Development of Abdomen Compression Measurement Sensors

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ABSTRACT

Prototypes of two new sensors for measuring abdominal compression of ATDs have been developed. One sensor uses multiple Hall sensors, arranged in a strip, to compute the deflection. Each Hall sensor produces output which is a function of the relative angle between it and an associated magnet. The second sensor is based on commercially available flexible resistive strips. The strips produce a voltage drop proportional to the average curvature within the strip.

Procedures and fixtures for calibrating both types of sensors were developed. Software was developed to estimate the contour of the 2 dimensional curve computed from the output of the sensors at a specified time. The deflection time history was obtained from the deformation of the curve in time.

The paper discusses the basic design of the sensors, calibration procedures, and results from tests using different deformable forms, including an ATD abdomen. Impacts with both a disk and a horizontal rod were performed. Comparison of the results of the displacements obtained from the sensors and external measurements using an LVDT are presented.

INTRODUCTION

Compression has been used as an important measure for estimating likelihood of abdominal injury in Anthropometric Test Devices (ATDs). Among the various measures proposed are included maximum compression (Miller, 1989; Rouhana et al., 1989), viscous criterion based on the maximum value of $V \cdot C$ (Lau and Viano, 1986), and the abdominal injury criterion given by $V_{max} \cdot C_{max}$ (Rouhana et al., 1984), where $C$ is the compression and $V$ is the compression velocity, i.e. the rate of change of compression.
Current Measurement Methods

Among the methods currently used for measuring compression in the abdomen are:

1. Mechanical: e.g. in the THOR ATD (Rangarajan et al., 1998), stringpots (part of a double-gimballed system) are used to directly measure compression (or expansion) at two points on the external surface of the abdomen.
2. Electrical: e.g. in the fluid abdomen developed by Rouhana (Rouhana et al., 2001), by measuring the electric resistance between several anterior surface points and a central posterior point.
3. Other: e.g. pressure as used by Mooney (Mooney et al., 1986), in a prototype abdomen bag; Ishiyama (Ishiyama, 1994), used a steel band with strain gauges to measure curvature and calculate deflection (similar to a chest band).

Limitations of Current Methods

The current methods have a number of limitations. These include:

1. Relying on one or two discrete points for determining compression can underestimate maximum compression. If the point does not lie at or near the point of maximum compression, then it is unlikely that it will pick up the maximum compression value. For oblique loading, this problem is more likely to occur, since the point of maximum loading will be away from the location of the sensor.
2. The electrical resistance method employed by Rouhana in the fluid abdomen does involve multiple points, but there appears to be differences in the response under differing boundary conditions.
3. For smaller children (3 year old and younger), there is currently no reliable method for measuring abdominal compression.

Exploring Alternative Methods

Three different sensor technologies were evaluated to determine their suitability in measuring abdomen deflections.

Hall Effect Sensors. Hall effect sensors can measure the relative rotation of two small segments in the range of –40 deg to +40 deg. A number of sensors can be linked to measure the total deformation of a linear strip. The sensor is quite small, with the longest dimension less than 0.5 cm.

ShapeSensors. These are sensors manufactured by Measurand, Inc. in Canada. They measure the displacement at the end of a flexible beam due to delay in the transmission of a light beam.

Resistive Flex Sensors. Functioning depends on the changing resistivity of a flexible strip as it is bent. It can be used to measure average curvature of small sections. These are described in greater detail in the sections below.

