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Development of Flexible Smart Fabric Sensor for Wearable Electrocardiogram

Giyilebilir Elektrokardiyogram İçin Esnek Akıllı Kumaş Sensör Geliştirilmesi

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ÖZET

Dış ortam koşullarını veya uyaranları algılayabilen, onlara yanıt verip akıllı bir şekilde adapte edebilen ve sağlık, spor ve otomotiv gibi çeşitli alanlarda kullanılabilen akıllı elektronik tekstiller, kumaşlara veya giysilere elektroniği entegre etmek için yeni çözümler üretmek amaçlı yeni modeller önerir. Akıllı tekstiller, elektroniklerin tekstil materyallerine entegrasyonundan büyük yarar sağlayan sağlık izleme sistemlerini gösterebilir. Elektronik tekstillerin temel amacı gündelik giysilerin bir parçası olmaktır. Hazır giyim ürünlerini algılama özellikleri taşıyan bir yapıya dönüştürmek için farklı işlevleri olan yumuşak, esnek ve konforlu yapısal bileşenlerle donatmak, akıllı / elektronik tekstiller için en uygun ortamı oluşturmaktadır. Bu çalışmada esnek bir akıllı kumaş sensörü geliştirilmiş ve insan kalp elektrokardiyografi izleme (EKG) amaçlı elektriksel aktivitesini saptamak adına akıllı bir giysi üretilmiştir. Kalp atışlarını gösteren akıllı giysi, vücuda bağlı dış elektrotlar yerine tekstil esaslı sensörleri içeren giyilebilir elektronik tekstiller için farklı bir bakış açısı sunmaktadır.

Anahtar Kelimeler: Sensör Kumaş, Akıllı Giysi, EKG, Elektronik Tekstiller, İletken Polimer

ABSTRACT

Smart electronic textiles which represent a new model for generating novel solutions for integrating electronics into fabrics or garments able to sense outer conditions or stimuli, reply and adapt behaviour to them in an intelligent way and exhibit a challenge in several fields such as health, sport, automotive and aerospace. Intelligent textiles may show health monitoring systems that greatly benefit from the integration of electronics in textile materials. The main purpose of electronic textiles is to become a part of everyday garments. Equipping the ready-made clothing with soft, flexible and comfortable structural components having different functions such as transforming into a structure with sensing properties makes it the most appropriate environment for the emergence of smart / electronic textiles. In this study, a flexible smart fabric sensor was developed and a smart garment was produced to detect the electrical activity of a human heart for electrocardiogram monitoring (ECG). The smart garment that displays heartbeats offers a different perpective for wearable electronic textiles that incorporate textile-based sensors instead of external electrodes connected to the body.

Keywords: Sensor Fabric, Smart Garment, ECG, Electronic Textiles, Conductive Polymer

1. INTRODUCTION

A smart textile is able to “sense” changes in the environmental condition with a sensing function. A sensor is a device providing information, mostly in the form of an electrical signal. It perceives the measured object or medium and emits a signal related to the variations of the measured quantity such as position, velocity, temperature, humidity, force, pressure and flow. Most signals are conveyed in the electrical form by sensors; therefore, using electro-conductive materials is the most efficient way to create a textile sensor. Textile sensors are usually used for the recording of electrocardiogram (ECG), respiration rate and heart rate (Özdemir and Kılınc, 2015). To create a smart textile system, the textile must contain that these functions detection, activation, data processing, operation/production/storage, connectivity and interconnect (Erol and Cetiner, 2017).

Electrically conductive textiles include conductive fibres, yarns and fabrics. Often they are prerequisite to functioning smart textiles,. Important part in smart textiles development has conductive polymers which are defined as organic polymers able to conduct electricity (Grancarić et al., 2017).

A new approach to highly conductive textile materials is the use of intrinsically conductive polymers. An interesting alternative is to create the conductive polymers by polymerization of monomers on the textile. Methods for in situ polymerization are well known for polypyrrole (PPy), polyaniline (PANI) and poly(3,4-ethylene dioxythiophene) (PEDOT). Recently, polymers derived from alkoxythiophenes like 3,4 ethylenedioxythiophene (EDOT) yielding poly(3,4-ethylene dioxythiophene) (PEDOT) find increasing interest (Knittel and Schollmeyer 2009). Therefore, a derivative of thiophene that has low oxidation potential and is free from the possible α , β and β , β linkages would be an ideal material for industrial applications as shown in Figure1 (Hong et al., 2005).

