ELSEVIER
International Journal of Industrial Ergonomics 17 (1996) 285-290
International Journal of Industrial Ergonomics

Short communication

A new method for extending the range of conductive polymer sensors for contact force

Aparecido A. Carvalho [a], Robert G. Radwin [b,*]

[a] Department of Electrical Engineering, Universidade Estadual Pulista, P.O. Box 31, 15.378-Ilha Solteira-SP, Brazil
[b] Department of Industrial Engineering, University of Wisconsin-Madison, 1513 University Avenue, Madison, WI 53706, USA

Received 4 June 1995; accepted 19 June 1995

Abstract

This paper describes a technique for extending the force range of thin conductive polymer force sensors used for measuring contact force. These sensors are conventionally used for measuring force by changing electrical resistance when they are compressed. The new method involves measuring change in electrical resistance when the flexible sensor, which is sensitive to both compression and bending, is sandwiched between two layers of spring steel, and the structure is supported on a thin metal ring. When external force is applied, the stiffened sensor inside the spring steel is deformed within the annular center of the ring, causing the sensor to bend in proportion to the applied force. This method effectively increases the usable force range, while adding little in the way of thickness and weight. Average error for loads between 10 N and 100 N was 2.2 N (*SD* = 1.7) for a conventional conductive polymer sensor, and 0.9 N (*SD* = 0.4) using the new approach. Although this method permits measurement of greater loads with an error less than 1 N, it is limited since the modified sensor is insensitive to loads less than 5 N. These modified sensors are nevertheless useful for directly measuring normal force applied against handles and tools and other situations involving forceful manual work activities, such as grasp, push, pull, or press that could not otherwise be measured in actual work situations.

Relevance to industry

Force measurement instruments are important for providing ergonomics practitioners with a quantitative means for assessing the magnitude of physical stress associated with a particular operation, and for measuring the reduction in force associated with an ergonomic intervention.

Keywords: Contact force; Force sensor; Physical stress measurement

1. Introduction

Conductive polymer devices, such as ones manufactured by Interlink Electronics, decrease electrical resistance when they are compressed. These devices are available as force-sensitive switch elements, but they have been found suitable for measurement of compressive loading in ergonomics studies (Jensen et al., 1991; Radwin et al., 1992; Fellows and Frievalds, 1991; Yan, 1993). Although these sensors are limited in accu-

* Corresponding author.

SSDI 0169-8141(95)00053-4

racy, their desirable features include a thin profile (less than 1 mm), light weight (less than 1 g), and ability to withstand very high loading, which make them very attractive for use as force sensors in ergonomics. Because they are durable, thin and light weight, they are useful for ergonomics field studies where direct force measurement is otherwise difficult to obtain.

Conductive polymer sensing elements require just a simple modification for use as force sensors for applied mechanical stress. Since the response of conductive polymer devices are highly dependent on the surface area of contacting structures, a stiff dome may be used for distributing applied force over the sensing area, making it insensitive to contact surfaces thus acting as a force sensor (Jenesen et al., 1991). The dome also helps reduce errors by providing stiffness to the sensing element, which is highly sensitive to bending. These sensors are suitable for practical ergonomics measurements of applied force at the fingers up to 30 N with less than 1 N error.

The 30 N force range is a significant limiting factor since hand forces can often exceed several hundreds of Newtons (Amis, 1987). Another notable limitation of this type of sensor is the tendency for it to bend as force is applied. This is particularly a problem when the sensors are attached to the fingers and hands, causing the sensors to bend when high forces greater than 30 N are applied. Since conductive polymer sensing elements are sensitive to bending, these sensors have to be calibrated every time they are used.

A new method was investigated and reported in this paper for increasing the force range of conductive polymer force sensors. The method employed a parallel spring system for controlling deformation of the sensor, enabling them to operate at greater forces. Construction of these modified sensors is described, and their calibration, dynamic properties, and response characteristics are measured. Measurement error is compared against a strain gage force instrument.

2. Methods and materials

A sensor similar to the sensor described by Jensen et al. (1991) was constructed (hereafter referred to as the conventional sensor) using an Interlink conductive polymer sensing element with a 12 mm circular sensing area. A 1.5 mm high, 13 mm diameter dome was made from Torlon, an easily machined polymer material, which was considered superior to epoxy in that it provided the sensor with greater stiffness and was less compressible than epoxy. The dome was attached to the sensor using a silicon rubber adhesive. The sensor was mounted on a 20 mm diameter, 1 mm thick aluminum disk for rigidity.

