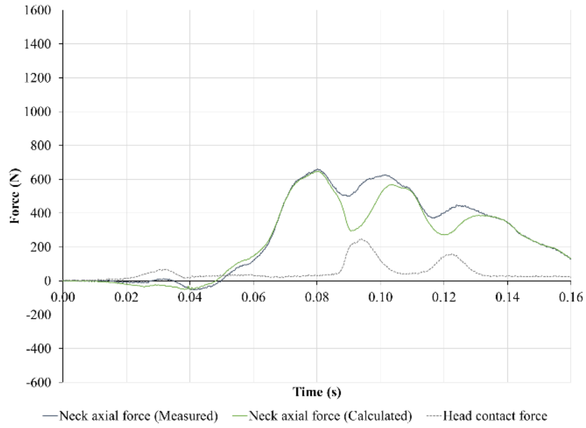
Q10: Front impact, forward-facing
Percentage change: 52%

Figure 3. Upper neck axial force and head contact force – representative examples with large percentage change from measured to calculated neck tension force

In tests where the peak calculated force was similar to the measured force, the representative time history plots showed that chin-to-chest contact was either marginal or occurred somewhat late in the impact event (Figure 4). In the examples with the Q1 and the Q3 (both rear impact, rear-facing), the external head contact force did not reach the 500 N threshold at which a significant contact is assumed to have occurred in SAE J2502, although it was quite close with the Q1 (400 N). In both cases, the inertial force followed the measured force very closely, but still diverged over the period of marginal contact. However, this did not influence the overall peak value. In the example with the Q1.5 (front impact, forward-facing), the external head contact force indicated a substantial chin-to-chest interaction, but although it increased the measured force compared with the inertial force, this second peak due to contact was only marginally larger than the inertial peak.

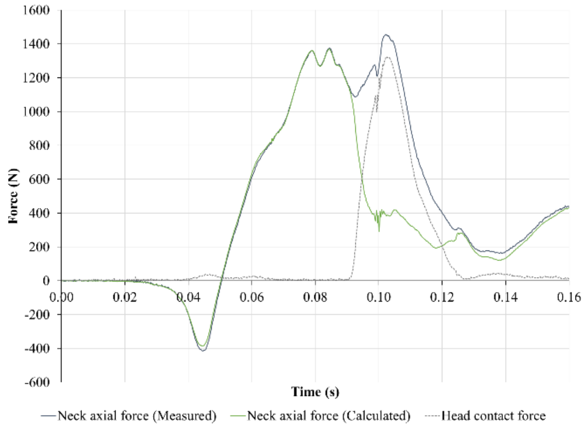
As mentioned above, there were five tests in which the calculated force exceeded the measured force (Figure 5). This was observed with the Q0 dummy only (rear impact and rear-facing child restraints). This occurred in cases where the contact was inconclusive or not sufficient to reach the threshold specified in SAE J2502. Further analysis is needed to understand what happened in these tests.





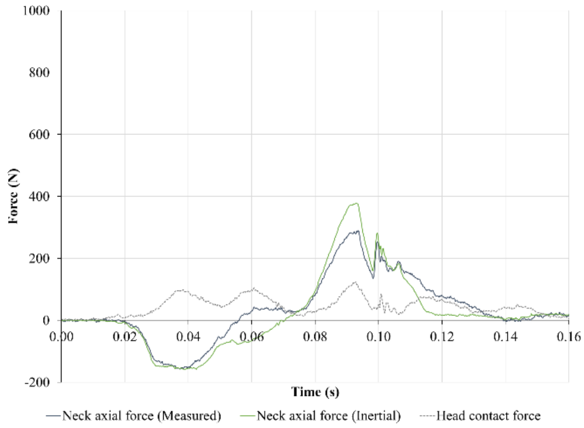
Q1: Rear impact, rear facing
Percentage change: 1%

Q3: Rear impact, rear-facing
Percentage change: 2%



Q1.5: Front impact, forward-facing
Percentage change: 6%

Figure 4. Upper neck axial force and head contact force – representative examples with negligible percentage change from measured to calculated neck tension force