HALL EFFECT SENSORS

The Hall effect sensor is encapsulated in a small package with length and width less than 0.5 cm and thickness less than 0.2 cm. The sensor can be obtained with relatively sophisticated control electronics embedded within the package. This allows the sensor to be programmed for sensitivity, range, and temperature compensation. The output of the sensor is a high voltage signal, usually in the range of 0 – 5V, and thus would not require further amplification. A special programming board, supplied by the manufacturer, is used to set the sensor parameters. The following shows a typical sensor and the programming board.
The Hall sensors used for the testing were the HAL-805 series, obtained from Micronas (Micronas, 2002). The sensor operates on the response of the sensor to the presence of a magnetic field. The response depends on the distance of the magnet from the sensor and also on its orientation, thus the sensors can be used to design both angular and linear displacement sensors. In our application, the aim was to design an angular sensor, where the angle would correlate with the deformation of the abdomen surface. A small, neodymium magnet was used and during the initial effort, the response for different orientations and separations were recorded. Once the optimum distance and orientation was obtained, a package was designed which would allow the repeatable measurement of the angle at a location. A small hinge mechanism was designed, with the sensor on one side of the hinge and the magnet on the other. A calibration fixture was also designed to allow one to calibrate the sensor mounted in the mechanism. During the design effort, a smaller hinge was tested, but it was found that the hinge was not robust enough in torsion, and the small footprint made it difficult to attach to another substrate. The photo on the left (Figure 3) shows the two hinge designs while the photo on right (Figure 4) shows the calibration fixture.

The sensor output shows good linear response between \( \pm 25 \) deg. with a \( R^2 > 0.99 \). A better fit is obtained using a cubic curve, with a \( R^2 > 0.9999 \). The repeatability between successive calibrations is also good with variation < 0.2\%. The following (Figures 5 and 6) shows the cubic fit and repeatability graphs.

Figure 1: View of Hall sensor.  
Figure 2: Hall sensor programming board.  
Figure 3: Halls sensor/magnet in hinged mount.  
Figure 4: Hinge angle calibration fixture.
The next stage in the sensor development process was to come up with a packaging scheme to actually measure the deflections across the abdomen. The design that was developed was to have the hinges securely attached to a flexible, non-stretchable, strip. The initial test strip was made of reinforced nylon, with the hinges attached to it using 5-minute epoxy. The sensors normally held up well to impacts, but after a number of tests (> 10) tended to gradually debond from the strip. Testing was performed on a foam section, cut to according to the dimensions for the lower abdomen in the Thor-NT. A groove was cut in the front of the foam to allow the sensors to be securely located. The following (Figures 7 and 8) shows the Hall sensor strip and placement on the foam, using three Hall sensors.

A series of quasi-static and dynamic impact tests were conducted to evaluate the response of the sensors. The front of the foam was loaded by a 76mm diameter impactor, with a moving mass of 8.3 kg. Figure 9 shows the output from each of the three sensors. The sensors at the end show positive output, indicating relatively large change of angle, and the sensor in the middle shows a much smaller, negative output. The output reflects the fact that the largest change in curvature is at the edges of the impactor and the foam in the middle, remains fairly flat (the part in contact with the impactor surface). The angle time histories at the three locations were used to calculate the maximum total deflection. The calculated deflection is compared with the LVDT output in Figure 10. There is generally good agreement in the maximum deflection and time duration, but there is discrepancy in the initial loading pattern and final unloading pattern. This difference is probably related to how well the strip holding the Hall sensors follow the deformation of the foam. There is a distinct lag in the time it takes for the sensors to pick up the change in angles on the foam surface. The amount of lag is approximately the same as the small step that is seen in
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the LVDT curve. Upon closer examination, it is seen that the central sensor does start to respond early, but does not have a significant effect on the maximum deflection until much later.

![Figure 9: Output from individual Hall sensors (quasi-static).](image1)

![Figure 10: Comparison of LVDT with calculated deflection (quasi-static).](image2)

Tests were also conducted to evaluate dynamic response, using the same impactor. The output from the Hall sensor strip is shown in Figures 11 and 12. As in the quasi-static case, there is an initial lag between the output of the Hall sensors and the LVDT. In this case, the calculated deflection is well below the deflection measured by the LVDT, though the general shapes are similar.

![Figure 11: Output from individual Hall sensors (dynamic).](image3)

![Figure 12: Comparison of LVDT with calculated deflection (dynamic).](image4)

The likely source of the discrepancy is that, under dynamic loading, the hinges may not change angles to follow exactly the curvature of the deformed foam surface. It was thought that having additional sensors may help to improve the situation. While the testing with the 3-sensor strip was being undertaken, a band was designed to accept seven of the hinges. It was also found it was difficult to keep the hinges securely attached to the nylon strip. The new strip was made of Urethane, and it was easier to bond the hinges to the surface. Figure 13 shows the strip with seven sensors attached and Figure 14 shows the strip attached to the abdomen foam.

