Application of a Deformation Measurement System to Biomechanical Systems

Alena V. Hagedorn	Transportation Research Center of Ohio East Liberty, Ohio USA
Rolf H. Eppinger Richard M. Morgan Howard B. Pritz	National Highway Traffic Safety Administration U. S. Department of Transportation Washington, DC USA
Nopporn Khaewpong	Chi Associates, Inc. Arlington, VA USA

INTRODUCTION

The External Peripheral Instrument for Deformation Measurement (EPIDM) -- commonly called chest band -- consists of a series of strain gages mounted on a metal strip covered by a urethane material to protect the strain gages [1][1]. Were the chest band to be wrapped around a deformable body, such as the thorax of a test dummy or human cadaver, these strain gages measure the curvature at their spatial location along the band. Using these curvature versus time signals, along with the location of the gages relative to the thorax, an analytical reconstruction of the cross-sectional shape of the thorax can be computed.

The purpose of this paper is to discuss the continual development of the chest band. To be specific, this paper will (1) give the status of a personal computer (PC) program which performs the analysis of the chest band signals and (2) examine the relation between gage density -- number of strain gages per inch along the chest band -- and error for thoracic impact.

PERSONAL COMPUTER PROGRAM TO PERFORM ANALYSIS

The chest band is both a sensing device and an analytical process.

Figure 1 illustrates the chest band process. The chest band is wrapped around the boundary of a body, e. g., the thorax. For classical beam theory, there is a relationship between curvature and strain [2]. The curvature signals generated by the chest band are processed by an analytical process, i. e., the curvature signals are analyzed by a PC computer program called RBAND_PC.

We will briefly review the analytical procedure discussed in Reference 1. For a closed plane curve, the location of any point along the curve may be specified by the arc length, s, as shown in Figure 2. The arc length is specified relative to an origin

[1] The number in brackets refers to the references at the end of the paper.

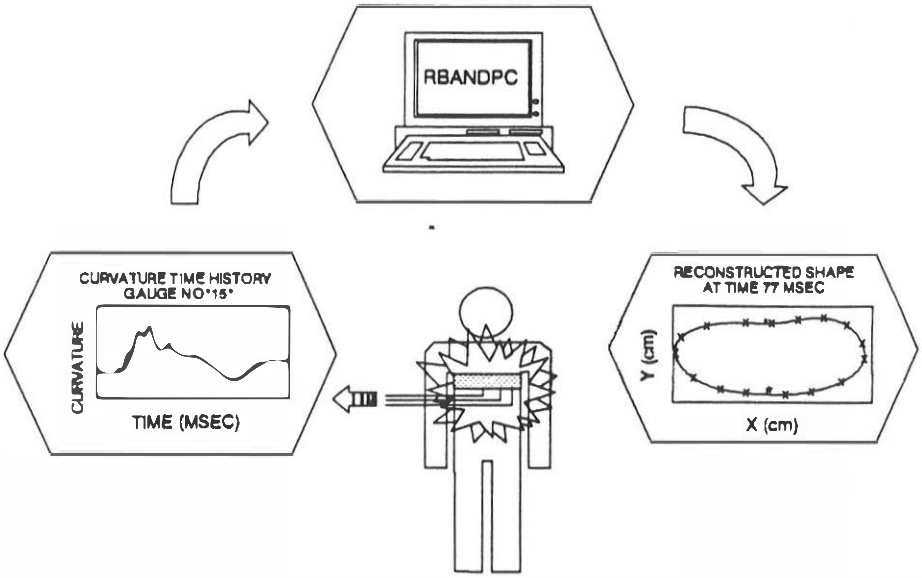
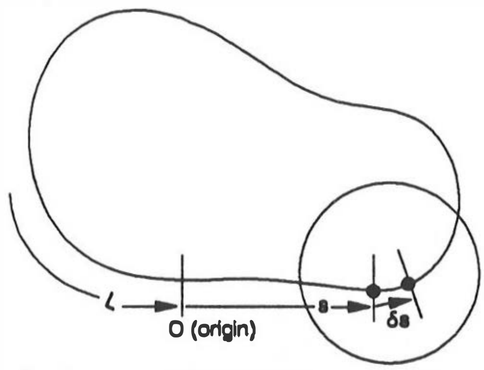


Figure 1 - Chest band process



Coordinate system along closed curve of length "L"

Figure 2 - Arc length of curve

which is indicated by zero. A small increment of the arc length is represented by δs.

