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Enabling Longitudinal Respiration Monitoring Using Vapor-Coated Conducting Textiles

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ABSTRACT: Wearable sensors allow for portable, long-term health monitoring in natural environments. Recently, there has been an increase in demand for technology that can reliably monitor respiration, which can be indicative of cardiac diseases, asthma, and infection by respiratory viruses. However, to date, the most reliable respiration monitoring system involves a tightly worn chest belt that is not conducive to longitudinal monitoring. Herein, we report that accurate respiration monitoring can be effected using a fabric-based humidity sensor mounted within a face mask. Our humidity sensor is created using cotton fabrics coated with a persistently p-doped conjugated polymer, poly(3,4-ethylenedioxythiophene):chloride (PEDOT-Cl), using a previously reported chemical vapor deposition process. The vapor-deposited polymer coating displays a stable, rapid, and reversible change in conductivity with an increase in local humidity, such as the humidity changes experienced within a face mask as the wearer breathes. Thus, when integrated into a face mask, the PEDOT-Cl-coated cotton humidity sensor is able to transduce breaths into an electrical signal. The humidity sensor-incorporated face mask is able to differentiate between deep and shallow breathing, as well as breathing versus talking. The sensor-incorporated face mask platform also functions both while walking and sitting, providing equally high signal quality in both indoor and outdoor contexts. Additionally, we show that the face mask can be worn for long periods of time with a negligible decline in the signal quality.

■ INTRODUCTION

In recent years, there has been an increase in demand for wearable health sensors. By integrating sensors with garments, we are able to create a means of noninvasive and long-term health monitoring, which is more accessible to patients and lay consumers. More recently, wearable respiration sensors have received a lot of attention and can be used for detecting and monitoring respiratory diseases such as asthma and respiratory viruses such as pneumonia.[1−9] Techniques that are used to accurately assess respiration involve tracking the rise and fall of breaths using a pressure sensing belt. This belt must be worn tightly around a person's chest to sense the expansion and contraction of the diaphragm and can cause discomfort for the wearer, as well as more difficulty breathing, especially when taking deep breaths. Nasal cannula can also be used to monitor respiration, where pipes are inserted into the nose, which are much more invasive. However, these techniques are not practical for large-scale or long-term monitoring.[10−12] Respiration allows for physiological signals, such as humidity and temperature, to be released from the mouth and nose through an airflow. By using a material that can sense these physiological signals, we can develop a functional and practical way of monitoring respiration as well as other health indicators.[13]

Respiration sensing has been shown to be possible through the use of pressure, strain, and humidity sensors.[13] Pressure and strain sensors measure abdominal expansion as a proxy for respiration. Alternatively, humidity sensors need to be placed around the face so that humidity changes can be measured as a proxy for breathing. Depending on the context, such differences in placement can render the sensors intrusive or imperceptible. For instance, when integrated into a mask that may need to be worn for personal protection, a sensor inside the mask can be largely unobtrusive to the wearer, whereas tight-worn chest belts can impede many normal activities. Herein, we will focus on the use of humidity sensors to monitor respiration. Resistive humidity sensors are materials where the electronic properties are altered with the introduction of moisture. Materials such as graphene oxide, carbon nanotubes, and polyaniline have been used to make flexible humidity sensors.[13−16] Graphene oxide is of particular interest and has been used in respiration sensing applications as the humidity sensing properties allow for the rapid detection of moisture in a person's breath.[17−20]

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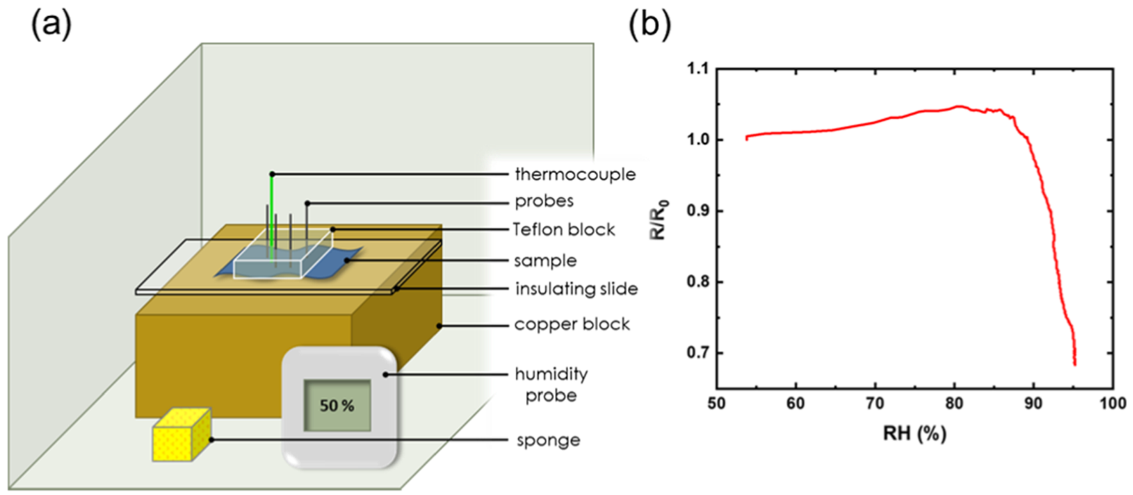