An Interlink conductive polymer sensing element, with a 12 mm circular sensing area, was sandwiched between two thin layers of tempered spring steel shim stock (McMaster 9503K11). Each shim was 51 μm thick. The sensing element was fastened directly to the spring steel layers using silicon rubber. The sensor and spring steel layers were supported on top of a 1 mm thick, 20 mm diameter annular ring containing a 16 mm hole. The conductive polymer sensing element was located directly over the center of the ring. The spring steel was attached to the aluminum ring using epoxy cement on the edges. A similar Torlon dome as the conventional sensor was attached on top of the assembly. This configuration (hereafter referred to as the modified sensor) is depicted schematically in Fig. 1.

The Interlink sensing elements were connected as resistors in voltage divider circuits and

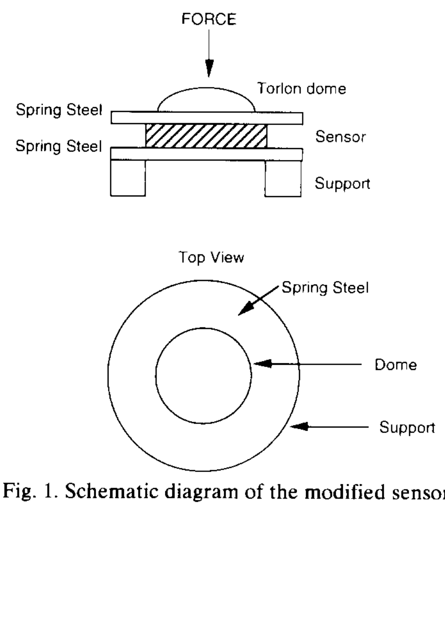

Fig. 1. Schematic diagram of the modified sensor.

amplified in two-stages using inverting 741 operational amplifiers. The sensors were calibrated against a strain gage load cell (Interface SM-100) and a full-bridge strain gage amplifier. The load cell was calibrated against known weights. The load cell was attached to a modified drill press for compressing the sensor.

Analog data was sampled using a 12-bit analog-digital converter and a Macintosh II microcomputer with LabVIEW data acquisition software. The sample rate was 30 Hz. Performance between the two sensors were compared. Both static and dynamic loading were used for evaluating sensor performance. Two replicates of each type of sensor were constructed and tested.

3. Results

3.1. Static calibration

Static calibration was performed by applying different forces in random order using the drill press while the sensor was positioned on an aluminum block. Sensor static calibration data were fit to third-order polynomial regression curves. Typical calibration curves for both the conventional and modified configurations are shown in Fig. 2. Each sensor was calibrated for two replications of 10 different levels of force up to 105 N. The average correlation coefficient was 0.99 for both the sensor-dome and sensor-spring steel-dome configurations.

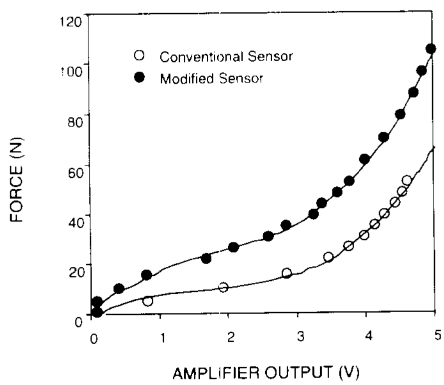

Fig. 2. Representative calibration curves.

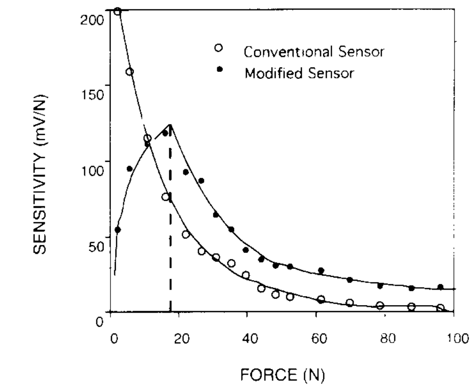

Fig. 3. Plot of force sensitivity between the two configurations.

