Effect of Chestbands on the Global Response of the Human Thorax to Frontal Impact

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ABSTRACT

Chestbands are commonly used instrumentation in injury biomechanics to measure the contour of the thorax during impact, which may be used to calculate chest deflection. There exists a concern that by tightly wrapping chestbands around the thorax, particularly of a small frail subject, that thoracic response to impact may be altered. This study examined the effects of chestbands on global thoracic response, characterized by chest deflection and thoracic stiffness. A series of eighteen frontal impacts were imposed on one post-mortem human surrogate (PMHS), using a 23 kg ram. Impacts were at speeds of 0.8 m/s, 1.0 m/s, 1.5 m/s, and 2.0 m/s, and had either 0, 1, or 2 chestbands on the subject during impact. The baseline case of 0.8 m/s with zero chestbands was tested initially three times to examine repeatability, then was repeated intermittently throughout testing. For each impact speed, the difference between response with chestbands and without chestbands was calculated. Results show an average increase of 1.7 mm in chest deflection when chestbands are used, but this increase was not statistically significant (t-test, p=0.6). Thoracic stiffness, on average, decreases by 0.84 N/mm when chestbands are used, which also is not statistically significant (t-test, p=0.36). The results provide support for the commonly employed assumption that chestbands do not alter the response of the thorax to impact.

INTRODUCTION

A chestband, also called an External Peripheral Instrument for Deformation Measurement (EPIDM), is a strip of steel with a series of strain gages attached to it, all encased in polyurethane (Eppinger, 1989). The gage readings provide a measure of the curvature of the chestband at each gage location. Chestbands are commonly used in biomechanics as an instrument to measure the contour of the thorax throughout impact, from which chest deflection may be calculated (Cesari, 1994, Pintar, 1997, Crandall, 2006, Shaw, 2014). Chest deflection is an important measurement to predict injury in many traffic safety related research projects. Several different values for percent deflection ([absolute deflection/chest depth]*100%) injury threshold in frontal and side impacts have been reported, including 30% (Tarriere, 1979, Pintar, 1997), 34% (Kroell, 1974), 35% (half-chest compression) (Stalnaker, 1979), 37% (Kuppa, 2003), and 38% (Viano, 1989). The current injury assessment reference value (IARV) in use for chest deflection in the Hybrid III 50th percentile male dummy is 63 mm (Eppinger, 1999).

Several studies have validated the accuracy of chestband contours reconstructed from strain gage measurements (Eppinger, 1989, Cesari, 1994, Pintar, 1996, Bass, 2000). Measurement errors were specifically examined and quantified in the study by Bass (2000). Although it has been verified that the measurements are accurate, there has not yet been a study which has examined whether, and to what extent, the use of chestbands may alter the actual response of the thorax to impact. Should such effects exist, the validity and value of the collected data could be compromised. Thus, there exists a concern that by tightly wrapping a chestband, or especially multiple chestbands, around the thorax of a post-mortem human surrogate (PMHS), the thorax characteristics and impact response may be altered. Of particular concern are the effects on small, frail subjects, as their low mass and low bone strength could amplify potential chestband effects. The purpose of the present work is to determine the effects of chestbands on the global response of the human thorax to impact.

METHODS

Chestband effects on global thoracic response were investigated through a series of eighteen low-energy frontal ram impacts using a single PMHS. The number of chestbands present on the subject was varied throughout testing in order to provide a comparison of response with and without chestbands. Speed was also varied in order to have multiple points for comparison. Chest deflection and thoracic stiffness served as the response characteristics of interest in determining chestband effects.

Subject Selection

A small, frail (osteopenic) female was used in order to evaluate chestband effects under conditions in which the effects should be most pronounced. The subject was 83 years old, 163 cm in height and 56 kg in weight. Bone mineral density (BMD) was measured using a DXA scanner and the dual femoral neck t-score was measured as -1.6, which indicates osteopenia (Kanis, 1994). The subject had not experienced previous open-heart surgery, and a pre-testing CT scan was performed to screen for pre-existing injuries and thoracic abnormalities. The subject’s anthropometry measurements were collected prior to instrumenting the body. Additionally, the breasts were removed in order to eliminate their influence on thoracic response and chestband effects.