Figure 1. (a) Hygroresistive measurement setup and (b) the hygroresistive behavior of PEDOT-Cl-coated cotton.

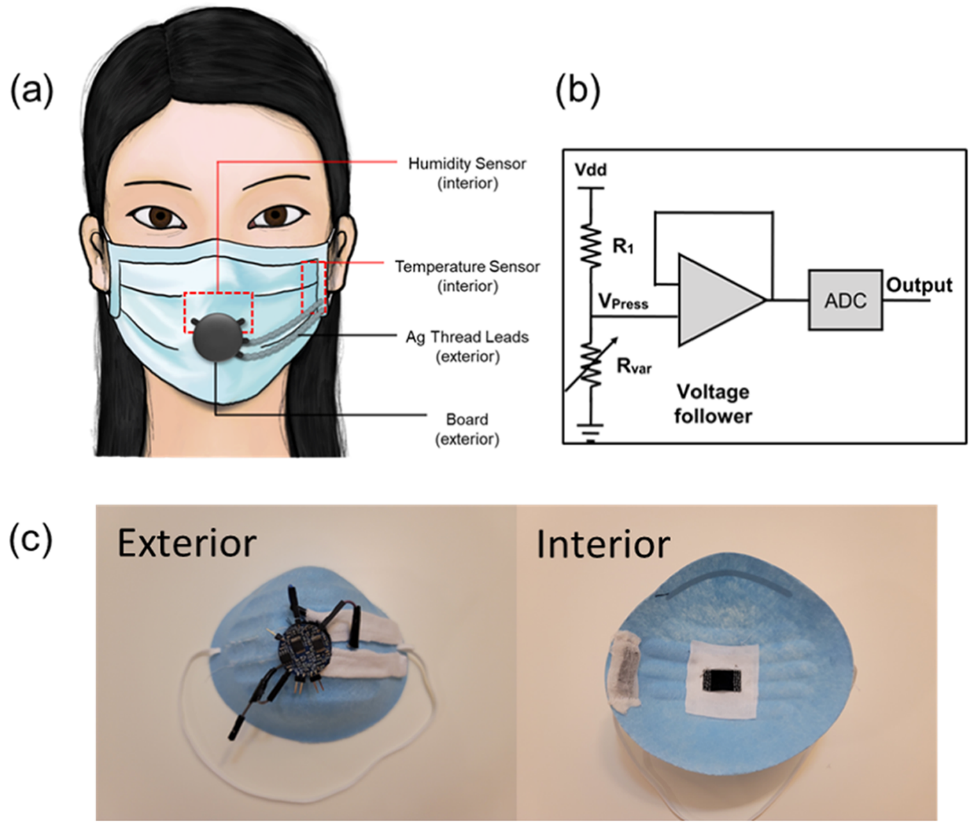

Figure 2. (a) Illustration of a smart mask for respiration monitoring. Illustration created by Linden K. Allison. Copyright 2021. (b) Circuit diagram of the control board. (c) Pictures of the exterior and interior of the mask. Photograph taken by Soha Rostaminia. Copyright 2021.

Borini et al. was the first to report an ultrafast graphene oxide humidity sensor with a 30 ms response and recovery time on a polyethylene naphthalate substrate.[21] These devices were able to distinguish between breathing and speaking based on the electrical response pattern of the device. Pang et al. and Chen et al. have reported success with monitoring respiration using a graphene and graphene oxide humidity sensor, respectively, mounted into face masks.[22,23] Graphene oxide, however, involves a complex synthetic process that mixes vapor-phase synthesis and solution synthesis, which would be difficult to scale up for commercial production.

