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Soft-structured sensors and connectors by Inkjet Printing

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Abstract

The properties of conducting polymers deposited onto textiles were studied over 10 years ago by workers at Los Alamos and Milliken who also tested these materials as gas sensors [1-3]. More recently, workers at Wollongong have demonstrated that elastic textiles impregnated with conducting polymers, by in situ chemical polymerization, can act as strain sensors that can be used to track the motion of human joints [4]. A similar approach can be used to make pressure-sensing foams [5]. Others have studied the strain sensing mechanism in more detail and have shown that two effects are important. In one case, cracking of the surface layer on conducting polymer on a fabric leads to a reduction in conductivity as the fabric is stretched [6, 7] . On the other hand, tests on yarns and loops of conducting yarn show that conduction from yarn to yarn decreases as stress is applied to pull their surfaces into contact [8].

Keywords

printing, connectors, sensors, inkjet, structured, soft

Disciplines

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SOFT STRUCTURED SENSORS AND CONNECTORS BY INKJET PRINTING

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Introduction

The properties of conducting polymers deposited onto textiles were studied over 10 years ago by workers at Los Alamos and Milliken who also tested these materials as gas sensors [1-3]. More recently, workers at Wollongong have demonstrated that elastic textiles impregnated with conducting polymers, by in situ chemical polymerization, can act as strain sensors that can be used to track the motion of human joints [4]. A similar approach can be used to make pressure-sensing foams [5]. Others have studied the strain sensing mechanism in more detail and have shown that two effects are important. In one case, cracking of the surface layer on conducting polymer on a fabric leads to a reduction in conductivity as the fabric is stretched [6, 7] . On the other hand, tests on yarns and loops of conducting yarn show that conduction from yarn to yarn decreases as stress is applied to pull their surfaces into contact [8].

Human skin could be regarded as a model for a strain sensing fabric [9]. There is a very high density of sensors, especially in areas such as the fingertips, and these sensors can apparently detect direction and magnitude of several components of the force tensor. The proprioceptive strain sensors of muscle and of arthropod cuticle could also be regarded as a model system [10, 11]. In this case the role of the sensors is to provide feedback on the state of the body itself rather than on its environment. With these models in mind we have been looking at printing methods that would allow us to put patterns of multiple sensors onto fabrics.

Among the conducting polymers, several polythiophenes combine processability and environmental stability. Polyethylene di-oxy thiophene (PEDOT) shows high conductivity, transparency and possesses great environmental stability. It is readily available as an aqueous suspension in combination with a soluble polyelectrolyte, poly (styrene sulfonic acid) (PSS), as a charge balancing dopant. In order to deposit both the sensors and the connecting conductors onto the fabric, we have used inkjet printing [12, 13] . The conductors are printed metal lines with a resistance much less than that of the conducting polymer sensor, such that any change in resistance of the connectors with strain is insignificant compared to that of the sensors. Conducting silver lines have previously been printed onto textiles by two-step printing of reducing agent and silver salt [14].

Thus, we have developed methods to inkjet print highly conducting lines to act as leads (connectors), printing more resistive conducting polymers to act as sensors and used them to provide semi-quantitative information about the motion of a human knee or wrist.

Experimental

The inkjet printing system

Printing was carried out using conventional HP cartridges, emptied and refilled with our test solutions. The drop rate was controlled by a custom-built pulse generator which pulsed a single nozzle on the cartridge. The cartridge was mounted on an arm above an xy motion system that moves the samples, figure 1. In this way, many print cycles could be carried out with controlled time and distance between drops and with the ability to control the temperature and humidity of the sample.

Formation of Connectors

Formation of conducting leads was attained in two steps. The first was to inkjet print seed layers which were then converted into metallic lines by electroless plating.

