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CrashStar- A post-processing program for chestband data analysis

T. T. Amenson, G. Xu, P.W. Brown, and K. Salaani

ABSTRACT

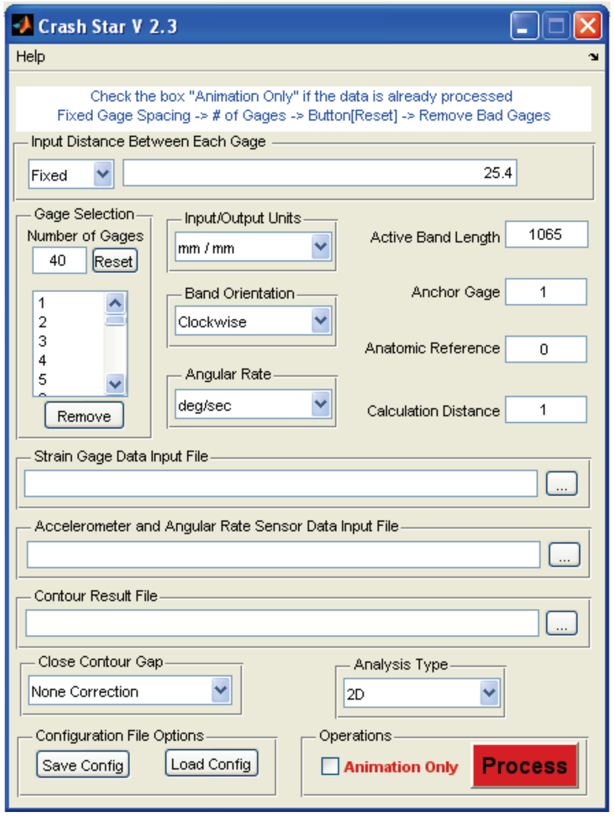
CrashStar was developed to overcome the difficulties of post-processing chestband data from post-mortem human subject (PMHS) side impact tests. The three main objectives of CrashStar were to design a software package that utilizes a single anchor point to better model a side impact, generate two-dimensional (2-D) and three-dimensional (3-D) graphical representations to visualize data as the torso deforms over time, and write the code in a user-friendly interface that allows the user to make improvements as sensor technology changes or more accurate algorithms are defined. Before CrashStar was developed, chestband data was post-processed in RBandPC to understand the torso deformation from frontal impact testing. The RBandPC code reconstructed the two-dimensional cross-sectional profile obtained from the chestband and reported the torso deformation over time based on two anchor points: one at the sternum and one at the spine. Although this software is useful for frontal impact scenarios, it does not allow for side impact analysis capabilities. To overcome these obstacles, CrashStar is written using MATLAB code and only requires one anchor point to calculate the x-, y- and z-axis coordinates of each strain gage location over time. In combination with 6 degrees of freedom (6DOF) instrumentation, CrashStar can generate a two-dimensional or three-dimensional graphical animation of chestband deformation, translation and rotation during side impact testing and the output data can be further analyzed to calculate deformation, displacement and compression of the torso. To improve the chestband contour accuracy produced in CrashStar, a sensitivity calibration procedure was developed and a gage sensitivity program was written to include the sensitivity of each gage. The gage sensitivities were used as CrashStar input and the two-dimensional chestband contour accuracy was confirmed using foam shapes of known geometries. The two-dimensional CrashStar contour accuracy was also validated using motion analysis and a 59-gage chestband wrapped around a side impact dummy (SID) abdomen during a lateral impact. Finally, the 40-gage chestband was wrapped around the thorax of a PMHS during an oblique impact test at 4.5 m/s. The PMHS had two instrumentation measurement units (IMUs) consisting of three accelerometers and three angular rate sensors on the sternum and spine. Combining the chestband data with the IMUs allowed for a three-dimensional CrashStar analysis of the cadaveric thorax motion over time. In summary, the results of the static tests and dynamic applications indicate that CrashStar is a useful tool for post-processing chestband data from lateral and oblique impact testing. Overall, CrashStar should improve our understanding of thoracic deformation which will aid in our understanding of injury thresholds for lateral and oblique impacts.

BACKGROUND

The chestband is a non-invasive measurement instrument used to capture the curvature of the human torso under dynamic impact conditions such as those occurring in the automotive crash environment. In the late 1980's, Dr. Rolf Eppinger developed the chestband to obtain a representative cross-section of a body as it deforms over time (Eppinger, 1989). Shortly after the chestband became operational, a computer program was written in FORTRAN to post-process the chestband data from frontal impacts (Eppinger, 1989). The RBandPC computer program requires two anchor points and chestband curvature data to reconstruct the two-dimensional (2-D) cross-sectional geometry of the human torso under impact. Although this software is useful for frontal impact scenarios it was not designed for side impact analysis capabilities. To overcome this obstacle, a new program was developed in MATLAB code to allow for a single anchor point in which side impact torso rotation and deformation could be analyzed in 2-D and 3-D space. The greatly improved CrashStar post-processing program only requires one anchor point, anywhere along the chestband, thereby minimizing the motion restriction of the chestband during side impacts.

CrashStar version 1.0 was developed in MATLAB by a student team from the Ohio Northern University in Ada, Ohio and consisted of Patrick J. McNaull, Alexander C. Mehlman, Jonathan R. Salontay, Micah J. Scott and Trey A. Shepherd. The team was directed by Drs. Juliet Hurtig and John-David Yoder. An advantage to developing CrashStar in MATLAB is that the code can be easily modified and updated to accommodate various testing conditions. The Transportation Research Center in East Liberty, Ohio was contracted by the National Highway Traffic Safety Administration (NHTSA) to modify the CrashStar code and improve the 3-D graphical representations of the chestband contours as they translated and rotated based on information from the instrumentation measurement units (IMU) on the sternum or spine of a post-mortem human subject (PMHS). NHTSA also wanted to validate and confirm the accuracy of the 2-D CrashStar output in various testing conditions including static measurements on foam shapes of known dimensions, the effect of variable gage spacing on a 59-gage chestband during dynamic loading and how the influence of the IMUs affects the translation and rotation of the chestband contour in 3-D space.

The purpose of this study was to further develop a post-processing program that would overcome the limitations of RBandPC and improve our understanding of torso deformation under side impact loading conditions. The three main objectives of CrashStar were to design a software package that allows for a single anchor point, generate 2-D and 3-D graphical representations to visualize chestband data as the torso deforms over time, and write the code in a user-friendly interface that allows the user to make improvements as sensor technology changes or more accurate algorithms are defined. To do this, the first step was to develop a chestband sensitivity calibration procedure with the goal of improving the chestband contour accuracy produced by CrashStar. The GageConvert program was written to model the strain gage sensitivity and the output from GageConvert was used to process chestband data in CrashStar. Chestband data collected from static foam shape tests was processed in CrashStar to validate 2-D contour accuracy. High speed video from a lateral side impact dummy (SID) test was used to confirm that the chestband measures deformation accurately under dynamic loading conditions. Finally, to analyze the kinematic output in 3-D space, CrashStar version 2.3 was developed and applied to an oblique thorax impact test on a PMHS. In the graphical user interface (GUI) of CrashStar v2.3, the user can simply input chestband data to obtain a 2-D contour plot of torso deformation or, if desired, the user can add accelerometer and angular rate sensor input from the spine or sternum to obtain a 3-D graphical representation of the chestband motion over time (Figure 1).



Check the box "Animation Only" if the data is already processed
Fixed Gage Spacing -> # of Gages -> Button[Reset] -> Remove Bad Gages

Input Distance Between Each Gage: Fixed 25.4

Gage Selection
Number of Gages: 40
1
2
3
4
5

Input/Output Units: mm / mm

Band Orientation: Clockwise

Angular Rate: deg/sec

Active Band Length: 1065

Anchor Gage: 1

Anatomic Reference: 0

Calculation Distance: 1

Strain Gage Data Input File

Accelerometer and Angular Rate Sensor Data Input File

Contour Result File

Close Contour Gap: None Correction

Analysis Type: 2D

Configuration File Options

Operations: ☐ Animation Only

Figure 1: CrashStar version 2.3 Graphical User Interface (GUI)

Establishing Gage Sensitivity

A new calibration procedure and software program was developed to establish strain gage sensitivity to improve chestband contour accuracy produced by CrashStar. First, strain data is collected from a flat, horizontal chestband to measure zero curvature at each gage (Figure 2). Next, three circles of known radii and circumference were used to define the boundaries of minimum, midrange and maximum curvatures that might be encountered during PMHS testing. Based on an analysis of chest circumferences of PMHS subjects, it was determined that three foam circles with circumferences of 40 inches, 30 inches and 20 inches would be acceptable for establishing the sensitivity for each strain gage within the belt (Figure 3). Static chestband data was recorded once for the 40 inch circle because all of gages on the 40-gage chestband were wrapped around its circumference. Data was recorded twice for each of the smaller circles to ensure that all gages were recorded while being wrapped around a 30 inch and 20 inch circumference circle. The gage positions were labeled on the foam shapes using a permanent pen so that tests could be repeated if necessary and to allow for gage location comparison with the CrashStar output. After the chestband data was collected, the GageConvert program was used to determine the sensitivity of each gage using a least-square method for a second order polynomial passing through the point (0, 0). Figures 4-6 show the four data points collected (zero curvature, 40”-, 30”- and 20”- circumference circles) in millivolts for a particular strain gage as well as a sensitivity curve based on all data points. Figure 4 shows a consistent sensitivity for gage 3 while figure 5 shows a slightly inconsistent sensitivity for gage 2. If the gage reading is considerably inconsistent, as shown in figure 6 with gage 1, the user can choose to keep the outlying data point or remove it from the sensitivity computation.

