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Article

Wearable and Flexible Humidity Sensor Integrated to Disposable Diapers for Wetness Monitoring and Urinary Incontinence

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Abstract: Disposable diapers are widely used by individuals with urinary incontinence. Diapers should be checked frequently for elderly, disabled, and hospital patients. Wet diapers that are not changed properly can cause health problems. The importance of electronic devices that provide warning in case of wetness is increasing in health monitoring. A disposable and wearable printed humidity sensor was designed and fabricated to detect wetness. The sensor was printed on polyamide-based taffeta label fabric by the inkjet printing method using specifically formulated PEDOT:PSS-based conductive polymer ink. The sensor sensitivity was tested under different relative humidity levels inside a controlled chamber. The resistance of the sensor decreased from 17.05 ± 0.05 MΩ to 2.09 ± 0.06 MΩ as the relative humidity increased from 35 to 100%, while the moisture value of the fabric increased from 4.8 to 23%. The response and recovery times were 42 s and 82 s. This sensor was integrated into the adult diaper to evaluate wetness. The sensor resistance change comparing to the dry state resistance (15.52 MΩ) was determined as 3.81 MΩ to 13.62 MΩ by dripping 0.1 mL to 100 mL salty water on the diaper. Due to its flexible structure and low-cost printability onto fabric, the wearable printed humidity sensor has the potential to be used as a disposable sensor for healthcare applications, particularly for urinary incontinence and capturing wetness in diapers.

Keywords: inkjet printing; humidity sensor; conductive ink; wetness monitoring; diaper; wearable; urinary incontinence

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1. Introduction

Urinary incontinence, which occurs as an involuntary loss of urine, is one of the most common health problems among elderly individuals, especially for women [1,2]. It can appear during sleeping, coughing, sneezing, physical exertion, or with a change of body position [3]. Urinary incontinence causes hygiene and skin problems. In addition, it creates psychological problems such as embarrassment, anxiety, depression, asociality, and sleep disturbances. Urinary incontinence decreases the quality of life [4,5]. As a result of studies conducted in different countries, urinary incontinence is seen between 25% and 45% in a population on average [1,6]. In addition, more than 50% of nursing home residents experience urinary incontinence in a nursing home [4,6–8]. Behavioral intervention, drug therapy, and surgical procedures can be used to solve urinary incontinence. These treatments may cause challenges for older individuals. Considering this situation, the most appropriate option for these individuals is to use absorbent products and urinary catheters [1,7]. In a study, it was stated that more than 85% of people with urinary incontinence prefer diapers [9]. According to the diaper market report, in 2020, the global diaper market reached $69.5 billion, while the adult diaper market is expected to grow by $3.01 billion in the period

2020–2024 [10,11]. However, there are some risks in the use of such a preferred product. For example, wet diapers that are not changed promptly can lead to incontinence-associated dermatitis (IAD) and infections caused by exposure to urine or feces. Particular attention should be paid to the diapers of bedridden patients with bedsores. This is because these infections cause bedsores to worsen [12].

Adult diapers, which are one of the liquid absorbent hygiene products, are frequently used in daily life. Most absorbent incontinence materials consist of cover stock, acquisition/distribution layer, absorbent core typically composed of fluff pulp, cellulose wadding, and a superabsorbent polymer (SAP). The cover stock also called the top sheet, is the most important part of the incontinence pads since this part is in direct contact with the skin of the user. Using low-quality products or harmful chemicals on this layer may cause skin rash or dermatitis. For these reasons, the pores on the top sheet of the adult diaper should be large enough for the diaper to breathe, but small enough to prevent urine from flowing out. ADL (Acquisition/Distribution Layer) is located between the top sheet and the absorbent core. It is used in the form of a patch or in the length of the core. This layer is especially necessary for diapers where the absorbent core is very thin. The layer absorbs, transfers, and distributes the liquid quickly. In addition, ADL maintains a feeling of dryness on the skin by providing separation between the wet surface and the skin [13]. The absorbent core is an essential part of the absorbent hygiene product. This part holds urine and other bodily wastes. This layer consists of a combination of cellulose fluff pulp and superabsorbent polymers (SAP). The use of only cellulose fluff pulp in the incontinence pads produced previously could not provide sufficient protection for the diapers due to the decrease in the liquid absorption capacity of the fluff pulp under pressure. This situation is eliminated by adding SAP to the absorbent core, and the production of ultra-thin diapers is made possible. The average weight of the absorbent core can vary from 0.003 to 0.015 g/cm. The main task of the back sheet is to prevent the absorbed liquid from leaking. The back sheet of the diaper is in the structure of a liquid impermeable polyethylene film. A breathable surface is created by allowing water vapor to pass through the micropores on the polyethylene film. Sometimes, a fabric appearance is given by adding polypropylene nonwoven structure to the back sheet film [13,14]. The efficiency of the diaper depends on the structure of the layers around the absorbent core, while the cover stock, the acquisition layer, and the back sheet allow the skin to dry and prevent leakage. Adult incontinence products can be divided into three groups as light, moderate, or heavy incontinence according to the severity of the incontinence problem [13]. According to EDANA, European Disposable and Nonwoven Association, the product composition offered for typical incontinence includes 62% fluff pulp, 12% SAP, 10% PE (polyethylene) film, 15% nonwoven PP (polypropylene), 3% adhesives, and 1% elastics [15]. The first step in the production of incontinence products is the fiberization of the fluff pulp. Next, SAP is added and filled with nonwoven substrates and laminated with elastic elements and tapes to form the absorbent core. The wetness indicator and traceability marks are printed, thereafter. The forming, cutting, folding, and packaging processes are carried out, respectively, in the final stage [13].