0.32gms of silver nitrate, dissolved in 50ml of water was printed on the woven fabric (Nylon 6, 6 Semi-dull, Taffeta

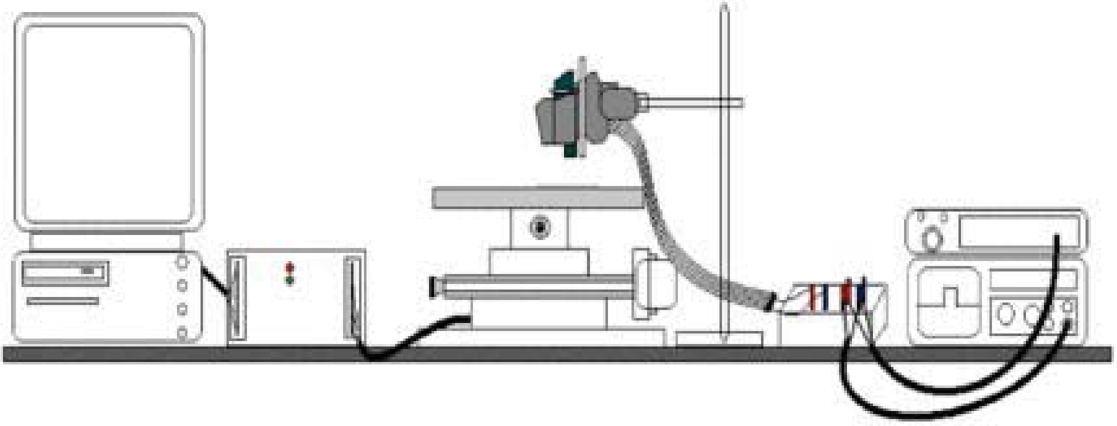

Figure 1. Ink jet printing apparatus

Since the ink, upon evaporation, leads to spreading on the substrate the woven fabric was mounted on a heating plate so as to avoid the spreading of the solution. This technique allows the individual droplets to fuse but hinders the formation of large droplets and thus prevents smearing of ink [13]. Lines were printed at 5 cm/sec and 500 drops/sec for 500 cycles. This repeated printing onto fabric at 60^{o}C allows the "ink" to dry on the fabric between cycles. Once the lines, 3 cm long and 0.5 mm wide, are printed, the sample was dipped in an electroless bath of silver [14]. The reducing agent, glucose, reduces the silver ions to metal which is deposited on to the already printed seed layer by an autocatalytic process.

The bath was maintained at a temperature of 50 degree Celsius and the hold time of 40 minutes. The pH of the bath was kept highly basic at around 12.5. After the sample is subjected to the required set of conditions, it is taken out of the bath and rinsed in hot water followed by a rinse in cold water along with mechanical action such as wringing.

A thick and uniform deposit of silver nitrate was needed on the nylon woven fabric so as to form a continuous network of silver on the printed regions during plating. The resistance of the samples, after they have dried, was measured using Keithley 196 electrometer and also by 4-probe electrical measurements. The probes were kept on the printed region, and the corresponding reading from the front panel is taken down. The value of resistance ranges from 0.7- 1.5 ohms/inch. Based on the linewidth, fabric thickness and volume fraction of silver, we estimate a conductivity of approximately 4×10^{3} Siemens/cm. This is about 100 times less than that of elemental silver (6.25×10^{5} Siemens/cm). Unprinted areas of the fabric remain non-conductive.

Formation of Sensors.

A suspension of Poly (3, 4 – ethylenedioxythiophene) - poly (4-styrenesulfonate) (PEDOT-PSS) from Bayer Scientific, 1.3 % by weight, was printed onto mercerized cotton fabric for 500 cycles. The printed lines were about 5 cm long and less than 1 mm wide. The samples were annealed at 90 degree

Celsius for about an hour. In this case the polymer partly penetrated the fabric and formed stable conducting lines. The resistance drops as more ink is deposited and is about 5 kiloohms at 500 cycles. The conductivity of the PEDOT in the coatings is about 25 S/cm.

For the strain sensing study, the fabric was clamped in jaw placed 2.54 cm apart on an Instron tensile testing machine and the corresponding resistance was recorded on a Keithley Multimeter 196 through a PC using General Purpose Interface Bus (GPIB) as a data acquisition mode.

The microstructure of the printed PEDOT and electroless silver was studied by JEOL JSM 5610 Scanning electron microscope equipped with Oxford Energy Dispersive X-ray System operating at 8 kV.

Integration of Sensors and Connectors.

Resistance of connectors was 1/ 100 of that of sensor in order to avoid any interference with the data recording. Sensors were integrated with connectors by printing lines of PEDOT, 1 cm in length and about 0.5 mm wide, onto Nylon 66 fabrics in between silver printed lines, as shown in figure 2. The connectors were connected to an external device and the resistance was recorded on Keithley 196 electrometer along, interfaced through GPIB.

