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Knitted Cotton Fabric Strain Sensor by In-situ Polymerization of Pyrrole

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Abstract. The purpose of this research work was to develop a textile-based strain sensor. A conductive textile fabric was produced by the coating of knitted cotton fabric with in-situ polymerization of polypyrrole. The sensor consists of a conductive textile as an electrode, stainless steel yarn as interconnection, Arduino Nano as a controller, HC05 Bluetooth module, and a Lithium polymer battery as a power source. For the demonstration, the sensor was placed on the upper arm and bicep stretch was performed. It was observed that the contraction of the arm muscle causes a reduction in resistance of the electrode. Therefore, change in swelling was successfully detected from the increase and drop of resistance during contraction and relaxation of the muscle. This principle could be applied to determine the status of peripheral edema, where the increase in resistance in this work indicates edema is becoming severe.

1. Introduction

Nowadays, textile materials are relied upon to exhibit extra functionalities other than comfort and durability in accordance with the movement of electronic and computerized correspondence [1]. Stretchable hardware is constructed from yarns, fabric textures, or other articles of clothing and has received extensive interest. The construction of textile-based sensors i.e. the sensor is a device that acquires a physical quantity and converts it into a signal suitable for processing (mechanical, electrical, optical) to provide a usable output in response to a specific stimulus [2] is booming a buzzword in the field of smart textile materials. Textile based sensors are preferable for wearable applications due to their matching flexibility, light weight and possibility of washing. As a result, textile-based pressure sensors [3], [4], biopotential sensors [5], [6] and strain sensors [7], [8] have been constructed in different formats. Applications, where a polymer is applied to conventional textiles to make them conductive and use for an appropriate type of sensing function, are under investigation. Polypyrrole is one of the most explored conducting polymers because of its acceptable electrical conductivity and flexibility [9].

This work is aimed at developing a homemade strain sensor from a textile-based electrode produced by in-situ polymerization of lower pyrrole monomer concentration on a knitted cotton fabric under



ammonium persulfate oxidizing agent. This type of sensors could have a typical use as stretching, swelling, relaxation and contraction sensor in biomedical and sports applications.

2. Material and Methods

A half bleached knitted cotton fabric having 140 GSM available at the Department of Materials, Textiles and Chemical Engineering, University of Ghent, was selected as a textile substrate. A reagent grade 98% pyrrole monomer obtained from SIGMA-ALDRICH, Belgium and a reagent grade, 98% Ammonium Persulfate oxidizing agent obtained from SIGMA-ALDRICH, Belgium were employed. The knitted cotton fabric was coated by in-situ polymerization of 0.3M of pyrrole monomer in the presence of 0.15M of ammonium persulfate. An aqueous liquor bath was prepared using a 2:1 molar ratio of pyrrole and ammonium persulfate. The fabric samples were batched to the prepared solution (figure 1-left) at 1:40 material to liquid ratio (MLR) and kept for two hours at room temperature and ambient atmospheric pressure. The sample was treated with ethanol in order to terminate polymerization and then with distilled water to remove unreacted components. Finally, the samples were dried in an oven drier at 100°C for 3 minutes to obtain the actual fabric (figure 1-right).

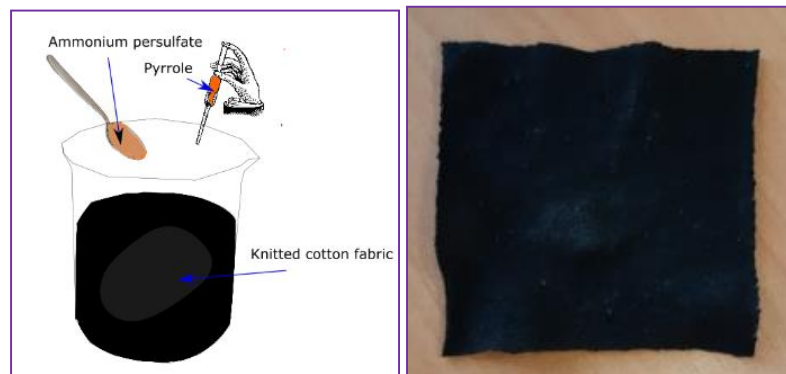


Figure 1. In-situ polymerization of pyrrole on knitted cotton fabric (left) and PPy coated knitted cotton fabric (right).