Elderly patients who wear adult diapers have difficulty understanding their urinary incontinence and reporting it to their caregivers or health personnel because most of them have dementia or cognitive impairment. Therefore, caregivers need to check the diapers of patients at certain intervals. However, with these controls, it is not possible to change the diaper at the ideal time. In addition, routine diaper checks disturb patients, especially at night, interrupting their sleep. Unnecessary routine checks are very troublesome for caregivers and increase their workload. To get rid of all these negative situations, systems that warn the caregiver or health personnel as soon as the diaper gets wet, are very necessary. In the study [1], a smart diaper system consisting of two carbon conductive lines embedded in the diaper, a sensing device, and a smartphone was presented. Bluetooth technology was used to automatically detect incontinence and its volume. In another study, a smart gadget attached to the outside of the diaper for urine detection determined the temperature increase and sent a notification to the caregiver's smartphone [16]. However, the external, inflexible, and rigid devices used in these studies may cause urinary incontinence patients to be uncomfortable with the presence of these devices. The use of flexible and small wearable sensors instead of these hard and externally integrated additional devices contributes positively to the comfort of the patients. In a study, a wearable humidity sensor was used to detect urinary incontinence. This capacitive humidity sensor was embroidered onto the textile substrate. The wearable system detected urine leaks on a bed sheet or underwear [17]. The system consisted of a humidity sensor, a control unit, and a remote server in reference [17].

Methods such as embroidery, knitting, weaving, coating/lamination, chemical treatment, and printing are used to integrate sensors onto textile substrates [18]. The printing method is one of the most used methods in sensors' integration onto textile substrates and it includes a wide range of application techniques. These are inkjet printing [19], screen printing [20], and gravure printing [21]. Among these techniques, the inkjet printing method is one of the most preferred techniques in terms of being both fast and low cost.

Many polymer-based materials and their combinations are used in the production of sensors. Among polymer-based materials, poly(3,4-ethylenedioxythiophene): polystyrene sulfonate) (PEDOT:PSS) draws attention. PEDOT:PSS polymer has many advantages such as high conductivity, low price, and easy processability at room temperature [22,23]. Hassan et al. produced a humidity sensor using the PEDOT:PSS, which is known to be a humidity-sensitive polymer. In addition to PEDOT:PSS polymer, methyl red, and graphene oxide were used to increase the sensitivity range and to improve the response and recovery times of the humidity sensor in this study [24]. In another study, a real-time humidity sensor based on a microwave resonator was designed using PEDOT:PSS conductive polymer [25]. Two humidity sensors (interdigitated electrode structure) were printed on glossy photo paper using PEDOT:PSS polymer and silver ink with the inkjet printing method. Relative humidity, temperature, compressive, and tensile bending tests were applied to the produced sensors. However, it was found that the PEDOT:PSS humidity sensor did not show good performance for the long-term bending test [26].

In this study, a wearable humidity sensor was designed to detect urinary incontinence and printed on polyamide-based taffeta label fabric using PEDOT:PSS conductive polymer with inkjet printing method. The behavior of the printed humidity sensor against humidity was tested by fixing the sensor inside of a closed chamber at different humidity levels. Finally, the printed humidity sensor was integrated into the adult diaper to simulate the incontinence situation. The performance of the sensor against wetness was observed.

2. Materials and Methods

2.1. Chemicals and Materials

In the study, humidity-sensitive PEDOT:PSS (poly(3,4-ethylenedioxythiophene): polystyrene sulfonate) conductive polymer was used to print the humidity sensor. The concentration of this conductive polymer from Sigma-Aldrich (CAS No: 0155090838, San Diego, CA, USA) is 3–4% by weight in water. Triton X-100 surfactant was purchased from Merck Millipore (CAS No: 9036-19-5, San Diego, CA, USA) to adjust the surface tension of the ink. Ethylene glycol used in the study was purchased from Sigma-Aldrich. The polyamide-based taffeta label fabric with a thickness of 0.105–0.115 mm, and an average weight of 62 ± 5 g/m^2 on which the sensor was printed, was purchased from Huzhou Hengxin Label Manufacture Co. (Huzhou, China). Silver-plated polyamide yarn was purchased from Shieldex (Bremen, Germany). Its yarn count was 235f $\times$ 34 $\times$ 2, and it had a linear electrical resistance <85 Ω/m. This yarn was placed at the electrodes of the humidity sensor for easier measurement. A translucent polyurethane welding tape (ST 604) purchased from Bemis (Shirley, NY, USA) is used to attach the silver-plated polyamide yarns to the two electrodes on the humidity sensor. The softening temperature of this elastic and washable tape is 105 °C. The softening process can be carried out under moderate pressure and temperature conditions.

2.2. Ink Formulation for Inkjet Printing

A schematic diagram of the sensor fabrication and its integration was shown in Figure 1. Firstly, a polymer solution was obtained by mixing PEDOT:PSS, and distilled water. After the mixing procedure, ethylene glycol was added to adjust the ink viscosity, and Triton X-100 was added to adjust the surface tension of the ink where both chemicals are added simultaneously. Details of the formulation study are given in [27]. In the end, a homogeneous printing ink was obtained suitable for the inkjet printing method.

