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Performance Assessment of the External Peripheral Instrument for Deformation Measurement Using Static Tests

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ABSTRACT

The External Peripheral Instrument for Deformation Measurement (EPIDM) or "chestband" is currently the only viable instrument capable of measuring chest deflection in dynamic tests with cadaver subjects. The chestband, a belt-like instrument that encircles the chest, uses a series of strain gages along its length to measure curvature. The curvature data is used to create a closed curve that describes the shape of the chest. Previous testing conducted at our lab, and at others, indicated that the chestband's accuracy was variable. In order to explore chestband performance, a series of static tests were conducted in which the independently measured chestband contour was compared to that calculated using chestband strain gage data. The chestbands were installed on a male Hybrid III 50th percentile dummy and four cadavers whose chests were loaded by either a rigid indentor or a simulated roped shoulder belt. Another test series involved fitting the chestband to various shapes that approximated a chest cross-section deformed by a restraint system. The test results suggested that inaccuracies in calculated chestband contours were due to the inability of the chestband to resolve subject ribcage surface discontinuities. In several of the tests, surface features created radii of curvature too small to be properly characterized by the present spacing of chestband strain gages. Insufficient gage density was also suggested by the sensitivity of contour error to the placement of individual chestband strain gages relative to the point of load application. Faulty gages were found to affect the contours in a manner similar to that of a lack of resolution. The results of this investigation suggest the need for improvements in chestband resolution and durability and the need to fully understand the chestband's capabilities and failure modes.

BACKGROUND

The External Peripheral Instrument for Deformation Measurement (EPIDM), commonly known as the chestband, is a device that records the surface contours of a body cross-section as it deforms in time. It was developed for the automotive crash environment to evaluate the response of the human cadaveric thorax in a noninvasive manner (FIG. 1) (Eppinger, 1989). In its current form, the chestband consists of a steel strip that is 140 cm x 1.25 cm x 0.025 cm with forty sets of four strain gages bonded every 2.5 cm along its length. Each strain gage set, configured as a Wheatstone bridge, is wired to a small flexible circuit board that provides the terminal for a ribbon cable. The entire assembly is potted in a medium-hard urethane rubber sheath approximately 3.5 mm thick. Each set of gages, commonly referred to as a single "gage", forms one data channel. Each "gage" provides curvature information for its location on the chestband. Software has been developed to use the curvature from the individual gages to create a closed curve that describes the shape of the thorax during crash loading.

In most of the tests conducted at the University of Virginia Automobile Safety Laboratory (UVA), installation of chestband involved tightly wrapping two chestbands around the test subject and securing the band with tape. In the Hybrid III 50th percentile male dummy tests, the bands encircled the ribcage at the level of the second and fifth ribs (FIG. 2). In tests with cadaveric subjects, the bands are installed at the level of the fourth and eighth ribs as defined by their location in the mid-coronal plane.

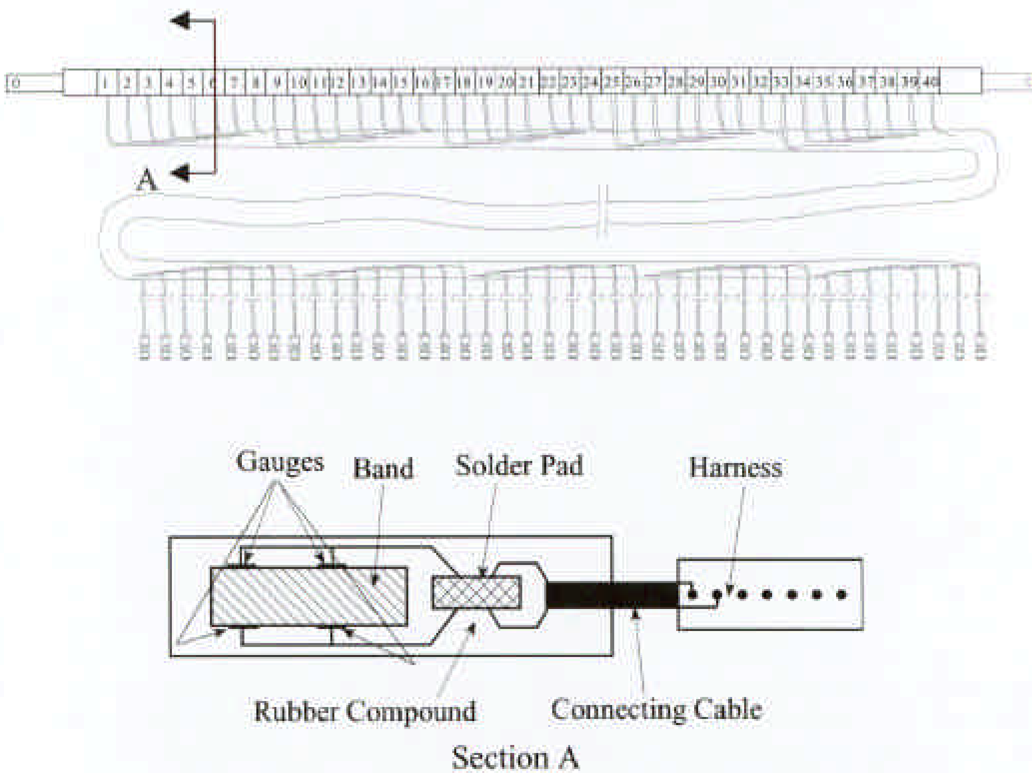


FIG. 1. Chestband construction cross-section.

Chestband Performance

Prior research suggests that the accuracy of the chestband is dependent on the loading environment. Eppinger (1989) reported that prototype chestbands mapped the actual contours of chest-forms to within 0.6 cm, but cautioned that chestband accuracy was a "function of both the complexity of the geometrical shape being measured and the number of sensing elements placed on the band and their location." An early 16-gage chestband was able to define the actual contours of foam chest-form to within approximately 0.8 cm (Shaibani and Khaewpong, 1990).