Test Setup

Frontal impacts were conducted on the PMHS using a 23 kg pneumatic ram, with a flat plate impactor surface (6”H x 12”W) centered at mid-sternum (Figure 1). The PMHS was placed against a 90^{o}, flat back fixture, thus creating a fixed-spine environment. The fixed-spine setup enabled the ram displacement, from initial contact to peak displacement, to be used as a measure of chest deflection. The weight of the PMHS was supported, and the seated stature maintained by use of a head harness which was placed on a linear track, allowing for anterior-posterior (A/P) motion of the head during impact. The PMHS' arms and forearms were flexed 90° anteriorly, which prevented impactor interaction without raising the thoracic region.

Figure 1: Test setup including a 23 kg ram, 90° back fixture, and PMHS with arms raised anteriorly 90°. The picture on the right also shows the 2 chestbands on the PMHS.

Instrumentation

Two chestbands were wrapped around the PMHS' thorax; the superior chestband at the level of the axilla (40 gage, Humanetics Innovative Solutions, Plymouth MI) and the inferior chestband at the level of the xiphoid process (59 gage, Humanetics Innovative Solutions, Plymouth MI). Strain gages (Model CEA-13-062UW-350/P2, Micro Measurements, Wendell NC) were placed anterolaterally (approximately 70% of the spine to sternum distance) on ribs 3-8 bilaterally, in order to identify fracture timing. A 6 degree of freedom motion block containing 3 accelerometers and 3 angular rate sensors (6DX Pro Sensor, Model 2000g 18K deg/sec, DTS, Seal Beach CA) was placed on T4 to verify that there was no spinal motion, and to provide a correction in the event of spinal motion occurrence. Instrumentation placement on the thorax is shown in Figure 2.

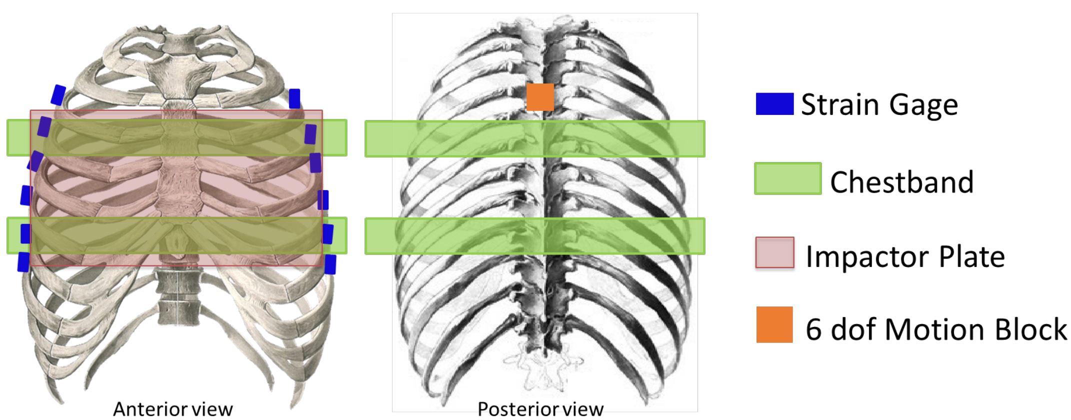

Figure 2: Instrumentation placed on the PMHS thorax prior to impact testing.

The test setup used a linear potentiometer (Model CLWG-600-MC4, Celesco, Chatsworth CA) on the ram, which served as the consistent measure of chest deflection throughout testing. Other instrumentation included an accelerometer (Model 7264C-2K, Endevco, Irvine CA) on the ram to acquire impact velocity, as well as a load cell (Model 2944JFL, Humanetics Innovative Solutions, Plymouth MI) between the ram shaft and the impactor face.

Test Matrix

The 18 impacts included variations both in the impact speed and the chestband status (the number of chestbands present on the subject during impact). The baseline case was defined as 0.8 m/s impact velocity with 0 chestbands present. The baseline scenario was tested first, repeated twice to check repeatability, then also repeated intermittently during the testing process. Deviations from the baseline scenario were systematically applied, including adjustments to impact velocity and to chestband status. Impact velocities were approximately 0.8 m/s, 1.0 m/s, 1.5 m/s, and 2.0 m/s. Chestband status was 0, 1, or 2 chestbands. At the 2.0 m/s velocity, impacts were conducted with 2 chestbands and then with 1 chestband, during which fracture occurred (impact #17), thus preventing an impact with 0 chestbands at that speed. A final baseline impact (#18) was conducted after the injurious impact. The order in which the impacts were conducted is presented in Table 1.