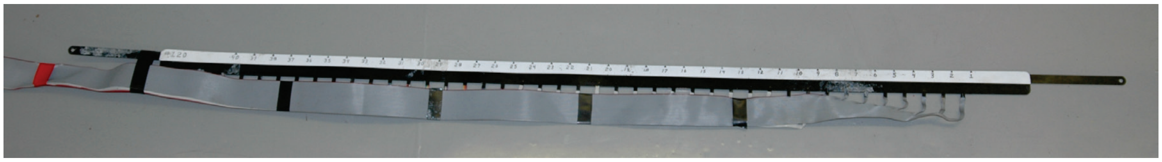


Figure 2: Flat chestband reading

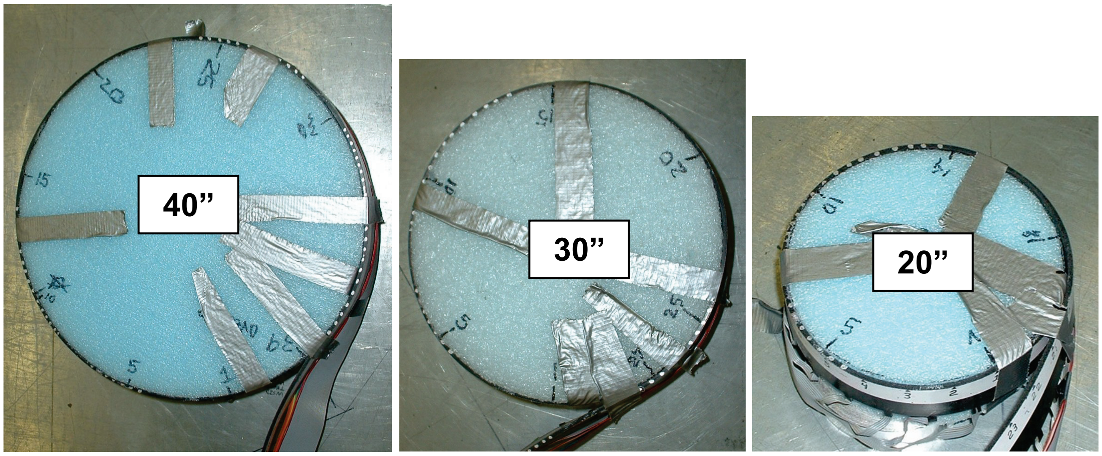


Figure 3: 40, 30, and 20 inch circumference circles wrapped with 40-gage chestband

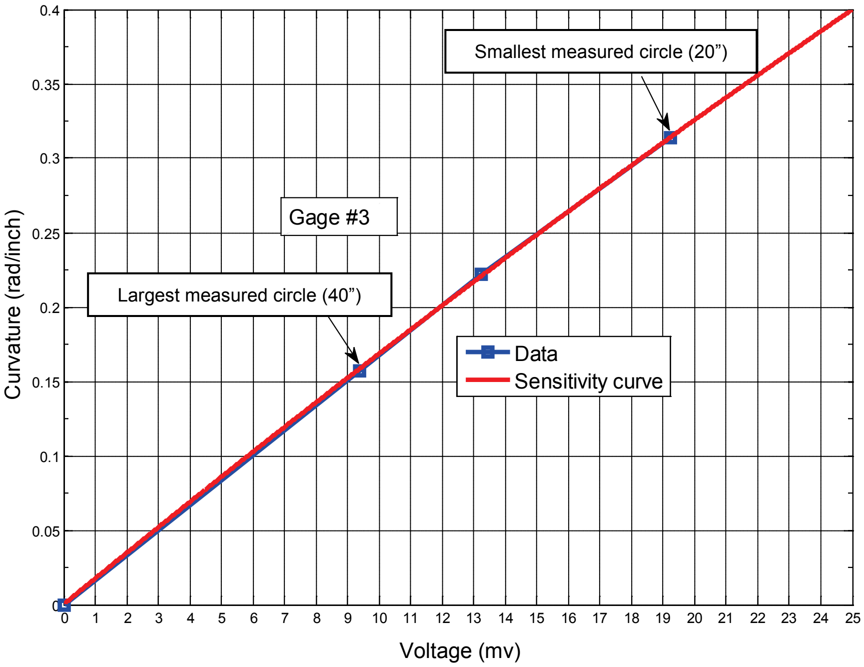


Figure 4: Consistent sensitivity

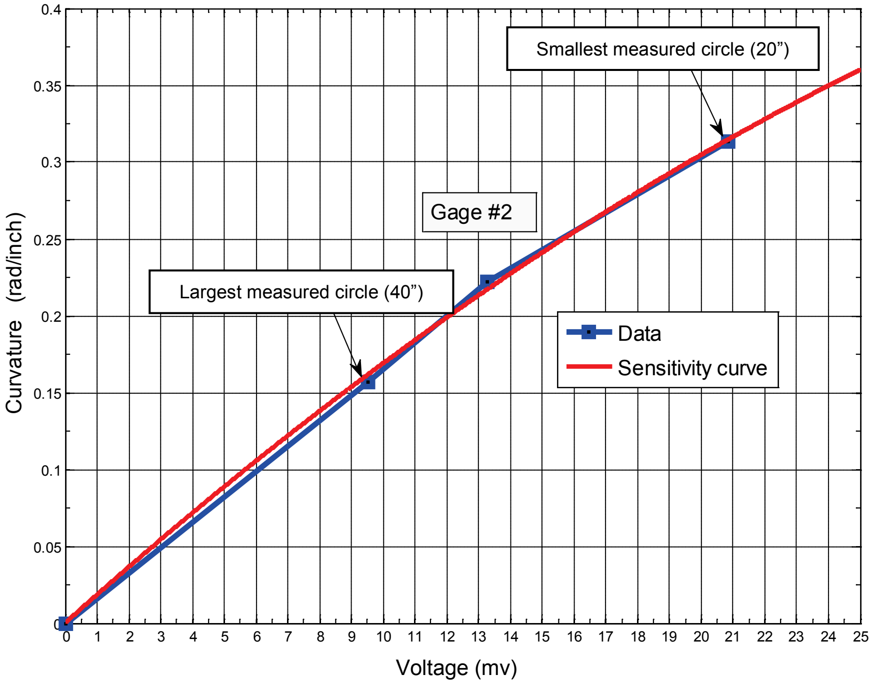


Figure 5: Slightly inconsistent sensitivity

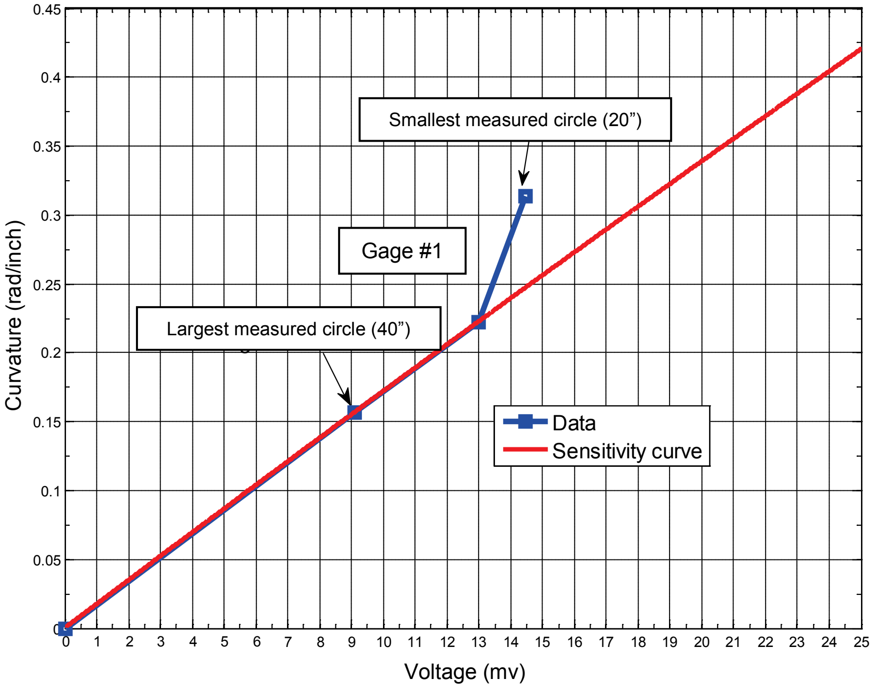


Figure 6: Considerably inconsistent sensitivity

Before using the sensitivity results as CrashStar input, one additional test was performed to validate the calibration method. Figure 7 shows a graph of the largest circle (40 inch circumference, 6.36 inch or 161.5 mm radius) with a minimum curvature and the smallest circle (20 inch circumference, 3.18 inch or 80.7 mm radius) with a maximum curvature which was used to generate an ellipse whose curvature span is between the two pre-defined circles. The chestband was wrapped tightly around the foam ellipse and the chestband data was post-processed in CrashStar. Figure 8 shows the CrashStar 2-D ellipse contour output indicating the radius of a, at the maximum curvature, and the radius of b, at the minimum curvature, match the foam dimensions fairly well and only vary by 1-3 millimeters. Visual analysis of the foam shapes and the CrashStar 2-D contour plot confirm that the gage locations, as shown in figure 8 by the location of strain gage 8, closely match the location of the strain gages as labeled on the foam ellipse.