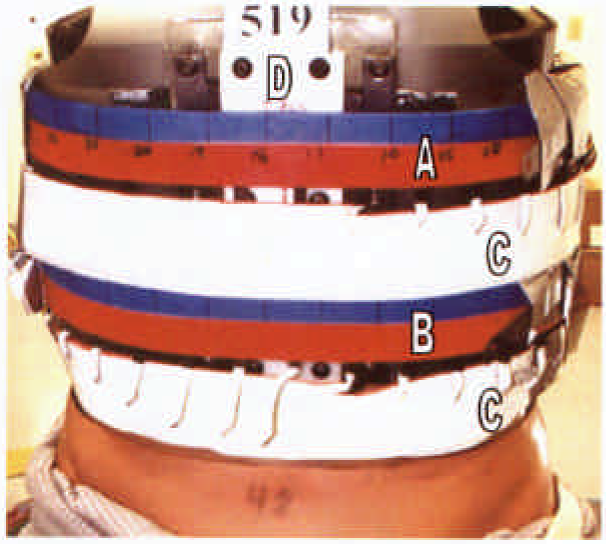


FIG. 2. Front view of the Hybrid III dummy torso showing chestbands installed directly on the ribcage.

A – Upper chestband installed at the level of the 2nd rib. The numbers and vertical lines indicate the location of the gages.
B – Lower chestband installed at the level of the 5th rib.
C – Cable harness.
D – The stiff plastic sternal plate of the dummy.

A 37-gage chestband reproduced the actual contour of a chest-form shaped to simulate deformation due to shoulder belt loading (Hagedorn and Pritz, 1991; Hagedorn, 1999). These authors also reported good results for tests conducted with 37 and 40 gage chestbands in which the dummy chest was compressed quasi-statically with a 17.8 cm x 5 cm indentor with a surface shaped to simulate a roped shoulder belt and with a flat 20.3 cm diameter indentor. Pintar et al., (1996) reported less than 2% difference between actual and chestband-derived chest breadth and width in side impact tests in which a wall loaded the side of the dummy's thorax.

In pendulum impact tests in which the chest was loaded by a 20.3 cm diameter circular indentor, a 40-gage chestband installed above the dummy skin performed inconsistently (Hagedorn and Burton, 1993). In a qualitative assessment of the test results, the authors concluded that poor results were more common when the chestband was installed directly on the ribcage and under the skin of the dummy as is illustrated in FIG. 2. Erroneous contours were produced in 7of the 50 impact tests Hagedorn, (1999) suggested that the poor results for the under the skin tests were due to the band being locally deformed by sternal plate bolt heads.

Recent sled testing, conducted with the chestbands installed under the subject's skin, produced effects similar to those reported by Hagedorn and Burton, (1993), namely the inability of the chestband to resolve local surface discontinuities. UV conducted a series of frontal 55 km/h sled tests with the Hybrid III 50th percentile male dummy using force-limited belts and standard (first generation) air bags. In an attempt to measure only ribcage deflection (and not the compression of the overlying skin and tissue), we installed the chestbands under the skin. The chest contours and chest deflection calculated by the chestband software did not agree with internally mounted chest deflection instruments (string potentiometers and chest slider). Evidence from these tests and those reported by

Hagedorn, (1999) suggested that these internal instruments provided more accurate deflection data than the chestbands.

In some of the tests, the upper chestband contour bulged out, rather than in, directly under the shoulder belt (FIG. 3). In one test, the contour failed to record substantial deformation until long after the peak shoulder belt load was achieved. We examined the chestbands' integrity and reviewed the chestband data processing procedures without finding evidence of malfunction or error. In order to

FIG. 3. Chestband contour for sled test. Contour axes are scaled in centimeters. The overlay plots are shown for 0.1 ms and 60 ms after the beginning of the impact. At 60 ms (bold line), the dummy's torso had loaded the shoulder belt which recorded more than 3000 N of tension. The shoulder belt loaded the chest in the area in which the 60 ms contour bulged out.

with local ribcage surface irregularities, the dummy's ribcage surface was made smoother. Screw heads under the chestbands were countersunk and a system of rubber shims were installed to fill the voids between the chestband and the ribcage. Sled tests conducted with these dummy modifications continued to produce erroneous contours.

The investigation described in this paper summarizes our efforts to assess the chestband's ability to measure chest deflection accurately.

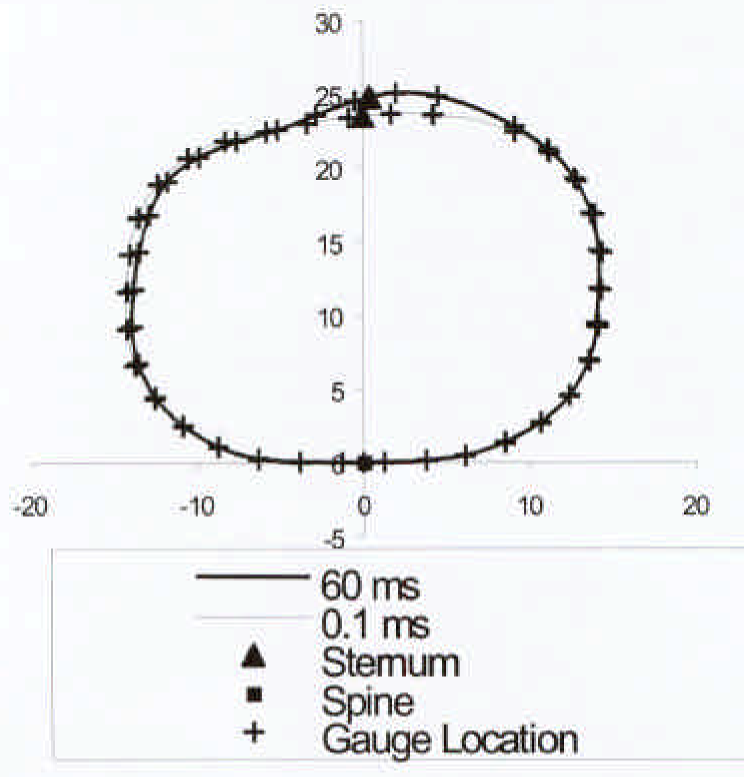


FIG. 3. Chestband contour for sled test. Contour axes are scaled in centimeters. The overlay plots are shown for 0.1 ms and 60 ms after the beginning of the impact. At 60 ms (bold line), the dummy's torso had loaded the shoulder belt which recorded more than 3000 N of tension. The shoulder belt loaded the chest in the area in which the 60 ms contour bulged out.