Thickness, bending length, tensile strength, elongation at break and SEM were tested to evaluate the mechanical property of the polypyrrole coated cotton fabric. The thickness was determined using ISO 5084:1996(E) (Determination of thickness of textile and textile products) using the Mitutoyo Digimatic Indicator. Bending length was analyzed following the BS 3356:1990 test method using bending length testing equipment. Using the appropriate bending length mean value, we calculated the flexural rigidity G , in mg cm, separately for the course and wale directions by the formula in equation 1.

$$G = 0.1MC^3 \quad (1)$$

Where C = Bending Length (cm), M = Mass/Area of Specimen (g/m^2)

The strength and elongation at break were tested using INSTRON universal strength tester. A tensile test according to ISO 13934-1 was used. The surface topology of the fabric before and after coating was studied using FEI Quanta 200 FFE-SEM. Images were taken with an accelerating voltage of 20 kV. The non-conductive samples were prepared prior to analysis by applying a gold coating using Balzers Union SKD 030 sputter coater.

The resistance of the fabric was measured by stretching of the samples using 3-7/8" MaxSteel Light Duty Drill Vise 83070 Stanley Hand Tool (figure 2-left) from 0 to 35% elongation. The surface resistance of all prototypes was measured by using a four-point probe measurement and a microcontroller (Arduino Nano). In the Arduino measurement, an "Arduino Nano" which was set up specifically for this particular purpose with the circuitry in figure 2-right was used. One end of

polypyrrole treated fabric was connected to 5V of Arduino input and the other was connected in series to a 10 k Ω pull-down resistor, with the midpoint connected to the analog input (ADC) of the Arduino (figure 2-right). The ground of the Arduino was connected to another end of the resistor.

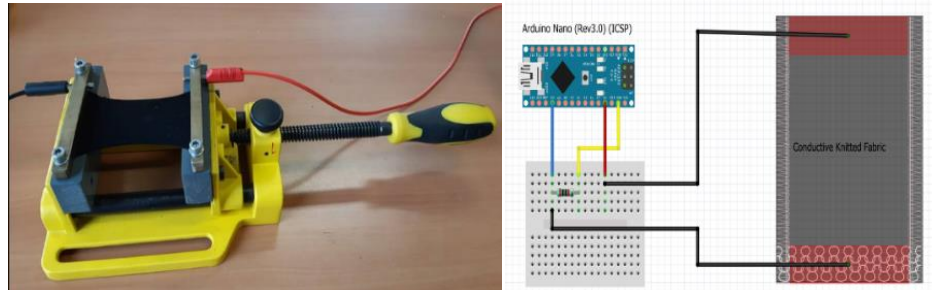


Figure 2. Electrical circuitry establishment and measurements: Duty Drill Vice Stanley Hand Tool (left), and Arduino Nano for dynamic test (right).

To test the performance of the sensor, a textile-based electrode was constructed by sewing a 5cm x 2cm conductive knitted fabric between two low extensibility of textile fabrics, see figure 3.

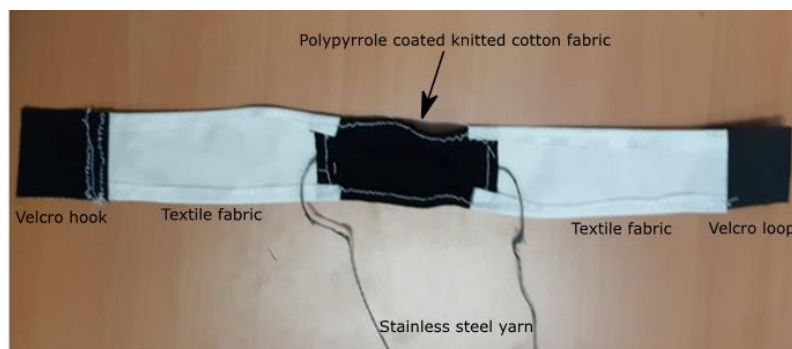


Figure 3. Actual textile-based strain electrode construction.

A stainless steel yarn was used as an interconnection between the textile-based electrode and the Arduino Nano controller. HC05 Bluetooth Module was used to transfer data from the controller to a Smartphone. A 6V battery was used to power the Arduino and the Bluetooth module.

By placing the strain sensor on the upper arm and subjecting the bicep muscle to physical relaxation and contraction, the effect on resistance was observed.

