Evaluation of Bend Sensors for Limb Motion Monitoring

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Abstract— **Bend sensors are composed of a flexible substrate and a conductive layer, which changes its electrical resistance with the bending or the angular displacement. They are flexible, light and low-cost devices, usually adopted to measure the human joint motion. For example, bend sensors can be mounted over the elbow, the knee or the finger measuring their angular position. Commercially, different types of bend sensors are available. In this paper, four types of sensor made of a carbon ink-based layer were studied. These sensors differ for the protective layer over the conductive ink. Their electrical resistance also decays over time and depends on how the sensor is fixed on the joint. A preliminary evaluation is reported on this paper. In particular, the behavior of the electrical resistance of the sensors varying the bending angle and the decay of the resistance over time are reported. The goal of this study is to give information about these sensors to the designers in order to increase knowledge for a metrological characterization and to choose the best strategies to design a biomedical device for limb motion monitoring.**

Keywords—bend sensors; piezoresistance; viscoelastic material; stress; strain; microcracks; tunneling effect; hopping effect

I. INTRODUCTION

Over the last thirty years, the study and the development of new techniques and devices for monitoring the motion and the human body health have been performed both in the academic and industrial environments. The applications can be different: in the manufacturing industry, for example, the use of telemanipulators allows operating in a remote harsh environment; in the electronic entertainment, many videogame consoles are based on the user interaction with the virtual reality; in the hospital, the medical personnel can conduct diagnostic tests on the patient's range of motion (ROM); in home environment, the patient can perform autonomously rehabilitation exercises with the supervision of medical personnel through the teleassistance. In 2030, it is expected that the population over 65 will be 20% of the total population in the United States; in Europe and Japan it will reach 30% [1]. Under these conditions, the growing demand for rehabilitation treatments would increase the public spending significantly. The adoption of robotic systems would reduce the healing time in the hospital and give the patient the ability to perform the exercises at home, thus reducing costs and difficulties of transport to a hospital. The devices for human motion monitoring should be wearable including one or more sensors, positioned on the monitored body part, a front-end and a display or a computer to read or collect the data. In this context, the devices must be low cost (because they are destined to personal used), easily wearable and also reliable. Furthermore, the sensors must not constrain the movements. Human motion measurement can be obtained using different techniques, for example using optical, magnetic, inertial sensors. The choice of the best type of the sensor depends on the application and also on the body part to be monitored. Carnaz et al. [2] compare the performance of an electrogoniometer, an inclinometer and a three-dimensional video analysis system for recording neck movement. The electrogoniometer is affected by crosstalk, the video system is bulky and the inclinometer does not measure the neck rotation. Many commercial devices are available in the market: Optrack Certus Motion Capture System [3] is a visual marker based tracking system; Kinect [4] is based around a camera add-on peripheral for the Xbox 360 console; Polhemus G4 [5] is based on a proprietary electromagnetic technology; MTw is a wireless inertial 3D motion tracker [6]. These systems are complex in the implementation and their cost limits the personal use. In the literature, many works propose new solutions and new techniques to track the human motion. The optical system for tracking human body motion requires one or more cameras and usually passive or active markers. To avoid the use of many camera and markers, Yoo et al. [7] elaborated a new method to recognize the human skeletal part and to divide them into many parts such as limbs, torso and face from a video stream. The use of camera needs good light conditions and the absence of body part overlaps in the image. In the domestic use, it is very difficult to control these aspects. The inertial system generally is composed by accelerometers, used as inclinometers, and gyroscopes to establish the orientation of the segment to be tracked. This system can be used, for example, to measure the knee movement [8], or wrist and elbow motion [9], integrating also a magnetic sensor. If the aim is to measure the angular displacement of a joint, two accelerometers must be mounted in two different segments of the limb. To avoid this problem, Lim et al. [10] used an optical encoder to measure the angular displacement of the elbow. In [11], an inductive sensor is integrated in a t-shirt for wireless measures of the posture monitoring. Furthermore, fiber-optic systems can be used to measure the lumbar curvature [12]. Bend sensors can be a good solution for measuring and