Investigation Of Chestband Performance

Because ine the cause for the observed contour errors in the dynamic sled test environment, we proceeded with an investigation that involved three series of carefully controlled static tests of chestband performance. The first series of tests used a rigid indentor to compress the chest of either a test dummy or a cadaver test subject. These tests were designed to investigate the 'bulging out" behavior recorded in the sled tests (FIG. 3). The second test series, involving cadaver test subjects, used a simulated roped shoulder belt to approximate the chest loading conditions in a frontal sled test more closely. The third series of tests explored the chestband's ability to accurately map the contours of models of the chest (chest-forms). The chest-forms were constructed in the shape of chest cross sections deformed by shoulder belt loading.

Static Chest Deflection Tests with a Rigid Indentor

Method. Two series of static tests, one with a Hybrid III dummy and one with a cadaver, were conducted to investigate spurious chestband performance. The tests were designed to simulate the normal loading due to a shoulder belt in a 55 km/h frontal crash. A 3.0 cm diameter rigid indentor was used to compress the anterior chest (FIG. 4).

FIG. 4. Rigid indentor test.

The chest was deflected using a 3.0 cm metal cylinder (A) attached to a clamping device. The cylinder was positioned over the upper chestband (B) and immediately to the right of the sternal plate (C). This area is designed to "hinge" in response to compressive chest loads. The upper right string potentiometer attachment point was near the point of deflection.

The first series of static tests was designed to investigate how forcing the chestband to conform to local ribcage irregularities affected chestband contours. We hypothesized that local band curvatures of significant magnitudes that were spaced too closely together to be sufficiently resolved by the 2.5 cm gage spacing of the chestband might cause unreasonable contours.

A chestband was installed directly on the ribcage of a Hybrid III dummy at the level of the second rib. We tried two different schemes that employed spacers or "shims" to fill voids created between the band and the underlying substrate in order to "smooth" the sternum area of the dummy thorax. The system used in the prior sled tests was modified to include additional shims and a one-piece plastic bridge to smooth the transition between the rib and the sternum plate further. This area "hinges" as the thorax is compressed and produces a "valley" into which the chestband can be forced. We suspected that this irregularity was responsible for the inconsistent sled test results.

In addition to testing the effects of the shim systems on the chestband contours, the effects of the position of specific gages relative to the above-mentioned "valley" irregularity were investigated in these tests. We suspected that the gages were spaced too far apart to record sufficient local curvature information. In order to conform to the narrow valley, the chestband exhibited both positive and negative contour in a section that had only one gage (FIG. 5). With each shim system installed on the dummy thorax, the chestband was rotated around the ribcage between installations in order to vary the orientation of a particular gage relative to the "valley".

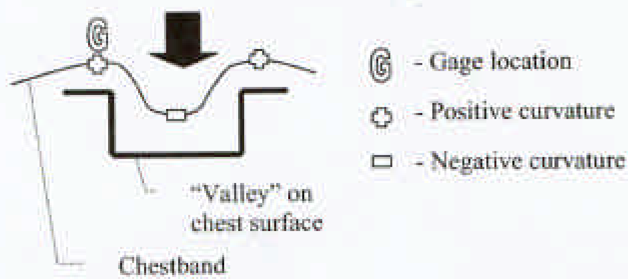


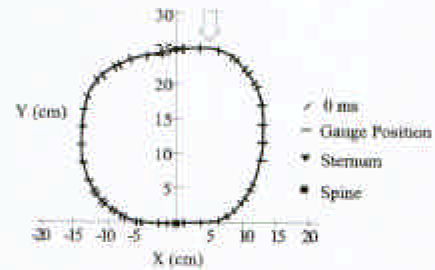
FIG. 5. Chestband forced into "valley" on chest surface. The only gage in this section of the chestband records positive curvature and fails to record the negative curvature in the bottom of the valley.

Results. The shims did not eliminate the "valley" produced at the rib/sternum junction during ribcage compression. The chestband results were sensitive to both the sternal plate/rib hinged junction and the gage locations relative to this feature. When gages were placed on either side of the junction, the contour bulged out where the indentor had pushed in (Test 1, FIG. 6). When a gage was centered under the indentor and over the junction, the resulting contour appeared more believable, but substantially overestimated the actual deflection (Tests 5, FIG. 6). The contours were extremely sensitive to small differences in the location of gages relative to local irregularities. Rotating the chestband around the torso resulted in markedly different contours.

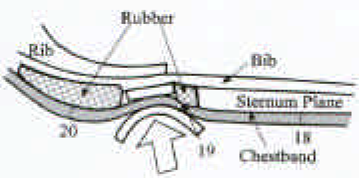
Observations. These tests successfully replicated the "bulging out" behavior seen in prior sled tests (FIG. 3). The results in these tests paralleled those reported by HAGEDORN and PRITZ, (1991) in which a 37-gage chestband was wrapped around a wooden chest-form shaped to simulate deformation due to shoulder belt loading. To investigating the effects of gage spacing, contours were generated using every second gage. The chestband underestimated the actual chest deflection when the gages lay on either side of the depression and overestimated the deflection when a gage was centered in the depression (FIG. 7). The 5 cm gage spacing was too great to resolve the 2.5 cm radius of curvature of the depression. When information from all 37 gages was used, the 2.5 cm gage spacing was sufficient to resolve the actual contour.

In our tests a similar effect occurred, only on a much smaller scale. The chestband was forced into a radius of curvature of 1.5 cm or less. Because the radius of curvature was substantially smaller than the 2.5 cm gage spacing, the 40-gage chestband was not able to resolve the actual contour. It should be noted that the effects of this lack of resolution might not reveal itself as an obvious bulge-out under the shoulder belt. In most cases, the effects will be more subtle, and similar to those seen in FIG. 7. Both the contour from the simulated 16-gage chestband and that from the 37-gage chestband would be plausible results from a cadaver sled test. Without the actual contour provided by the wooden chest-form, it would be difficult to know which contour was accurate.