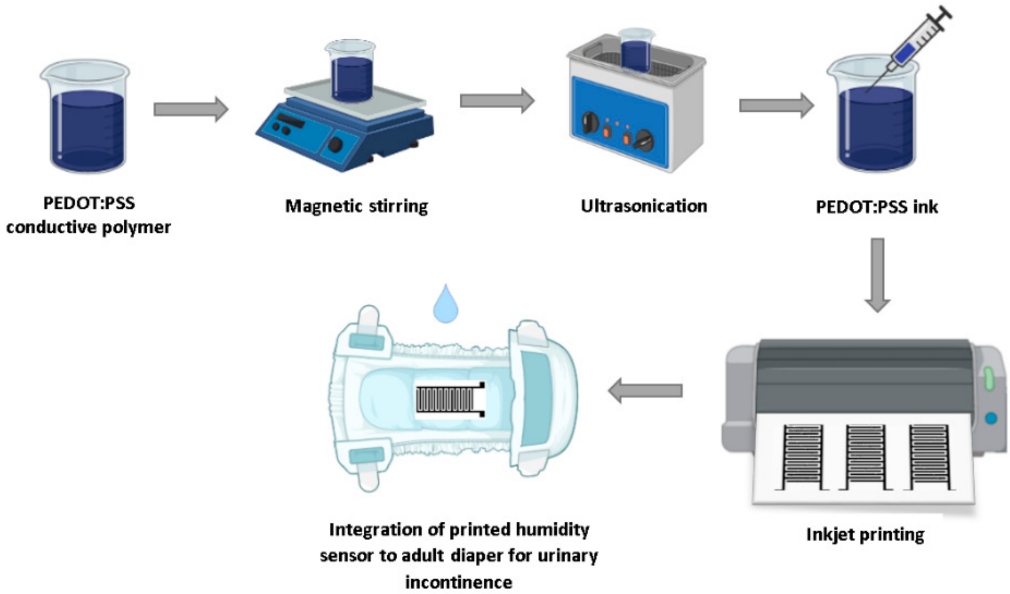

Figure 1. Schematic view of inkjet-printed humidity sensor fabrication, and integration into an adult diaper.

To print the prepared printing ink with the inkjet printing method, many ink parameters need to be examined. These parameters are expected to be within certain ranges. Otherwise, inkjet printing is not possible. The most important of these ink parameters are the viscosity, surface tension, and contact angle of the ink [27]. The dynamic viscosity of the prepared printing ink was measured with the Fungilab alpha device (L model, İstanbul, Turkey). Theta Lite optical tensiometer (Ontario, ON, Canada) was used to measure the surface tension of the prepared ink. This measurement was done using the pendant drop method [28,29]. In addition to these measurements, the contact angles at the points where the ink comes into contact with the fabric surface were made with the Theta Lite optical tensiometer device using the sessile drop method [28].

2.3. Humidity Sensor Design and Fabrication

There are two types of sensors which are capacitive and resistive. The sensor presented in this study is a resistive humidity sensor. The operating principle of this humidity sensor is based on the measurement of changes in electrical impedance. The sensors usually consist of metal electrodes. These metal electrodes are obtained by placing conductive polymer, salt, or different hygroscopic chemicals on the substrate. As the hygroscopic material absorbs water, the ionic groups dissociate. This causes an increase in conductivity. As the humidity in the environment increases, the conductivity increases and the resistance of the material decreases. Resistive sensors provide a linear response to humidity changes [30–32]. The humidity sensor in the study was designed according to the interdigitated electrode (IDE) structure. The humidity sensor design was made larger for easier urinary incontinence detection following the purpose of the study. The total area of the sensor was 46.74 $\times$ 24.13 mm. Inkscape commercial software was used to draw the designed sensor. The sensor consists of 20 IDEs, with each electrode 1 mm wide and 15 mm long. The gap between the electrodes was determined as 1 mm. Figure 2 indicates the dimensions of the designed sensor.

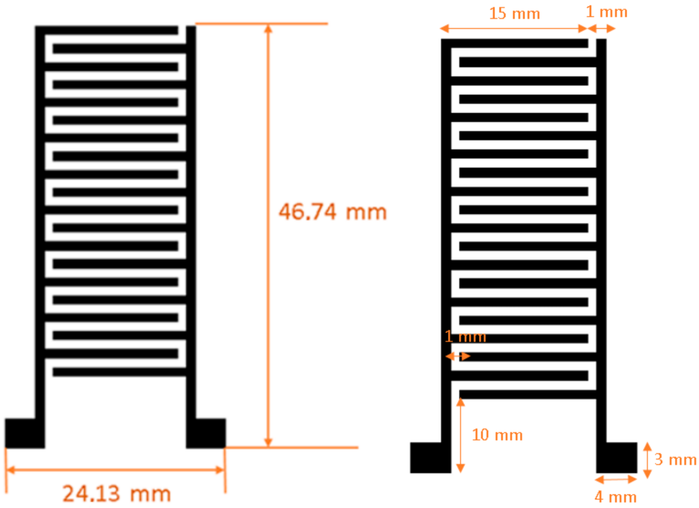

Figure 2. Dimensions of the humidity sensor design.

Dimatix inkjet printer, which is frequently used in studies, is quite expensive. In this study, the printing process was done with Canon office-type printer. Thus, more cost-effective fabrication was realized. Polyamide-based taffeta label fabric was chosen as the substrate. The prepared printing ink was injected directly into the cartridge and rested for 5 min prior to printing to spread the ink properly in the cartridge. Preprint and printing processes were carried out at room conditions. Multiple printing processes were applied onto the polyamide-based taffeta label fabric to increase the conductivity and to have more uniform printing lines. The number of passes applied was 15. After each printing, a drying process was applied at 120 °C for 2 min to prevent slipping and dispersion [27]. After the printing process, silver-plated polyamide yarn was placed at both ends of the humidity sensor. Then, a polyurethane tape was placed on the ends of the humidity sensor where it only came into contact with the conductive yarns. To activate the tape, 5.5 bar pressure was applied at 80 °C for 10 s in the hot-press machine. The printed humidity sensor and conductive yarns connected to its ends were indicated in Figure 3.