The curvature at any point along the arc length may be established as follows. Look at δs in Figure 3. In Figure 3, let s(P) be a specific point along the arc length with a tangent to the curve at that point as shown. Let s(P) + δs be a neighboring point on the curve with a different tangent vector. Then $\delta\Phi$ is the angle through which the tangent vector turns when one moves along the plane curve from s(P) to s(P) + δs. The angle $\delta\Phi$ is to be measured in radians. The ratio $\delta\Phi / \delta s$ describes the average variation in direction of the curve along a unit of arc length. As δs approaches zero, the proportion $\delta\Phi / \delta s$ becomes the derivative of Φ with respect to s. The derivative of Φ with respect to s is called the curvature, K, of the curve at the point s(P). The curvature is

$$K = d\Phi/ds.$$

The chest band is a closed curve. Initially, the tangent vector on the chest band has an orientation of zero radians. As the "tangent vector goes around the chest band," the angle Φ goes through an assortment of values which could be constantly recorded. However much the tangent vector turns in a clockwise or counterclockwise direction, the final value of Φ must be $\pm 2\pi$ radians.

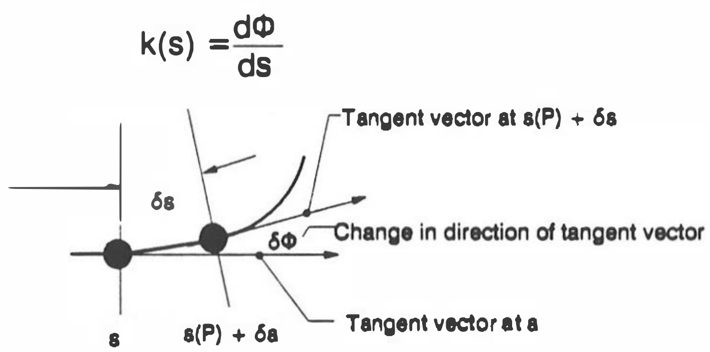


Figure 3 - Determination of curvature at location "s"

The curvature at any point may be compared to the angle Φ where it is traced through the relation $d\Phi = K\, ds$. Figure 4 represents a hypothetical variation of the curvature as one moves along the chest band from zero to the total chest band length L. The area under the curvature and between the points s(P) and s(P) + δs is a rectilinear figure (or shape). The change in Φ is represented by this rectilinear area, or

$$d\Phi = \int_{s(P)}^{s(P) + \delta s} K \, ds.$$

The total change in angle as one move from s = 0 to s = L is 2π. If the integration of the curvature over the total arc length does not equal 2π, then an error term (correction factor) is added to K(s) until the integral is equal to 2π.

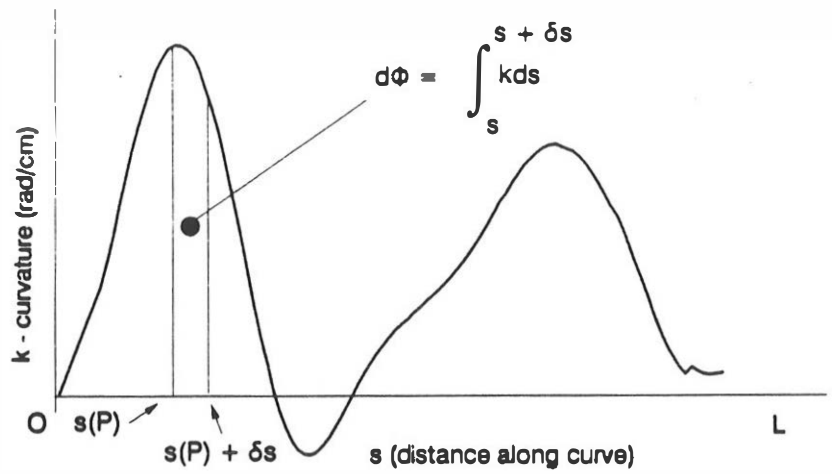


Figure 4 - Closed curve characterized by k-s method

This discussion treats the curvature, K(s), as having continuous values all along the arc length from s = 0 to s = L. In the laboratory, the curvature is measured at certain discrete points as shown in Figure 5 for a 16 gage chest band. For the computer to treat K(s) as a continuous function, many intermediate discrete values must be generated between each physical strain gage location on the chest band. The intermediate values of K(s) are computed by an interpolative approximation cubic spline algorithm.

All the discussion has taken place in a space defined by an s and Φ coordinate system. One can transform to the more familiar x and y coordinate system. For a closed curve in the rectilinear coordinate system, the first and last point should be one and the same, i. e., the location of s = 0 and s = L along the chest band should be identical because the chest band is a closed curve once the band is wrapped around a thorax. If the first and last point are not identical -- and the curve did not obtain closure -- then a further adjustment on the interpolated curvature is needed. This is done by adding a correction factor of the form

$$k_x \cos(2\pi s/L) + k_y \sin(2\pi s/L)$$

to the curvature, K. The coefficients k_x and k_y are determined by an optimization subroutine. Values of k_x and k_y are found which make the first and last points concomitant. Since the integral of this correction factor with respect to s from $s = 0$ to $s = L$ is zero, the integral of the curvature remains equal to 2π.

In short, these are the analytical steps which RBAND_PC performs.