![Figure 13](image5)

![Figure 14](image6)
Limitations of Hall Sensors

There were a number of problems that had to be solved to get a workable strip that would be able to measure deformation of the foam in a repeatable and accurate manner. These included:

1. Proper sizing of hinges: It was found that if the hinges were made too small, they were difficult to attach to the underlying strip. Also the two flaps could twist more easily if the hinge was too small. This led to the design of a larger hinge, which would reduce the overall accuracy, but improve the robustness.

2. Hinge material: The material for the hinge was also important. Proper adhesives could not be found for hinges made of Delrin. With PVC, standard epoxy was adequate for attaching to a Urethane strip.

3. Mounting of strip: It was found that the strip had a lag when following foam deformation. During dynamic testing, it also tended to move away from the foam after impact. Because of the flexibility of the strip, it requires additional tension to keep the lag to a minimum. The problem that may arise is the influence of the extra tension on the effective foam stiffness.

SHAPESENSOR

A ShapeSensor (Model 700) was obtained from Measurand, Inc (Measurand, 2005). This is a single channel device which has a linear output with respect to angle as the tape is bent between two points on the tape. It measures change in bend angle of a sensitive strip from the change in the intensity of light passing through a light tube. Measurand also produces ShapeTapes which contain a number of individual sensors that can be used to reconstruct the 3-D shape of strip. The output increases relative to the straight configuration when bent in one direction and decreases when bent in the opposite direction. The excitation voltage is 5V and the output is amplified using an electronic system supplied with the tape. The optimum output when straight is 2.5V and the tape can be bent to +/- 90 deg. The linearity begins to deteriorate at the higher angles.

A fixture which allows bending at specified angles in intervals of 15 deg from -90 deg to +90 deg was used to test the output of the ShapeSensor. Photos of the setup when straight and at 90 deg. are shown in Figures 15 and 16, respectively.
The output of the sensor at 15 deg intervals is shown in the graph below (Figure 17). The linearity is fairly good between −45 deg and +45 deg, and gradually deteriorates as it gets closer to 90 deg.

**Limitations of ShapeSensors**

1. Requires multiple sensor array to cover perimeter of abdomen, which would make the resulting device fairly expensive, since the cost per single sensor is significantly higher than the Hall sensors and the resistive flex sensors described in the next section.

2. The multiple sensor array would require a separate processing box, especially for high speed applications.

3. Previous user experience indicated special procedures for using with soft foam substrates. The recovery of the tape might be hindered with such foam structures.

The objective of the current project was to develop a device, which could be customized to the measurement of abdominal deformation for various sized dummies. It was felt that the ShapeSensor (and Tape) would be too restrictive due to the limitations described.
The final sensor that was evaluated was the resistive flexible sensor. These have normally been used to measure bending in beams, e.g. in data gloves for measuring finger motion. They consist of a resistive layer, usually painted on a Mylar backing. Conductive sections are painted on one side to tune the total resistance of a strip. Strips can be manufactured of different lengths as shown in Figure 18, while Figure 19 shows one with the wiring in place.

The flex sensor is obtained from the manufacturer with solder tabs attached at the very end to allow for the measurement of the resistance of the whole strip. But the resistance in any section of the strip is dependent on the amount of bending in that section. The strip was divided into equal segments and wires were epoxied to the conductive portion at the location, such that the voltage drop between adjacent wires would be proportional to the resistance in the segment, which in turn would be dependent on the curvature or bending in the segment. A problem that arose in this construction, was the fragility of the epoxied contact. Silver epoxy was used, and even with some strain relief, the contact would get loose after a number of dynamic impacts.