Q0: Rear impact, rear-facing

Figure 5. Upper neck axial force and head contact force – representative example where the calculated neck tension force exceeded the measured tension force

Potential implications for the development of pragmatic neck tension thresholds

Despite fewer tests and less product diversity, the sample used in this study shared many characteristics with that used by CLEPA in [2-3] to derive pragmatic limits for the Q0, Q1 and Q1.5 (Table 3). Our sample featured slightly lower measurements overall for the Q0 and Q1.5 dummies, compared with the larger sample, but slightly higher measurements for the Q1. If the same approach used to derive pragmatic thresholds from the full type-approval monitoring data were used in our sample, it would yield similar thresholds for our measured neck force data (i.e. for the Q0, Q1 and Q1.5). However, if the method was used on our calculated inertial data, it would yield much lower thresholds than those proposed for UN Regulation No.129. In fact, the neck tension force thresholds proposed by EEVC in [6] for a 20% risk of AIS≥3 injury are quite similar to the upper range of the inertial force for the Q0, Q1 and Q10. However, the EEVC thresholds are somewhat higher than the upper range for the Q1.5 and Q3, and are closer to the mean value instead.

Table 3.
Measured and calculated neck tension force parameters and comparison with threshold proposals

					Neck tension force					Threshold	
Sample	**Dummy**	**Impact direction**	**CRS orientation**	**n**	**Min.**	**Max.**	**Mean**	**95th %ile**	**Mean + (2*SD)**	**CLEPA [2-3]**	**EEVC [6]**
CLEPA [2-3]	Q0	Rear	RF	*71*	*83*	*884*	*347*	*720*	*720*	700	498
CYBEX				33	217	911	446	723	741		
CYBEX: inertial				33	140	415	265	342	387		
CLEPA [2-3]	Q1	Rear	RF	40	242	1004	642	905	1018	950	1095
CYBEX				9	620	1139	858	1110	1196		
CYBEX: inertial				9	597	1127	823	1092	1169		
CLEPA [2-3]	Q1.5	Front	FF	54	204	2914	1509	2122	2443	2000	1244
CYBEX				16	1057	1996	1379	1909	1942		
CYBEX: inertial				16	1057	1420	1242	1409	1468		
CYBEX	Q3	Front	FF	30	1154	3177	1913	2779	2906	-	1555
CYBEX: inertial				30	1065	2039	1535	1888	2063		
CYBEX	Q10	Front	FF	7	2725	3563	2986	3408	3539	-	2241
CYBEX: inertial				7	1467	2137	1712	2040	2160		

* RF: rear-facing; FF: forward-facing

DISCUSSION

The neck tension force measured by the upper neck load cell was highest in front impact tests with forward-facing child restraints. However, there were overlaps such that the lowest measurements in this 'worst-case' combination of conditions were consistent with the highest measurements in other conditions with the same dummies, notably rear impact with rear-facing child restraints. This was somewhat surprising given that the rear impact test in UN Regulation No. 129 is performed at a lower severity than the front impact test (i.e. 32 km/h, 14-21 g vs. 50 km/h, 20-28 g). Rear impact is not currently viewed as a high priority for child occupant protection, but that may change in the longer term, if automated vehicles lead to more frequent rear impact collisions as suggested by some studies [12]. Currently, consumer tests of child restraints encourage improved performance in front and side impact, but rear impact is left to the regulatory test.

Calculating the inertial neck tension force from the head vertical acceleration reduced the mean value and the spread of values for each combination of impact direction and child restraint orientation. Nevertheless, the same general trends were observed in terms of the worst-case combinations of impact direction and child restraint orientation. That said, compared with the measured force, the inertial force reduced the differences between the child restraint orientations in front impact, particularly with respect to the mean value. Ultimately, predicting non-contact, inertial neck injury risk is challenging. Aside from the complicating factor of chin-to-chest contact, the stiff thoracic spine of child dummies results in high neck forces and moments that are not representative of the true injury potential [13]. Real-world data on the risk of neck injury in child restraints is inconclusive. The most recent studies suggest neck injury rates are very low [14]. Case studies with serious neck injury continue to be reported, but it is not always possible to rule out head impact, high collision speed or child restraint misuse as a factor [15]. Specifying a limit on (resultant) head acceleration likely provides some measure of control on tensile neck loading. However, UN Regulation No. 129 specifies thresholds for the head, chest and abdomen, and so adding thresholds for the neck could reduce the potential for uninstrumented load paths to be exploited.