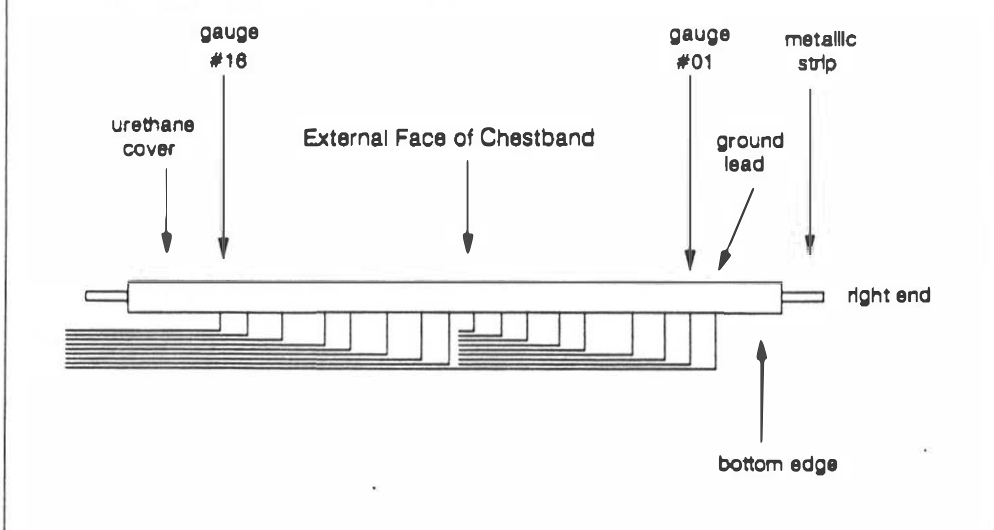


Figure 5 - Physical chest band

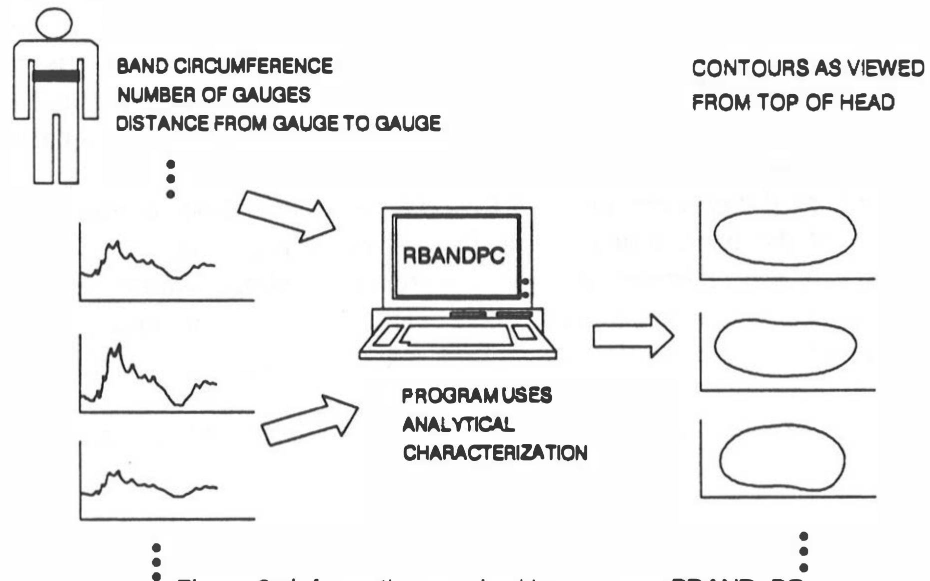


Figure 6 - Information required by program RBAND_PC

The RBAND _PC program requires certain information as shown in Figure 6. This information is furnished to the RBAND _PC computer program. The production of RBAND _PC is a series of thoracic contour plots over the time period of the impact. The orientation is such that the contours are viewed as from the top of the head looking downwards (looking from the superior to the inferior direction).

In the way of ancillary information about RBAND _PC, the object code is available on floppy disks. RBAND _PC runs on "Intel 286," "Intel 386," and "Intel 486" personal computers (PCs). The graphics for RBAND _PC run on a number of popular monitors and printers. We can alter RBAND _PC for other monitors and printers. There is a users manual for the RBAND _PC program. We designed RBAND _PC to be "user friendly." For example, input may be entirely through files or else through a combination of keyboard and file.

ACCURACY OF THE CHEST BAND

Laboratory experiments were performed with a 16 gage chest band -- illustrated in Figure 5 -- and with a 37 gage chest band. The 37 gage chest band had a strain gage bridge positioned every 2.54 centimeters for 91.5 centimeters. A series of tests were performed using both the 16 gage band and the 37 gage band so that the two bands could be directly compared in static and dynamic tests. These included tests with a wooden form (similar in shape to a deformed dummy thorax), a Hybrid III dummy thorax in a quasi-static testing machine, and a Hybrid III in a 3 point belt restraint on a sled.

Tests with a Wooden Form

Each gage was wrapped around a wooden form of known shape. A predicted shape was then mathematically created from the strain gage information. The wooden form contains both positive and negative curvatures with the smallest radius of curvature of roughly 2.54 centimeters at the bottom of a dip.