2.4. Measurement of the Humidity Sensor Behavior

To perform the humidity tests, a closed humidity chamber was designed and built. The resistance variations of the printed humidity sensor were measured with a Keithley 2700 multimeter according to the four-wire measurement method. The four-wire method ensures more accurate measurement results than the two-wire method. The measured resistance values were transferred from Keithley 2700 Data Acquisition System to the computer with Excelinx software via the universal serial bus (USB) converter cable through RS232 terminal. While the humidifier placed in the chamber increased the humidity of the chamber inside, the commercial humidity and temperature meter (Achem HTC-1, İstanbul, Turkey) measured the relative humidity and temperature in the chamber. Humidity and temperature in the chamber were also checked by another commercial humidity sensor (SHT30 V1.0, İstanbul, Turkey) connected to the Keithley 2700 Data Acquisition System to ensure accurate measurement of humidity and temperature inside the chamber. A clip-on fixing tool was used to prevent the cables from slipping and to improve stability while measuring the resistance. A Trotec T510 moisture meter (İstanbul, Turkey) was used to measure the moisture content on the fabric surface. Figure 4 shows the closed humidity chamber and the devices in it.

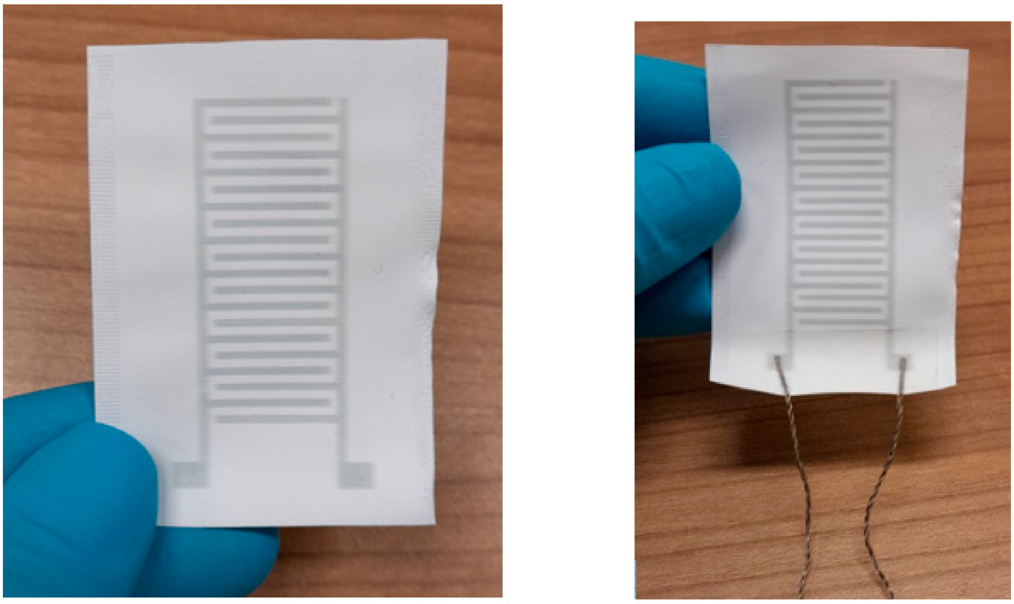

Figure 3. Printed humidity sensor and conductive yarns connected to its ends.

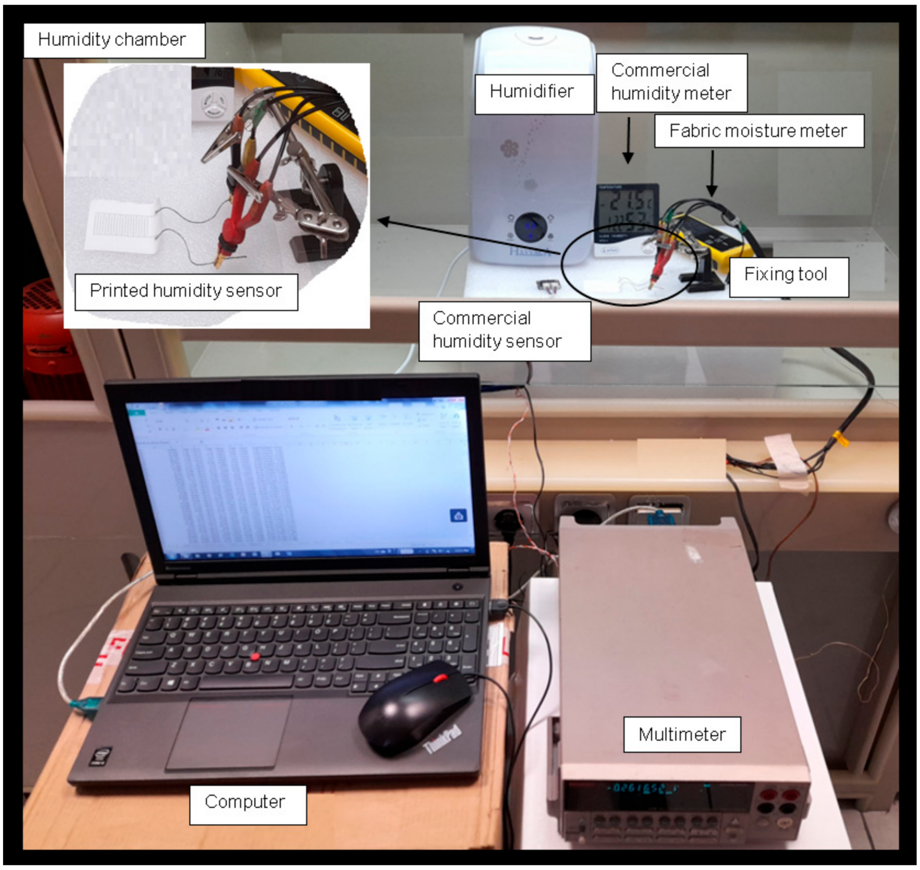

Figure 4. Humidity chamber.