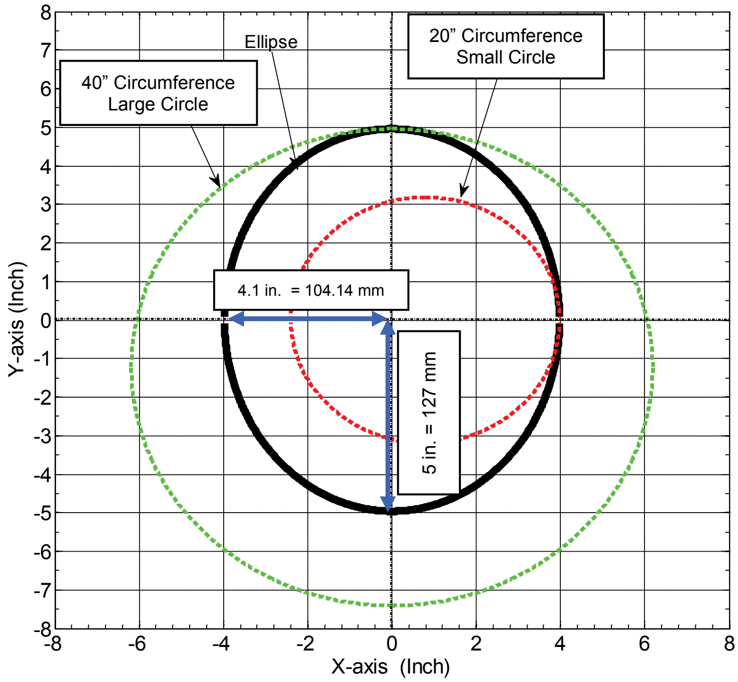


Figure 7: Ellipse geometry

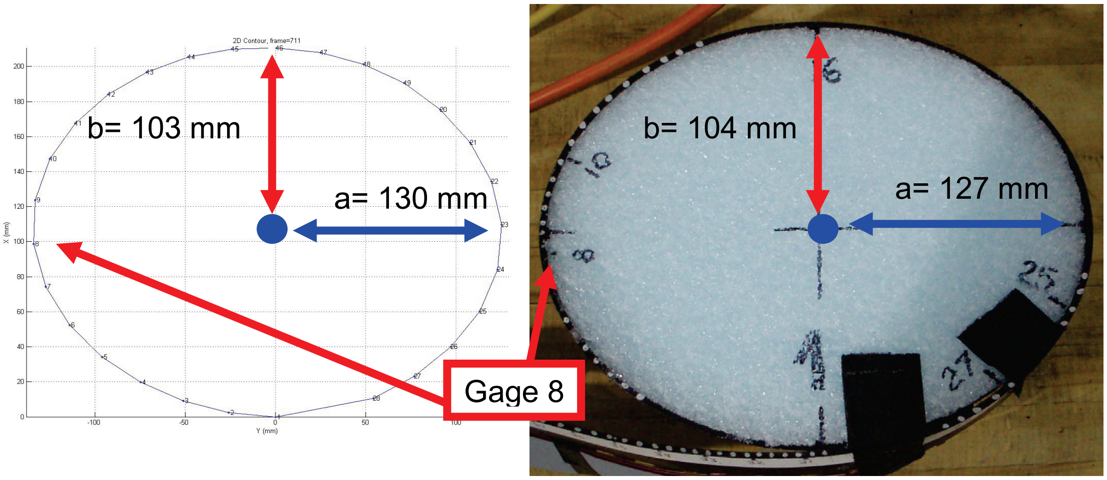


Figure 8: Ellipse geometry comparison

Static Shape Deformation Tests

To validate the 2-D output from CrashStar, a set of static shape deformation tests were performed using a 40-gage chestband with fixed gage spacing, wrapped around foam shapes of known dimensions. The foam shapes were made to represent lateral and oblique impacts using a curved or flat impact surface (Figure 9). Initial contours were collected with the chestband wrapped around the foam circumference followed by contours collected from the deformed shape. Chestband data was collected in these static orientations and processed in CrashStar to generate 2-D contours. The CrashStar results were then compared back to the measurements of the initial and final foam shapes.

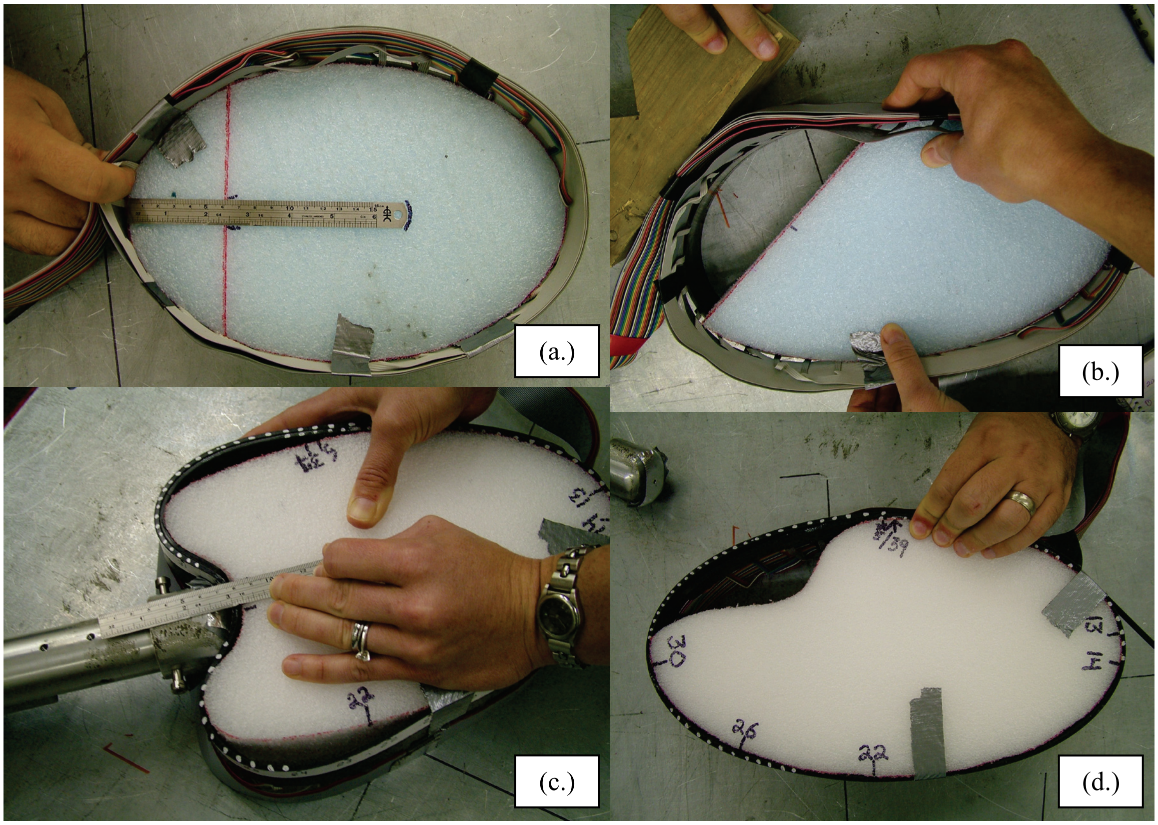


Figure 9: Static foam shapes

(a.) Representation of lateral impact with flat surface. Initial shape shown prior to impact.
(b.) Representation of an oblique impact with flat surface. Foam section removed prior to chestband being pushed into foam shape.
(c.) Representation of a lateral impact with curved surface. Final chestband shape and deformation shown.
(d.) Representation of an oblique impact with curved surface. Initial shape shown prior to impact.

The 2-D, static shape results of the initial contour and the deformed contour showed fairly accurate results when compared to actual foam shape dimensions. Some bulging of the chestband did occur because it was difficult to keep the band tightly wrapped around the foam shape, especially at tight radii. It is important to note that bulging also occurs during PMHS testing as the chestband does not stay tightly wrapped around human tissue in all cases. To quantify the deformation and bulging, distance measurements from the edge of the foam to where the chestband had deformed or bulged were taken prior to deformation and during deformation (Figure 10). These measurements were compared to the results produced by CrashStar and figure 11 shows an overlay of the initial contour in red and the deformed contour in blue. Using a single gage measurement for comparison, the deformed space was measured to be 71 mm while the CrashStar output calculated the deformed space to be 68 mm. The bulge between the foam and chestband was measured to be 49 mm while the bulge was calculated by CrashStar to be 48 mm. These results indicate that actual chestband measurements match the CrashStar output within millimeters. To compare CrashStar contour shape with the actual foam shape, the contour was overlaid onto images of the foam ellipses before and after deformation (Figure 12). Results from these overlays show that the gage locations match CrashStar output and the chestband bulging area matches the chestband contour from CrashStar.

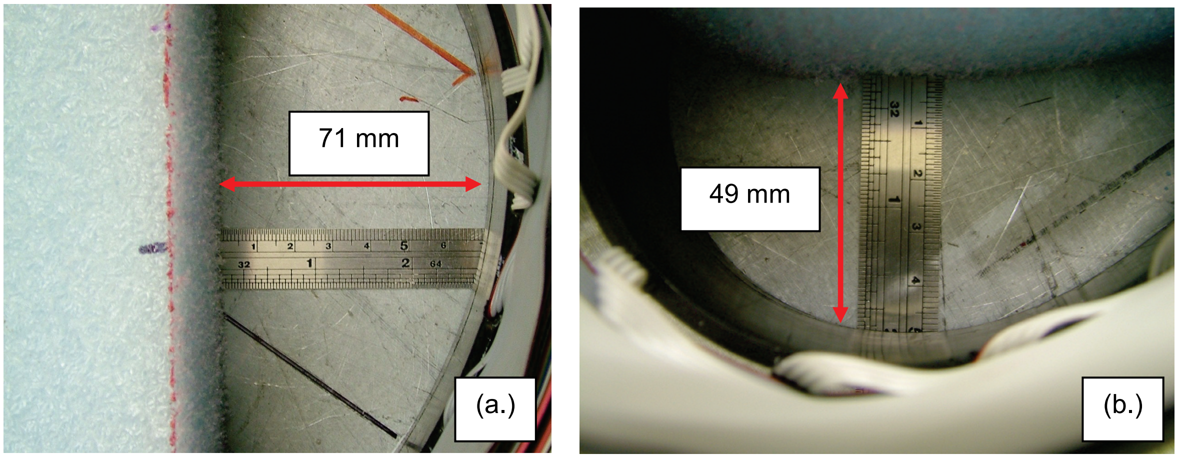


Figure 10: (a.) Measurement of deformation site prior to being deformed (71 millimeters)

(b.) Measurement of chestband bulging during deformation (49 millimeters)

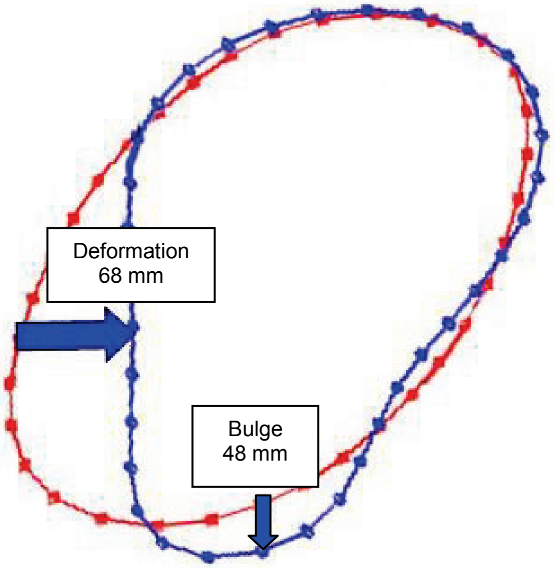


Figure 11: Chestband contour output from CrashStar: Initial shape (red), Deformed shape (blue)