Persistently doped conducting polymers, which are mixed ion/electron-conducting polymers, are a promising substitute for the graphene oxide active material in humidity sensors. The conductivity of such polymers is linearly responsive to changes in moisture due to increased ionic mobility with increasing humidity.[24] Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) or PEDOT:PSS has emerged as a candidate for respiration sensing, showing rapid response rates that are comparable to those exhibited by graphene oxide.[24−26] However, because PEDOT:PSS is a composite material, its integration with fabrics is nontrivial (often leading to uncontrollable phase separation when deposited onto fabric

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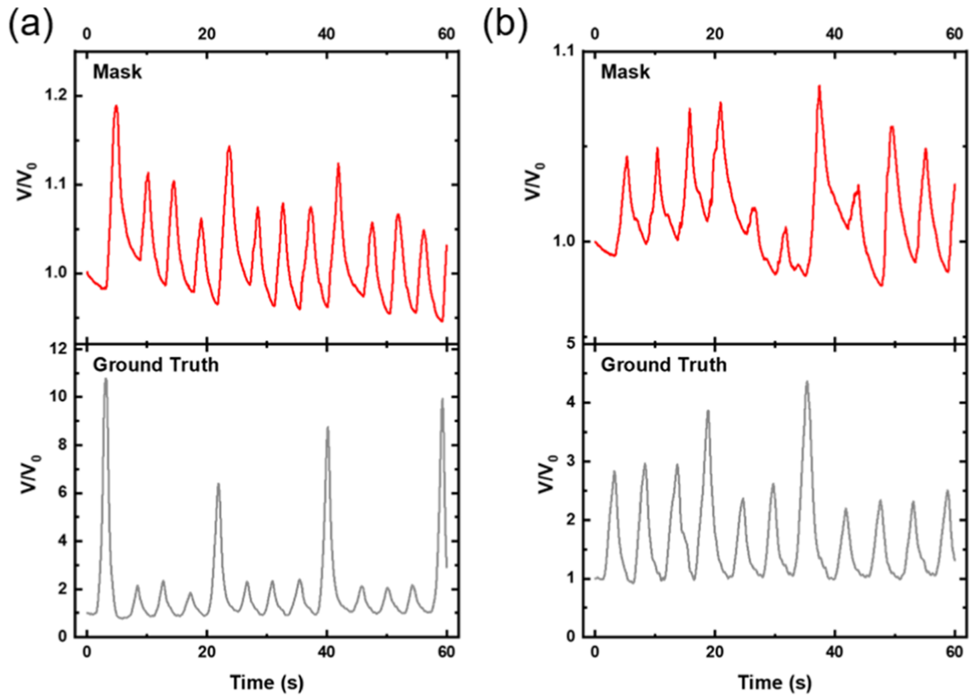

Figure 3. Shallow vs deep breaths sensed by the mask and compared to the ground-truth belt (a) indoors and (b) outdoors.

surfaces) and the hygroscopic PSS component can act as a trap for water, which will lead to undesired saturation behavior in a respiration sensor. Ultimately, a holistic and straightforward synthesis and fabrication method is needed to create humidity sensors incorporating conducting polymers.

Herein, we report a one-step synthesis of poly(3,4-ethylenedioxythiophene):chloride (PEDOT-Cl) using the reactive vapor deposition (RVD) technique. The PEDOT-Cl is coated onto a commercial cotton textile, which allows for the fabrication of a flexible humidity sensor that can easily be mounted in face masks. We integrate the device into a heat-molded mask as well as a cotton mask and analyze the electrical response of the sensor to monitor a person's respiration. We show that these devices can be used longitudinally to differentiate between shallow breathing and deep breaths, as well as differentiating between breathing and talking, in both indoor and outdoor environments. These functions have the potential to be implemented in health care and could allow our wearable sensor to alert wearers to potential respiratory distress as they go about their lives.

■ RESULTS AND DISCUSSION

Humidity Sensors and Mask Design. The humidity sensors, also known as hygristors, were made out of a standard cotton coated with poly(3,4-ethylenedioxythiophene) (PEDOT-Cl), using a reactive vapor deposition (RVD) process. This procedure has been previously reported by our group, and details of the deposition process can be found in the Materials and Methods section.[27] The resulting fabrics have a conformal and uniform coating of the polymer, which makes them very robust. The fabrics were subjected to 10 wash cycles, using traditional textile laundering parameters, to assess the robustness; the resulting resistance being 1.16 ± 0.0894 kΩ was unchanged after washing, which indicates excellent adsorption of the polymer to the textile fibers.[28]