Chestband Contour:



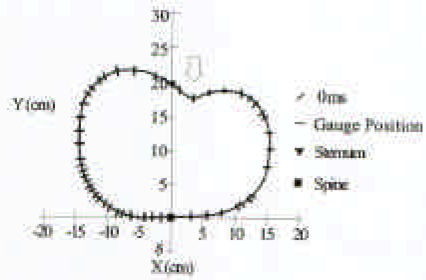
Local Conditions:



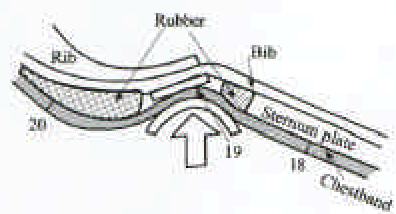
Test Conditions:

Mandrel Diameter:	30 mm
Applied Compression:	13 mm
Measured Rib Deflection:	NM
Chestband Max. Deflection (Est):	+22 mm
String Pot Deflection:	-8 mm

Chestband Contour:



Local Conditions:



Test Conditions:

Mandrel Diameter:	30 mm
Applied Compression:	30 mm
Measured Rib Deflection:	-27 mm
Chestband Max. Deflection (Est):	-52 mm
String Pot Deflection:	-26 mm

FIG. 6. Test conditions and results for the rigid indentor (a) test 1 and (b) test 5.

The drawing shows a top view cross-section of the cylindrical indentor, the chestband and dummy right anterior chest wall. The numbers along the chestband indicate the gage locations. The rubber wedges were added lateral to the sternal plate in order to smooth the substrate over which the chestband was installed. In Test 1, as in the sled test (FIG.3), the contour bulged out where compressive force was applied. In Test 5, the contour overestimated the actual deflection. The arrow on the contour plot indicates the direction of force applied by the cylindrical indentor. "NM" indicates that this parameter was not measured.

Cadaver Test Subject. The second series of static tests involved installing a chestband on a 52 kg male cadaver above the skin and over the junction of the sixth rib with the sternum. The 30 mm diameter rigid indentor used in the Hybrid III dummy tests was used to deflect the chest.

Despite modest deflections ($\leq$ 2.3 cm), the calculated values differed significantly from the measured values (FIG. 8). As in the Hybrid III tests, when the indentor was placed near or directly over a gage, the chestband contour overestimated the actual deflection. When the indentor was placed between gages (FIG. 8, Tests A and B), the program underestimated deflection for Test A and overestimated deflection for Test B. A post-test review of the loading sites suggested that the differences between these tests may have been due to differences in the ribcage underlying the gages.

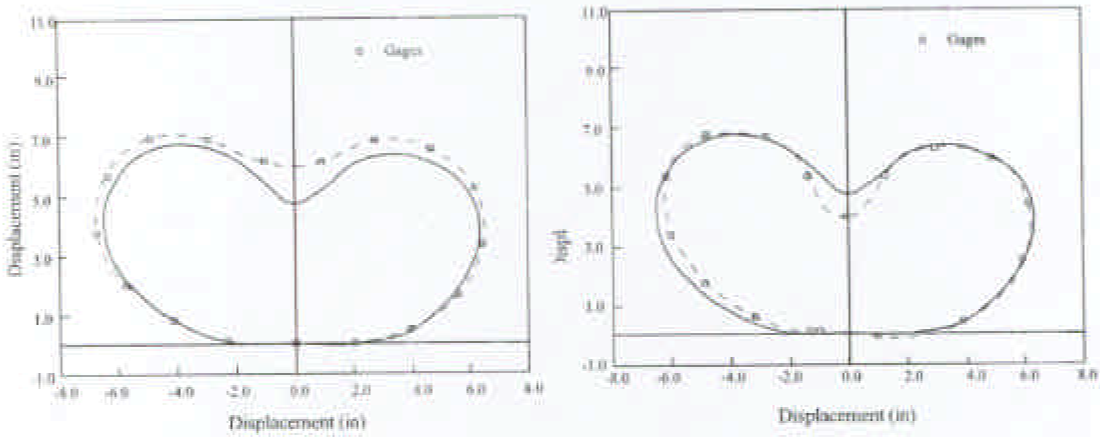


FIG. 7. Hagedorn and Pritz, (1991) wooden chest-form test results. The solid lines represent the outline of the wooden chest-form. The dashed lines represent the outline as calculated using the chestband gage outputs. In the top drawing, gages, depicted as small squares, were positioned on either side of the central depression. In the bottom drawing, a gage was centered over the depression. The simulated 5 cm gage spacing was too great to allow accurate calculation of the chest-form contour.

In the case of Test A, the indentor pressed the chestband into the centerline "valley" between the ribs just below the sternum. In Test B, the indentor was over the right side of the ribcage that had no prominent discontinuities.

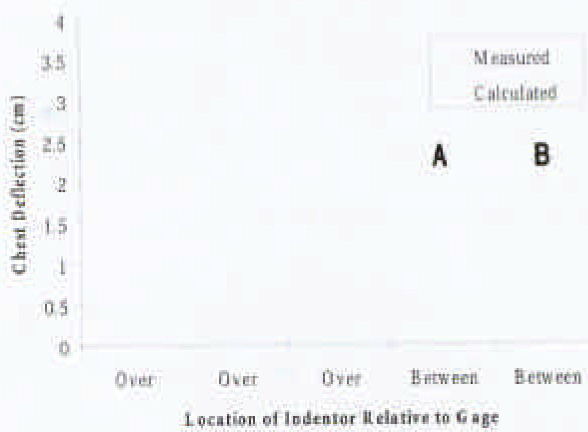


FIG. 8. Rigid indentor test results for cadaver test subject.

In both the dummy and cadaver tests with a rigid indentor, the accuracy of chestband contours was affected by ribcage surface discontinuities and the position of these discontinuities relative to individual gages. These results suggested that the chestband lacked sufficient resolution for this loading condition, which was an approximation of shoulder belt loading in a frontal crash test.

The calculated values were scaled from the chestband contour plots or, in case of centerline deflections, the calculated value was derived from the contour program's reported chest depth value. Estimated error is $\pm$ 0.2 cm for all values.

Static Chest Deflection Tests With a Simulated Roped Shoulder Belt

Method. A series of static tests was conducted with three cadaver test subjects to evaluate both under-and over-the-skin chestband installation. Instead of using a rigid indentor that was used in the previous test series, the chest was loaded with a 2.5 cm wide belt to simulate a roped shoulder belt (FIG. 9). We considered this condition to be a reasonable worst-case scenario for a 55 km/h frontal crash.