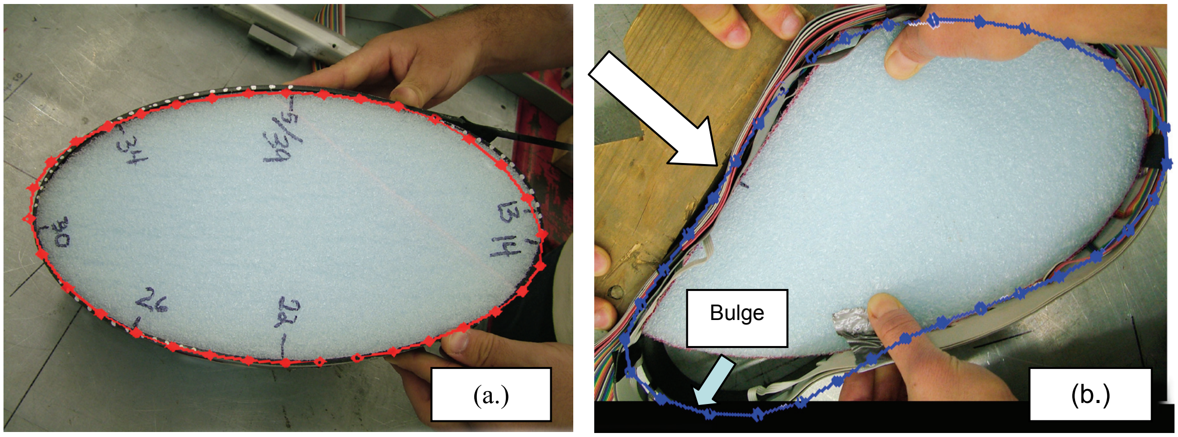
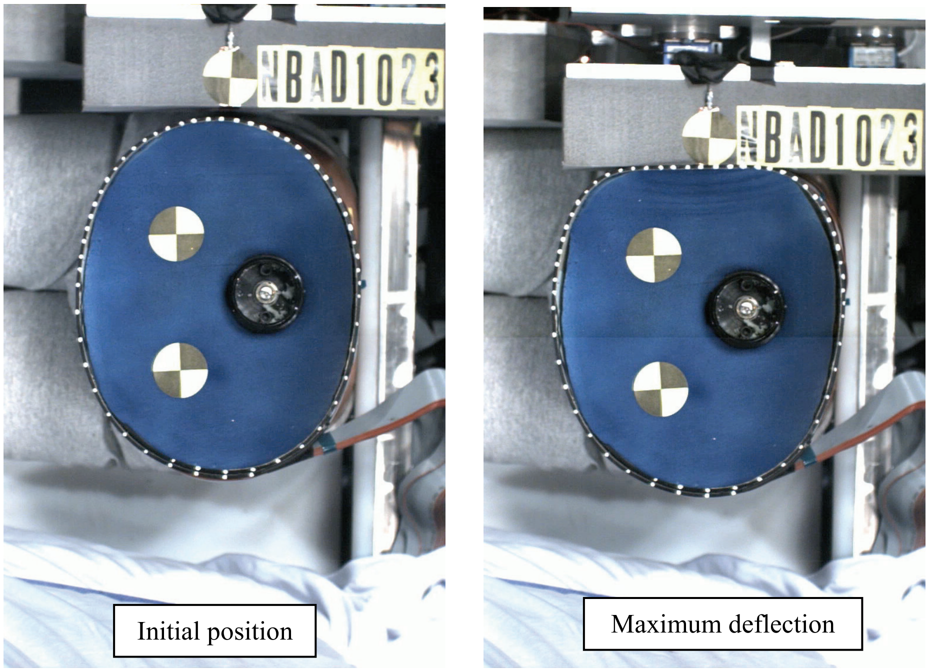


Figure 12: (a.) Initial foam shape with chestband contour overlay from CrashStar
(b.) Deformed foam shape with chestband contour overlay from CrashStar

Dynamic Motion Analysis of a Lateral Impact Using a 59-gage Chestband

The University of Michigan Transportation Research Institute (UMTRI), wrapped a 59-gage chestband around a side impact dummy (SID) abdomen to determine how accurately the chestband measured abdominal deflection from lateral impacts (Figure 13). The thorax of the SID was removed and a piece of blue foam was inserted into the abdominal region for support. Overhead, high-speed video was used to perform motion analysis of the chestband and the results were compared to CrashStar results. The chestband used in this application did not undergo the sensitivity calibration procedure previously mentioned.

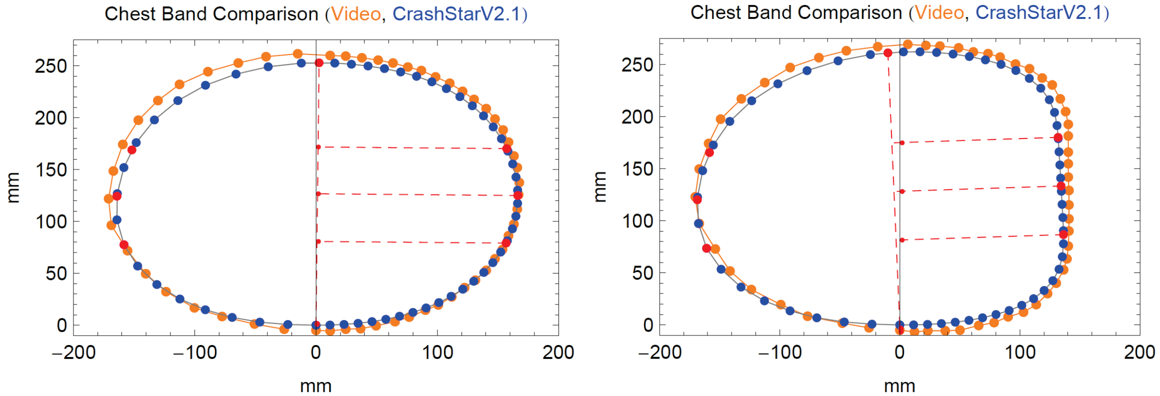


Initial position

Maximum deflection

Figure 13: 59-gage chestband wrapped around SID abdomen

Using the 59-gage chestband with variable gage spacing, the 2-D CrashStar output was compared to the motion analysis from high speed video recorded at UMTRI. Any rotation that occurred during the lateral impact was not considered and may explain the offset between the CrashStar data and the digitized video. Figure 14 shows the CrashStar output compared to the motion analysis and the contour results are very similar at the initial position (left image) and at maximum deflection (right image). This suggests that the CrashStar 2-D output matches the motion of the chestband during a lateral abdominal impact.



Initial position

Maximum deflection

Figure 14: 59-gage chestband results

Dynamic Oblique Thorax Impact of Post-Mortem Human Subject (PMHS)

An unembalmed, PMHS with a 40-gage chestband wrapped around the thorax at the level of the xiphoid process was subjected to oblique loading by a flat 6” x 12” impact surface. Three uni-axial accelerometers and three angular rate sensors were mounted on an aluminum block to form an inertial measurement unit (IMU). The subject was instrumented with one IMU mounted on the spine at the level of T4 and one mounted mid-sternum (Figure 15). Pre-test measurements provided the necessary CrashStar input parameters such as chest circumference, chest breadth, chest depth, gage locations, chestband level, band orientation and IMU location in the global coordinate system.

The data from the accelerometers was filtered at CFC 1000 while the angular rate sensors were filtered at CFC 60. Before running CrashStar, all IMU data was transformed into the subject coordinate system. The anchor point chosen for the 3-D analysis was dependent upon which input, spine or sternum, was used to measure rotation and translation of the chestband in the 3-D animation. Thus, if the spine IMU input was used for the 3-D CrashStar analysis, then the spine was identified as the anchor point and vice versa for the sternum. CrashStar assumes the chestband is aligned with the IMU coordinate frame and the IMU initial position is aligned with the global coordinate frame. In order to calculate the chestband positions in 3-D, CrashStar assumes that 1) the IMU is fixed on the chestband and 2) all gages move in a chestband plane when the chestband is being impacted.

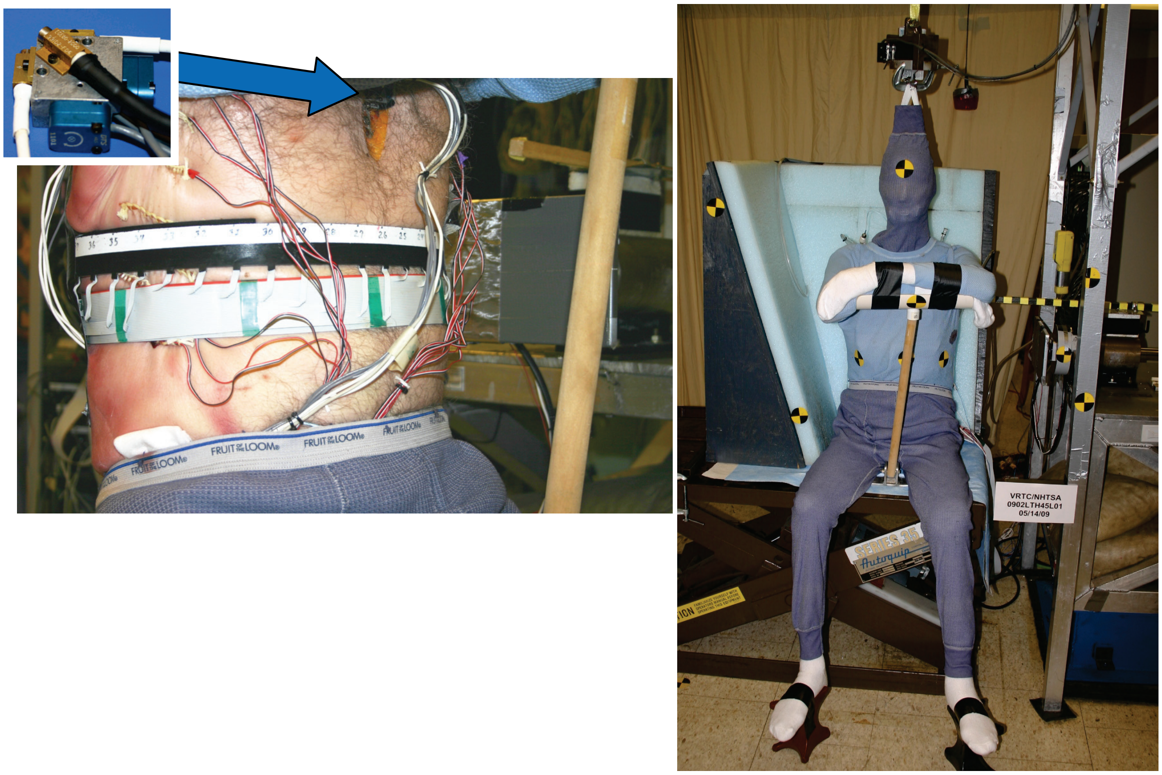
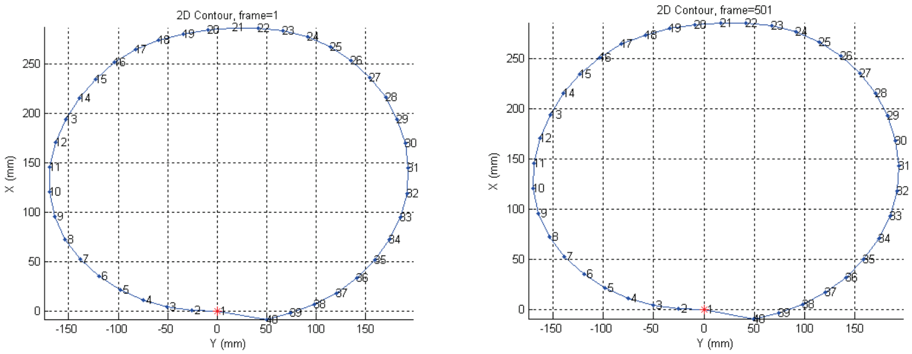