Average sensitivities (mV/N) for the two sensor design configurations are plotted as a function of applied force in Fig. 3. Sensitivity for the conventional configuration was greatest for low force and continuously decreased rapidly as applied force increased. The modified sensor sensitivity was treated as a piece-wise function; sensitivity increased to a maximum of 120 mV/N as applied force increased to 16 N, and then decreased as input force increased. The force sensitivity for the modified sensor was greater than the conventional configuration for force inputs greater than 12 N where the sensitivity curves intersect (Fig. 3).

3.2. Dynamic response

Dynamic loading was applied by slowly but steadily increasing the applied force up to 105 N and then decreasing back to zero. The modified configuration produced more desirable linearity characteristics in terms of hysteresis. Average maximum hysteresis for the conventional configuration was 13% while the modified sensor configuration was 6% when loading the sensor to 96 N.

3.3. Step response

The sensors were also tested using a force step input. Five replications of step inputs were made for 40 N and 80 N step forces. Rise time was estimated from the time needed for the sensor output to achieve 63% of its steady state value for each step input. The average rise time for each configuration is shown in Table 1. The average rise time for the conventional configuration was 0.85 ($SD = 0.07$) ms while the modified sensor configuration was 1.25 ms ($SD = 0.10$). Although the modified configuration had a statistically significant greater rise time ($F(1,16) = 108.2$, $p < 0.01$), the magnitude of this 0.4 ms difference was considered small.

3.4. Static sensor error

Finger mounted tests were performed when attaching the sensors to the distal thumb pad. Each sensor was taped to the thumb using surgical tape. A dual beam strain gage dynamometer (Radwin et al., 1991) was pinched between the index finger and thumb containing the force sensor. A comparison between absolute error observed when measuring finger forces against the strain gage dynamometer is shown in Fig. 4. The two sensors were compressed by applying forces between 5 N and 100 N. Force conditions were randomized for each sensor. The modified sensor was insensitive to force less than 5 N and did not respond to these inputs. Therefore no error was measured for the modified configuration using 5 N loading.

When force inputs were greater than 5 N, average error for the modified sensor was significantly less than for the conventional sensor ($F(1,14) = 213.3$, $p < 0.001$). Error for the conventional sensor, averaged over the force range between 10 N and 100 N, was 2.2 N ($SD = 1.7$). Average error for the modified sensor was 0.9 N ($SD = 0.4$). The interaction between load force and sensor type was also significant ($F(6,14) = 14.7$, $p < 0.001$). Average error for the conventional configuration increased as force increased from 0.4 N for a 5 N load to 4.9 N for a 100 N load. This trend was not observed for the sensor-spring steel-dome configuration (see Fig. 4). Tukey multiple contrasts revealed that significant differences ($p < 0.01$) between the error for the two sensors were observed for force inputs greater than 50 N.

Table 1
Average rise time ($N = 5$)

Sensor	Step force (N)	Rise time (ms)
Sensor-dome	40	0.86 ($SD = 0.06$)
	80	0.84 ($SD = 0.08$)
Sensor-spring steel-dome	40	1.22 ($SD = 0.11$)
	80	1.28 ($SD = 0.08$)

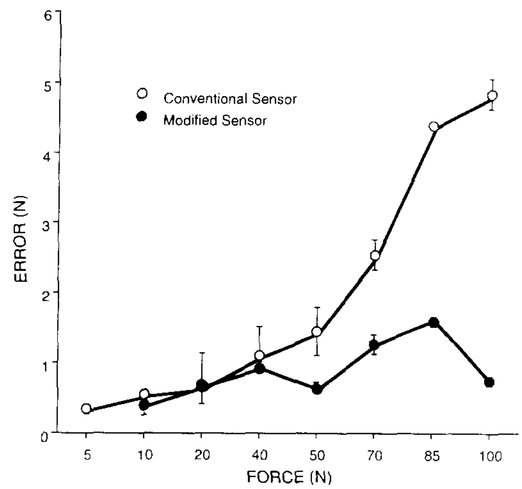

Fig. 4. Average measured error ($N = 5$ replications) between each sensor configuration and a strain gage load cell.

Percent error for the conventional sensor ranged from a minimum of 2.5% for 50 N loading to a maximum of 7% for 5 N. The average percent error for the conventional sensor was 4.4% over the 5 N to 100 N force range. Percent error for the modified sensor ranged from a minimum of 0.8% for 100 N loading to a maximum of 4% for 100 N. The average percent error for the modified sensor was 2.3% over the 10 N to 100 N force range.