The humidity inside the chamber was fixed at relative humidity ranging from 40 to 100% in 5% RH increments. To show a stable structure for the printed humidity sensor against humidity, the sensor was kept in the chamber for 5 min at each fixed humidity level. Then, the resistance values were measured at the predefined relative humidity level for 3 min with the automatic measurement system and the recordings were directed to the computer. In addition, fabric moisture values were measured with a moisture meter in response to the varying humidity values in the chamber.

3. Results

3.1. Conductive Polymer Ink (PEDOT:PSS) Characterization

Dynamic viscosity, surface tension, and contact angle measurements of the ink were made to investigate whether the developed PEDOT:PSS conductive polymer ink is suitable for the inkjet printing method or not. Conductive polymer ink formulation studies were also carried out. Since the rheological behavior of the ink used in the inkjet printing method is very important, the viscosity and surface tension values of the ink have been well defined in the literature. While the viscosity value specified in the literature is between 1–25 mPa·s, the surface tension is between 25–50 mN/m [27,33] The viscosity and surface tension of the prepared PEDOT:PSS ink were measured as 6.53 mPa·s, and 25.83 mN/m, respectively. They are coherent with the specifications given in the literature. The sample volume for viscosity measurement was 20 mL. All measurements were done at room conditions and by taking the average of five measurement results. Thus, the measured values of the prepared ink are compatible with the inkjet printing method according to the literature [27].

One of the measured values of the prepared ink was the contact angle. The contact angle is defined in the literature as the angles measured at the point where the solid surface and the liquid come into contact after a liquid is dropped on a solid surface. Near zero contact angle for full wetting, contact angle below 90° for partial wetting, and contact angle values above 90° for hydrophobic structures are seen [34]. The measured contact angle values were 27.8° on the left, 27° on the right, and 27.4° on average. Therefore, when the prepared ink comes into contact with the substrate (polyamide-based taffeta label fabric), it makes partial wetting. This case is suitable for the inkjet printing method [27].

3.2. Humidity Sensor Characterization

The humidity sensor produced with conductive polymer measures the resistance according to changing relative humidity. Since PEDOT:PSS conductive polymer is a humidity-sensitive polymer, first of all, the resistance value of the printed humidity sensor was measured at room conditions (21 °C, 35% RH). Then, the humidity sensor was placed in the humidity chamber and a silver-plated polyamide yarn, which was fixed to the ends of the humidity sensor, was connected to the clamp cables of the multimeter. A fixing tool was used to prevent any movement on the yarns while taking measurements. The humidity inside the chamber was fixed at 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, and 100% RH. The sensor was kept in the chamber for a while without taking measurements to let the sensor satisfy a mass concentration balance with the ambient moisture content and to equalize to the ambient temperature, satisfying a complete local thermodynamic equilibrium. The behavior of the sensor against humidity did not change after waiting in the chamber for more than 5 min. Therefore, the conditioning time of the sensor in the chamber has been determined as 5 min. The resistance measurements of the humidity sensor were conducted with the Keithley 2700 Data Acquisition System using the four-probe method. The experiments were repeated 10 times and each one of the experimental measurement results was recorded covering a three minute time interval. The results were averaged and presented with error bars. The graph showing the change in resistance of the sensor in the chamber against increasing relative humidity is shown in Figure 5.

The increase of the relative humidity in the chamber caused the resistance of the sensor to decrease (Figure 5). The resistance value of the sensor at room conditions (21 °C, 35% RH) was measured as 17.05 ± 0.05 MΩ. When the humidity chamber reached 100% RH, the resistance of the sensor decreased to 2.09 ± 0.06 MΩ. The decrease in resistance is expected to be linear as the relative humidity increases for resistive sensors. When the graph in Figure 5 is examined, it is seen that the resistance-relative humidity relationship is almost linear. In addition, resistance values can be found for certain relative humidity from the given equation in Figure 5.

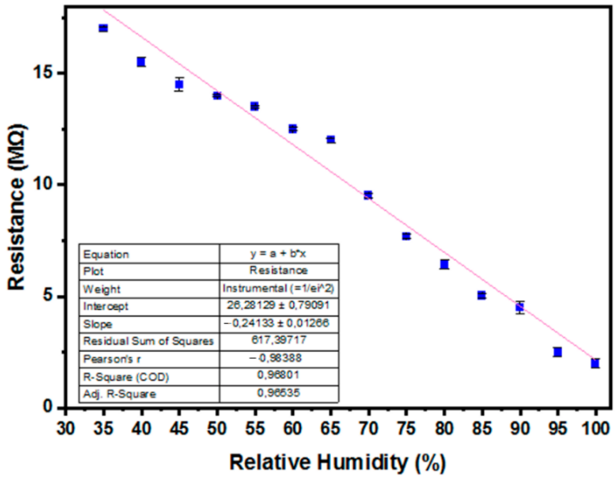

Figure 5. Graph of the resistance change of the sensor against relative humidity.

Fabric moisture was measured with a fabric moisture meter to understand how the changing relative humidity in the chamber affects the fabric moisture values. The fabric moisture meter uses the resistance measurement method to determine the moisture of the material. While the moisture of the fabric was 4.8% at room conditions, it was measured as 23% when the inside of the chamber was increased to 100% RH. As the relative humidity in the chamber increased, the moisture of the fabric increased as expected (Figure 6). However, moisture on the fabric did not increase linearly with increasing humidity in the chamber. This situation may be related to the ability of the textile material to absorb moisture in the air. Herewith, it has been proven that fabric moisture increases with the relative humidity of the surrounding environment while the resistance of the sensor decreases due to its conductive polymer.