Figure 15: PMHS test set-up with chestband and sternum IMU

The dynamic PMHS kinematics were compared to 2-D and 3-D CrashStar animation results from a non-calibrated chestband. Because clothing was covering the chestband and IMUs, it was difficult to make a direct comparison with the CrashStar output. Figure 16 shows a series of 2-D chestband contours from the oblique thoracic impact. The spine was chosen as the anchor location and is indicated on the plot as a red star at (0 mm, 0 mm). The subject was 1,065 mm in circumference meaning the 40-gage chestband was too small to complete a loop which left a gap of 50.8 mm (2 inches) between the first and last gage on the chestband. The 2-D CrashStar contour confirms the gap is 50.0 mm wide between gage 1 and gage 40 (Figure 17). Since a gap was unavoidable between gage 1 and gage 40, the methods used by CrashStar to close the gap were investigated. It is also important to note that accumulated gage curvature error or a non-calibrated chestband can also produce a gap between the first and last gage in the chestband contour plot.

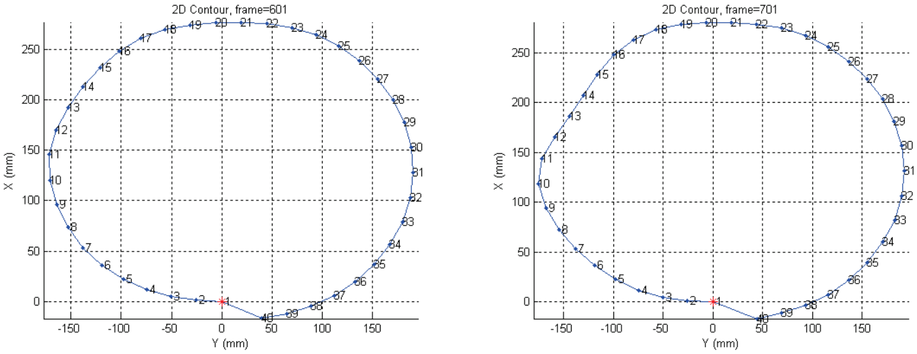
To close the loop by minimizing the gap, three options are available in CrashStar. If no correction is desired, the "No Correction" option is chosen and an uneven gap will remain between the first and last gage (Figure 17). If the user wants to apply a correction to close the gap by adjusting the sum of all curvature angles to equal 2π (360°), then the "2π Adjustment Only" option should be chosen (Figure 18). Finally, the "Close Gap" option applies a correction to close the gap by adjusting the sum of all curvature angles to equal 2π (360°) and then distributes the rest of the gap evenly to each gage displacement (Figure 19). To analyze the oblique thoracic PMHS impact, the "No Correction" option was chosen and the uneven gap is visible in figures 16 and 17.

Table 1 shows the pre-test subject dimensions, taken while the chestband was wrapped around the subject, compared to the dimensions generated by the different gap closure options in CrashStar. Results from oblique thorax test 0906OTH45L01 show that the "No Correction" dimensions match closely with the pre-test measurements however, any correction factor applied to the non-calibrated chestband data increases the contour dimensions by several millimeters. The "2π Adjustment Only" and "Close Gap" option increase the gap distance by 13-23 mm respectively. With each additional correction, the chest depth and chest breadth increased by 5-6 mm.



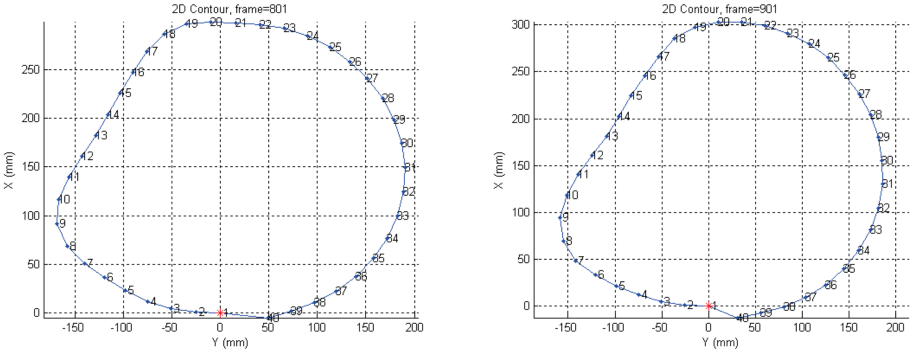
Initial contour at 0 ms

Contour at 5 ms



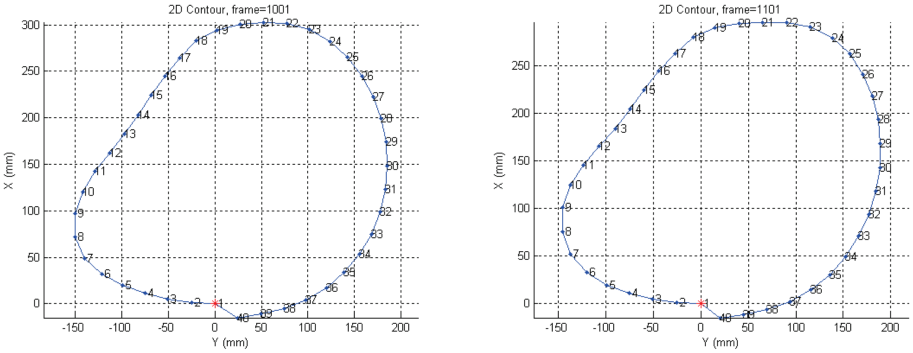
Contour at 10 ms

Contour at 15 ms



Contour at 20 ms

Contour at 25 ms



Contour at 30 ms

Contour at 35 ms

Figure 16: CrashStar 2-D output for oblique thorax PMHS impact

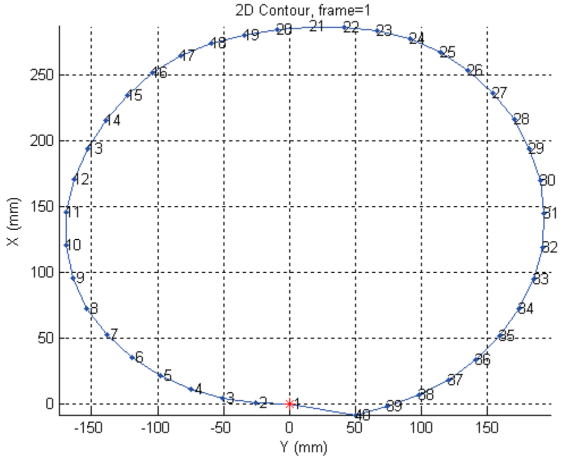


Figure 17: No correction

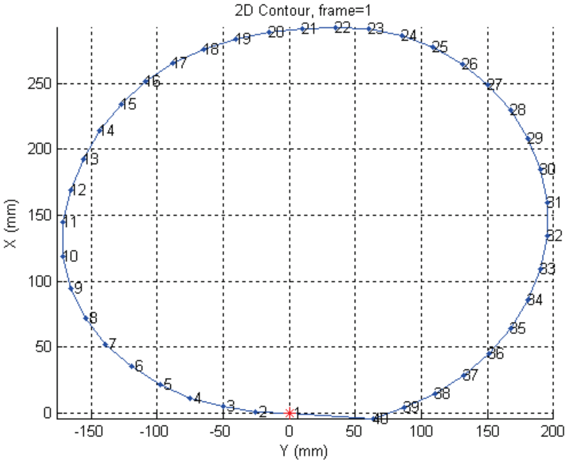


Figure 18: 2π Adjustment Only

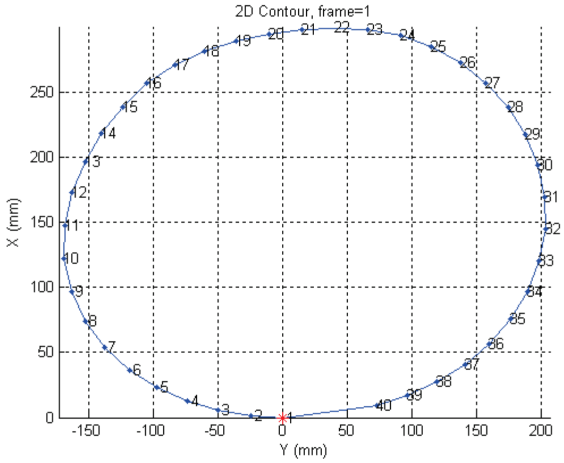


Figure 19: Close Gap

Table 1. Test 0906OTH45L01 dimensions

PRE-TEST SUBJECT DIMENSIONS							
	Chest Circumference	**Chest Depth**	**Chest Breadth**	**Gage at Spine**	**Gage at Sternum**	**Gage at impact site**	**Gage opposite impact site**
0906OTH45L01	1065 mm (gap 50.8 mm)	274 mm	369 mm	#1	12.7 mm from # 21 12.7 mm from # 22	12.7 mm from #14 12.7 mm from #15	#35
POST-PROCESSING MEASUREMENTS							
	Gap Distance	**Chest Depth**	**Chest Breadth**	**Anchor Gage**			
No Correction	50 mm	287 mm	361 mm	#1			
2π Adjustment Only	63 mm	292 mm	367 mm	#1			
Close Gap	73 mm	298 mm	372 mm	#1			

To further analyze the 3-D kinematics, the “No Correction” option was selected to process the PMHS chestband data and the spine (Gage 1) was designated as the anchor point. If the spine location was the chosen anchor point, then the spine IMU data was used to translate and rotate the chestband in 3-D space. In contrast, if the sternum location was the selected anchor point, then the sternum mounted IMU would be used to translate and rotate the chestband over time. Figures 20-23 show the spine anchor as a red star and each gage number is labeled according to its position along the chestband. The chestband was wrapped clockwise around the subject with a 50.8 mm (2 inch) gap between gage 1 and 40. Five millisecond screen captures of the 3-D animation from the left side, oblique PMHS thorax impact show deformation beginning at 10 milliseconds and continuing through 35 milliseconds (Figures 20-21). After 35 milliseconds, the chestband begins to rebound and expand back to the initial contour shape (Figures 22-23). At the end of the impact test, the subject slouches into the +z-axis until it comes to rest at the final position (Figure 23). Overall, the 3-D animation proves to be a useful tool for understanding the translation and rotation kinematics occurring during a PMHS impact test. To expand our understanding of the 3-D subject kinematics, CrashStar has several animation features allowing the user to manipulate and change the views to better visualize the chestband dynamically.