A 37 gage chest band was wrapped around the wooden form. The wooden form has a circumference of 87 centimeters. Gages 1 through 35 are used in this analysis because the circumference of the wooden form does not allow the use of the last two gages. The band was then moved 0.64 centimeters clockwise from its initial position and a reading of all the curvature gages was taken. The contour -- based on the nominal 35 gages -- was computed.

Two additional readings were taken following successive 0.64 centimeter clockwise movements of the band along the surface of the form. Only four readings were taken at 0.64 centimeter increments since additional readings would be repetitive due to the 2.54 centimeter spacing between gages. The resulting contours produced by the chest band at each of these orientations are shown in Figure 7. The overlays at 0, 0.64, 1.28, and 1.92 centimeters "clockwise band rotation" suggest that the 37 gage chest band accurately measures the shape and is independent of position along the surface of the form.

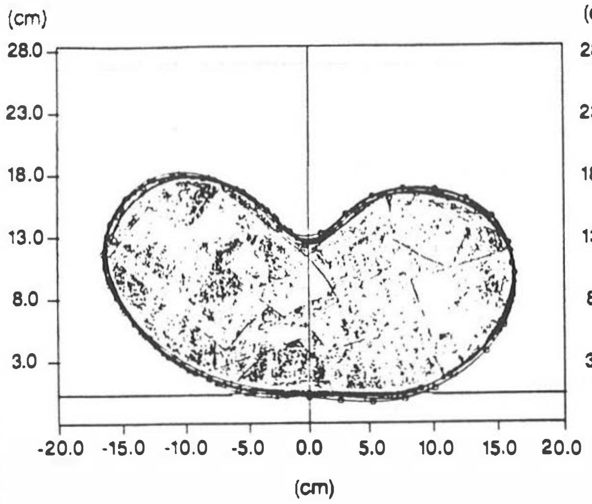


Figure 7 - 37 gauge band overlays

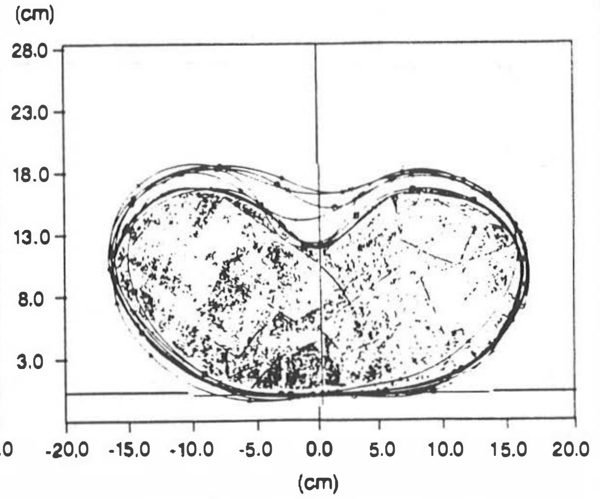


Figure 8 - 16 gauge band overlays

The same protocol was performed using the physical 16 gage chest band [1]. That is, the same initial position and three 0.64 centimeter increment movements were used as in the previous experiment. Additional orientations were used at 2.54 centimeters and 3.8 centimeters since the gage spacing on the 16 gage chest band ranges from 5.1 to 8.9 centimeters. The graphical representation of these 6 orientations along with the overlay of the actual shape are shown in Figure 8.

The graphical representations in Figure 8 reveal the adverse affect that fewer gages -- and therefore greater spacing between gages -- has on the analytically generated shape. The physical 16 gage chest band does not correctly generate the "thoracic like shape" of the form. Important surface areas of the form -- with a small radius of curvature -- are missed due to the greater spacing between gages.

There is a fine point to be made about these experiments. Physical experiments were done using actual 16 gage and 37 gage chest bands. However, the process for the 37 gage chest band contains the information needed to replicate the performance of a 16 gage chest band. Were one to pick out the subset of the 37 strain gage locations which are proximal to the 16 gage chest band locations, then one would have 16 curvature signals from the 37 gage chest band. These 16 curvature signals will give an excellent approximation of how the 16 gage chest band of Figure 5 would perform. Naturally, one could choose any subset of n strain gage locations from the 37 gage chest band. The analytical reconstruction would give an exact indication of how a n gage chest band would perform where n is < 37.

If the 37 gage chest band accurately reproduces the "thoracic like form" and the 16 gage chest band does not, one might ask if there is a minimal number of gages, n, which will just recreate the "thoracic like form." Using subsets of the 37 gage chest band curvature signals, we found that the 24 gage chest band shown in Figure 9 would recreate the form as in Figure 10. Looking at Figure 9, it can be seen that the approach is to position a high density (gages per length of about one gage every 2.54 centimeters) of gages about the surface which has -- or will have -- the smaller radii of curvature. Various tests using gage spacings greater than 2.54 centimeters in this region (smaller radii of curvature) more or less gave results similar to the unacceptable performance shown in Figure 8. The rest of the chest band has about one gage every 5.1 centimeters which is adequate to maintain an acceptable contour reconstruction.