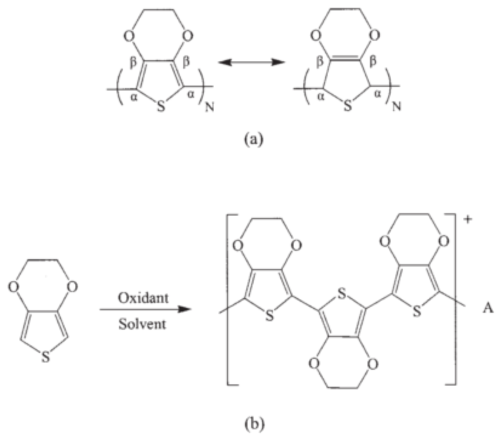

Figure 1. (a) The Molecular Structure of PEDOT and (b) Chemical Synthesis of PEDOT (Hong et al., 2005).

Recent developments in smart conductive polymeric fabrics for electrocardiogram (ECG) have encouraged a notable growth of interest in wearable ECG sensor technology. The interest for comfortable smart fabric-based ECG systems originates from the need for patients' monitoring over extensive periods as the normal clinical or hospital ECG monitoring provides only a concise window on the status of the patient (Haghdoost et al., 2015). Wearable electronics which combine low-power circuits, wireless transmission and advanced packaging allow the emergence of smart clothing for the monitoring of a human (Trindade et al., 2015). A shirt was developed by basic weft structures such as jersey, locknit and simple pique to use in health, risk environments and sport monitoring. The electrode areas were knitted by silver coated textured polyamide yarn. The ECG connections were routed to a single line, located on the back of the shirt and from there to a single place to connect to the specific acquisition circuit (Carvalho et al., 2014). An elastic garment was produced by a private funded project in Europe with a name Wealthy System. It contained seamless knitting technique, integrating knitted electrodes to capture ECG signals realized with commercial electro-conductive yarns and consisted of stainless steel monofilament surrounded by twisted cables of viscose. In this garment, hydrogel membranes placed between the knitted electrodes. In another health monitoring system consisted of a T-shirt integrating smooth, dry ECG electrodes, with leads and treatment modules incorporated into textile woven fabrics (Axisa et al., 2005). An active belt integrating washable textile electrodes from TITV Greiz was proposed (Mankodyia et al., 2010). Organic sensors fabricated by conductive polymers have potential for smart clothing because they are lightweight and may be realized inexpensively with properties tailed by engineering. The fabrication of fabric sensors with in-situ chemical polymerization method could be practical and an alternative for sensors in ECG, sport test and Holter's device. A commercial electrode could cause skin troubles such as reddish skin and stinging pain by using conductive gels when used to measure ECG for a long time. Hence dry electrodes without using hydrogel could be used to measure for long time physical signal monitoring (Haghdoost et al., 2015).

Focus of interest of this paper is to present a conductive polymer-based a smart electronic textile garment to detect the electrical activity of the heart for electrocardiogram (ECG) monitoring. For this purpose a textile based sensor was produced by in-situ polymerization of 3,4-ethylenedioxythiophene (EDOT) on polyethylene terephthalate (PET) woven fabrics. The electrical activity of the human heart was sensed by PET-PEDOT conductive polymeric fabric sensor on a smart garment. The fabrication of fabric sensors with in-situ chemical polymerization technique could be an alternative for commercial sensors used in ECG monitoring and it could be used to measure for long time physical signal monitoring without using hydrogel. The sensors produced in this design are lightweight, washable and suitable for integration in clothing, and have versatility in terms of sensor design, sensor size and integrating materials.

2. EXPERIMENTAL

2.1. Materials

A conductive monomer, Edot (97%), iron(III) chloride ($FeCl_3$) and *p*-toluensulfonic acid monohydrate (*p*-TSA) were used without further purification. All reagents were supplied from Sigma-Aldrich. Acetonitrile, Acetone, ethanol and methanol were supplied from Merck. A scoured and undyed 100% PET woven fabric with a 256 gr/m^2 was supplied from Kipas, Turkey. Electrically conductive yarns (Elitex- Art. 235/f34_PA /Ag) with the electrical resistance values of 20 ohm/meter were used to perform the connection between the sensors and snaps.