Chin-to-chest contact occurred frequently in our sample of child restraint type-approval tests (as indicated by the discrepancies between the measured and the calculated neck tension force). It appeared to be particularly prevalent with the Q0 in rear impact, and with the Q1.5, Q3 and Q10 in front impact (with forward-facing child restraints). It was unclear why certain combinations of impact direction or child restraint orientation were more susceptible. Previous studies have highlighted that dummy posture and child restraint design can influence chin-to-chest contact characteristics [16-17]. A broad range in the effect of chin-to-chest contact was observed within each combination of impact direction and child restraint orientation in our sample (denoted by the percentage change from the measured to the calculated force). It seems plausible that dummy positioning and posture played a role, but a much larger study sample would be needed to investigate such influences. The prevalence of chin-to-chest contact in real-world collisions and its effect on child injury potential, if any, does not appear to have been reported. Chin-to-chest contact has been observed in child cadavers [13] and in human body models [18]. However, the severity of contact and its effect on neck forces seems to be much greater in dummies, primarily due to the stiffness of their components [19].

The calculated inertial neck tension force was used primarily as a means of identifying where significant chin-to-chest contact occurred. It was also used to comment on the likely neck tension force under purely inertial loading, for example, if chin-to-chest contact was not present. Although it was proposed for that purpose [7], the reliability of the calculation is unclear. The calculated neck force predicted the measured force up to the point of chin-to-chest contact very well in most tests; however, in some tests, the calculated force fell away very quickly when contact began. This might indicate that the chin-to-chest contact itself influenced the vertical head acceleration and consequently the calculated neck force. Similar findings were observed in an impact test study with prototype adapted heads with little chin structure [10] and in a large analysis of consumer tests of child restraints (under different impact conditions) [20].

Despite reservations over the reliability of the calculated neck force to predict the true inertial force in all tests, it was useful in confirming that the pragmatic neck tension force thresholds proposed for UN Regulation No. 129 were likely to have been influenced greatly by chin-to-chest contact (i.e., assuming our limited sample reflected the larger monitoring sample). Unfortunately, it is unknown whether the measured force (and thresholds derived from it) was skewed to the extent predicted by the calculated force, or whether chin-to-chest contact masked a more moderate increase in the tension force that the calculated force could not detect. However, if the calculated inertial force was meaningful, it suggests a marked influence on the pragmatic thresholds proposed for the Q0 and Q1.5 dummies. In fact, the inertial force reduced the values to such an extent that previously proposed thresholds scaled from Hybrid III child dummy injury assessment reference values appear to become more meaningful. That said, scaling with child dummies (from adult dummies, or between child dummy families and/or sizes) requires significant assumptions to be made about the difference in geometry, stiffness and failure stress between subjects [21]. Combinations of human and dummy ratios are used, which do not take account of differences in behaviour and performance between the dummies used [6].

Limitations

Our study sample comprised type-approval tests from CYBEX child restraint systems only. Although our data shared many characteristics with the larger type-approval monitoring sample used to derive pragmatic neck tension thresholds, child restraints from other manufacturers may be less susceptible to chin-to-chest contact (or even more susceptible). A larger sample, comprising a broad range of manufacturers and products, is needed to validate our findings fully. Nevertheless, this study demonstrated a useful method for identifying and characterising chin-to-chest contact from a large dataset.

Similarly, the limited nature of our sample meant that some combinations of dummy, impact direction and child restraint orientation yielded very low sample sizes from our database. For example, there were very few tests with the Q1 dummy, and none with Q6. UN Regulation No. 129 requires that the smallest and the largest dummies corresponding to the stature range of the child restraint must be used in the dynamic tests. For most of our product range, these are ‘intermediate dummies’ and are consequently less likely to feature in our database.