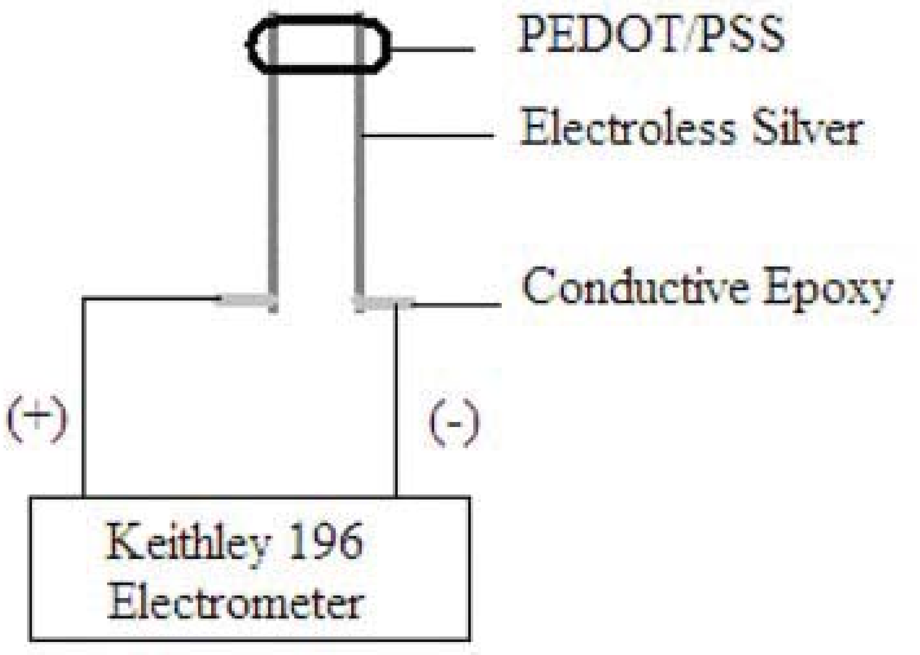

Figure 2. Integration of sensors (PEDOT-PSS) with connectors (Electroless silver)

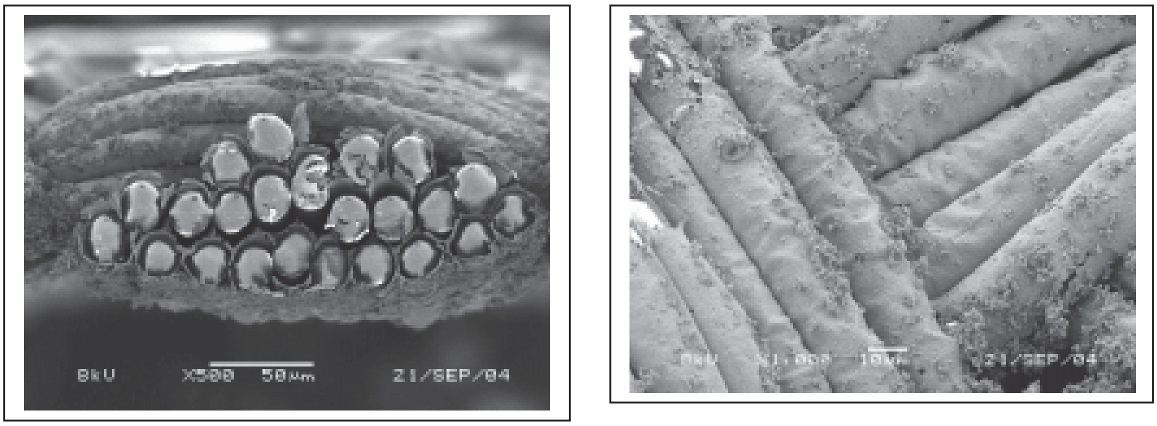

Figure 3. Cross section and top view of silver printed region of a Nylon fabric.

Results and discussion

SEM and EDX observation

Figure 3, shows a coating of silver around every fiber through the thickness of the fabric. EDX analysis confirms the presence of silver on the fabric, table 1. The second silver immersion step does also result in some silver being deposited on the unprinted regions and some staining but these do not become conducting. EDX also shows that some silver penetrates into the individual Nylon fibers.