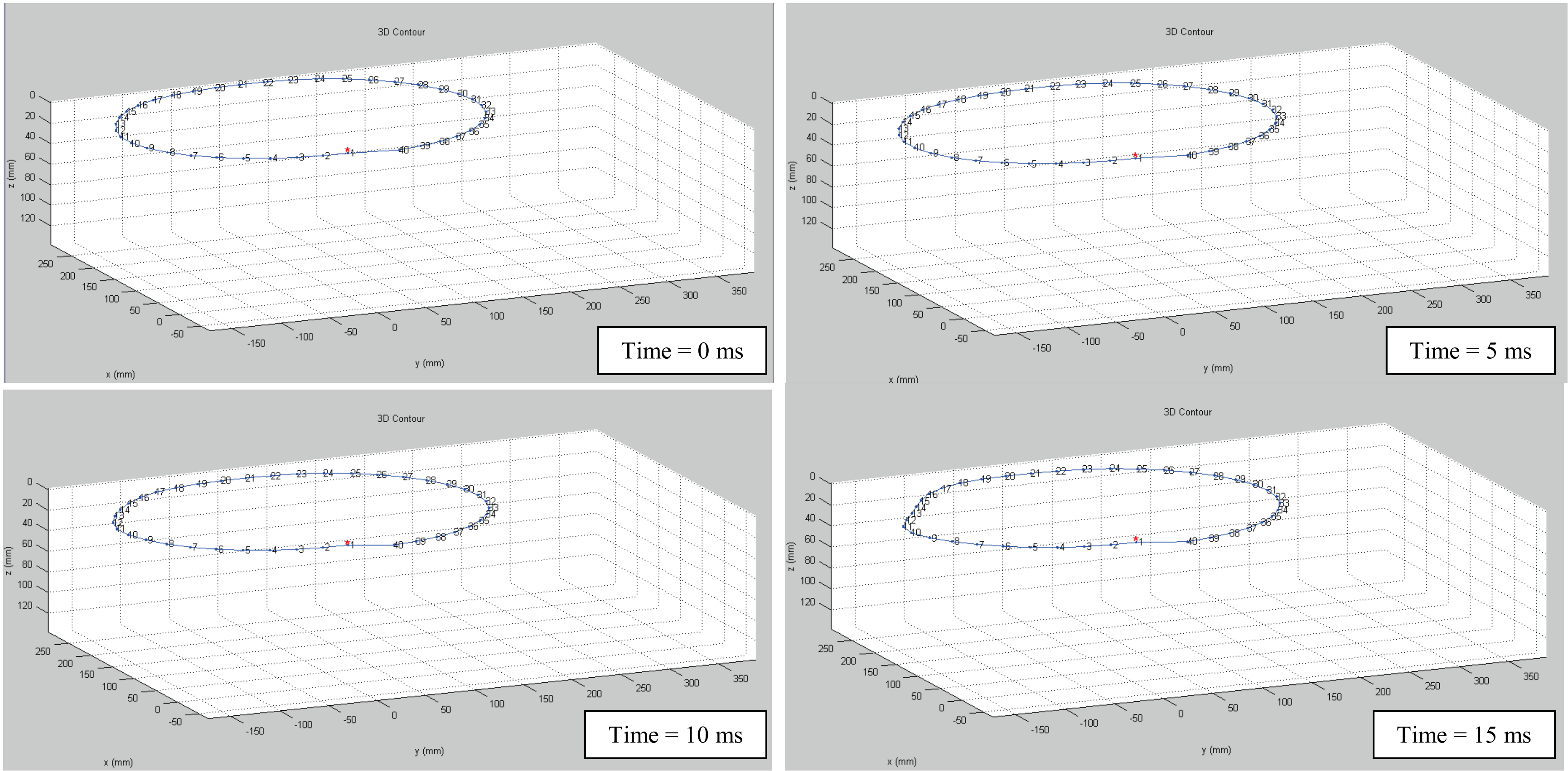


Figure 20: 3-D Animation of chestband motion from 0-15ms

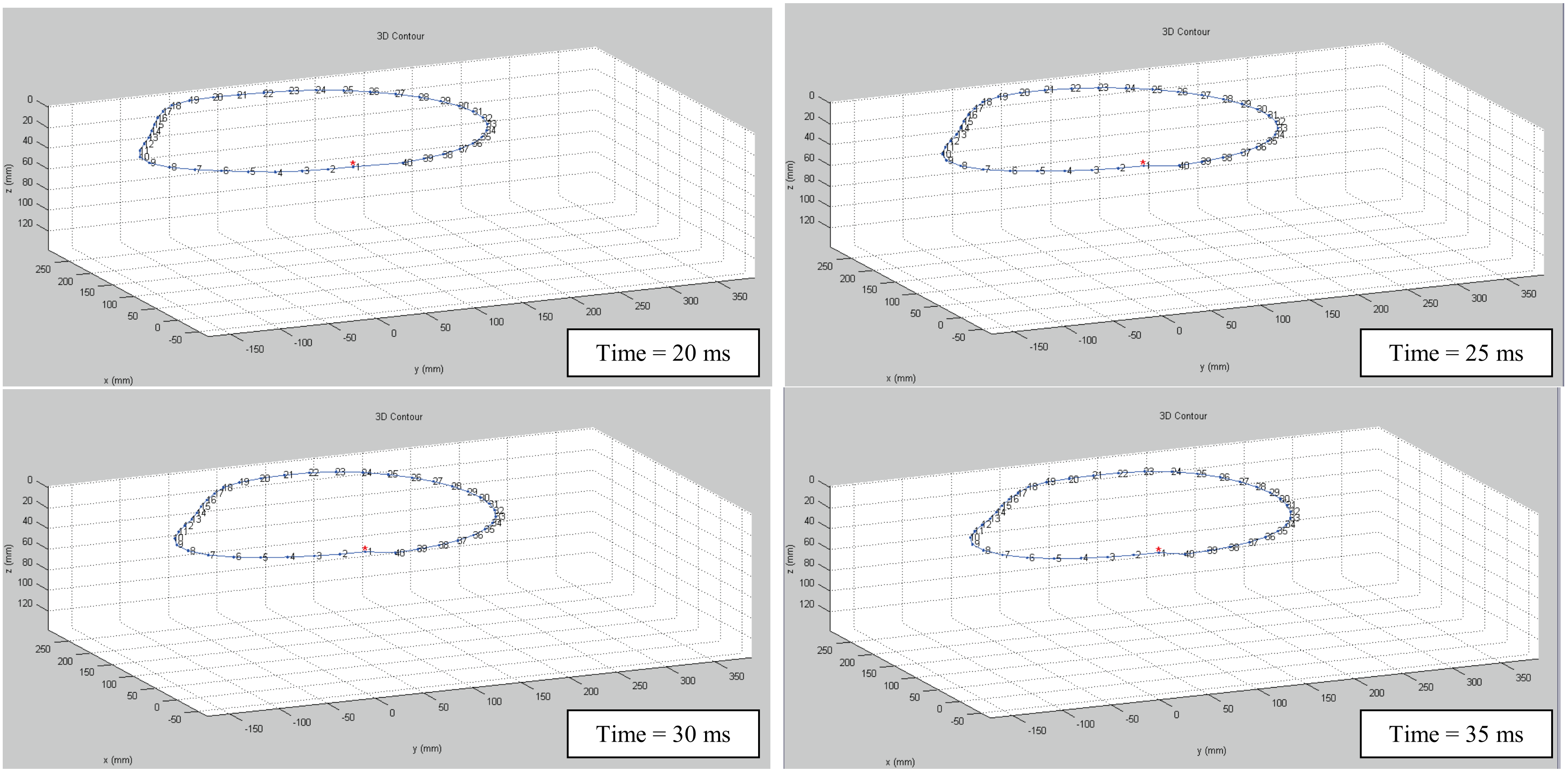


Figure 21: 3-D Animation of chestband motion from 20-35ms

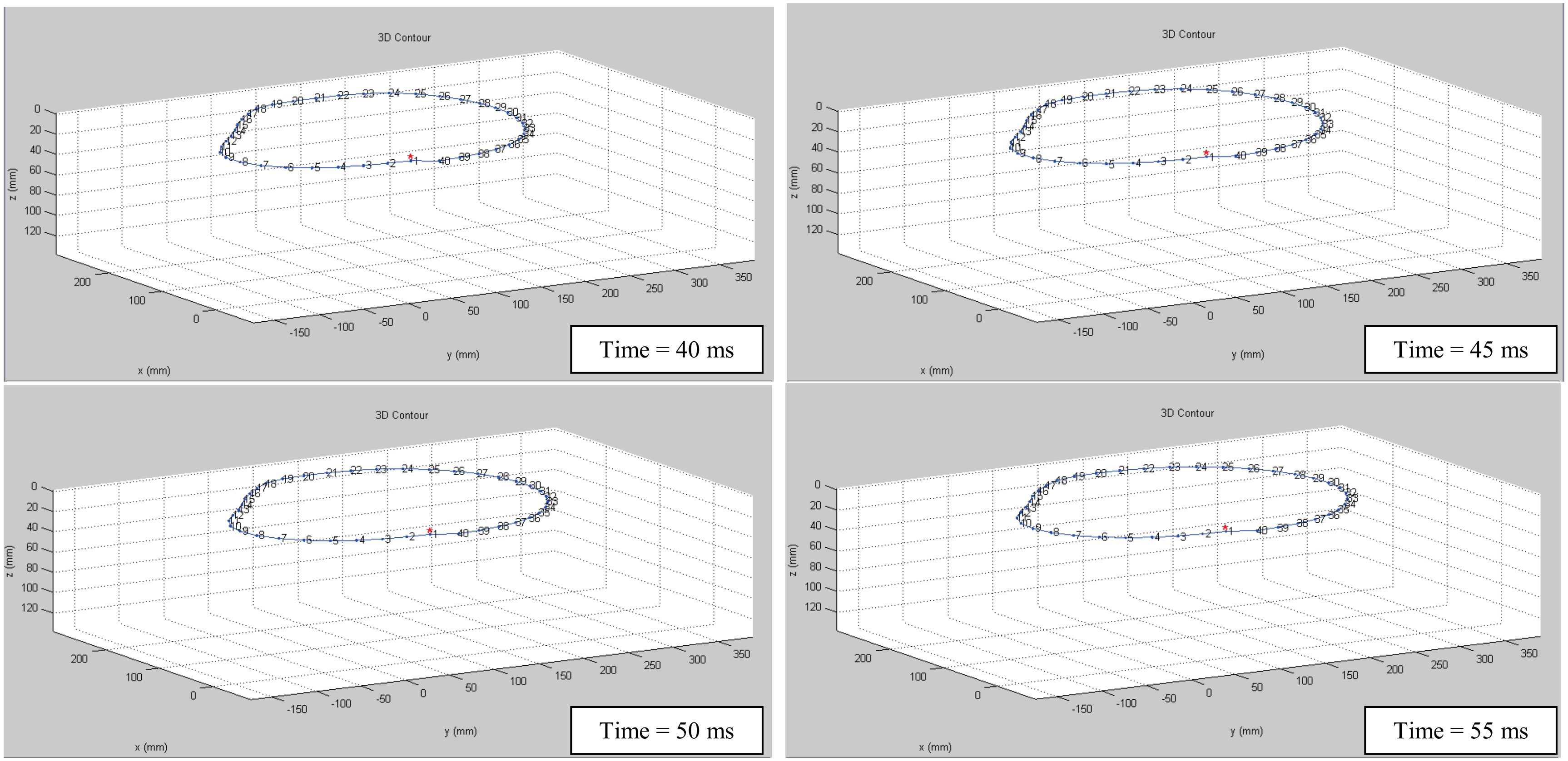


Figure 22: 3-D Animation of chestband motion from 40-55ms

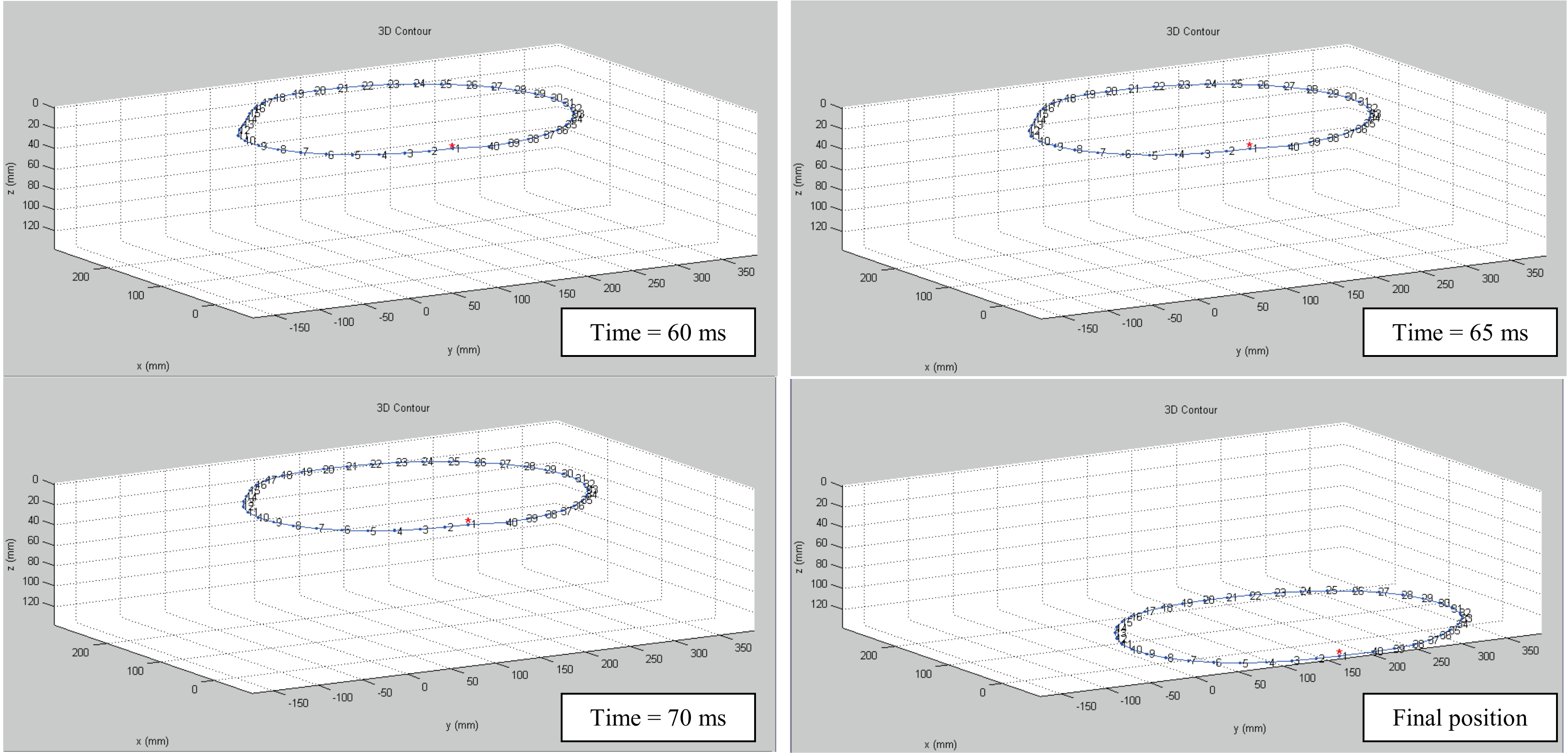


Figure 23: 3-D Animation of chestband motion from 60-70ms and final position

Animation Viewing Features in CrashStar

CrashStar has several animation features that allow the user to change the view, rotate the plot and change the speed of the animation. Figures 24-25 show the "Keep First Contour" feature, in 2-D and 3-D, which plots and keeps the initial chestband contour as the animation plays. Keeping the first contour allows the user to visually understand where the chestband started and how it deforms, translates and rotates relative to the initial position. Figure 24 also shows the gage number labeling feature where the initial contour is plotted