Table 1: Test matrix indicating the order in which eighteen impacts were conducted, by impact velocity and chestband status

	No Chestband	**Axillary Chestband Only**	**Both Chestbands**
0.8 m/s	1-3,5, 7,11,16,18	8	12
1.0 m/s	4	9	13
1.5 m/s	6	10	14
2.0 m/s	---	17	15

Data Collection and Analysis

All data were collected using a SlicePro data acquisition system (DTS, Seal Beach CA) at a sampling rate of 20,000 Hz. Time zero in each test was defined as the time of initial contact between the impactor face and the thorax, and was determined using event tape. All data were filtered during post-processing in Matlab using a two-direction, second order Butterworth filter with a cutoff frequency of 300 Hz, which is equivalent to CFC180. Normalized chest deflection and thoracic stiffness were examined as the basis for evaluating the effects on global response. The overall structure of the data collection and analysis process is shown in Figure 3. The analytical methods for the impact velocity, deflection, and stiffness are explained in greater detail in the following subsections.

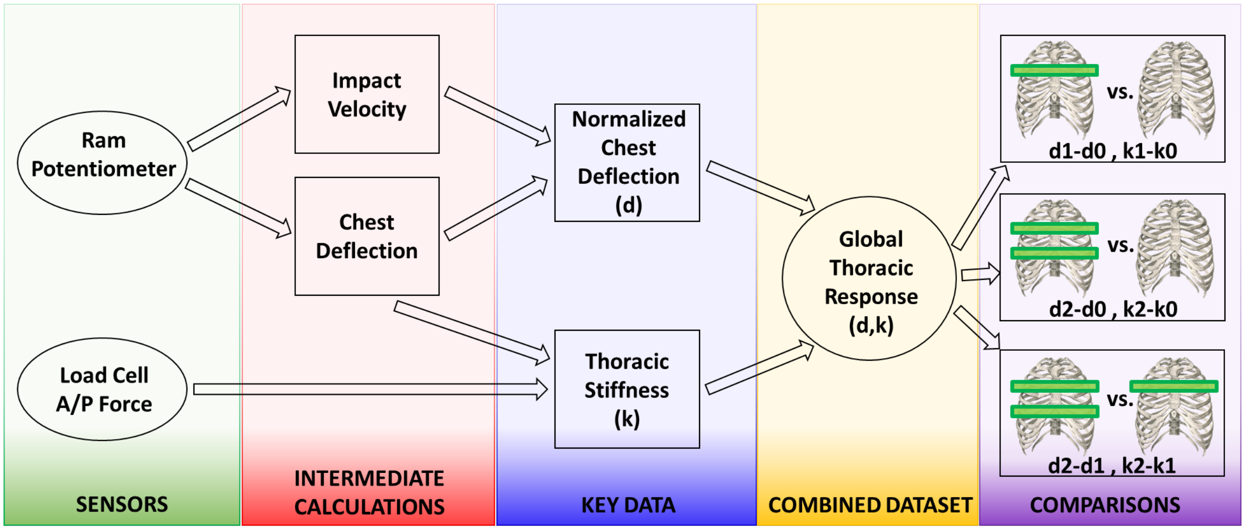

Figure 3: Flow of data collection and analysis.

Impact velocity. Multiple redundant sensors were used to calculate impact velocity. The filtered ram acceleration (from accelerometer) was integrated to get the ram velocity. Additionally, the filtered ram position (from potentiometer) was differentiated to get the velocity. The differentiated ram position was selected as the best method for calculating velocity because of vibrational noise experienced by the accelerometer. Impact velocities for each test are included in Appendix A.

Chest deflection. The values for absolute chest deflection (c) were obtained for each test as the ram displacement after contact. In order to remove variation in actual impact velocity (v_a) as a potential factor for variation in peak chest deflection, the deflections were normalized (d) about the target impact velocity (v_t). The normalization is shown in Equation 1. Target velocities, actual velocities, and peak absolute deflections are included in Appendix A.

$$d = c * \frac{v_t}{v_a} \qquad \text{Equation (1)}$$

With the normalized chest deflections calculated, deflection differences were then calculated as the basis for comparing the deflection for each chestband status. Uncertainty was then calculated for individual deflections and extended to deflection differences. The individual uncertainty was calculated as the 3-degree-of-freedom 95% confidence interval, which was 3.2 times the standard deviation of the first 4 baseline impacts. The uncertainty in each chest deflection difference was calculated as the root sum of squares of two impacts, each impact having an uncertainty equal to the individual deflection uncertainty (Moffat 1982).

In order to determine whether observed differences were significant, a two-sided t-test with five degrees of freedom was conducted on the combined set of deflection differences. The null hypothesis of the test was that there is no difference between response with and without chestbands ($d_{1 \text{ or } 2} - d_0 = 0$). The alternative hypothesis was that there is a difference between response with and without chestbands ($d_{1 \text{ or } 2} - d_0 \neq 0$).