4. Discussion and conclusions

Technology available for ergonomics practitioners and researchers for directly measuring applied hand force in forceful manual work activities such as grasp, push, pull, or press in field studies has been very limiting. Force is often approximated in practice by estimating the load, or by approximating the force necessary for accomplishing a task. Sometimes practitioners measure force indirectly using spring scales or electronic load cells. Special handles containing strain gages have been constructed for measuring hand force directly (Radwin et al., 1991; Oh and Radwin, 1993), but this approach is impractical for most practical ergonomic investigations in industrial settings. Electronic instruments are needed for attaching directly to handles, objects, or the hands so the actual force exerted can be directly assessed. Such instruments should be small enough to not interfere with normal grasp yet provide accurate measurements of forceful exertions in manual operations. Force measurement is not only important to ergonomics researchers, but provides ergonomics practitioners with a quantitative means for assessing the magnitude of physical stress associated with a particular operation, and for measuring the reduction in force associated with an ergonomic intervention.

Although strain gage load cells are more accurate and linear than conductive polymer force sensors, strain gage load cells are often too cumbersome for use in routine ergonomics assessment studies. Furthermore strain gages themselves lack durability and are difficult to attach to arbitrary objects. Conductive polymer sensors are thin, durable, and easy to use, but they have limited force range, nonlinearities, and large errors which limit their use for many practical ergonomics applications. The modifications tested in this paper help reduce these limitations, particularly when they are used for relatively high force applications.

The modified sensor provided more sensitivity and less error than the conventional sensor for high force inputs. The observed response characteristic of the conductive polymer force sensor fit a cubic polynomial (see Fig. 2). Since sensitivity decreased greatly for forces greater than 30 N (see Fig. 3), the output response was less for an incremental force input less than 30 N than for the same input increment when force is greater than 30 N. Consequently the output error increased when input force was greater than 30 N. This increase in error as input force increased was also observed by Jensen et al. (1991).

The change in response characteristics resulted from changing the sensor force response from changing electrical resistance when the sensor is compressed to a change in resistance when the sensor bends and compresses. The modified force sensor operated on the principle that conductive polymer sensing elements are responsive to bending as well as compression. When force is applied, the spring steel is deformed around the conducive polymer sensor acting as a parallel spring. This has the effect of attenuating the compressive force applied to the sensor, by making it deform for much greater force as it would for less force. Consequently the modified sensor had less sensitivity and increased force range, and thus more accurate measurements than the conventional sensor.

The spring steel provided a restoration force allowing the sensor to straighten after bending. Since deformations of the spring steel layers were small, it behaved as a linear system and improved linearity characteristics of the overall sensor. Rise time for the modified sensor may have been affected by the added inertia introduced by the spring steel. Future work should develop a theoretical model for the conventional and modified sensors.

The modified sensor is relatively small and compact and suitable for attaching to portions of the hand or directly to handles and tools. Although a 1 mm thick aluminum ring was used, it is anticipated that a ring half that thickness may suffice. The design of a thin force sensor is made possible by the high durability of conductive polymer sensors. Other sensor technologies, such as strain, would not be capable of withstanding the stress and it would be difficult to secure the integrity of lead connections to strain gages in a similar manner. The modified sensor should be useful for both practical ergonomic studies as well as for industrial ergonomics research.

References

Amis, A.A., 1987. Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters. Journal of Biomedical Engineering, 9: 313–320.

Yan, H.M., 1993. A hand posture measurement system for evaluating manual tool tasks. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, 2: 754–758.

Fellows, A. and Frievalds, A., 1991. Ergonomic evaluation of a foam rubber grip for tool handles. Applied Ergonomics, 22(4): 225–230.

Jensen, T.R., Radwin, R.G. and Webster, J.G., 1991. A conductive polymer sensor for measuring external finger forces. Journal of Biomechanics, 24(9): 851–858.

Oh, S. and R.G. Radwin., 1993. Pistol grip power tool handle and trigger size effects on grip exertions and operator preference. Human Factors, 35(3): 551–569.

Radwin, R.G., Masters, G.P. and Lupton, F.W., 1991. A linear force summing hand dynamometer independent of point of application. Applied Ergonomics, 22(5): 339–345.

Radwin, R.G., Oh, S., Jensen, T.R. and Webster, J.G., 1992. External finger forces in submaximal five-finger static pinch prehension. Ergonomics, 35(3): 275–288.