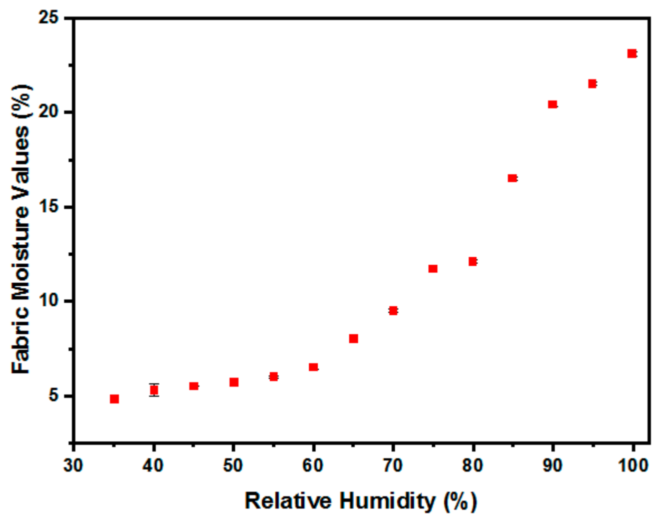

Figure 6. Graph of fabric moisture change against relative humidity.

Humidity sensors produced are expected to have many potential applications in various application areas. Two of these characteristics are response time and recovery time [35]. Response time is defined as the required time from the initial value of the resistance to a stable value, while recovery time is defined as the inverse of the response time. The response time and the recovery time of the produced humidity sensor were measured 42 s and 82 s, respectively. While measuring the response time of the sensor, the sensor was taken into the humidity chamber (100% RH) from the room conditions (35% RH) and then the required time from the initial value at room conditions to a stable value at 100% RH was measured. Conversely, the recovery time of the sensor was measured as the time taken when the sensor was removed from the chamber at 100% RH and brought to room conditions (35% RH). In the study [24], the response time and recovery time of the humidity sensor created using PEDOT:PSS, methyl red, and graphene oxide were measured as 1.0 s, and 3.5 s, respectively. In another study, the response time of the humidity sensor created using PEDOT:PSS and PVA composite ink was measured as 0.625 s, while the recovery time was measured as 0.53 s [36]. Therefore, the response time and recovery time of the humidity sensor presented in this study are low compared to other studies. It is thought that the response and recovery times of the sensor will be shortened by adding different materials to PEDOT:PSS polymer, as in other studies. However, since our sensor is designed to integrate a disposable diaper for single usage, the response time of the sensor would be also quite acceptable.

Moreover, a repeatability test was applied to the humidity sensor. The room ambient conditions where the sensor was located were 30.9% RH and 23.5 °C before the test. Then, a repeatability cycle was completed by measuring the resistance change of the sensor between 35% chamber indoor air relative humidity and 100% RH. Altering the relative humidity between 35 to 100% and back to 35% is considered a cycle. This cycle was repeated for 50 consecutive cycles. At first, the cabin RH was increased from 35 to 100% RH and then it was decreased to 35% RH to 100% RH. To observe the changes clearly, sensor repeatability for five cycles is depicted in Figure 7a, while 50 cycles are given in Figure 7b. It can be seen from Figure 7 that the printed humidity sensor shows good repeatability. For the humidity test and repeatability test performed in the chamber, different resistances were measured at the same humidity levels. It is thought that this difference is due to the difference in humidity and temperature on the days of the tests.

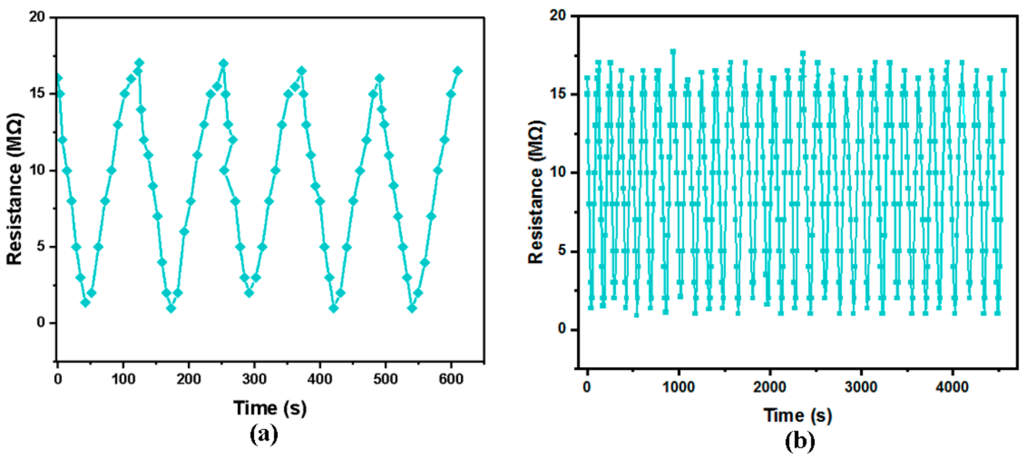

Figure 7. Graph of repeatability test of the sensor while working at the interval of 35–100% RH (from 35% RH to 100% RH and then 100% RH to 35% RH). (**a**) For five cycles, (**b**) for 50 cycles.

The humidity sensor to be integrated into the adult diaper for urinary incontinence is expected to be wearable and flexible. At the same time, it should maintain its mechanical stability and conductivity in cases such as bending or twisting. Therefore, multiple bending cycles should be applied to wearable sensors [37,38]. Wrist joint bending was applied to the sensor to understand how bending movements alter sensor electrical resistance values. Figure 8 indicates the resistance change of the sensor when applied to repeated wrist bending movements. The maximum resistance change measured between the initial state of the sensor and its state after 16 bending cycles was 1%. According to the bending test result, the resistance change measured between the initial state of the sensor and its state after 10 bending cycles was 0.41%, while the measured maximum resistance change after 16 bending cycles was 1%. Accordingly, it can be said that the electrical conductivity and mechanical resistance of the sensor slightly change after 10 bending cycles.