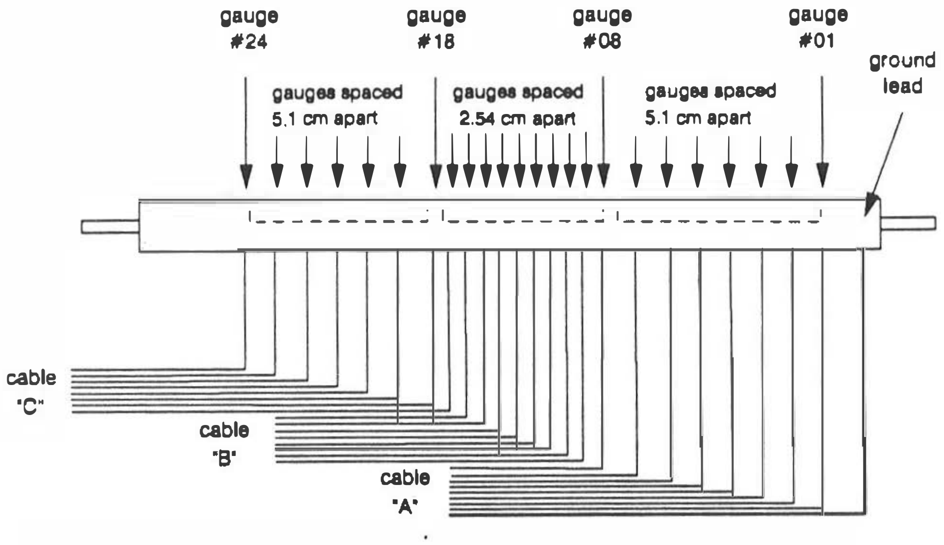


Figure 9

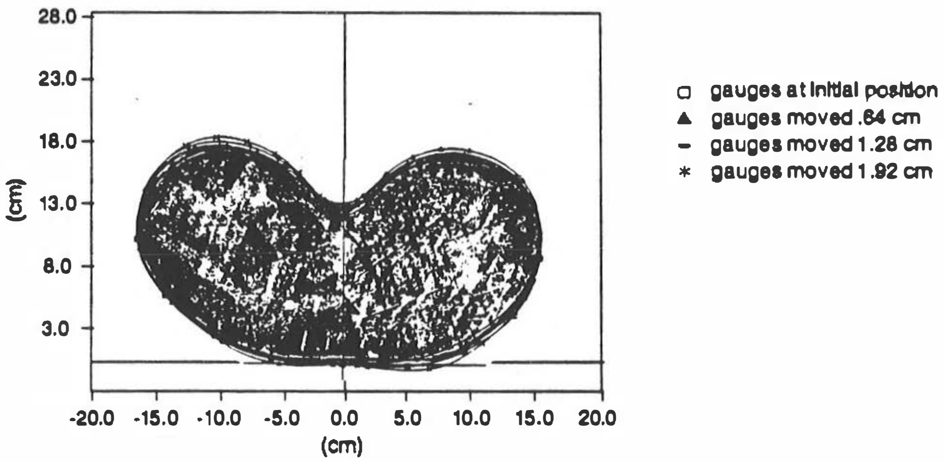


Figure 10 - 24 gauge band

Crush Tests with a Dummy Thorax

A Hybrid III dummy thorax was positioned under a quasi-static testing machine (Instron) such that the thorax of the dummy could be slowly compressed. A 15 centimeter flat plate -- slightly rounded at the edges -- pushed on the thorax. A chest band was wrapped around the thorax and secured with a hook and loop fastener (Velcro like) so that the thorax edge was visible. A camera filmed each test so that the band's shape could be determined at any time interval for comparison with the mathematically produced shapes calculated from the chest band gages.

The crush test with the Hybrid III thorax was physically performed using both the 16 gage and the 37 gage chest band. The contours for these thorax contours are oriented in the following manner. The spine is at the origin while the middle of the sternum is positioned on the y-axis. Overlays of the actual shape were obtained from film by tracing the band's shape at the appropriate time. These tracings were scaled to compare with (match) the analytically produced plots.

In Figures 11 and 12 it can be seen that the physical 16 gage chest band does not mimic the motion of the Hybrid III thorax as it is slowly compressed.

When the compression test is conducted with the 37 gage chest band, the analytical process reproduces the actual band shape as illustrated in Figures 13 and 14. Again, the 37 gage chest band does an admirable job while the 16 gage chest band is shown to be wanting.

Using the curvature signals from a 24 gage subset of the 37 gages, we found it was possible to create the actual thoracic band shape as shown in Figures 15 and 16. The 24 gage configuration used was that in Figure 9, a greater density of strain gages in the vicinity of the expected smaller radii of curvature and a constant but lesser density where the radii of curvature are not expected to be as small.