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monitoring the limb-joint motion. In fact, these sensors can overcome some problems like cost and usability [13]. A bend sensor is a resistive sensor which changes the electrical resistance when bent; it consists on a resistive strip deposed on a flexible polymeric substrate. As magnetic sensors or accelerometers, also bend sensors require a initial calibration procedure. Furthermore, their resistance decays also over the time. For these reason, the knowledge about the bend-sensor behavior is necessary in order to find out a simpler calibration procedure. This paper analyzes the behavior of four ink bend sensors; three types, with different protection layer, are produced by Flexpoint and one by Spectra Symbol. The manufactures do not provide information about the production process, the ink composition and manufacturer specifications, so it’s very important to evaluate their behavior and to compensate the decay over time. In the Section II, the description of the sensors is reported; also the charge transport through the conductive ink and the physical effects of the resistive layer at rest and after bending are supposed. In the Section III the experimental setup is described and in the Section IV the experimental results are shown; in particular, the relationship between the electrical resistance and the bending angle is obtained. Furthermore, the resistance decay over time and the relationship between the bending angle and the resistance of four types of sensors are reported. In Section V, the experimental are discussed.

II. SENSORS

In this paper, four sensors are considered: three produced by Flexpoint and one produced by Spectra Symbol. They are shown in Fig. 1. The three Flexpoint sensors differ from the overlamination: one has not an overlamination and is more exposed to the environmental condition variations; one is overlaminated with a polyester layer; the last one with a polyimide layer, particularly suitable for harsh environment. The electrical resistance depends on the overlamination, as shown in the following section. The three sensors of Flexpoint have the external dimensions (119 x 8 x 0.127) mm^3 and their sensitive area is (95 x 2.5) mm^2. Spectra Symbol sensor is (112.24 x 6.35 x 0.43) mm^3, and the sensitive area is (95.25 x 3.5) mm^2. All of these sensors are bend sensors, consisting of a single thin flexible plastic substrate and a carbon/polymer ink-based strip. These two layers are coated together in order to have a strong bond between them. At the strip ends, two conductive pads and tracks are deposed connecting the sensor to the metallic pins. The resistive substrate is the same used for thick film resistors [14]. The resistance differs from one sample to others, with tolerance about of the 30% [14-15]. Though the electrical resistance differs among samples of the same type, the behavior of the resistance is similar over the various bend angles. Supposedly, the ink is composed by a polymeric matrix (insulator) and conductive particles. The electron conduction is possible thanks to a conduction path through the conductive particles starting from one terminal to the other. In the insulator-conductor compound, when it is above the percolation threshold, there are two possible ways of transport of electric charge. Firstly, if the conductive-particles concentration is high, the particles are in contact with each other and the resistivity only depends on the conductive-material resistivity. Secondly, for a lower concentration, the transport of charge happens for tunneling effect and hopping effect. So an amount of energy is necessary to transport a charge from a conductive particle to the other. In this case, the resistivity depends on the polymeric-matrix, the conductor characteristics and their interfacing [16]. The sensor changes its electrical resistance when is bent. Two physical effects can happen when the sensor is bent: the first effect is the elastic deformation of the polymeric matrix. When the ink is bent, the distance among the conductive particles increases, thus its resistance, because the ink is partially stretchable. In fact, the ink is composed by polymeric matrix and conductive filler: the polymer is viscoelastic. Due to the viscoelasticity, the change of the piezoresistance depends also on the time. In fact, this type of material is affected by relaxation stress. When it is subjected to a step constant stress, the viscoelastic material strain is time-dependent. Equally, when it is subjected to a step constant strain, viscoelastic material stress is time-dependent. This effect is named creep deformation. These two phenomena cause the hysteric effect. For these reasons, the bend sensor must be placed on the joint in the way that the sensor slides inside the binding, reducing any kind of friction and any viscoelastic effects. In this way the time-dependence of the resistance, which is correlated with the strain and the stress, is reduced. The second effect is the formation of microcracks transversally with respect to the bending direction. An example of microcrack formation is reported in Fig. 2, with 40X magnification. The result of this phenomenon is the increase of the distance among the particles and thus a sensor resistance increasing. This effect is more significant with respect to the stretch effect. The microcracks cause an increase of the distance in the fillers. The mechanism of the charge transport is the tunnel effect and in this the resistance is increased. The presence and type of overlamination reduces the dimension of these microcracks and therefore, the resistance value, as proved later. When the sensor is bent, if the microcracks are exposed to the air, the humidity particles can deposit inside the microcrack, causing the change of the resistance. One reason