SEM of cotton fabric coated with conducting polymer, in figure 4, shows that part of the polymer forms a thick film on the upper surface of the fabric and cracks on elongation.

Table 1: EDS elemental analysis of silver-coated yarn

	Carbon wt%	**Oxygen wt%**	**Silver wt%**
Yarn cross section	**52.6**	**17.9**	**29.5**
Single fiber cross section	**63.0**	**21.7**	**15.3**

Strain Sensitivity

The reversible change in the electrical resistance of PEDOT-PSS printed fabrics with external mechanical strain relaxation reveals that these fabrics show piezoresistivity. For this study 2.54 cm long PEDOT printed cotton fabric was subjected to an elongation of 5% at a rate of 5mm/min on an Instron tensile testing machine, figure 5.

It can be seen that there is an initial increase in the resistance of the PEDOT printed fabric with strain. We believe that this initial increase corresponds to the cracking seen in figure 4 and reported by Li et al. for Lycra fabric with a coating of polypyrrole [6]. Subsequently our samples show a cyclic change in resistance with strain. In this case the resistance decreases as the sample is strained and increases again as the strain is relaxed. It can be seen that a strain of 5% results in a resistance decrease of about 25%, corresponding to a (negative) gauge factor of –5. A similar large decrease in resistance with strain was observed for polypyrrole-impregnated Lycra [4]. This compares with a gauge factor of +2 for most metals, which reflects the normal decrease in cross-section with increase in length. Some semiconductors do show a large positive gauge factor due to the influence of strain on band conductivity [15]. Our samples thus show two zones of conductivity. The surface layer of conducting polymer cracks on stretching while the polymer that penetrates into the yarn becomes more conductive on stethcing, probably through better surface-surface contacts within the yarn [8].

However it was not possible to attain original resistance soon after the experiment because PEDOT is printed on cotton woven fabric which shows only 61% of recovery from strain as compared to Nylon fabric (91%) and some knit fabrics (almost 100%),although with time original resistance is recovered..