Chin-to-chest contact can also influence Q-Series chest deflection [22-23] and abdomen pressure [24]. This study focussed on axial neck force only. We don't currently have a method to investigate the potential influence on these other measurements based on a simple analysis of peak type-approval measurement parameters. A detailed study of time history plots, possibly including the use of adapted dummies would be needed to investigate the effect of chin-to-chest contact on these other measurements.

CONCLUSIONS

Child restraints are very effective in reducing the risk of serious neck injury to children in collisions. Nevertheless, a relatively large spread of neck loads can be measured during type-approval. In our study, the neck tension force measured by the upper neck load cell of the Q-Series dummies was influenced primarily by the impact direction and the orientation of the child restraint. Front impact with forward-facing child restraints generated the higher neck forces than other scenarios. However, there were overlaps with rear impact tests with rear-facing child restraints, despite the lower rear impact severity. The calculated neck force (derived from the head vertical acceleration) displayed similar trends as the measured force in terms of the influence of the impact direction and child restraint orientation on the magnitude of the force. However, the level of difference between certain combinations of impact direction and child restraint orientation we reduced. This was likely due to the influence of chin-to-chest contact on the measured data, which was particularly pronounced with front impact tests on forward-facing child restraints.

Chin-to-chest contact occurred frequently throughout our study sample of internal child restraint type-approval tests. If the frequency and magnitude of chin-to-chest contact observed in our study was reflected in the larger type-approval monitoring sample in [2], it is likely that the pragmatic limits proposed for UN Regulation No. 129 are also likely to have been affected (i.e. increased). Subsequent measurements in future type-approval tests would also likely to be affected in the same way and hence mitigating chin-to-chest contact rather than inertial loading might become the priority for child restraint design. However, although the calculated inertial force was useful for identifying chin-to-chest contact and estimating its effect on the neck tension force measurement, it may also be influenced by chin-to-chest contact, such that encouraging contact at a certain time in the impact might be a means of reducing the vertical head acceleration and hence the calculated neck force value.

REFERENCES

[1] United Nations. 2019. Report of the Working Party on Passive Safety on its sixty-fifth session. Geneva, May 13–17.

[2] European Association of Automotive Suppliers (CLEPA). 2020. "Explanatory presentation to CLEPA neck load limits proposal". Informal Document GRSP-68-10, 68th session of GRSP, 7-11 December 2020.

[3] Visvikis, C., Pitcher, M., Bendjellal, F., Le Claire, M., Müller, T. 2020. "The development of pragmatic thresholds for upper neck tension force and flexion moment in Q-Series dummies in UN Regulation No.129 tests". Proceedings of the 18th International Conference Protection of Children in Cars, Munich, Germany.

[4] Johannsen, H., Trosseille, X., Lesire, P., Beillas, P. 2012. "Estimating Q-dummy injury criteria using CASPER project results and scaling adult reference values". IRCOBI Conference Proceedings; p. 580–596, Dublin, Ireland.

[5] Hynd, M., Pitcher, M., Hynd, D., Robinson, B., Carroll, J.A. 2010. "Analysis for the development of legislation on child occupant protection". TRL Client Project Report 821.

[6] Wismans, J., Waagmeester, K., Le Claire, M., Hynd, D., de Jager, K., Palisson, A., van Ratingen, M., Trosseille, X. 2008. "Q-dummies report. Advanced child dummies and injury criteria for frontal impact". European Enhanced Vehicle-Safety Committee (EEVC) Working Group 12 and 18 Report No. 514.

[7] Martinez Sáez, L. 2020. "Effect of Q1.5 chin-thorax contact in measuring upper neck forces". Informal Document GRSP-68-26, 68th session of GRSP, 7-11 December 2020.

[8] Visvikis, C., Thurn, C., Kettner, M., Müller, T. 2020. "The effect of chin-to-chest contact on upper neck axial force in UN Regulation No. 129 frontal impact tests of child restraint systems". Traffic Inj. Prev. 21(sup1):S173-S176. doi: 10.1080/15389588.2020.1829923.

[9] European Association of Automotive Suppliers (CLEPA). 2021. "R129 neck limits: effect of chin-to-chest contact and potential solutions". Informal Document GRSP-70-22, 70th session of GRSP, 6-10 December 2021.