without gage number labels and the deformed contour plot with gage number labels. Figure 25 shows both initial and deformed contour plots with all gage numbers labeled.

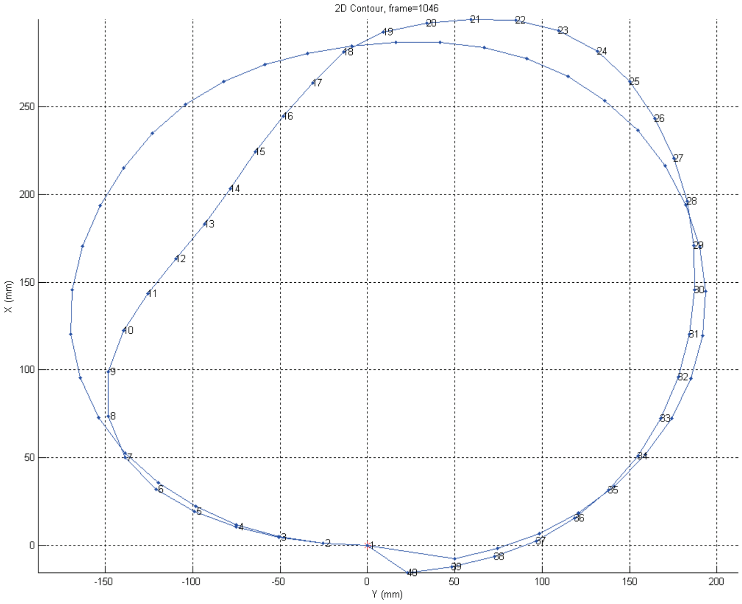


Figure 24: 2-D Contour plot with first contour and maximum deformation

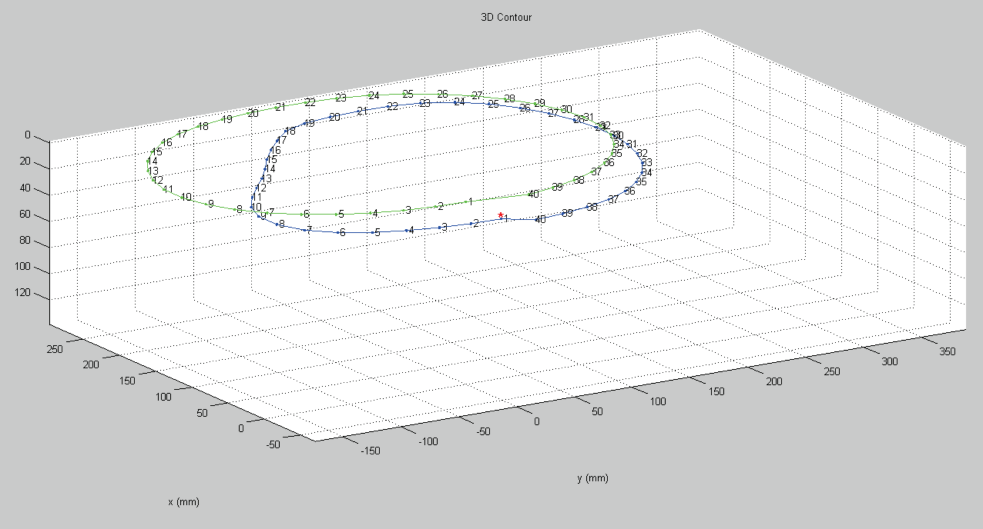


Figure 25: 3-D contour plot with first contour and maximum deformation

In the 2-D and 3-D animations, CrashStar allows the user to select a ‘waterfall plot’ feature that keeps the chestband contour plot at each interval as chosen by the user. Figures 26-27 show the 2-D and 3-D waterfall plot feature utilized every 200 frames. The 2-D waterfall plot anchors each contour at (0 mm, 0 mm) while the 3-D waterfall plot allows the anchor point to move in space based on the input from the IMU. The 3-D plot can be rotated to view the x, y, and z planes simultaneously (Figure 27) or the two plane view can be selected including the x-y, x-z, and y-z planes (Figures 28 and 29).