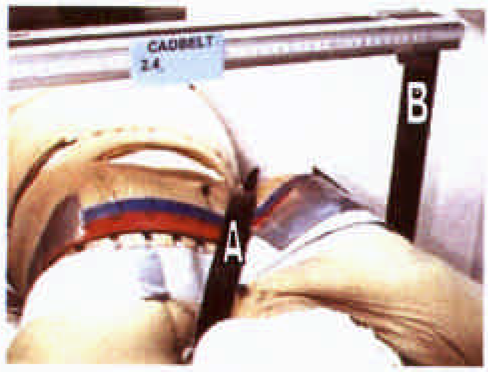


FIG. 9. Roped shoulder belt (A) test setup.

In this view, the subject's head is at the center bottom of the photo. The subject was on his back under a measurement frame (B). The shoulder belt has been tightened via a scissors jack under the support surface to compress the chest 5.2 cm, as measured at the intersection of the shoulder belt centerline and the upper chestband. The scale on the frame above the subject was used to define the laboratory measurement system.

For each test, the belt was tightened in stages. At each of the five stages, we measured the change in position of six gages near the intersection of the belt with chestband relative to the laboratory. The data from the chestband gages was taken prior to the physical deflection measurements. During the time between the data collection and the physical measurements, the chest continued to deflect. For the two in which it was monitored, this deflection or "creep" was no more than 0.2 cm.

Results. Figure 10 summarizes the test condition and results. The calculated deflections underestimated the actual deflection by various amounts (FIG. 10A). For actual deflections less than 5 cm, three of the four tests recorded calculated values that were less than 0.5 cm lower than the actual values. For actual deflections of more than 5 cm, one of the under-the-skin tests indicated calculated values more that 2.5 cm lower than the actual values. Figure 10B presents the results of an above-the-skin test at the level of 4^{th} rib. After the test, we found that a chestband gage malfunctioned near the location of belt loading. We calculated the deflections with and without the faulty gage. This gage provided an inconsistent signal resulting in calculated deflections that varied from the actual value by +3 to –2 cm. After the gage was removed from the chestband calculations, the predicted value was within 1 cm of the actual value.

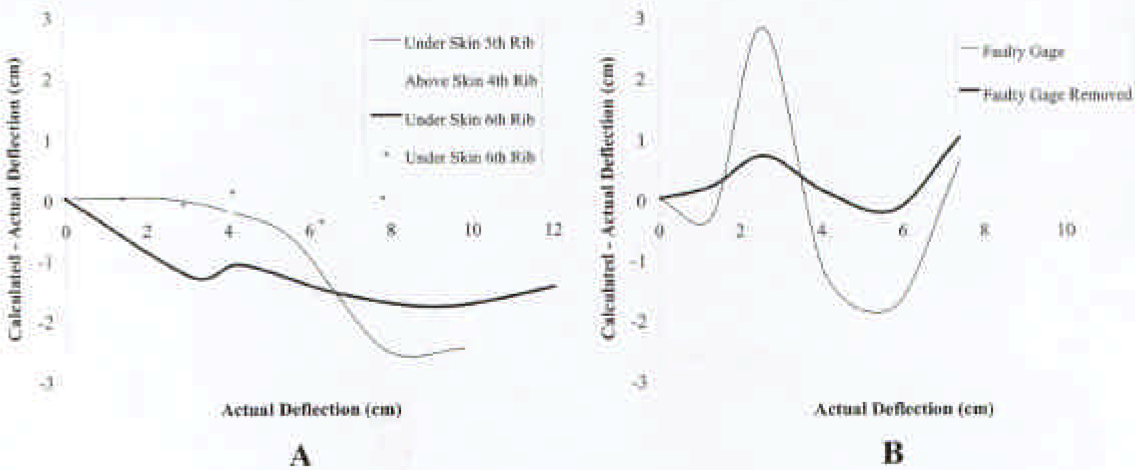


FIG. 10. Roped belt test results.

Negative values indicate that the chestband calculation underestimated the actual chest deflection. Zero values indicate no difference between chestband-calculated and actual deflection. "Under the Skin" and "Above the Skin" describe the chestband installation. The chestbands encircled the chest at the level of the indicated rib and its intersection with the mid-coronal plane. Graph B test conditions included a chestband installed above the skin at the level of the 4th rib. Calculations of chest deflection were made before and after removal of data from a faulty chestband gage.

Observations. The results of these tests suggest that under-the-skin chestband installations do not provide a reliable estimate of chest deflection. The calculated chest deflection deviated substantially from the actual values at the higher deflection levels for the under-the-skin tests. The deviation may have been caused by a combination of sufficient normal force from above (supplied by the belt) and a sufficiently rigid corrugated or hinged substrate (the locally fractured ribcage). We suspect that small chestband radius of curvature (0.6 cm est.), gage placement relative to the point of load application, underlying corrugations, and substrate rigidity combined to produce erroneous chestband results.

Under most conditions, above-skin installations provided reasonably accurate estimates of chest deflection despite the small radii of curvature required of the chestband in the large deflection conditions. The chestband did not demonstrate the obviously aberrant behavior seen in prior Hybrid III tests with the rigid indentor. In most of the tests, the chestband-calculated chest depth agreed will with the actual chest depth under minimal to moderate chest deflection. The greatest differences between calculated and actual values were seen between at the higher deflection levels and with under-the-skin chestband installation. The tests demonstrated the potential for erratic behavior when a faulty gage is in a critical area.

Chest-Form Test

Methods. In order to examine chestband behavior under more controlled conditions, we conducted tests with the chestbands wrapped around a chest-form constructed using nails in a board. The baseline test consisted of wrapping the chestband around nails that were arranged to form the perimeter of a cross section of an undeformed dummy chest. In subsequent tests, the chestband was wrapped around nails that constrained its path to simulate various symmetrical and asymmetrical deflection conditions. A tracing was made of the chestband path and the gage locations. The test procedures were similar to those of tests of early chestband prototypes conducted by Shaibani and Khaewpong (1990). Chest depth, as defined as gage-to-gage distances from the tracings, was compared to those calculated by the chestband processing software.

Results. Table 2 summarizes these tests. In all but test G, the difference between the actual and the calculated chest deflection was less than 1.0 cm. In Test G, a difference of 1.6 cm was recorded. Inspection of the chestband data after this test revealed a gage that produced an unrealistic curvature. When data from this faulty gage was removed from the calculation of the contour for test G, the difference reduced substantially, to 0.2 cm. Differences in tests F, H, and I were also reduced with the removal of the same faulty gage. However, the difference in test E increased when the gage was removed.