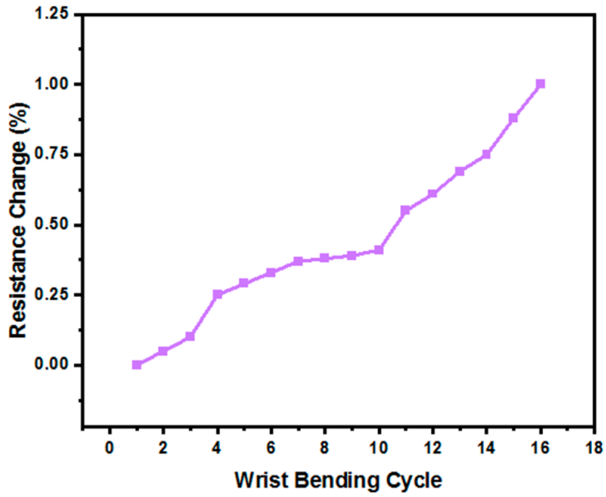

Figure 8. Graph of wrist bending test of the sensor.

3.3. Application of the Humidity Sensor to Disposable Diapers for Urinary Incontinence

The humidity sensor was printed onto the adhesive polyamide-based taffeta label fabric in order to integrate easily it into the adult diaper. Firstly, the top layer of the adult incontinence diaper, the cover stock, has been completely removed. The length of the absorbent part of the diaper was measured as 36 cm where the sensor was attached to the 16–22 cm part. Then, the cover stock was put back to prevent the sensor from coming into direct contact with the skin. As a result, the sensor was placed between the ADL and the cover stock. Silver-plated polyamide yarns, which are located at both ends of the sensor (providing easier measurements) were passed through the cover stock of the adult diaper, employing a needle hole to attach to multimeter probes.

Salty water was used to simulate urinary incontinence. While the conductivity of the water was 340 µS/cm, its pH was measured as 7.05. Five different amounts of water, 0.1 mL, 0.5 mL, 1 mL, 10 mL, and 100 mL, were used for the incontinence test with a micropipette. The distance of the micropipette to the adult diaper was determined as 2 cm. The test setup for the urinary incontinence simulation is shown in Figure 9.

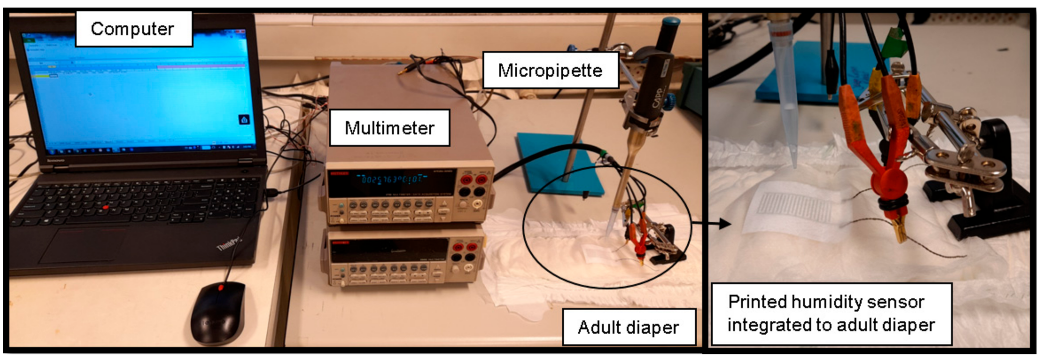

Figure 9. The test setup for urinary incontinence detection.

Resistance measurements were carried out with the Keithley 2700 Data Acquisition System using the four-probe method. There were in total six resistance measurement reference points. Out of the six points, one was conducted at room conditions (24.5 °C, 42% RH) without any added water and the other five points were considered at five different amounts of water dripping (0.1 mL, 0.5 mL, 1 mL, 10 mL, and 100 mL) at the same room conditions. The clamped ends of the multimeter cables connected to the fixing tool were attached to the conductive yarns placed at the ends of the sensor. Thus, a possible move that would affect the measurement result while taking a measurement was prevented. Data were recorded for 60 s for each measurement condition (room conditions, 0.1 mL, 0.5 mL, 1 mL, 10 mL, and 100 mL). The graph of the resistance change of the humidity sensor integrated into the adult diaper for different amounts of water is given in Figure 10.