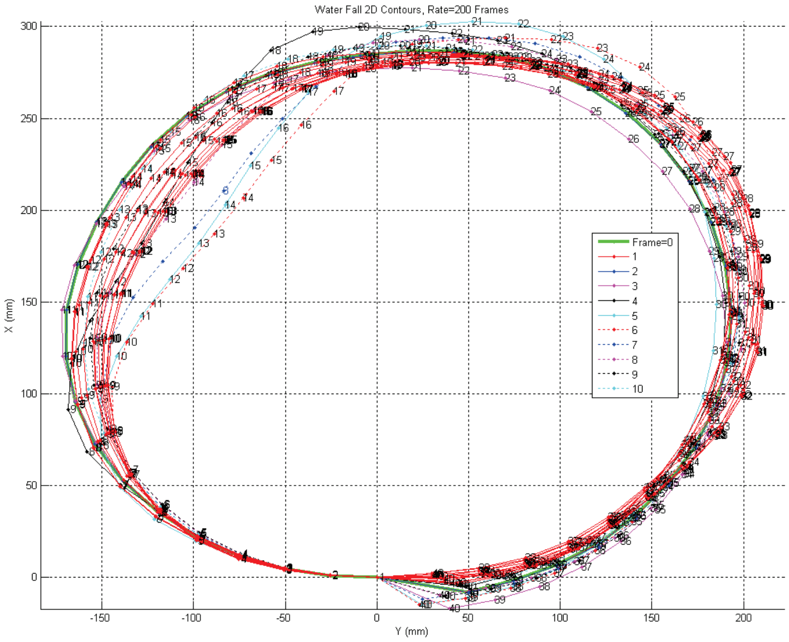


Figure 26: 2-D waterfall plot of chestband deformation over time

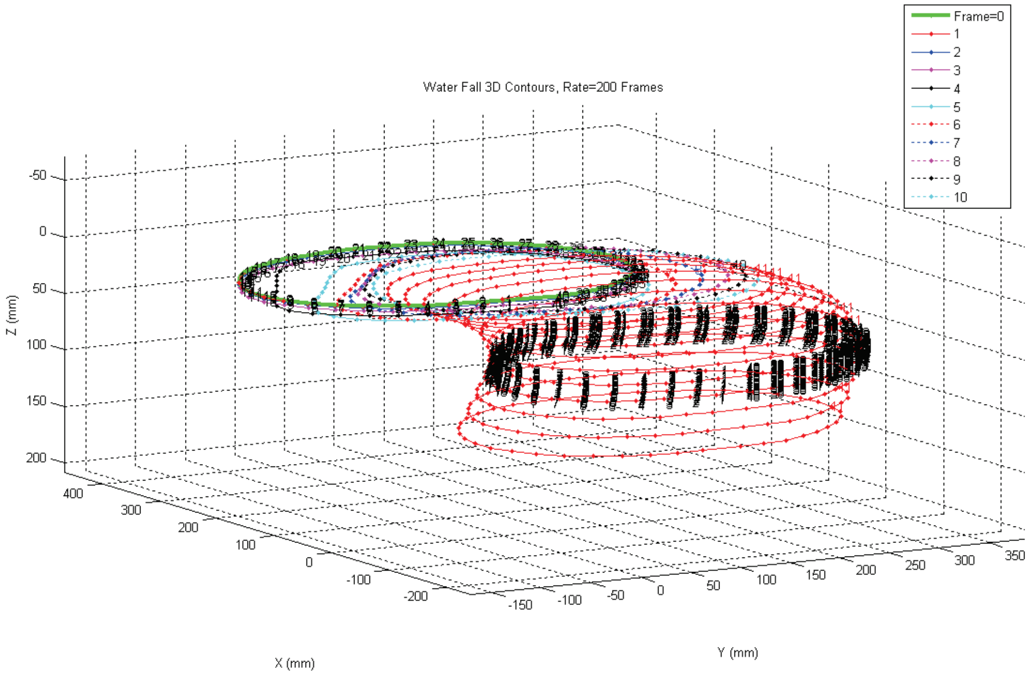


Figure 27: 3-D waterfall plot of chestband deformation, translation and rotation over time

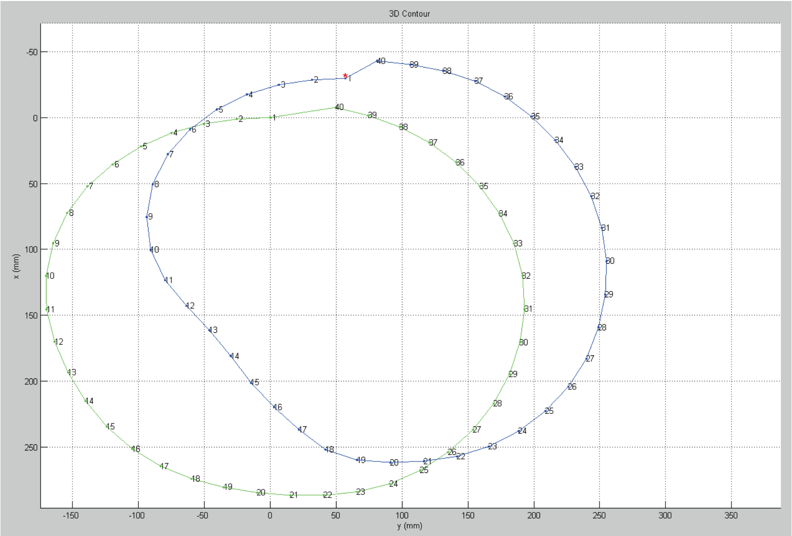


Figure 28: X-Y plane view

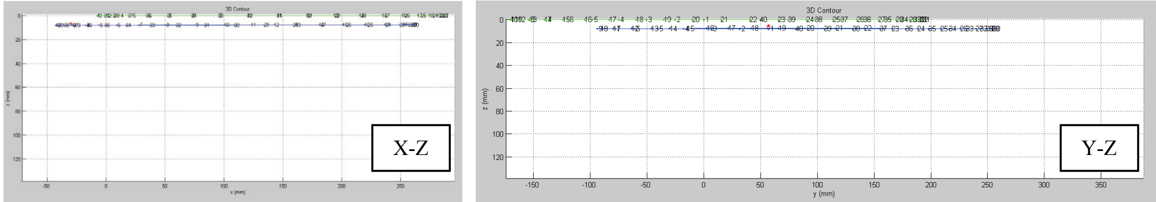


Figure 29: X-Z (a.) and Y-Z (b.) plane views

SUMMARY

In summary, CrashStar was developed to overcome the difficulties of post-processing chestband data from post-mortem human subject (PMHS) side impact tests. The three main objectives achieved by developing CrashStar are a software package utilizing a single anchor point to better model dynamic side impact loading, generation of 2-D or 3-D graphical representations to visualize chestband data as the torso deforms over time, and code written in a user-friendly interface that allows the user to make improvements as sensor technology changes or more accurate algorithms are defined. A significant improvement over RBandPC is the 3-D kinematic analysis feature that combines chestband data and 6DOF instrumentation to generate a 3-D graphical animation of chestband deformation, translation and rotation over time. Such data can be further analyzed to calculate deformation, displacement and compression of the torso during side impact loading. To improve the performance of CrashStar, accurate calibration and sensitivity results should be obtained prior to impact testing. Using the GageConvert program results, as CrashStar input, produces more accurate chestband contours and should be used to minimize gage location discrepancies.

The chestband and CrashStar performed very well under most conditions but some limitations were identified when the chestband was wrapped around tight radii with large curvatures or when the chestband had a gap greater than 50.8 mm (2 inches) between the first and last gage. Gietzen et al. (1990) identified similar limitations when comparing high speed film to chestband data post-processed using RBANDPC verses in-house software, Bndplt. Overlap between the first and last gage, gaps between gages and a 6-inch round impactor face were all identified as possible causes of error in the post-processed chestband contour output (Geitzen, 1990). CrashStar has the advantage of giving the user three options to view the effects of error causing agents such as gap closure numerical methods. The user may choose the 'No Correction' option to process unaltered chestband output or; similar to RBandPC, the user may choose the "2π Adjustment Only" option to complete the 360 degree loop or; the "Close Gap" option which applies the 2π correction and evenly distributes the error throughout the chestband contour. These new features allow the user to view the chestband data with or without any correction factors.

Results from the static shape tests and dynamic applications further support the fact that CrashStar is a useful tool for post-processing chestband data from lateral and oblique PMHS impact testing. In conclusion, CrashStar improves our understanding of torso deformation which will aid in our understanding of injury thresholds for lateral and oblique impacts. Future work will focus on the validation of the 3-D CrashStar code which will improve the kinematic analysis capabilities for PMHS impact testing using the chestband and 6DOF instrumentation on the sternum or spine.

CrashStar is available, at no cost, so if you are interested in receiving a copy of the GageConvert and CrashStar program, please contact Tara Amenson at tara.amenson.ctr@dot.gov or by phone at (937) 666-4511 ext. 273. The CrashStar program is continuously being improved to accommodate different testing conditions and newer versions will be released periodically upon request.

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REFERENCES

EPPINGER, R.H. (1989). On the Development of a Deformation Measurement System and Its Application Toward Developing Mechanically Based Injury Indices. Proc. 33rd Stapp Car Crash Conference, SAE Paper No. 892426.

GIETZEN, D., HARDY, W., BEGEMAN, P., AND KING, A. (1990). Impact Performance Evaluation of the EPIDM (Chestband). International Workshop on Human Subjects for Biomechanical Research, National Highway Traffic Safety Administration, pages 1-14.

NHTSA, (2010). CrashStar v2.1 User's Manual and Troubleshooting Guide., National Highway Traffic Safety Administration.

RBANDPC AND DEFLECT USER'S GUIDE, v 3.0 (2001). Prepared by Conrad Technologies, Inc for U.S. Department of Transportation, National Highway Traffic Safety Administration.