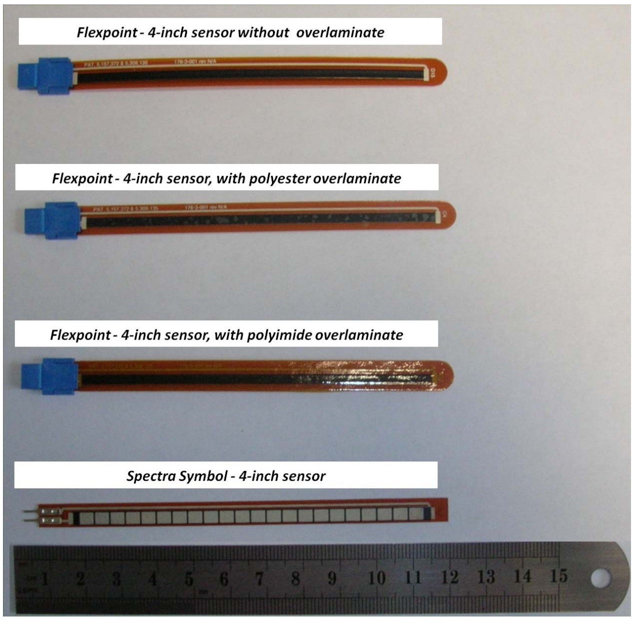

Fig. 1. Commercial bend sensor

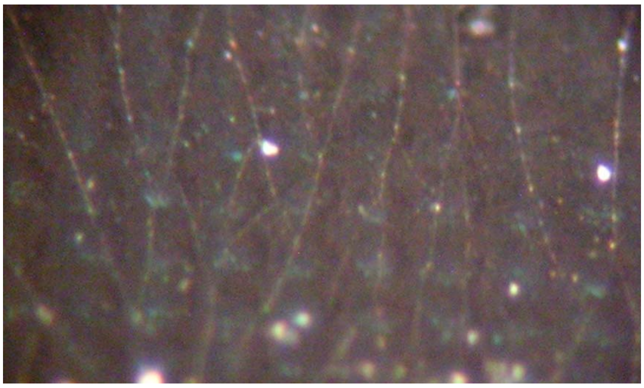

Fig. 2. A focus on the bend sensor of Flexpoint without overlaminate. The microcracks are trasversal with respect to the bending direction

for the overlaminate on the Flexpoint sensor is to protect the microcracks. Due to this, the resistance change over the bending is less because the overlamination reduces the microcrack phenomenon, but the response is more stable in the time, as confirmed in many research [17]. Instead, Spectra Symbol applies over the ink layer a series of high conductive segments, in order to reduce the resistance and the hysteresis effects (Fig.1). The electrical resistance of the bend sensor depends also by the curvature radius. In [18], the relationship between the electrical resistance of the sensor wrapped around calibration tubes of different diameter and the curvature radius of the tube is shown.

III. EXPERIMENTAL SETUP

An experimental setup is designed (Fig 3), in order to evaluate the behavior of the four sensor types described in the Section II.