3. Results and Discussion

The thickness of the fabric has increased from 0.5 mm to 0.66 mm due to Polypyrrole coating. This increment in thickness imparted stiffness on the fabric. The fabric has gotten stiffer after treatment which is clear from the increase in bending length and weight of fabric. The bending length of the polypyrrole treated fabric has been increased from 1.225 mm to 1.45 mm in wale direction and 1.25 to 1.375 mm in course direction. The respective calculated flexural rigidity ($G = 0.1 MC^3$) has also increased from 25.74 to 62.8 gm cm in wale direction and from 27.34 to 53.55 gm cm in course direction.

Both the tensile strength and strain at break of the fabric were reduced due to treatment from 107.3 to 100.7 N and 71.34 to 70%, see figure 4. This could be due to the effect of the coating process and drying after treatment that could cause very fabric degradation in addition to the presence of the polypyrrole.

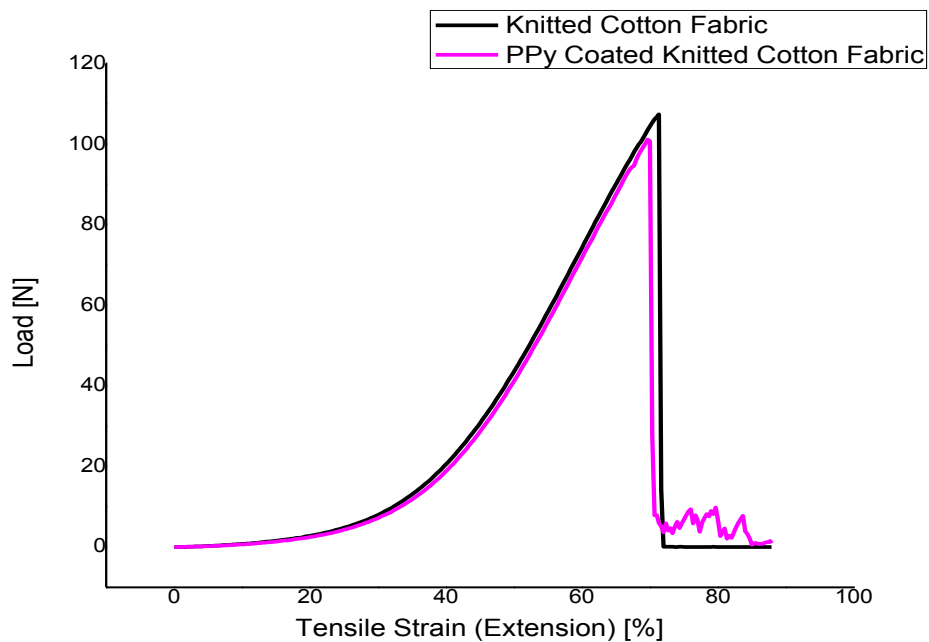


Figure 4. Example typical Load-Extension curve

The SEM results in figure 5 showed that the yarn loops interstices in the fabric were covered by the addition of the Polypyrrole. In addition, many protrudes loops were observed in the fabric but not after the polymers were applied. The presence of Polypyrrole made the smoothness better and led to coverage of the yarns.

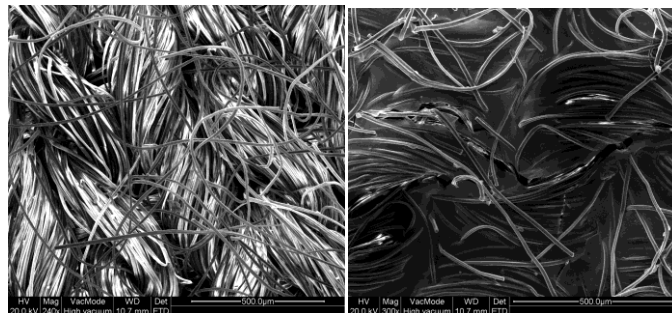


Figure 5. SEM Results: Knitted cotton fabric (left), Polypyrrole coated knitted cotton fabric (right)

The four-point probe measurement showed the surface resistance of the polypyrrole coated knitted cotton fabric was $60\Omega/\text{sq}$ and a linearly increasing function of the distance between the electrodes.

Of great importance to use the fabric as a sensor is to obtain a dependency of the resistance on elongation. This was the case, the surface resistance of the conductive fabric has increased to 350Ω at 35% elongation. Next, a 5cm x 5cm stripe was used for demonstration, using the Arduino Nano to read out the resistance. The sensitivity of the coated fabric was found to be fairly stable, raising the resistance from $0.48\text{ k}\Omega$ to $6.7\text{ k}\Omega$ (+1,295.8 %) at 60% elongation. The typical dynamic response at 0.12 cm/s constant rate of stretching is shown in figure 6.