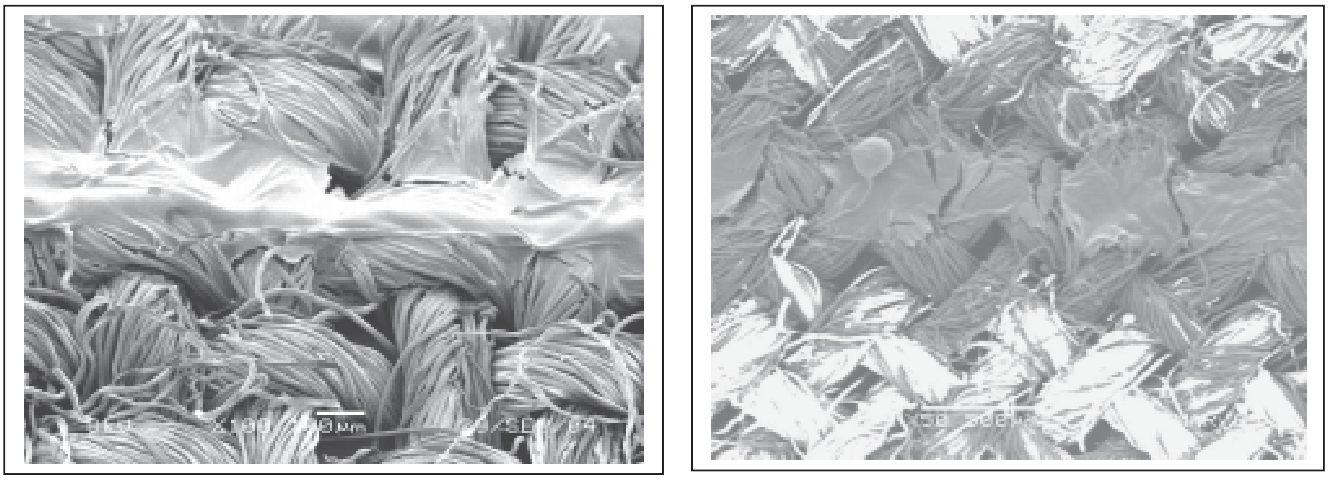

Figure 4. PEDOT-printed cotton before and after 10% elongation

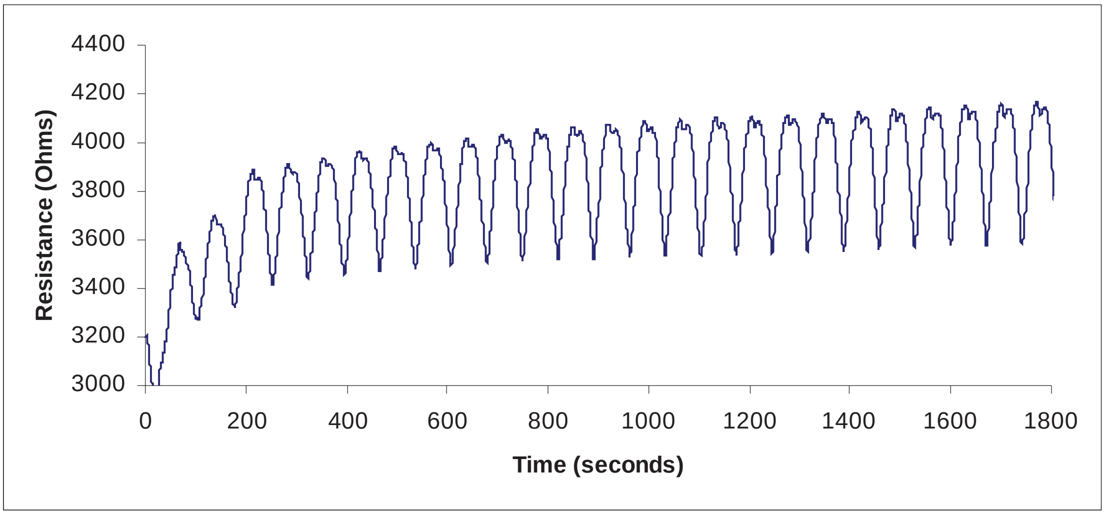

Figure 5. Resistance of PEDOT-PSS sensor with 25 repeated cycles of strain to 5% and relaxation.

Identification of Human Motions.

In order to explore the applicability of this system to analyzing joint motion, an assembly of sensors and connectors was placed on human knee, as shown in figure 6, and wrist with the help of tape.

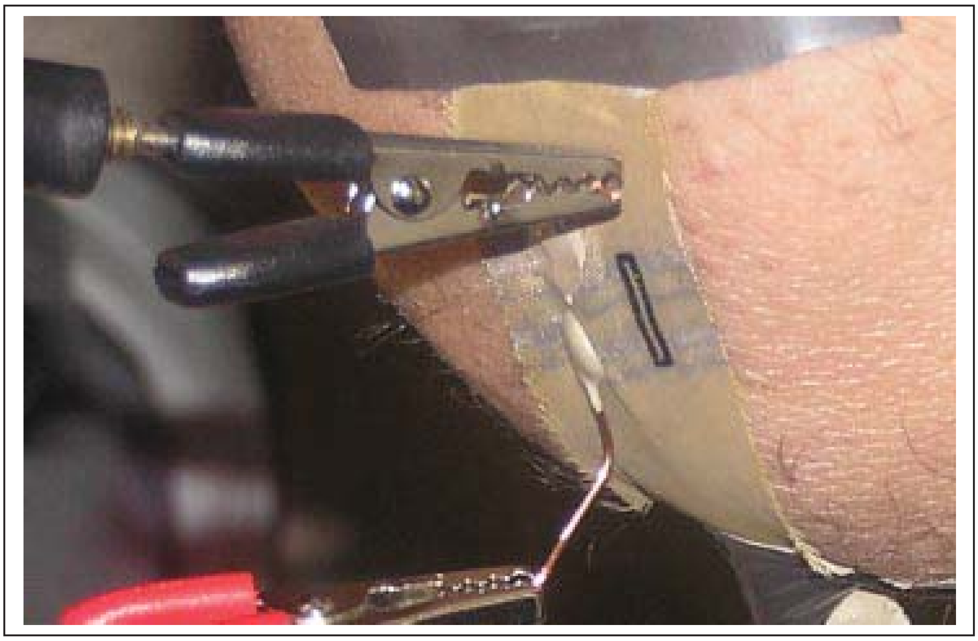

Figure 6 Sensor for bending of knee

Four trials for each motion, bending of knee and twisting of wrist, was carried out at both slow and fast speed and corresponding change in resistance was recorded with the help of Keithley 196 Electrometer and GPIB. Both time and frequency domain analysis was carried out of the readings as a part of digital signal processing.