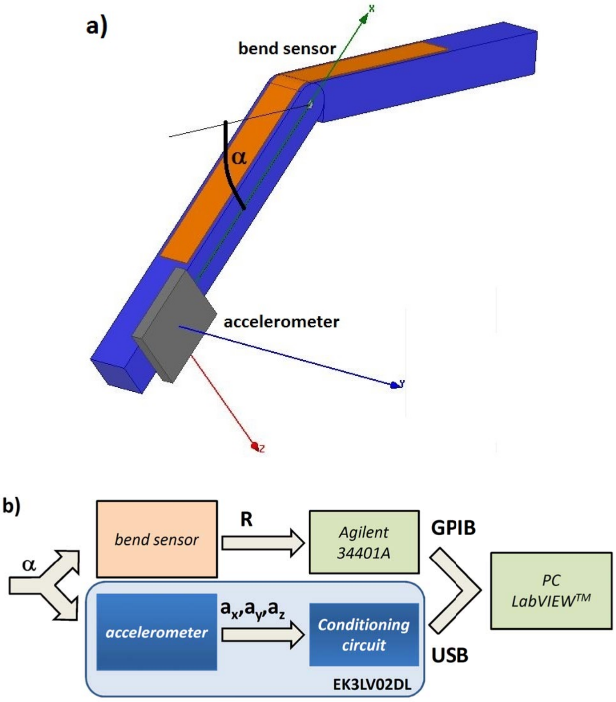

Fig. 3. Experimental set up. a) Structure for bending. b) Block diagram.

In this way, we obtained the relationship between the angular position and the electrical resistance of these sensors and their resistance decay over time. The structure used to bend the sensors is composed of two wooden rods with a central hinge, as reported in Fig. 3a.

The hinge has a diameter of 2 cm. The sensor is fixed on one rod and it is free to slide over the other rod; in this way the longitudinal strain along the sensor is negligible and the change of resistance is caused only by the bending of the sensor. The angular position of 0 degrees is imposed manually when the two rods are parallel. The resistance of the bend sensor was measured with the multimeter Agilent 34401, with 5½ digits and sampling rate of 10 Hz. The resistance and angular-position data were collected and managed by a program implemented in LabVIEW^{TM} environment. The block diagram of the measurement system is reported in Fig. 3b. The angular position is measured by a digital accelerometer and the data are sent to the PC via USB. In this work, one aim is to find the relationship between the resistance and the bending angle. The bend-angle step is about 10 degrees, starting from 0° to 90° and vice versa, in order to take into account the hysteresis effect. The angular position is maintained for 20 seconds. The values reported in the following graphs have been obtained averaging the measures. Another aim is to measure the resistance decay over time, bending the sensor at 90°. In future studies, the movement of the rod will be controlled by a motor and the measure of the angular displacement will be provided by an encoder with high resolution. In this way, a metrological characterization will be obtained both in steady state and in the transient state.

IV. EXPERIMENTAL RESULT

The relationship between the bend angle and the electrical resistance of the bend sensors has been found, using the experimental setup described in the Section II. In Fig. 4-7, the relationship between the resistance and the bending angle is shown with a step of 10 degrees. The measurements refer to one sample for each sensor type described in section II. We verified that the sensor behavior shown in the graphs is similar in many samples of the same type. The sensors are unidirectional, that is the sensitive area must be external with respect to the bending.

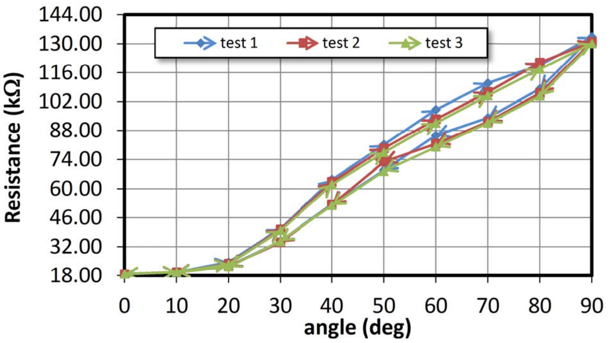

Fig. 4. Relationship between the bend angle and the change of sesnor resistance of Flexpoint sample without overlaminate.