Thoracic stiffness. The A/P force from the load cell was inertially compensated to account for the mass of the impactor plate, thus representing the complete force exerted on the thorax. The compensated force was then used to produce force-deflection curves as well as to calculate the thoracic stiffness. Stiffness was calculated for the linear spring model containing equal potential energy as the thorax at peak deflection (Equation 2). Stiffness values are included in Appendix A.

$$k = \frac{2*PE}{(c)^2} \quad \text{, where} \quad PE = \int_0^{Peak\ Deflection} F * dc \qquad \text{Equation (2)}$$

The methods for calculating stiffness differences, stiffness difference uncertainty, and for testing the significance of stiffness differences were identical to the methods evaluating the differences in the chest deflection.

RESULTS

Table 2 provides a summary of the key results, and the subsequent sections provide a more detailed look at each of the results.

Table 2: Summary of results presented

Characteristic	Observation	p-value
Injuries	2 transverse fractures, one on R3 and one on R4, each located at approximately 60% of curve length	N/A
Chest Deflection	Average increased deflection of 1.7 mm with chestbands	0.06
Thoracic Stiffness	Average decreased stiffness of 0.84 N/mm with chestbands	0.36

Injuries

Rib fractures were identified during testing by sudden drops in the strain gage readings, as shown in Figure 4.

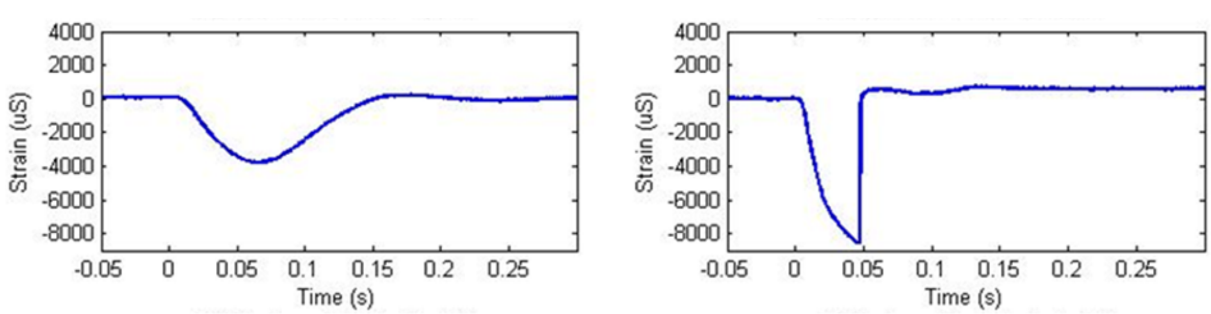

Figure 4: Rib strain vs. time for an uninjured case (left) and an injured case (right). The sudden strain relief indicates that fracture occurred at that instant.

Fractures occurred in the 3rd and 4th right ribs during the 17th impact, which was the second impact to occur at the 2.0 m/s impact velocity (see Figure 5). One chestband, at the level of the axilla, was present on the subject during the injurious impact. Both fractures were transverse and were located slightly posterior of the strain gages, but still anterior of lateral (approximately 60% of rib curve length).