2.2. Preparation of PET-PEDOT Conductive Polymeric Composites

PEDOT coated PET fabrics were produced by *in-situ* chemical oxidative polymerization method. The iron(III) chloride and *p*-toluensulfonic acid monohydrate were mixtured at room temperature with a magnetic stirrer for ½ h in a 50mL of acetonitrile. The PET fabric with the dimensions of 6cm x 6 cm was rinsed in acetone and distilled water to remove the contaminations of oil residues and was dried in an oven at 80ºC. Then PET fabric was wetted in acetonitrile which contains dissolved of iron(III) chloride and *p*-toluensulfonic acid monohydrate. The calculated amount of EDOT was added drop by drop to the acetonitrile-PET solution and mixtured for 3 hours with a magnetic stirrer at room temperature.

At the end of the polymerization, the PEDOT coated conductive PET fabric was rinsed with methanol, ethanol and distilled water for 5 minutes to remove the unpolymerized particles. The polymerization mechanism was given in Figure 2.

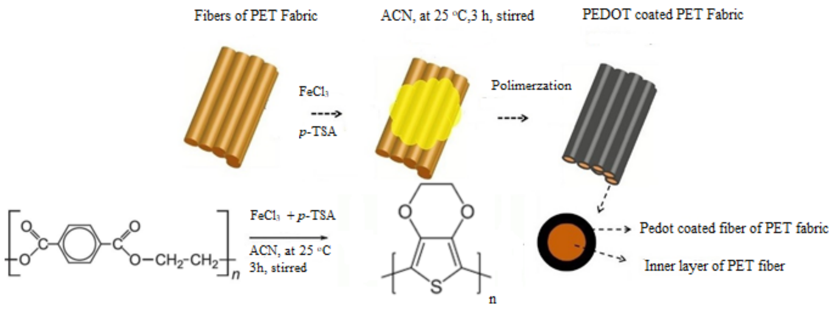

Figure 2. Schematic Illustration of PET-PEDOT Conductive Composite

2.3. Characterization of PET-PEDOT Fabrics

Fourier transform infrared-attenuated total reflectance (FTIR-ATR) analysis of the PET-PEDOT fabric was carried out by a FTIR reflectance spectrophotometer (Perkin Elmer, Spectrum One, with a Universal ATR attachment with a diamond and ZnSe crystal). The morphology of the PET-PEDOT composite fabrics was observed with a Carl Zeiss Evo LS10 scanning electron microscope. The AD8232 ECG monitor was used as signal analysis integration for electrocardiogram monitoring. The lock stitch tecqnique was used to combine the flexible fabric sensors with garment.

3. RESULTS AND DISCUSSION

3.1. FTIR Spectrophotometric Analysis of PET-PEDOT Fabrics

Figure 3 presents the IR spectrum of the uncoated PET fabric and PEDOT coated PET fabric.

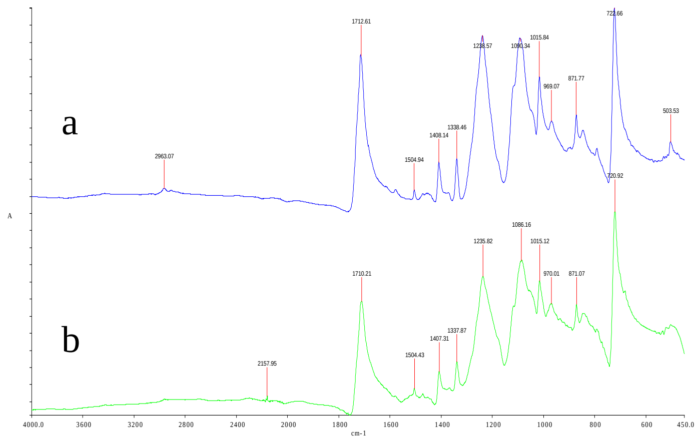

Figure 3. Fourier Transform Infrared Spectra of (a) PET Fabric, (b) PET-PEDOT Fabric