Observations. In general, the chestbands performed very well despite high deflection. In one case, a faulty gage, rather than the lack of chestband resolution, was the reason for the large disparity between the actual chest deflection and that calculated from the contours. The minimum radius of chestband curvature was not related to the difference between the actual and the calculated values for the range of curvatures produced by this test condition.

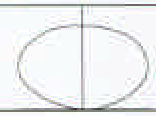
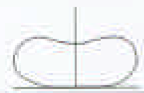
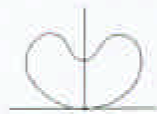
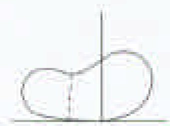
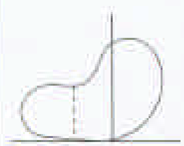
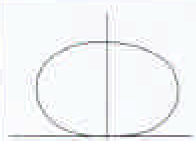
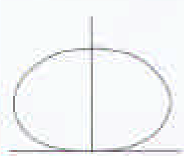
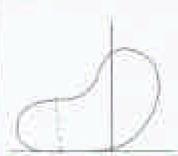
DISCUSSION

The static test results suggest that chestband performance varied widely. Under some conditions, the calculated deflection agreed very well with the actual deflection (Table 1). In the chest-form tests, the chestbands produced accurate chest deflection for rather severe applied deflection (8-9 cm). However, under other conditions, the accuracy of the calculated deflection was compromised. The results of the Simulated Roped Belt tests indicated that accuracy suffered for applied deflection exceeding 5 cm. Only 1.3 cm of applied deflection was required to produce erroneous results in the Rigid Indentor test (FIG. 6, Test 1). We attributed the inaccurate calculated deflection values to two factors, insufficient chestband resolution and faulty gages.

Table 1. Test Conditions And The Accuracy Of Calculated Deflection

Accurate Calculated Deflections	Inaccurate Calculated Deflections
Less than 5 cm deflection	Greater than 5 cm deflection
Less than 9 cm deflection	Under-the-skin chestband
Simulated Roped Shoulder Belt Test	Simulated Roped Shoulder Belt Test
Chest-form Test	Rigid Indentor Test (Dummy and Cadaver)
	Simulated Roped Shoulder Belt Test

Table 2. Chestband Deflection Results In Tests Using A Chest-Form

	Test Description		Actual Chest Deflection[b] cm	Calculated Chest Deflection[c] cm	Calculated Chest Deflection After Removal of Suspect Gage cm
A	Undeflected [a] Condition Actual chest depth 19.0 cm		0	0.3	-
B	Symmetrical loading on centerline. 5.6 cm min. radius of curvature.		-8.0	-7.7	-
C	Symmetrical loading on centerline 2.4 cm min. radius of curvature.		-8.0	-7.7	-
D	Asymmetrical loading. 4.7 cm min. radius of curvature.		-8.1	-7.2	-
E	Asymmetrical loading. 4.5 cm min. radius of curvature.		-8.4	-8.8	-7.6
F	Undeflected Condition Actual chest dept 19.3 cm		0	-0.6	0.2
G	Asymmetrical loading. 3.4 cm min. radius of curvature.		-9.0	-10.6	-8.8
H	Undeflected Condition Actual chest dept 19.3 cm		0	0.3	0.2
I	Asymmetrical loading. 4.1 cm min. radius of curvature.		-8.7	-8.2	-8.6

Notes:

- **Undeflected Chest Depth** is the distance from the spine gage to the gage nearest the sternum before deflection occurs. Chest deflection was taken at the location where the greatest change in chest depth in comparison to the non-deformed chest has occurred. In these tests, this location was within 10 cm of the non-deformed contour centerline. In Tests D, E G, and I, the dashed line indicates where the chest deflection measurements were taken. For the other tests, the deflection measurements were taken along the vertical axis.
- The **actual chest deflection** is the physically measured displacement along the vertical axis of an identified gage on the anterior aspect of the chest. Negative values indicate movement toward the spine.
- The **calculated chest deflection** is the displacement along the vertical axis of an identified gage on the anterior aspect of the chest derived from the chestband contour algorithm.

Insufficient Chestband Resolution. The chestband did not have gages spaced sufficiently close to resolve the features and the discontinuities of the subjects' chests. The radius of curvature of the chestband under the belt in one of the Simulated Roped Belt tests was only 0.6 cm, much less than the 2.5 cm gage spacing was capable of resolving. Accuracy was lower in the Rigid Indentor and the Roped Belt tests in which the chestband was installed directly over the ribcage (under the skin). Normal loading of the rigid indentor or roped shoulder belt deformed the chestband over abrupt ribcage surface discontinuities. Evidence of insufficient gage spacing was provided by the rigid indentor tests in which the gages were shifted relative to the position of the indentor. The results of our tests and conclusions drawn from them were similar to those reported by Hagedorn and Pritz, (1991).

Faulty Gages. Although the test results pointed strongly to the lack of chestband resolution as the limiting factor, we discovered that the malfunctioning of a gage or gages could affect the contour in a matter similar to that of a lack of resolution. Faulty gages and their affects were demonstrated by tests conducted with the roped shoulder belt and the chest-form.

The most obvious effect of a gage that has catastrophically failed during an event is reduced resolution due to a doubling in distance between active gages. If the gage failure occurs at a critical point along the contour, such as under or near the shoulder belt, the calculated contour usually underestimates the actual decrease in chest depth. In some cases, gage failure is easy to detect by conducting a pre-test gage assessment or, post-test, by looking for gage time-history traces that suddenly exceed the full scale of the gage. Unfortunately, we have found that gages can appear to be operating correctly but produce signals that produce errors in the contours (FIG. 11). Without an independent means of verifying the contour, subtle errors, such as a reduced peak chest deflection, are very difficult to identify.

Gage failures are a common problem at UVA and at other laboratories (Hagedorn and Pritz, 1991; Yoganandan, 1999). According to the chestband manufacturer, Robert A. Denton, Inc., (1999), the primary cause of faulty gages is partial or total separation of the multi-strand wire that connects the gages to the flexible circuit board (FIG. 1). This failure mode can result in intermittent gage operation and can change the apparent gage resistance. Flexing the chestband in the area of a total break of the connecting wire can make the gage appear to be operational in one position and faulty in another. In the case of a partial break, flexing causes individual wire strands to separate resulting in an increase in resistance in the connection from the gage to the circuit board and may produce a signal with an intermittent offset. Because there is no abrupt over-ranging of the signal, as would be seen in the case of the total wire break, identifying a partial break during a test is very difficult.