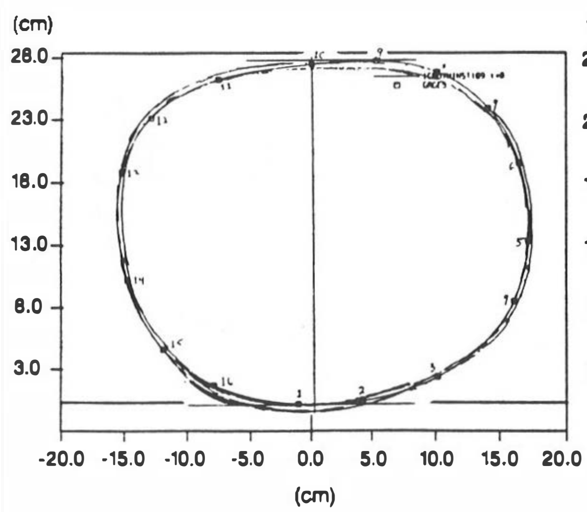


Figure 11 - 16 gauge band T = 0 sec

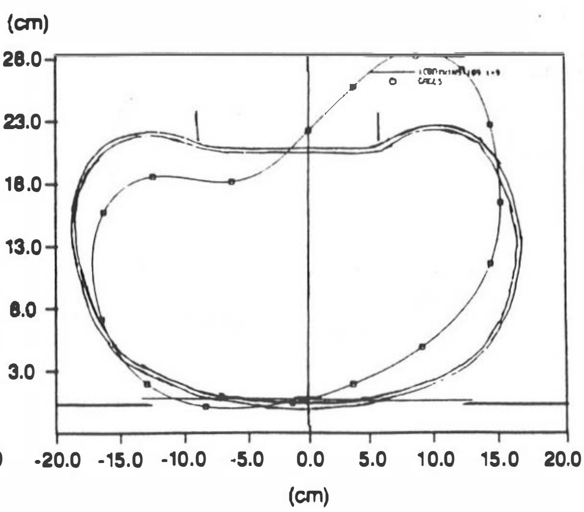


Figure 12 - 16 gauge band T = 9 sec

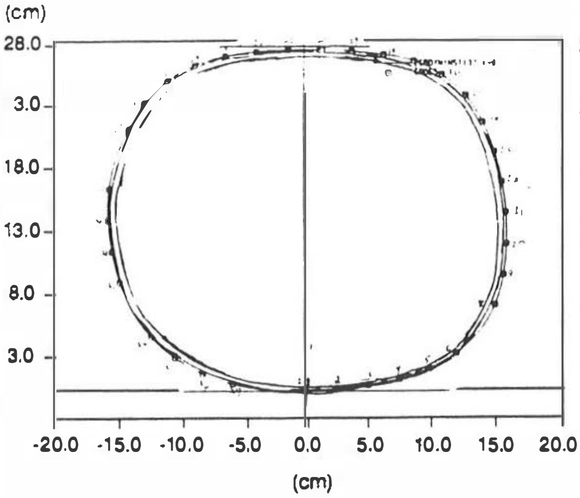


Figure 13 - 37 gauge band T = 0 sec

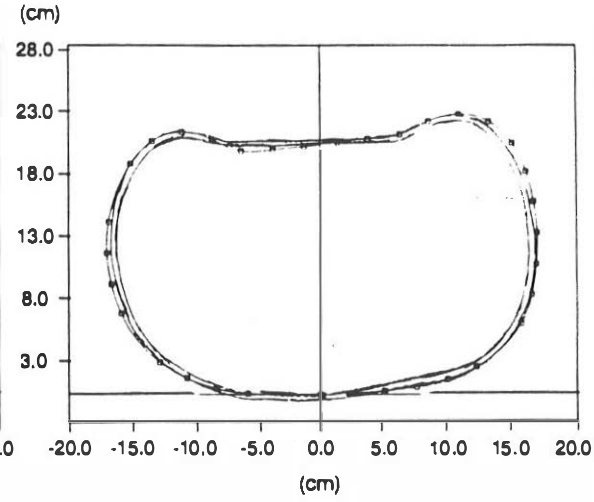


Figure 14 - 37 gauge band T = 9 sec

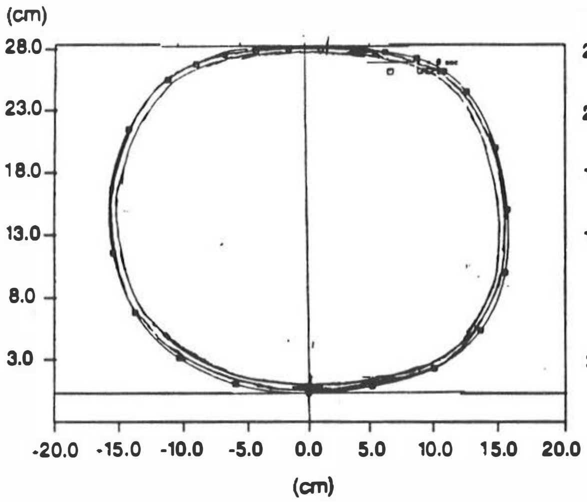


Figure 15 - 24 gauge band T = 0 sec

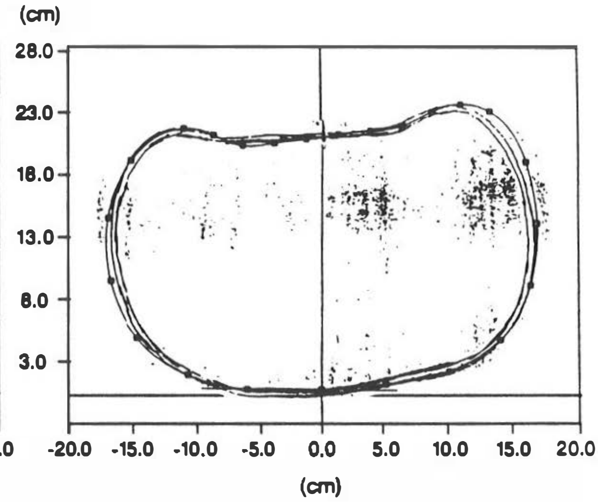


Figure 16 - 24 gauge band T = 9 sec

Sled Tests with 3 Point Belt Restraint

Three sled tests were performed with the 16 gage and 37 gage chest bands enfolded around a Hybrid III dummy restrained by a 3 point belt restraint. The belt was configured like a driver's side restraint. The sled pulse for these three tests had a 54.4 km/hr change of velocity and 30 G's maximum acceleration. The 37 gage chest band was wrapped around the thorax jacket of the Hybrid III dummy close on the third rib level. The 16 gage chest band was positioned lower at approximately the fifth rib level. The spacing between the two bands was about 1.27 centimeters.

For these three sled tests, a direct comparison between the two physical chest bands is not possible using this setup because the bands are not at the same location on the chest. Since a shoulder belt crosses the thorax diagonally, the major deflection areas of each band will not be at the same location, and therefore an overlay of each of these bands cannot be directly compared. We assume the deflection magnitudes should be similar, and therefore, a determination of the relative performance of each chest band is possible through plot overlays.