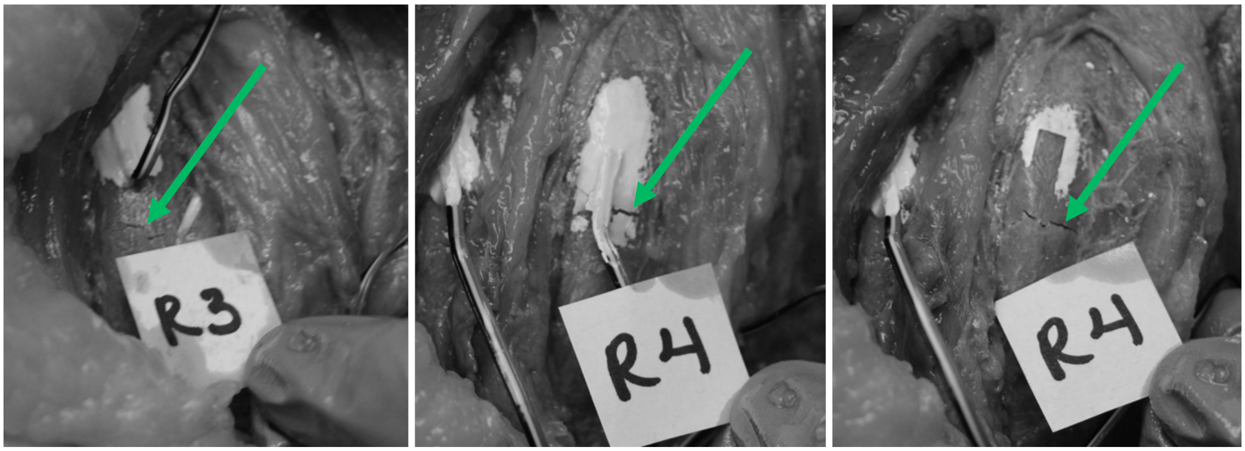

Figure 5: Transverse fractures in ribs R3 (left) and R4 (center and right). The center and right images are of the same fracture, with and without the strain gage still in place.

Chest Deflection

Normalized chest deflections for each impact were plotted, and were sorted by impact velocity. Shown in Figure 6 are the normalized chest deflection plots for the 0.8 m/s and 1.5 m/s impacts, with the color of each line indicating the chestband status. Deflection increased for the baseline scenario in impact #18 (after rib fractures had occurred on #17), as observed with the outlying red curve.

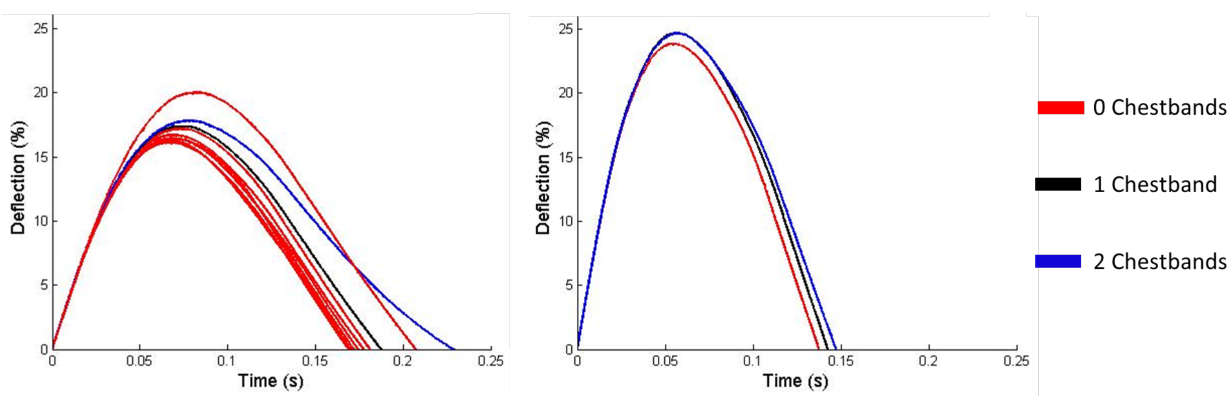

Figure 6: Chest deflection vs. time for the 0.8 m/s impacts (left) and 1.5 m/s impacts (right).

The effect of chestbands on chest deflection is shown in Figure 7 as differences in the normalized chest deflection. For nearly all impact speeds tested, adding any number of chestbands increased the chest deflection by 1.5-2.0 mm (1.7 mm average) when compared to an impact without any chestbands. Differences in chest deflection when going from 1 chestband to

2 chestbands varied around 0 mm. In all cases, a difference of 0 is contained within the 95% confidence interval for the deflection difference. The t-test identifying the level of significance of the consistent difference in chest deflection from using chestbands produced a p-value of 0.06.