The hygroresistive properties of the sensors were measured using the setup shown in Figure 1a. The resistance of the sample was measured using a custom-built 4-point probe. A water-soaked sponge was added, and the testing setup was sealed. The increasing relative humidity (RH) of the testing environment was monitored using a humidity probe, and the resistances were recorded as the RH in the testing environment increased. Figure 1b shows the hygroresistive properties of PEDOT-Cl coated on cotton. We see that as the humidity increases, the resistance of the sample decreases. Therefore, we are able to categorize PEDOT-Cl as a resistive humidity sensor. Furthermore, the trend we see for hygroresistive behavior can be confirmed by previous reports on the hygroresistive behavior of various PEDOT derivatives.[24]

The PEDOT-Cl cotton was made into hygristor devices by sewing silver thread to each end of a 1 cm × 2 cm rectangle of PEDOT-Cl-coated cotton with a hydrophobic fabric to protect the silver-plated threads used as electrodes. The hygristor was then mounted in the mask in a location that sits between the nose and the mouth to sense respiration coming from both (Figure 2a). The silver thread leads were yarned and threaded through the mask, stabilizing the sensor in the desired location, and connected to the electrical board, which is mounted on the exterior of the mask. The electrical board measures the voltage changes of the hygristor; the circuit diagram can be found in Figure 2c. Motion artifacts are able to be reduced through the use of cotton tubing, as shown in the previous work from our lab.[29−31]

Respiration Monitoring. Real-time outputs from the mask were recorded for two separate participants in various settings. Representative data for user 1 is provided in Figure 3; data for user 2 can be found in the Supporting Information (Figures S1−S6). To assess the accuracy of the humidity sensor, a ground-truth respiration belt was also worn, which senses respiration from expansion and deflation of the diaphragm. It should be noted that the respiration belt senses a respiration event slightly before the mask as the belt is

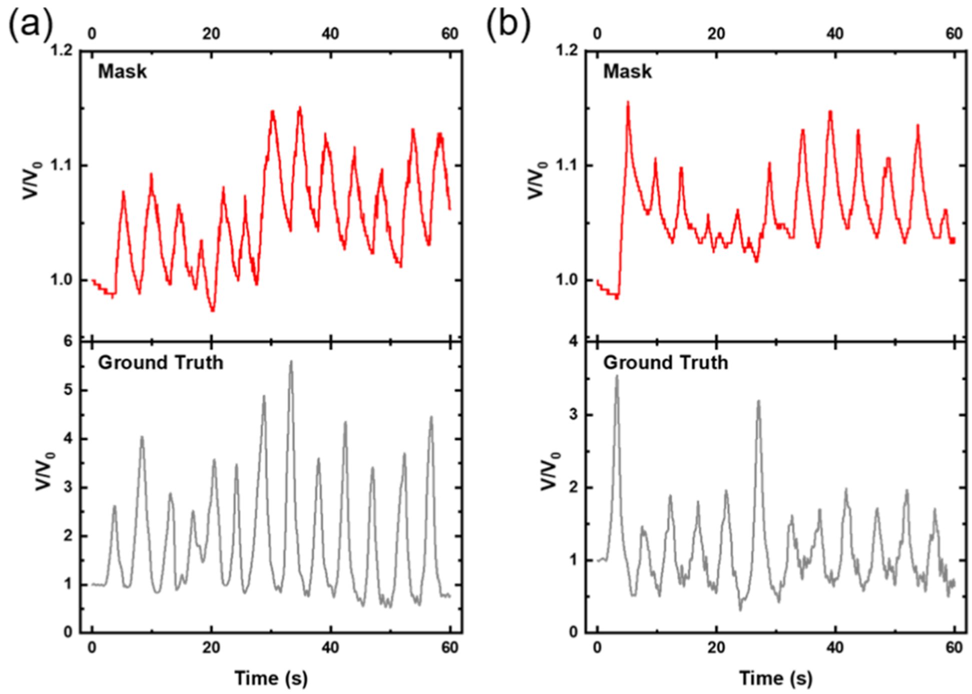

Figure 4. Sensing respiration while the user is walking (a) indoors and (b) outdoors.