In the absence of PEDOT; a strong absorption band at 1712 cm^{-1} is attributed to C=O stretching vibrations of PET. Other absorption peaks of polyester fabrics are aromatic ring stretching (1408 cm^{-1}), carboxylic ester or anhydride (1338 cm^{-1}), O=C–O–C or secondary alcohol (1090 and 1015 cm^{-1}), C=C stretching (969 cm^{-1}), five substituted H in benzene (871 cm^{-1}), two neighboring H in benzene (847 cm^{-1}) and heterocyclic aromatic ring stretching (722 $csssm^{-1}$) (Köse, 2015; Li et al., 2010).In the presence of PET-PEDOT composite fabric, the absorption peak at 1,710 cm^{-1} is usually associated with the doped state of PEDOT. An absorption band appeared at 1504 cm^{-1} is assigned to asymmetric stretching mode of C = C that correspond to thiophene rings of PEDOT. Vibrations at 1407 and 1337 cm^{-1} are attributed to the stretching modes C–C in the thiophene ring. The vibration peaks of the C–S bond in the thiophene ring can be seen at 970, 871 and 842 cm^{-1}. The bands at 1235 and 1086 cm^{-1} are assigned to the stretching vibrations of the ethylenedioxy group (Selvaganesh et al., 2007; Wu, 2011). Sotheseresults showed that the PEDOT formation could be followed by FTIR measurements in PET-PEDOT composite fabric structures.

3.2. Surface Morphology of PET-PEDOT Fabrics

Figure 4 shows the surface morphology of uncoated and PEDOT coated PET fabrics.

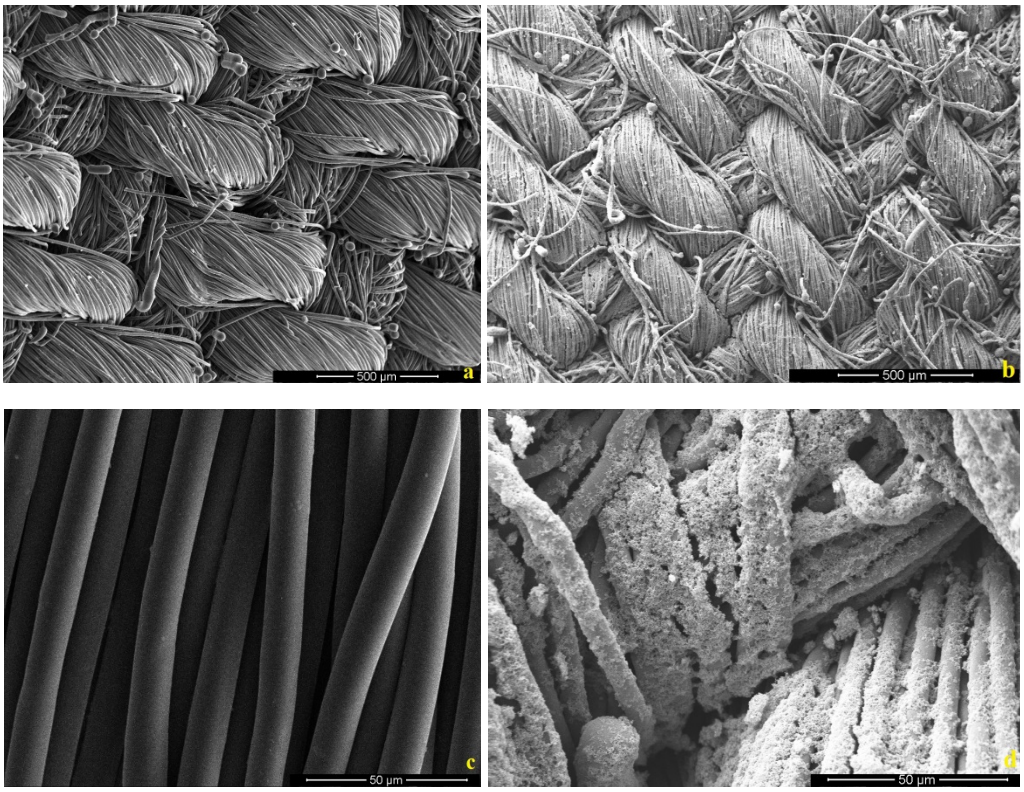

Figure 4. Surface Morphologies of Pristine PET Fabric (a,c) and PET-PEDOT Fabric (b,d)

When the uncoated PET fabric had a quite smooth surface, a significant change on the surface of PET fabric was occurred after PEDOT coating.The homogeneously distributed PEDOT nanoparticle coatings were observed on the PET-PEDOT fabric structures by scanning electron microscope. The SEM images of PET-PEDOT composite fabric surface was coated uniformly by PEDOT layers. The SEM results showed that the *in-situ* polymerization process could change the surface morphology of PET fabric effectively and confirmed the conductive polymeric coatings on fabric surfaces was a remarkable effects that could be used for modifying the microstructure of the polyester fabrics (Figure 4).