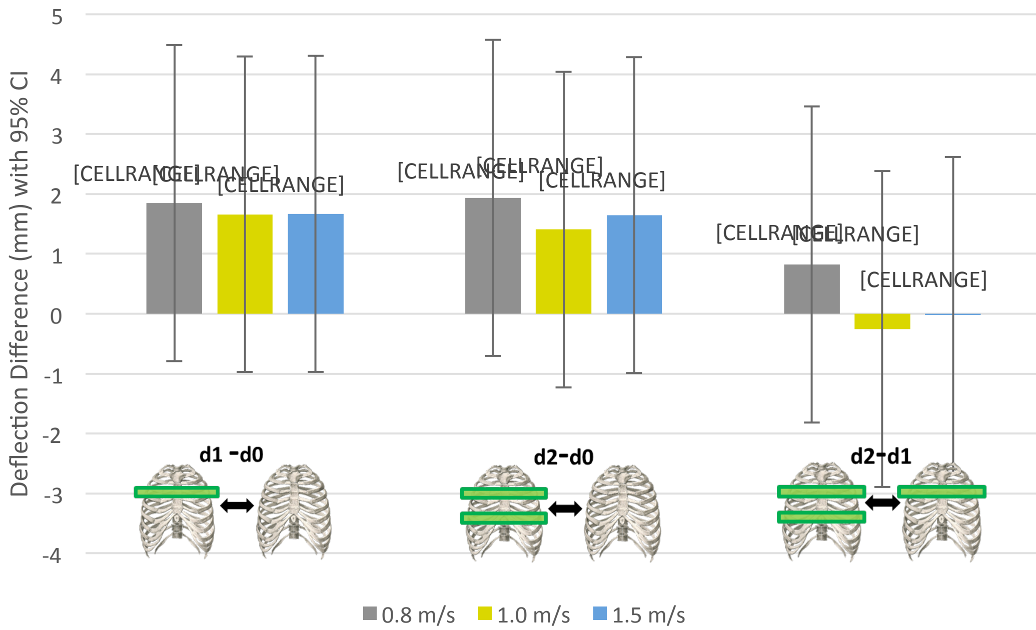

Figure 7: Differences between peak deflections for impacts at the same speed, comparing 0 chestbands with 1 chestband (d1-d0), 0 chestbands with 2 chestbands (d2-d0), and 1 chestband with 2 chestbands (d2-d1). Error bars indicate the 95% confidence interval for the difference in measured deflection.

Thoracic Stiffness

Force-deflection curves were produced in the same manner as the chest deflection curves. Shown in Figure 8 are the force-deflection curves for the 0.8 m/s and 1.5 m/s impacts. As with the deflection, one curve (impact #18) is observed with exceptionally low stiffness compared to the others, and is due to the presence of fractures.

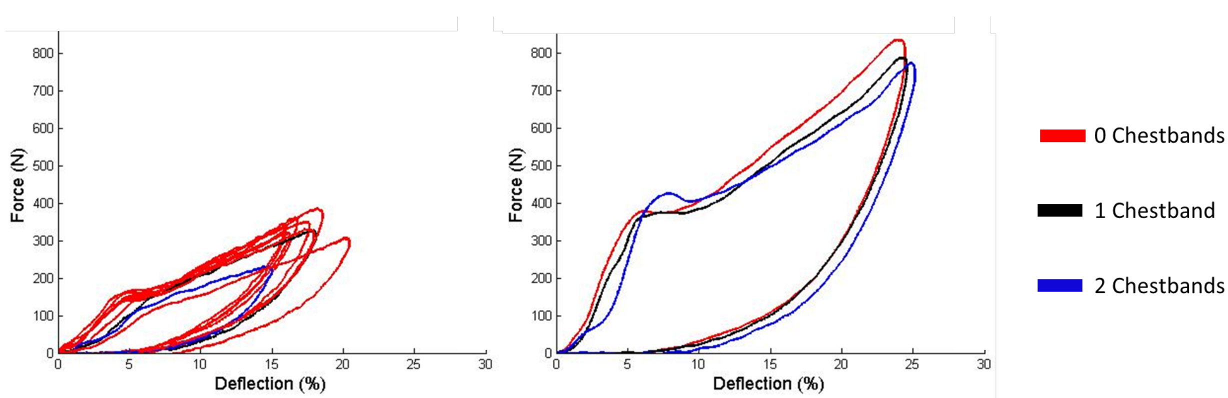

Figure 8: Force vs. deflection for the 0.8 m/s impacts (left) and 1.5 m/s impacts (right).

The differences in thoracic stiffness as chestbands were added to the system are shown in Figure 9. As with the chest deflection, the 95% confidence interval for the stiffness difference crosses the line for zero difference in every instance. The t-test identifying the level of significance of the difference in thoracic stiffness with and without chestbands produced a p-value of 0.36.