To reduce the noise in the original data a mean filter was employed. This is a simple sliding-window spatial filter that replaces the first value in the window with the average (mean) of all the data values in the window. The plots, shown in figure 7, are the two trials after removing running average and taking twice mean filtering in the time domain. A pseudo-sinusoidal wave is shown in the data after doing signal processing. Approximate 7 pseudo-sinusoidal cycles are contained in 50 sec. In the frequency domain, existing data was used to estimate the power spectral density.

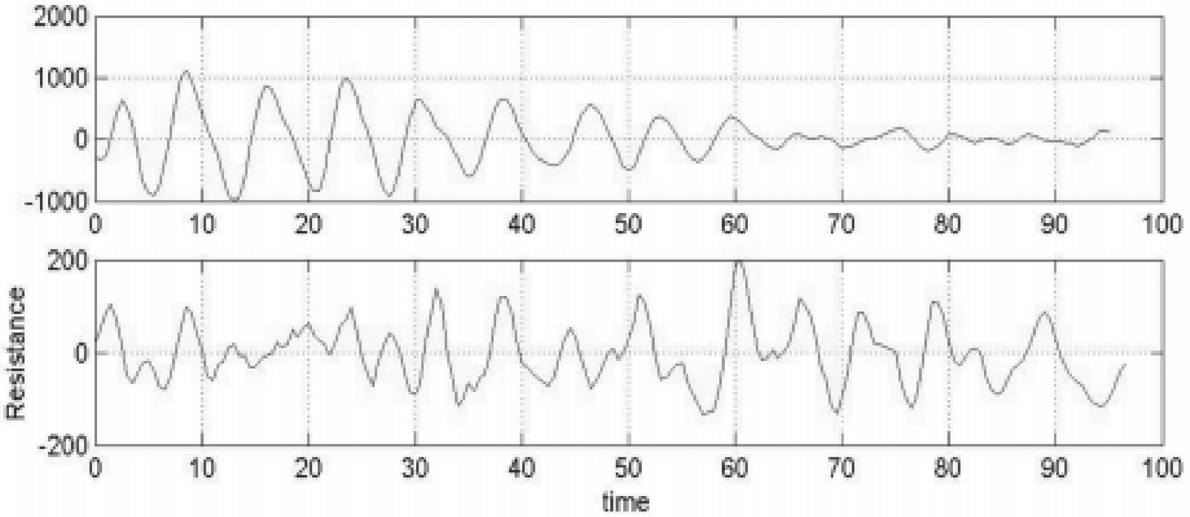

Figure 7 Sensor resistance during knee bending after removing running average and 2nd mean filtering. 2 trials.

The plots, shown in figure 8, are the power spectral density for two trials. From the two trials, the frequency peaks do show variation from trial to trial. This may be caused by the human motion data collection. However from trials, there exist three major frequency peaks in the PSD. Although the peaks are shifting, they all concentrate below normalized frequency 1. If there exists features for the slow bending motion, we can say that from the four trials that most of the power is concentrated below a normalized frequency of 0.5.

Slow Speed: From the analysis including four trials from slow knee bending motion as well as four trials from slow wrist twisting motion, we were able to identify and trace down some distinguishable features in both the time domain and frequency domain.

In the time domain, in general, there were approximate 7 pseudo-sinusoidal cycles contained in 50 sec for slow knee bending motion. For slow wrist twisting motion, approximate 12 pseudo-sinusoidal cycles were contained in 50 sec.