The 37 gage chest band exhibits a high degree of repeatability throughout the duration of the sled tests. Overlays of the 37 gage chest band in the three sled tests -- at times 0 and 75 milliseconds during the sled tests -- are shown in Figures 17 and 18. (Recall that the contours are viewed as from the superior to the inferior direction.) Similarly, the same three overlays are shown in Figures 19 and 20 for the 16 gage chestband. The 16 gage chest band does not offer a degree of repeatability similar to that of the 37 gage chestband.

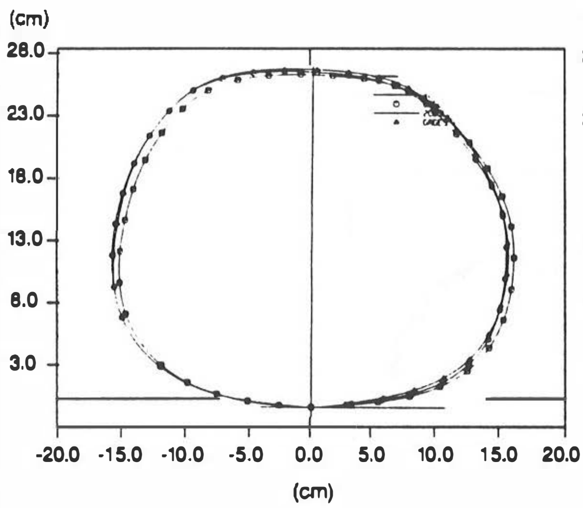


Figure 17 - 37 gauge band Sled Runs 1,2,3
T = 0 sec

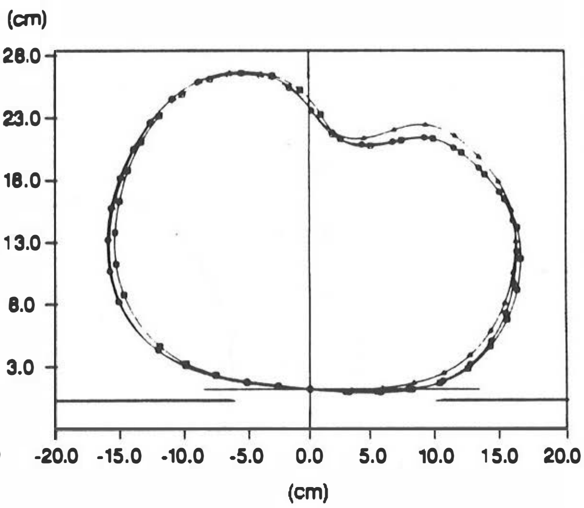


Figure 18 - 37 gauge band Sled Runs 1,2,3
T = .075 sec

A 24 gage subset of the 37 gage chest band was chosen to represent the 24 gage chest band of Figure 9. The contours at near maximum deformation for the 24 gage and the 37 gage chest bands are exhibited in Figure 21. The higher density portion (of our selection of 24 gages) was aligned with the surface where a smaller radius of curvature might be expected. The 24 gage chest band can be seen (in Figure 21) to have a sufficient information content to reproduce the same contour as the entire 37 gage chest band. Figure 21 is for one of the 3 point belt restrained sled runs, but the same similitude (of the 24 and 37 gage chest band contours) emerged when this process was applied to the other two 3 point belt sled runs.