3.3. Design of A Smart Garment For Electrocardiogram Monitoring

The AD8232 ECG monitor was used as signal analysis integration for electrocardiogram monitoring to demonstrate the ability of PEDOT coated PET composite fabric as ECG sensor. The design of ECG monitor allowed for ultralow power analog-to-digital converter (ADC) to acquire the output signal easily for this smart garment. The remarkable step in the smart garment production process that displays the electrical activity of the heart was to fabricate textile based sensor.

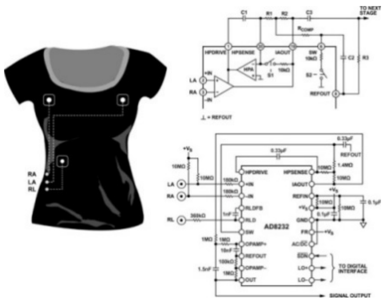

Figure 5. Block Diagram of Three Probes ECG Monitor

The sensing activity of PEDOT coated conductive PET fabric sensor was detected by three probes heart rate (ECG) monitor and the obtained signals were related to a person in the stable standing position with normal cardiac function. The three sensing points (RA: Right Arm, LA: Left Arm, RL: Right Leg) were required for the ECG sensor system designed in this study (Figure 5).

Figure 6 shows the design of PET-PEDOT fabric ECG sensor on a smart garment.

Figure 6. Design and Assembly of PET-PEDOT Based ECG Sensor on Garment

PEDOT coated conductive PET fabric sensors were sewn at these sensing points and the connection paths were provided by lock-stitch machine with electrically conductive yarns. Three snaps were located at the right bottom side of garment to connect with the electronic module (Figure 6).

In general, an ECG signal is composed of several wave pieces. Each cardiac cycle begins from a P-wave and continues until the next P-wave. Each ECG signal has four main intervals: RR, PR, QRS and QT. The P-wave, the first wave of the ECG, provides an electric current passing through the atrium. During normal atrial depolarization, the main electrical vector directs from the spreads of the right atrium to the left atrium. This turns into the P-wave on the ECG (Haghdoost et al., 2015).

Figure 7 shows the heart rate signal transfer from smart garment to a smart phone via a portable ECG module. The ECG signals were recorded and displayed on computer (with specific longitudinal and transverse dimensions) to compare the performance of the reference electrode sensors and PEDOT coated PET fabric ECG sensors for a human with normal heart activity.

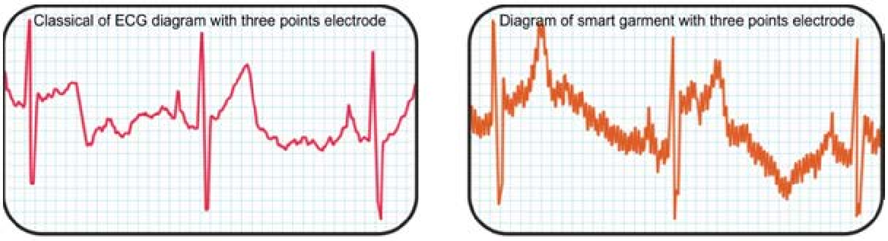

Figure 7. Heart Rate Signal Transfer From Smart Garment to a Computer Via Portable ECG Module

AD8232 ECG monitor perceived the electrical activity of a human heart via PET-PEDOT fabric sensor in this design. Then the signals were amplified and filtered. The received data as signals was transferred to a computer through a USB connection. The results of flexible PET-PEDOT fabric sensor showed an acceptable agreement with the result of commercial reference electrode means that there was applicability of receiving of cardiac signals through PET-PEDOT fabric sensors on garments (Figure 7).

4. CONCLUSION

The aim of this study is to present a conductive polymer-based a smart garment to detect the electrical activity of a human heart for electrocardiogram (ECG) monitoring. For this purpose a textile based sensor was produced by in-situ polymerization of 3,4-ethylenedioxythiophene on polyethylene terephthalate woven fabrics. The electrical activity of the human heart was sensed by PET-PEDOT conductive polymeric fabric sensor on a smart garment. AD8232 ECG monitor was used as signal analysis integration for electrocardiogram monitoring. AD8232 ECG monitor perceived the electrical activity of a human heart via PET-PEDOT fabric sensor and received data as signals was transferred to a smart phone through a USB connection successfully. The ECG monitoring results of PET-PEDOT fabric sensors showed a feasibility deal with the result of commercial reference electrodes.

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