**Calibration**

A number of circular wood templates were cut to allow for the calibration of the strips. The radii of the templates varied from the largest with a radius of 25.4 cm (10 in) to the smallest with a radius of 5.08 cm (2 in). The templates are shown in Figure 20, and a typical measurement is shown in Figure 21.
When the strips are wrapped around the template, some attention had to be paid to the way the end of the flex sensor was placed, since the solder tabs at the end would slightly raise the edge of the strip and could induce a small error in the curvature of the last segment. Figure 22 shows the output from the strip (with six segments) with voltage as a function of the curvature. Upon evaluating various fit functions, it was found that a simple quadratic provided good agreement with each of the segments (each segment had a different coefficient). The fit of the output from one of the segments to a quadratic curve is shown in Figure 23.

![Figure 22: Calibration curves for six segment flex sensor.](image)

![Figure 23: Graph of typical output from flex sensor showing quadratic fit.](image)

The differences between individual segments arise from the effective resistance of each segment. (They are not equal because the relative length of the conductive portion of the curve varies segment to segment.) With a quadratic curve the correlation parameter $R^2 = 0.99$. This would indicate that the accuracy of the readings would be in the range of 1-2%.

Because the flex sensors could be made in different lengths, and it conformed more closely to the shape of the abdomen foam, it was evaluated more thoroughly as a candidate for developing the new abdomen deflection sensor. Preliminary testing was conducted using small foam components. The rationale for using a small surrogate was that a desired application was measuring the deflection in the Aprica 3.5kg Infant Dummy that was developed by GESAC for Aprica Kassai, Inc (Wang et al., 2005).
Preliminary Testing

Both quasi-static and dynamic tests were conducted. The tests were conducted using a small, transfer pendulum testing device. This was developed specifically for testing the Aprica Infant Dummy. Tests were performed with the flex strips oriented vertically, as well as, horizontally with respect to the fixture. The initial setup of the foam is shown in Figures 24 and 25.

Two different impactors were used. One was a circular disk with diameter of 50 mm and the other was a rod with a diameter of 10 mm and length of 114 mm. The impactor masses were in the range of 1.5 – 2.0 kg. Testing was done using a single strip at the region of impact and with strips near the region of impact. The results from the testing are shown in Figures 26 and 27.

The results from the preliminary tests show that peak deflection and peak time are predicted to within +/- 5%. The unloading occurs more rapidly than seen by the LVDT. In the arrangement using two strips, the peak deflections show similar time histories, and the LVDT deflection time history falls in between the response seen by the two strips.
Testing with Infant Dummy

Following the tests using the foam components, tests were performed with the Aprica 3.4 kg infant dummy. Both disk and rod-shaped impactors were used, and the flex strips were applied in both horizontal and vertical configurations, with some tests using two strips and some three strips as shown in Figures 28 and 29.

Results with the infant dummy tests, show that the flex sensors show similar response as in the case of the component tests, but in this case the peak is underestimated by about 4%. As seen in Figure 30, the impact actually shows two peaks, arising from the impactor hitting the abdomen twice (due to the rebound of the pendulum). There is good agreement in the time of the first peak. The faster unloading is still present, and results in the second peak being significantly underestimated. The responses from both strips are close.

A series of tests were also conducted with the impactor hitting 12.7 mm (0.5 in) and 25.4 mm (1.0 in) above and below the flex sensor. These were done to see the change in the deflections measured by the sensor as the impact point was moved away from the sensor. Table 1 shows the change in maximum deflection measured by the sensor compared with the deflection measured by the LVDT at the point of impact.
Table 1. Response of Resistive Flex Sensor to Offset Tests.

<table>
<thead>
<tr>
<th>Offset</th>
<th>LVDT (mm)</th>
<th>Flex (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>center</td>
<td>33.7</td>
<td>32.5</td>
</tr>
<tr>
<td>+12.7 mm</td>
<td>35.1</td>
<td>21.2</td>
</tr>
<tr>
<td>+25.4 mm</td>
<td>38.6</td>
<td>5.7</td>
</tr>
<tr>
<td>-12.7 mm</td>
<td>31.3</td>
<td>22.7</td>
</tr>
<tr>
<td>-25.4 mm</td>
<td>32.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The expected variation with distance is seen, with the deflection falling off quickly when the point of impact of the rod moves to about 25 mm above or below the sensor. This points to the need of being able to measure the deflection near the point of impact. The actual deflection could not be confirmed for these tests, since a separate measuring device, such as a stringpot, was not available for these tests.