[10] Visvikis, C., Thurn, C., Müller, T. 2021. "The effect of Q-Series dummy adaptation on the prevalence of chin-to-chest contact and its influence on upper neck tension force in UN Regulation No. 129 tests". Proceedings of the 19th International Conference Protection of Children in Cars, Munich, Germany.

[11] Society of Automotive Engineers (SAE) 2016. "Test device head contact duration analysis (SAE J2502)". https://www.sae.org/standards/content/j2052_201607/.

[12] Schoerrle, B. and Sivak, M. 2015. "A preliminary analysis of real-world crashes involving self-driving vehicles". University of Michigan Transportation Research Institute (UMTRI). Report No. UMTRI-2015-34.

[13] Sherwood, C.P., Shaw, C.G., Van Rooij, L., Kent, R.W., Crandall, J.R., Orzechowski, K.M., Eichelberger, M.R., Kallieris, D. 2003. "Prediction of cervical spine injury risk for the 6-year-old child in frontal crashes". Traffic Inj. Prev. 4(3):206–213. doi:10.1080/15389580309885.

[14] McMurry, T.L., Arbogast, K.B., Sherwood, C.P., Vaca, F., Bull, M,, Crandall, J.R., Kent, R. 2018. "Rear-facing versus forward-facing child restraints: an updated assessment. Injury prevention", 24, 55-59. doi: 10.1136/injuryprev-2017-042512.

[15] Gan, J.H., Davison, C., Prince, N., Gour, A. 2018. "Car seats: Facing backward is the way forward". Trauma, 21(1), 68-72. doi:10.1177/1460408618755811.

[16] Klinich, K.D., Reed, M.P., Ritchie, N.L., Manary, M.A., Schneider, L.W., Rupp, J.D. 2008. "Assessing child belt fit, volume II: Effect of restraint configuration, booster seat designs, seating procedure, and belt fit on the dynamic response of the Hybrid III 10YO ATD in sled tests". University of Michigan Transportation Research Institute (UMTRI). Report No. UMTRI-2008-49-2.

[17] Stammen, J.A., Sullivan, L.K. 2008. "Development of a Hybrid III 6yr. old and 10 yr. old dummy seating procedure for booster seat testing". National Highway Traffic Safety Administration (NHTSA) Technical Report. NHTSA Docket 2007-0048-0002.

[18] Maheshwari, J., Duong, N., Sarfare, S., Belwadi, A. 2018. "Evaluating the response of the PIPER scalable human body model across child restraining seats in simulated frontal crashes". Traffic Inj Prev. 19(sup2):S140–S142. doi:10.1080/15389588.2018.1532204.

[19] Stammen, J.A., Bolte, J.H., Shaw, J. 2012. "Biomechanical impact response of the human chin and manubrium". Ann. Biomed Eng. 40(3): 666–678. doi:10.1007/s10439-011-0419-x.

[20] Ratzek, A. 2022. "Influence of the chin-to-chest contact to the neck tension force". Proceedings of the 20th International Conference Protection of Children in Cars, Munich, Germany.

[21] Carroll, J.A., Pitcher, M., Hynd, M. 2011. "Extension of biofidelity and injury risk curve development for the Q10. EPOCh Project Report". Work Package 1, Task 1.3a and Task 3.2a.

[22] Visvikis, C., Carroll, J., Picher, M., Barrow, A., Cuerden, R., Broertjes, P. 2013. "Research findings for the optimised evolution of the new regulation on enhanced child restraint systems" Proceedings of the 11th International Conference Protection of Children in Cars, Munich, Germany.

[23] Pitcher, M., Carroll, J., Broertjes, P. 2015. "Research findings for setting dummy injury thresholds for Regulation 129 phase 2 regarding chest and abdomen loading". Proceedings of the 13th International Conference Protection of Children in Cars, Munich, Germany.

[24] Visvikis, C., Thurn, C., Müller, T. 2020. "Investigation of different methods of improving the assessment of booster seats in light of Dummy and sensor capabilities". IRCOBI Conference Proceedings; p. 487–498.