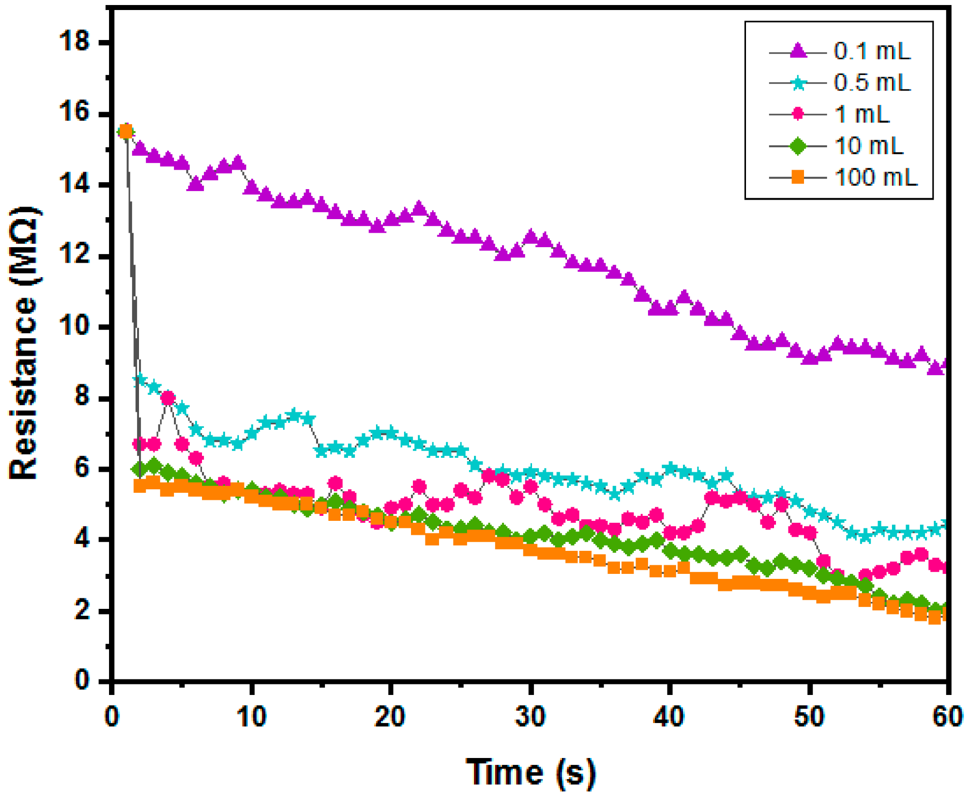

Figure 10. Graph of the resistance change of the humidity sensor against different amounts of water.

Firstly, the resistance values were recorded while the sensor was dry. Then, a determined amount of water was dropped on the sensor and the resistance values were recorded for 1 min. When the resistance change graph in Figure 10 is examined, it is seen that very small urinary incontinences of 0.1 mL were even detected by the sensor. When 0.1 mL of water was dropped, the least resistance change was observed according to the dry condition of the sensor. As the amount of dripped water increases, the measured resistance value decreases. The intensity of urinary incontinence can be understood from the resistance changes of the sensor (Figure 10).

The graph of the measured average resistance values of the sensor against different amounts of water is indicated in Figure 11. While the resistance value of the dry state of the sensor was measured as 15.52 ± 0.01 MΩ at room conditions (24.5 °C, 40% RH), the average resistance decreased to 11.71 ± 0.04 MΩ when 0.1 mL of water was dropped on the sensor. The average resistance values measured were 5.96 MΩ ± 0.03, 4.81 MΩ ± 0.04, 2.12 ± 0.06, and 1.90 MΩ ± 0.07 when 0.5 mL, 1 mL, 10 mL, and 100 mL water were dripped, respectively. The inset graph shows the resistance values of the dry sensor after dripping 0.1 mL, 0.5 mL, and 1 mL water amounts on the sensor. When the graph is examined, there is no great difference in the resistance change of the sensor at water amounts above 0.5 mL.

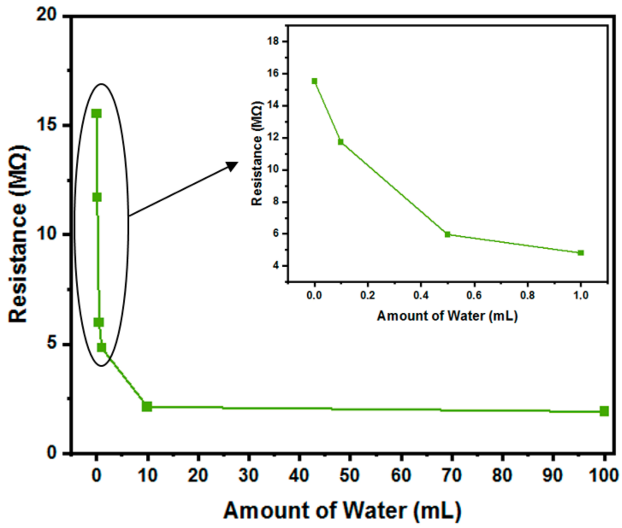

Figure 11. Graph of the resistance values of the humidity sensor against different amounts of water.

4. Conclusions

In this study, a wearable and flexible humidity sensor was designed to be used in wetness monitoring and urinary incontinence detection. Conductive PEDOT:PSS polymer was used in the production of the humidity sensor. Formulation studies were carried out to make PEDOT:PSS polymer suitable for inkjet printing method. Using an office-type inkjet printer, conductive polymer ink was printed on polyamide-based taffeta label fabric. In order to determine the sensitivity of the printed and disposable humidity sensor, a closed humidity chamber was designed and the resistance change of the sensor was monitored against the relative humidity varying from 40 to 100%. The resistance of the sensor decreased from 17.05 ± 0.05 MΩ to 2.09 ± 0.06 MΩ as the relative humidity increased from 35 to 100%, while the moisture value of the fabric increased from 4.8 to 23% as the relative humidity increased. The response time and recovery time of the humidity sensor were found to be 42 s and 82 s, respectively, which are sufficient for the proposed applications. The sensor was then integrated into the adult diaper between the cover stock of the adult diaper, and ADL for urinary incontinence detection. Thus, the sensor was positioned close to the surface, although direct contact with the skin was prevented. The resistance change of the humidity sensor comparing to the dry state resistance (15.52 MΩ) was determined as 3.81 MΩ to 13.62 MΩ by dripping 0.1 mL to 100 mL salty water on the adult diaper to simulate urinary incontinence detection. The results showed that the resistance changes of the sensor differ depending on the amount of water. Even the information on very small incontinence status (solution of 0.1 mL) can be obtained easily and the intensity of urinary incontinence can also be detected with the developed humidity sensor. Making urinary incontinence detection by using a wearable and flexible sensor instead of solid, large, and uncomfortable gadgets is the innovative and promising part of the study. In future studies, it is planned to transform the developed sensors' output into a system that wirelessly communicates with the caregiver or the user in cases of urinary incontinence.

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