Other failure modes, such as the gage separating from the metal band due to adhesive failure, or physical damage to the gage itself, are reported by the manufacturer to be much less common. However, Denton staff reported that UVA chestbands needing repair had a permanent deformation of the metal band.

The estimated limits relative to the minimum radius of chestband curvature and resulting chestband elongation are summarized in Table 3. According to a prominent warning in the original chestband users manual published by Shaibani (1990), the chestband may be damaged if it is forced into a radius of curvature of less than 7.6 cm.

Figure 12 (FIG. 12) summarizes the results of a retrospective study of the minimum radius of curvature calculated by the chestbands during selected sled tests with cadaver and Hybrid III dummy subjects. The estimated curvature and elongation limits suggest that many of the 55 km/h frontal impacts conducted at UVA have been severe enough to damage the chestbands.

However, the chest-form test results indicate that the estimated minimum radius of curvature limits may be too conservative. Chest-form tests C and G produced radii of curvature of 2.4 and 3.4 cm respectively. A radius of 2.4 cm corresponds to chestband elongation that may damage the metal band (Table 3). A radius of 3.4 cm is smaller than that suggested as a lower limit by Shaibani, (1990). Nevertheless, the calculated deflection for both of the chest-form tests was within 0.3 cm of the actual deflection. The chestbands appeared to be unaffected by smaller-than-recommended radii of curvature in these tests. This result suggests that we do not fully understand the effects of radius of curvature on chestband performance.

The finding that both the lack of chestband resolution and malfunctioning gages can produce similar errors in the contour compounds the problem of evaluating the validity of chestband data. Evidence from past tests indicates that failed or failing gages are quite common. Although we attempted to eliminate obviously bad gages in the course of our static chestband testing, some of the effects attributed to lack of resolution may also have been due to malfunctioning gages.

Table 3. Chestband Performance Limits Relative To Minimum Radius Of Curvature

Radius of Curvature cm (in)	Approx. Stress in band [A] kPa (kpsi)	Chestband Elongation [A] %	Comment
7.6 (3)	345 (50)	0.17	Minimum diameter specified in Shaibani (1990). Minimum mandrill radius for calibration tests.
5.1 (2)	517 (75)	0.25	
2.5 (1)	1034 (150)	0.50	Approximate yield point for the steel band within the chestband.
1.9 (0.75)	1379 (200)	0.67	
1.3 (0.5)	2068 (300)	1.0	Minimum diameter of wooden chest form contour used in Hagedorn and Pritz, (1991). Seen in Hybrid III belted sled tests by Hagedorn, (1993). Good results with simulated belt of same diameter in static tests above skin.
0.6 (0.25)	4136 (600)	2.0	The estimated minimum radius of curvature recorded by UVA in static roped belt tests with cadaver subjects.

Notes:
A – Assumes present steel band thickness of 0.0254 cm (0.010").

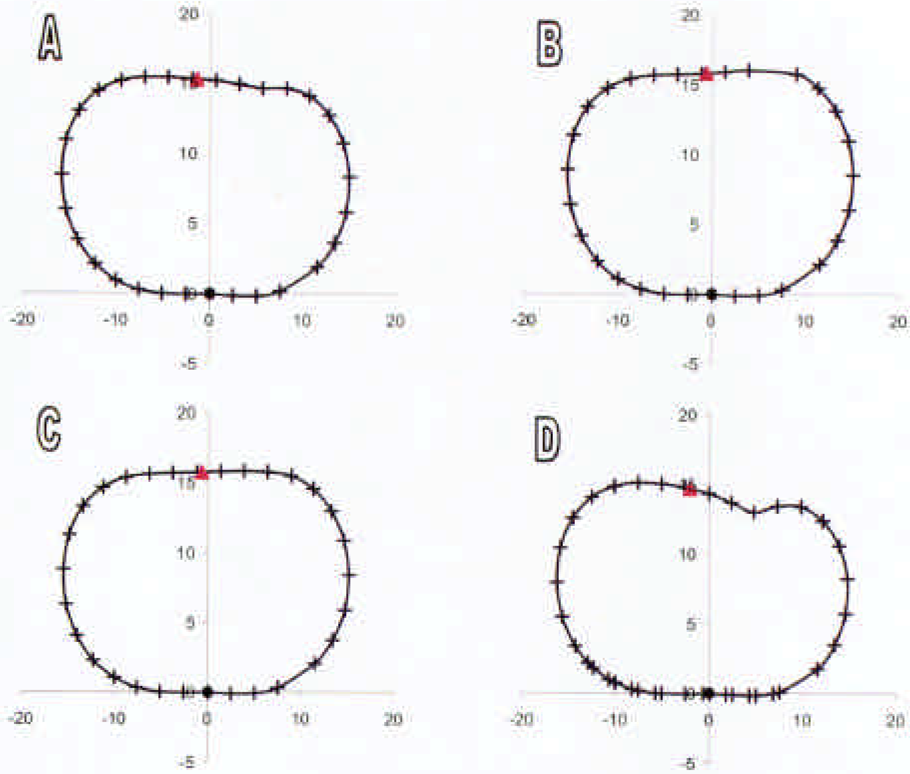


FIG. 11. Chest-form results showing the effects of a sporadically faulty gage.

Contour axes are scaled in centimeters. The triangles indicate the location of the simulated sternum. The crosses indicate gage locations.

A – The chest-form was symmetrical. Note the slight "bump" in the calculated contour's upper right quadrant.

B – Post-test analysis made us suspicious of gage # 22 that had not given indication of malfunction in pre-test evaluations. This gage, located near the "bump" was removed from the calculation of the contour. The contour closely matched that of the chest-form.

C – The chest-form test was repeated and data was retaken. As in (B), the contour was accurate. Although gage #22 was included in the calculation, it did not adversely affect the contour as it did in (A).

D - The chest-form test was repeated and data was taken for a third time. As in (A) gage #22 was included in the calculation and adversely affected the contour.