**Limitations of Resistive Flexible Sensors**

With the current configuration, there are still some problems to resolve. These include:

1. With the present fixation procedure, care must be taken to ensure that the wire contacts do not break off. A possible solution would be to have conducting strips etched directly on the Mylar substrate with solder tabs crimped.

2. It is necessary to maintain good contact between the strip and the material, along the length of the strip. The calculation procedure depends on accurate measurement of curvature from each segment. Especially, during beginning of loading and unload, the end segments may deform a little differently than the rest of the strip. This can lead to wrongly estimating overall deflection.

3. The number of segments that are required to provide accurate estimation of deformation over the whole length of the strip may have to be increased. The proper balance of obtaining an accurate measurement of the deformed shape and keeping the number of required channels small may have to be tested in additional test configurations.

**DISCUSSION**

Three different sensors were evaluated to determine their suitability for measuring deflection of the ATD abdomen. A system to measure abdomen deflection is needed since it is one of the best measures of predicting abdomen injury. Some problems of current systems is they are mainly point-based and may not provide accurate predictions of maximum deformation when loading is away from the sensor locations. The objective of the current project was to design a system that would be easy to install, relatively inexpensive, and be able to measure maximum deformation for oblique loadings. The sensors tested were based on the Hall sensors, a specialty sensor known as ShapeSensor, and the third based on flexible, resistive strips.

During the evaluation, the ShapeSensor design was found to be limited by the fact that multiple sensors would be required, with a special signal conditioning system, making the system fairly expensive. In addition, problems had been reported about loss of accuracy when the system was used with materials undergoing large deformations such as foams. Thus this design was not pursued further after the initial evaluation.

Both Hall sensors and resistive flex sensors showed promise as possible instruments for measuring dynamic abdomen compression. The designs were developed to a point where they could be installed on a model abdomen foam. A hinged fixture was developed for inserting the Hall sensor and associated magnet and the relative angle of the hinge was the measured variable. The Hall sensors had excellent calibration and repeatability characteristics. For the calibration, the best fit was with a cubic function, with a $R^2 \approx 0.9999$. Some problems were encountered during testing. In dynamic tests, the hinges did not always conform to the
local curvature, since they acted as potential stiffeners within the flexible strip. The hinges could also separate from the flexible strip to which they were bonded. Because of the limitations, further work using the Hall sensors were stopped, until a viable solution could be found.

The design using the resistive flex sensors was the one considered for further development. The flexible strip conformed better to the shape of deformable foam, though care had to be taken to keep the ends of the strip firmly attached to the underlying shape without affecting the slip conditions. The flex sensors had the additional advantage that their lengths could be modified to correspond to the application: smaller lengths for smaller ATDs and longer lengths for larger ATDs. It was found that a segment length between 35 mm to 50 mm provided good coverage for estimating curvature. This implied that a strip of length 100 mm (appropriate for the infant dummy) would have 3-4 segments and a strip of length 380 mm (for 50th percentile male dummy) would have 6-8 segments. To provide good coverage, multiple strips can be used, e.g. two strips when placed horizontally over the middle of the abdomen, or three strips when placed vertically.

The calibration results were not as precise as the Hall sensor, with the output being predictive in the range of 1 – 2% (while the Hall sensor was in the range of 0.1%). But the flex sensor had the advantage that the output represented the average curvature over a segment, rather than the curvature at a point on the segment, as in the case of the Hall sensor. This meant that it was possible to reconstruct the approximate shape with fewer sensors. The biggest problem encountered with the resistive flex strip was the relative fragility of the solder joints between the external wiring and the terminals on the strip. If they were not properly secured, they could break off and damage the conductive paint on the strip.