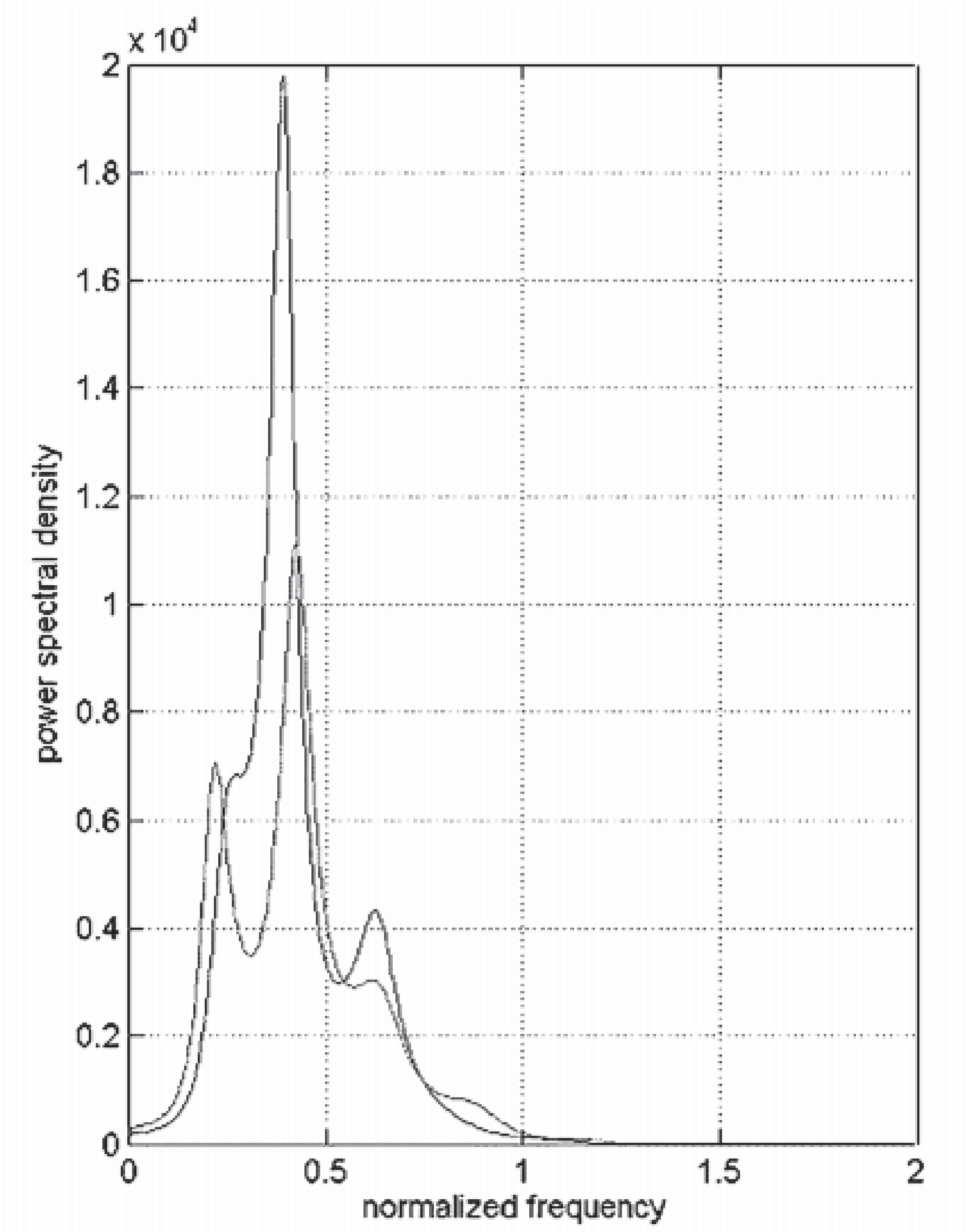

Figure 8 Data from figure 7 shown as a power spectrum.

In frequency domain, one can set up a threshold for the power ratio to distinguish the bending and twisting motion in the fixed slow speed. Based on the eight trials, the power ratio threshold was set at 0.5.

Fast Speed: In the time domain, the periodicity from the smoothed signals was used to separate the two motions. For fast twisting motion (wrist) the period was approximately 8 to 9 sec. per cycle, and for fast bending motion (knee) the period was about 3 sec. per cycle. In frequency domain, the peaks in each trial were not fixed and also the power ratio method did not work with the fast motion.

Conclusion

Controlled inkjet printing of PEDOT onto cotton fabric resulted in selective conductivity, which increased with curing of the printed sample. Inkjet printing and electroless plating lead to the deposition of silver on nylon 6, 6, as connecting leads, with width of 0.5 mm. SEM and EDX observations revealed thick deposition of silver on Nylon 6, 6 fabrics even after washing and rubbing which indicates reasonable adhesion between silver and fabrics. PEDOT-PSS printed fabrics showed a reversible change to applied external strain. Electrical analysis proved that human motions can be sense by the printed assembly of sensors and connectors.

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