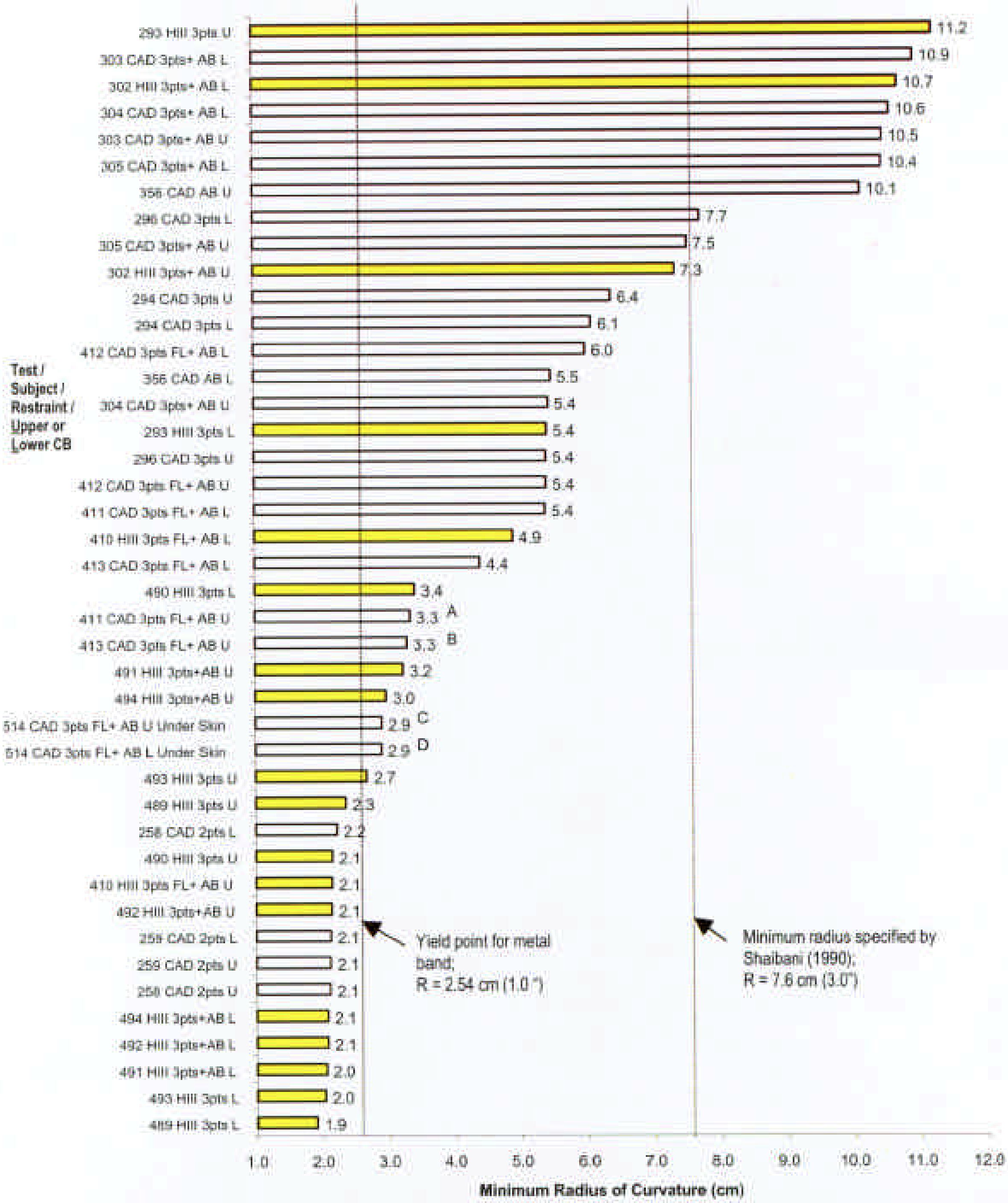


FIG. 12. Review of minimum radius of curvature for chestbands in UVA 55 km/h frontal sled tests. The sled tests included a variety of restraint conditions and were conducted with both the Hybrid III 50th percentile male dummy and with cadaver test subjects seated in the driver's position.

Notes: A - Due to a bad gauge near the spine. B- Force limited belt failed. 8 kN upper shoulder belt load. Possible bad gage. C- Worst case for cadaver test with a 3-pt. belt. Unusually high number of rib fractures. D - Due to a bad gage near the spine. Cadaver tests in white, Hybrid III tests in gray. **Abbreviations**: HIII – Hybrid III 50th percentile male dummy. CAD – Cadaver test subject. 3pts – 3 point belt system. 2pts – Shoulder belt only. FL – Force limited belt system. U – Upper chestband. L – Lower chestband. AB – Air bag. The numbers identify UVA sled tests.

SUMMARY FINDINGS

The static tests of chestband performance and the subsequent investigation of chestband radius of curvature limits produced the following findings:

1) Inaccuracies in calculated chestband contours and deflection values are a product of two factors, insufficient chestband resolution and faulty gages. These factors can have a similar and compounding effect on accuracy

2) Chestband accuracy was affected by ribcage surface discontinuities and the position of individual gages relative to these features. Accuracy generally was poorer when the chestbands were installed in direct contact with the ribcage. Without the smoothing effect of the skin, the chestband was forced to conform to surface features with radii of curvature too small to be resolved by the gage spacing.

3) Gage failures are common. It is difficult to identify a gage or gages responsible for subtle or transitory errors.

4) Evaluating the accuracy of calculated deflections is difficult without an independent means of verification.

5) Frontal sled tests using shoulder belt restraints may produce chest contours with radii of curvature small enough to damage the chestband. Chestband performance limits are not well understood.

CONCLUSIONS AND RECOMMENDATIONS

The chestband is currently the only viable instrument capable of measuring chest deflection in dynamic tests with cadavers and it has proved quite accurate under some test conditions. However, this study and studies conducted at other laboratories have identified test conditions under which the chestband produced erroneous contours. Research is required to understand fully the chestband's capabilities and failure modes. Improvements are needed in chestband durability and resolution. The following efforts should be undertaken.

Diagnostic tools should be developed to enable the rigorous validation of a chestband before a test, including identifying gages that are bad, going bad, or that may go bad during a test.

A post-test diagnostic tool is required to identify errors in the calculated contour due to bad gages and/or the lack of sufficient gage density to resolve surface discontinuities.

Strategies should be investigated to improve chestband resolution.

Chestbands should be reengineered to withstand the deformations commonly seen in frontal sled tests. Existing design parameters, materials, and manufacturing techniques produce a product that is too fragile and costly to repair.

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