A number of tests were initially conducted using the flex sensors with foam components with approximate size and shape of an ATD abdomen. Following the preliminary tests, additional tests were conducted with the 3.4 kg Aprica Infant Dummy. The results from both types of tests, indicated that the maximum deflection, and the time at which maximum deflection occurred, were being computed fairly well, when compared to the measurement from an LVDT. The final unloading portions of the time history did not compare well with the LVDT data.

Further testing is planned with a full size abdomen component, and with the abdomen installed in a complete dummy. Tests using a belt loading the abdomen are also planned. There are several areas where improvements in the design are being made. One is improving the approximation procedure with variable end conditions. Another is making the ends of the strip follow the deformation of the abdomen more closely, since they have a tendency to rebound faster than the abdomen foam.

ACKNOWLEDGEMENT

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REFERENCES


DISCUSSION

PAPER: Development of Abdominal Compression Measurement Sensors
PRESENTER: Tariq Shams, Gesac, Inc.

QUESTION: Kristy Arbogast, Children’s Hospital of Philadelphia
I have two questions for you. The first question is thinking about a more realistic loading pattern as in a belted occupant--

ANSWER: Yes.

Q: And how your sensors perform when they’re loaded, not just in a linear way but as the belt kind of wraps around the abdomen.

A: Okay. Actually, we have been doing that with an adult abdomen model because we haven’t been able to tuck up a rig to do belt testing on the infant. So we have one for the adult abdomen and we have been testing. Right now, it has been semi-successful. One of the problems is that now it covers a much larger parameter and the one we get—Again, the loading starts—The loading phase is matched pretty well. I’ll try to see if I can get a graph of that, but the unloading starts earlier than we see with the rigid impactors. One reason we think is the same issue that with the belt because it is compressing the edges of the abdomen more than the rigid impactor is. The ends of the strip start moving away and that is—Again, I think it—if we can solve the retention problem, retaining it without causing harm to the sensor because we have to have a slip condition still available without destroying. So we would basically have a slip condition but no displacement laterally from the surface of the abdomen. So I think if we can solve that, we should be able to use it in a belt environment. And again, because it is based on our results from the offset testing, we think it will be, for example, if you have two bands in a child, it should cover basically all of the sensitive areas for a, say, three year-old if that’s the age of interest. And, it should pick up the major points of loading in that case.

Q: Okay. And then my second question is with regard to the pediatric dummies. The challenge of measuring abdominal compression is one, a sensor issue, which you’re trying to address here; but the second is a biofidelic material that sensor is--

A: Yes.

Q: Attached to or imbedded in. Have you thought about how you might alter the pediatric dummies, which are limited in that regard?

A: Yes. The experience we have had with the dummy we made—this is a newborn dummy—we have limited testing because all of the data we used was scaled data. This was the standard scaling on material properties and geometry. So we are looking for—that means more realistic and dynamic data that’s available, especially related to strain rates and then what kind of materials would be useful. On the adult dummies, we have, for example, in order to simulate strain rate affects, we have been working with silicone, which is similar to Dr. Rouhana’s fluid abdomen. And, we get fairly good strain rate response there and this seems to work on that. So—because those are two separate. I think, again, if we resolve the retention issue on the surface, it should work on pretty much any material with which the abdomen would be made.

Q: Thank you.

A: Sure.

Q: Guy Nusholtz, DaimlerChrysler
Just a quick question: How do you know it’s the retention issue and not something else?
A: Because we have been doing some high-speed video that were not very good in presenting that here, but we could see the ends start moving after maximum loading was reached. And if we tried to, sort of—We were trying to tape it, sort of brut-force methods, to the sides without—trying to not allow it to slip, which would cause the thing to start breaking at the contacts. We noticed that it was moving.

Q: Okay. So it’s just a speculation at this time that you’re going to try and test.

A: It’s right. And so, what we are trying to do is we are trying to work out a good retention method and then compare. If that still shows big differences, then obviously my claim is false.

Q: Okay. We’ll go with that. Thank you.