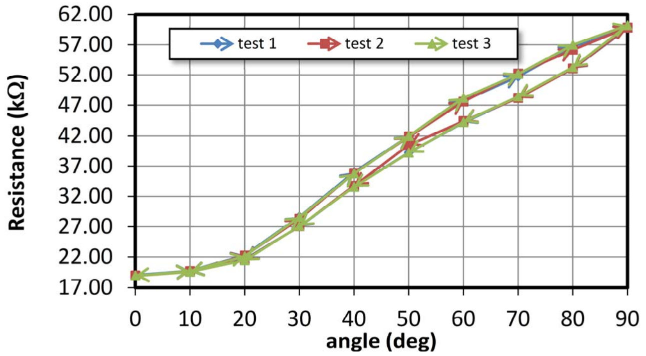

Fig. 5. Relationship between the bend angle and the change of sesnor resistance Flexpoint sample with polyester overlaminate.

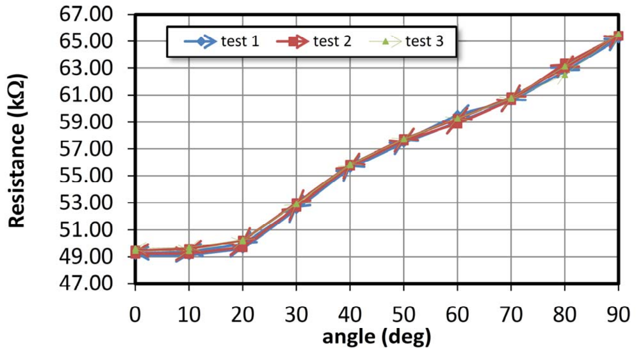

Fig. 6. Relationship between the bend angle and the change of sesnor resistance Flexpoint sample with polyimide overlaminate.

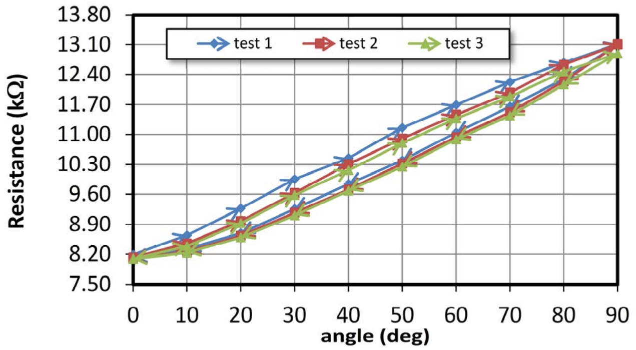

Fig. 7. Relationship between the bend angle and the change of sesnor resistance Spectra Symbol sample.

In Fig. 8, the behavior of the three sensors of Flexpoint is reported, one for each type, to highlight their different sensitivity. In Fig. 9, the step response of the four sensors, one for each type analyzed in this paper, is shown. For these measures, the sensor is positioned on the goniometer and, initially in the flat position, was bent at 90 degrees and was left in this position for 180 seconds. After, the sensor is brought back in the flat position.

As all the resistive film sensors, also these sensors are influenced by temperature and humidity of the environment. The resistance drift is under study.

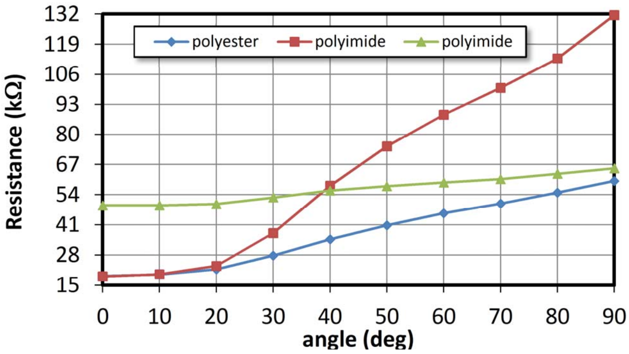

Fig. 8. Comparison of the resistance response of the Flexpoint sensors with different overlaminate.