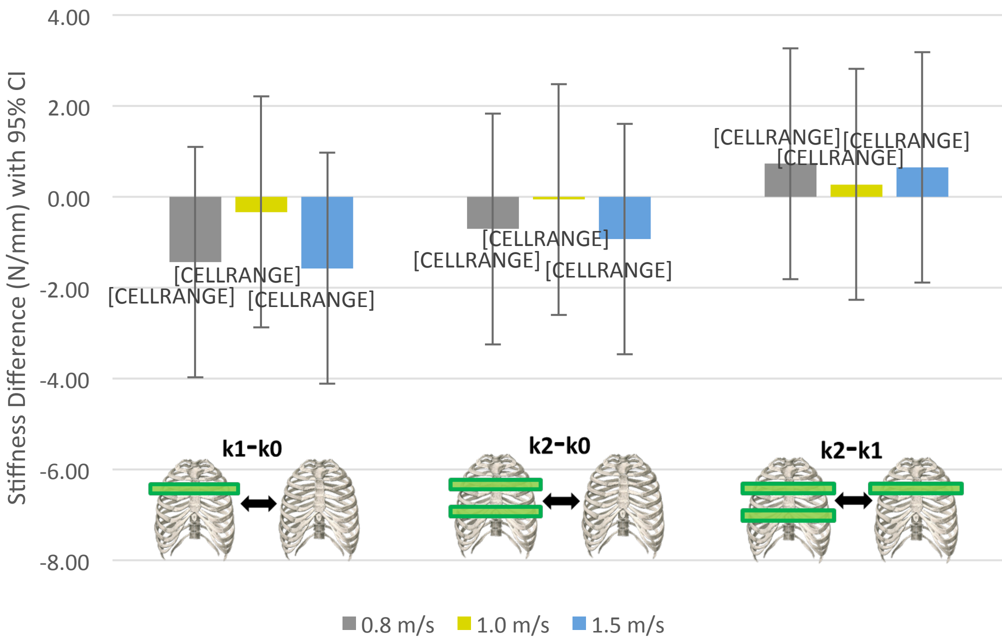

Figure 9: Differences between thoracic stiffness for impacts at the same speed, comparing 0 chestbands with 1 chestband (k1-k0), 0 chestbands with 2 chestbands (k2-k0), and 1 chestband with 2 chestbands (k2-k1). Error bars indicate the 95% confidence interval for the difference in measured deflection.

DISCUSSION

The addition of chestbands to the system consistently increased the chest deflection by approximately 1.5 – 2 mm. There does not appear to be any additive effect from additional chestbands, as no difference was seen in deflection when comparing 1 chestband versus 2 chestbands. The increase in deflection is attributable to the thickness of the ribbon cables on the chestband (2 mm). The ribbon cables of the axillary chestband (for 1 chestband) and xiphoid chestband (for 2 chestbands) rested at the level of initial contact, thus initiating contact 2 mm earlier in the travel of the ram. The ribbon cables would then compress into the soft tissue of the thorax, after which the impactor would engage the entire thorax the same as it did without any chestbands present.

The observed difference in deflection, though consistent, was not statistically significant at a 95% confidence level, ($p=0.06$). However, recognizing that only one subject was tested, it could be argued that the results may become significant with additional data points. In such a case, supposing the deflection difference *was* statistically significant, it would follow for us to consider whether the 2 mm difference is practically significant. In the present study, the 2 mm deflection difference changes the percent deflection ([deflection/chest depth]*100%) by a value of 1%. The predicted AIS injury level would then change by 0.2 (Kroell, 1974). Applying the deflection values to the Hybrid III risk curves at the small female critical chest deflection of 52 mm, the 2 mm increase in chest deflection increases the probability of AIS 3+ injury from 22% to 24% (Eppinger, 1999). Such a small difference in chest deflection will likely be negligible for many applications, such as full body sled tests. Thus, the observed chestband effect on chest deflection appears to be neither statistically significant nor practically significant.

Stiffness differences were less consistent than the deflection differences. Each of the 1.0 m/s impacts had nearly identical stiffness, regardless of chestband status, leading to the conclusion that thoracic stiffness is not affected by the use of chestbands. This conclusion was supported statistically, as the t-test produced a p-value of 0.36.

The use of chestbands in the past has inherently assumed that chestbands do not alter the thoracic response to impact (Cesari, 1994, Pintar, 1997, Crandall, 2006, Shaw, 2014). The results of the present work provide evidence to support the assumption of negligible effects on the global thoracic response, specifically in the chest deflection and thoracic stiffness.

While the present work provides essential evidence to support the assumption of negligible thoracic effects from chestbands, there are also important limitations to consider in the application of the results. First, the sample size of one PMHS makes it difficult to provide definitive conclusions. Additionally, the need to avoid fracture for the repeated loading necessitated low-energy impacts and thus did not replicate impacts of the same energy typically utilized in vehicle occupant crash studies. It was expected, though, that any observed chestband effects should be most greatly manifested in low-energy impacts and should become more negligible as the impact energy increases. Thus, effects should be negligible at higher energy impacts because the effects are negligible at lower energy impacts. Another limitation in the application of this study is that it specifically examined frontal impact, assuming that the results will be similar for oblique and lateral impacts.