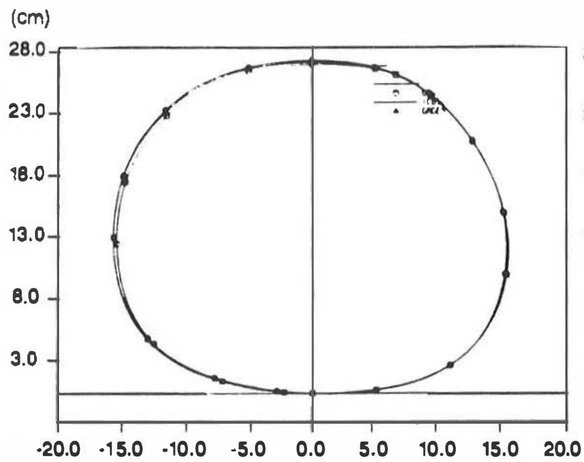


Figure 19 - 16 gauge band Sled Runs 1,2,3
T = 0 sec

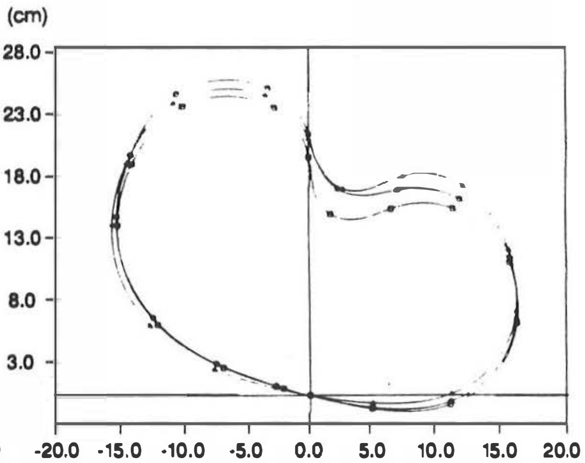


Figure 20 - 16 gauge band Sled Runs 1,2,3
T = .075 sec

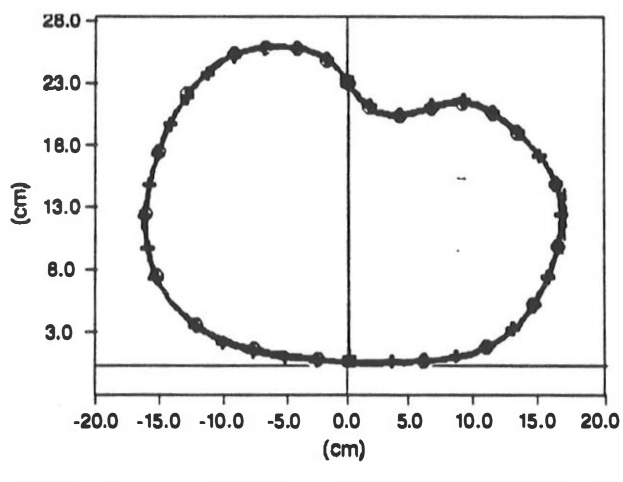


Figure 21 - Contours from 37 gauge and fictitious 24 gauge bands

CONCLUSIONS

1. The analytical process associated with the chest band system can be implemented on a personal computer.

2. The analytical process is robust in the sense that it seems to give a reasonable shape. The extent of error appears to be small for a 37 gage chest band used for thoracic impact studies.

3. Since the analytical process can be put on a personal computer, any laboratory -- regardless of size -- can use the chest band instrument.

4. A variety of thoracic static shape tests, thoracic compression tests, and Hybrid III impact tests illustrate the previously reported 16 gage chest band does not accurately reproduce the pertinent contours.

5. For the same variety of thoracic tests, a 37 gage chest band did accurately reproduce the pertinent contours.

6. It appears that 24 gages is more or less the minimum number of gages required for measuring the surface response of the thorax during impact.

DISCLAIMER

The views presented are those of the authors and are not necessarily those of the National Highway Traffic Safety Administration, U. S. Department of Transportation.

REFERENCES

1. Eppinger, R. H., "On the Development of a Deformation Measurement System and Its Application Toward Developing Mechanically Based Injury Indices," 33rd Stapp Car Crash Conference, October 1989.

2. Shaibani, S. J., and Khaewpong, N., "Identification of Chest Injuries from Changes in Transverse Sections of the Thorax During Blunt Impact," Final Report for Contract No. DTNH22-87-D-07098, Task Order 7, February 1990.