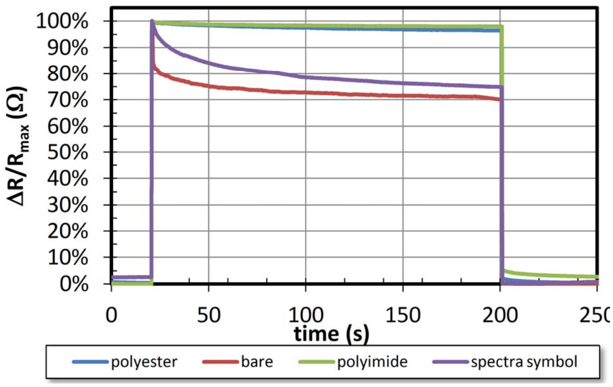

Fig. 9. Decay over the time of the resistance of the bend sensors after the step function.

V. DISCUSSION

In the Section IV, two characteristics of four types of bend sensors are obtained experimentally, using a structure shown in Fig. 3. The hinge of the structure has a 2 cm diameter. For this reason, the relationship between the angle and the resistance is referred for a curvature radius of 2 cm. Changing the curvature radius, the resistance values change, as shown by Simone et al. [18], but the behavior is similar. As reported in the Fig. 4-8, the sensor of Spectra Symbol and the sensor without overlaminate of Flexpoint show a clearer hysteresis effect due to the viscoelastic effect of the polymeric matrix which is not covered by an overlaminate layer. The polyimide overlaminate determines a low hysteresis effect. The different type of the lamination determines the sensitivity of the sensor as reported in Fig. 7 and explained in the Section II. Furthermore, their electrical resistance decays over time, as showed in Fig 9. In fact, the variation of the resistance after 180 second is about 2% in the case of polyester and polyimide sensors, while is over 25% in the case of the other two types of sensors for the reasons reported in Section II. The viscoelastic effects (that is the creep and relaxation deformation) cause the resistance decay over time, because the polymeric layer is more stressed when a protective layer over the conductive ink is absent. The Flexpoint sensors do not return at the same value when return in the flat position. The sensitivity of all the analyzed sensors is not constant over the range but has a non-linear trend between 0° and 30°. This behavior is confirmed also in many works [12, 18] and in the manufacturer specification [14, 15]. The resolution of the sensors is less than 1°, as confirmed by the manufacturers, except of the polyimide sensor that is more than 5°; one reason is due to the structure used for this work to bend the sensor, in particular due to the curvature angle of the hinge. If the design specification requires good accuracy less than 10°, the best choice is the polyester sensor, because it has high sensitivity, low hysteresis effect and low variation of the resistance over the time. The dependences of temperature and humidity are ongoing. Also more theoretical study on the viscoelastic effects described in the Section II will be carried out.

VI. CONCLUSIONS

In this paper, the charge conduction in four types of bend sensor is studied. The sensors are composed mainly of one conductive layer deposed on a polymeric support. The conductive layer is a carbon/polymeric ink deposed in the same way of the thick film resistors. The electrical resistance of the ink depends on the sensor bending for two effects; firstly, the viscoelastic characteristic of the polymeric matrix causes the variation of the distance among the conductive particles; then, the microcracks are formed when the sensor is bending, causing the significant increasing of the among between the conductive particles for large bending. Supposedly, the transport of charge occurs for tunneling and hopping effects when the sensor is bending. The material viscoelasticity causes the resistance decay over time. For this reason, the bend sensor must slide over the joint and any kind of frictions must be dramatically reduced. The overlaminate layer can reduce the viscoelastic effect but the sensitivity is less than the sensor without overlaminate. In this paper the relationship between the electrical resistance of the sensors and the bending angle is shown. Also the resistance drift over time is measured. A more in-depth study of the physical sensor effects during the bending with the aim of confirming the experimental results, are in progress. Finally the study of influence of the temperature and of the humidity on variation of the resistance is still ongoing.

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