NEXT STEPS

Interesting observations were revealed as data from the strain gages were examined closely, despite being beyond the scope of the study design. Post-impact resting strain values were offset from the pre-impact strain values for the 1.5 m/s and 2.0 m/s tests, suggesting the ribs may have surpassed yield and undergone plastic deformation. Such effects started to become evident when the peak strain was approximately 6000 uS or above. It is recommended that damage accumulation be specifically studied in order to better understand it, as it may be an important factor in future studies utilizing repeated loading.

In addition to damage accumulation, the strain gage data raised some questions regarding the localized loading of the chestbands. It was observed that for impacts with one chestband, there was a slight average increase (+2%) in the observed strain in the ribs contacted by the chestband, when compared to an impact without a chestband. Simultaneously, the ribs not contacted by the chestband showed a decrease (-20%) in peak strain. Furthermore, the two rib fractures occurred on an impact with only 1 chestband, and the fractured ribs were both in contact with the chestband. While nothing conclusive can be drawn from these observations, it seems to suggest that the chestbands may be redistributing the impact load to be focused on the ribs contacted by the chestband. Further investigation into this observation is also recommended.

CONCLUSIONS

Differences in chest deflection based on chestband status were quantified, and were found to be NOT statistically significant. No consistent difference was found in thoracic stiffness based on chestband status, and again the differences were not statistically significant. These observations provide evidence to support the commonly held assumption that chestbands do not alter the response of the thorax to impact. Further study is recommended into understanding potential localized loading effects of chestbands.

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APPENDIX A: RESULTS GENERAL SUMMARY

Table A1 contains the general summary of test data and results, presented in the testing order. Although strain data was collected for ribs R8 and L8, only peak strains for ribs 3-7 are shown here.

Table A1: General summary of testing data and results

Impact #	# of Chestbands	Target Velocity (m/s)	Actual Velocity (m/s)	Peak Deflection (mm)	Stiffness (N/mm)	R3 Peak Strain (uS)	R4 Peak Strain (uS)	R5 Peak Strain (uS)	R6 Peak Strain (uS)	R7 Peak Strain (uS)	L3 Peak Strain (uS)	L4 Peak Strain (uS)	L5 Peak Strain (uS)	L6 Peak Strain (uS)	L7 Peak Strain (uS)
1	0	0.8	0.85	33.63	10.89	2082	3794	4310	5020	3621	1249	2349	3667	3682	3082
2	0	0.8	0.79	30.45	12.03	2037	3698	4248	4896	3514	1176	2258	3599	3524	2890
3	0	0.8	0.78	30.41	11.68	2014	3642	4153	4761	3397	1187	2219	3526	3417	2794
4	0	1.0	0.92	33.48	13.27	2268	4463	4909	5437	4097	1564	2754	4174	4060	3476
5	0	0.8	0.83	32.06	12.13	2149	4047	4528	4958	3710	1412	2478	3836	3699	3070
6	0	1.5	1.54	45.64	20.06	2943	7948	8373	7364	7174	2992	4714	6647	6473	6648
7	0	0.8	0.79	31.01	11.28	2127	4170	4601	4626	3582	1367	2394	3819	3631	2884
8	1	0.8	0.83	34.49	10.10	2116	3951	4209	3657	2909	1434	2399	3475	2955	2310
9	1	1.0	0.98	37.32	12.94	2453	4907	5218	4378	3761	1749	2968	4196	3676	2997
10	1	1.5	1.49	40.87	18.49	3168	7172	7740	5865	6177	2869	4410	5802	5419	5217
11	0	0.8	0.91	28.09	12.23	2403	4603	5117	4845	4159	1654	2839	4501	4246	3487
12	2	0.8	0.68	28.63	10.82	1339	1995	2399	2366	1967	911	1476	2242	2289	2056
13	2	1.0	0.93	35.42	13.22	1879	3361	3873	3442	2943	1406	2292	3498	3457	3048
14	2	1.5	1.53	48.00	19.14	2954	6318	6910	5144	5123	2576	4004	5717	5537	5363
15	2	2.0	2.02	55.72	24.02	3460	8144	8939	5724	6462	3397	4984	6979	6603	7031
16	0	0.8	0.84	34.24	10.91	2296	4170	4629	4293	3783	1552	2591	4067	3987	3262
17	1	2.0	2.01	54.39	21.51	2931	8583	11018	6671	8004	3853	5570	7182	6879	7611
18	0	0.8	0.82	38.91	7.88	270	354	4949	4423	3845	1457	2529	4067	4026	3290