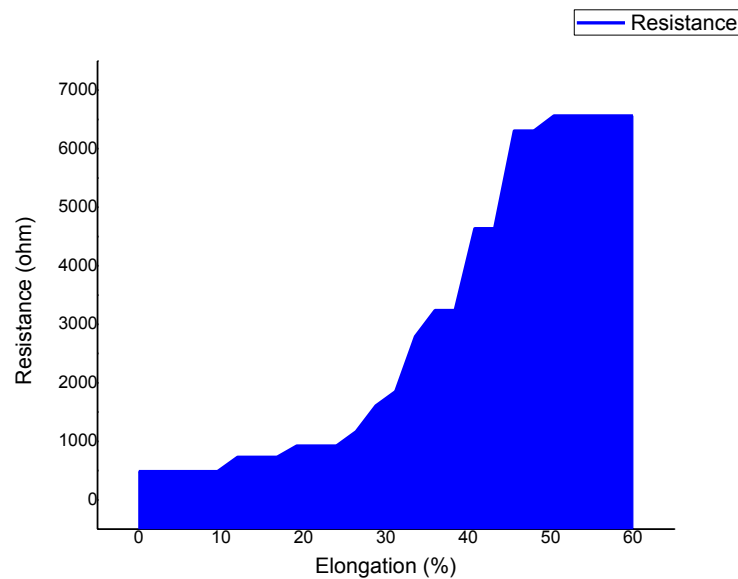


Figure 6. Dynamic testing of coated fabric resistance at constant rate of stretching.

It was noticed that the resistance of the textile-based strain sensor electrode (5cm x 2 cm) increases during muscle contraction (flexion) and vice versa during relation (extension), see figure 7. This is due to the increase in circumference of the upper arm during contraction causing stretching of the sensor placed on it.

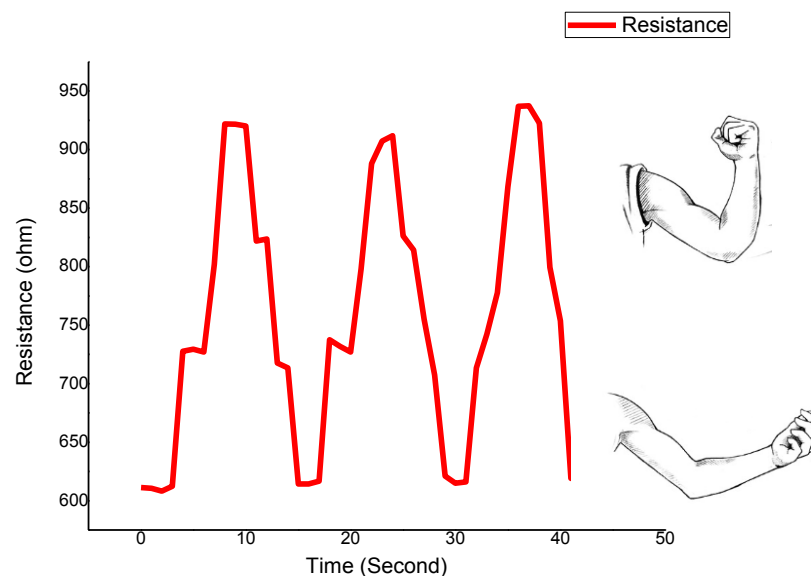


Figure 7. Performance testing of the strain sensor.

This principle could be applied to determine the status of peripheral edema, where the increase in resistance indicates edema is becoming severe. Peripheral edema is swelling of body parts due to excessive trapping of fluid which can happen in hands, arms, feet, ankles, and legs[10].

4. Conclusion

We have successfully developed a conductive knitted cotton fabric by in-situ polymerization of polypyrrole which was then used to produce a textile-based strain sensor. For demonstration, the strain sensor was placed on the upper arm and bicep flexion and extension were performed. It was observed that the swelling of the arm muscle due to bicep flexion causes an increase in resistance of the electrode. The swelling extent was noticed from the increase and drop of resistance during contraction and relaxation of the muscle. Therefore, the developed textile-based strain sensor can be used to determine the status of peripheral edema in biomedical applications and as a swelling/contraction and loading/unloading sensor in different areas.

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