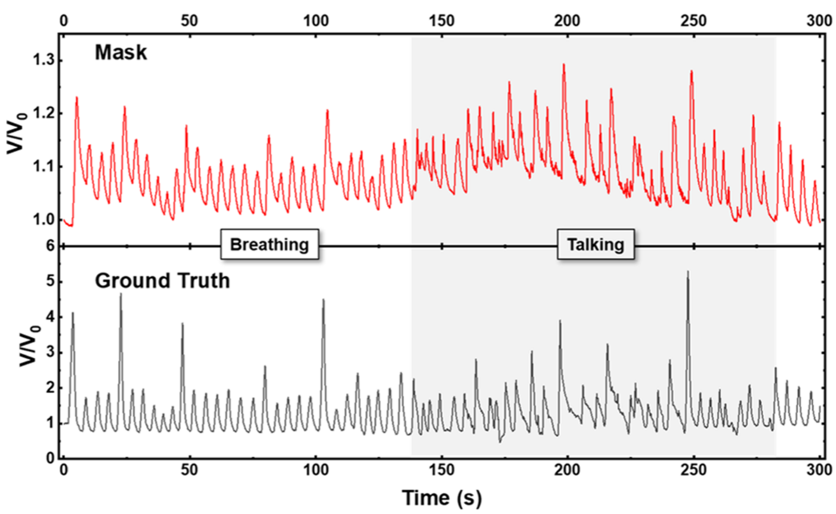

Figure 5. Respiration pattern of the user breathing vs talking.

sensing the diaphragm and the humidity sensor is sensing the breath. We show that the humidity sensor is able to accurately sense the moisture in a breath and recover quickly enough to sense the next breath. We also show that the humidity sensor can distinguish between deep and shallow breaths taken by the wearer (Figure 3a). The signal quality remains constant even when the breaths were measured outdoors (Figure 3b). It should be mentioned that the respiration belt shows an unchanging baseline, while the hygristors show an occasional increase in the baseline. We attribute this to the lingering presence of humidity in the mask between these breaths. We observed this phenomenon to be more prominent after the user exhales a deep breath but proceeds to take shallow breaths.

The sensor was also tested by measuring respiration while the wearer was walking, and the results show that there are very little motion artifacts (Figure 4a). We believe that these artifacts can be effectively eliminated or significantly reduced using a Bluetooth connection between the board and the software. The outdoor walking results show a small amount of motion artifacts, but the overall respiration is still distinct (Figure 4b).

We found that the humidity sensor is sensitive enough to be able to differentiate breathing from talking (Figure 5). We see that the signal pattern from breathing is very systematic. However, the signal from speaking is less systematic than breathing, which is representative of the variations in the breath that are released from a person's mouth while they are talking. The signal of the ground truth shows that when the user is talking there are variations in the peak widths as well as the distance between the peaks, which is also reflected in the signal of the hygristors. This is an important difference to note because, during remote or long-term monitoring using this

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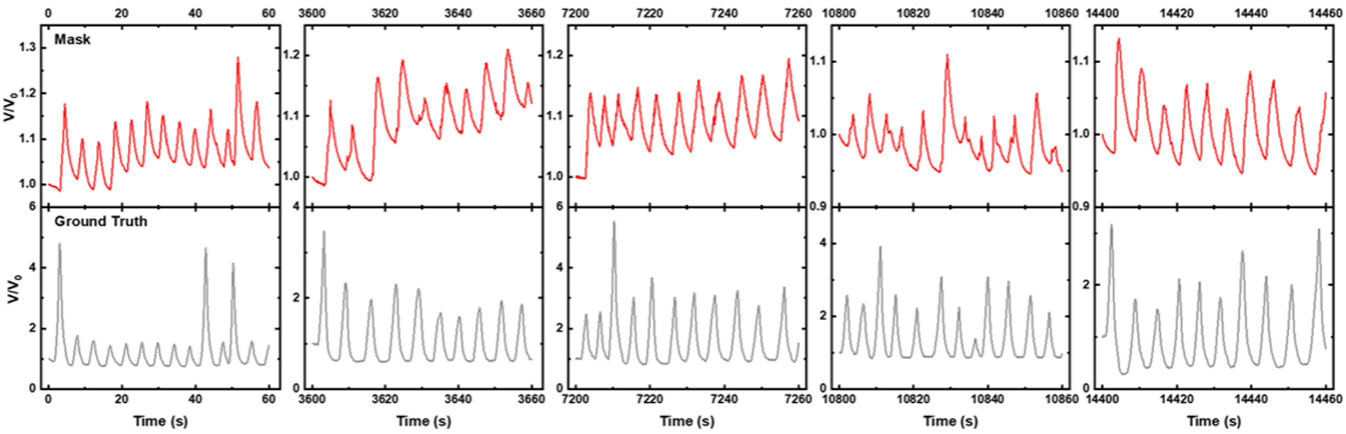

Figure 6. Longitudinal data of the user where measurements were taken every hour from 0 to 4 h.

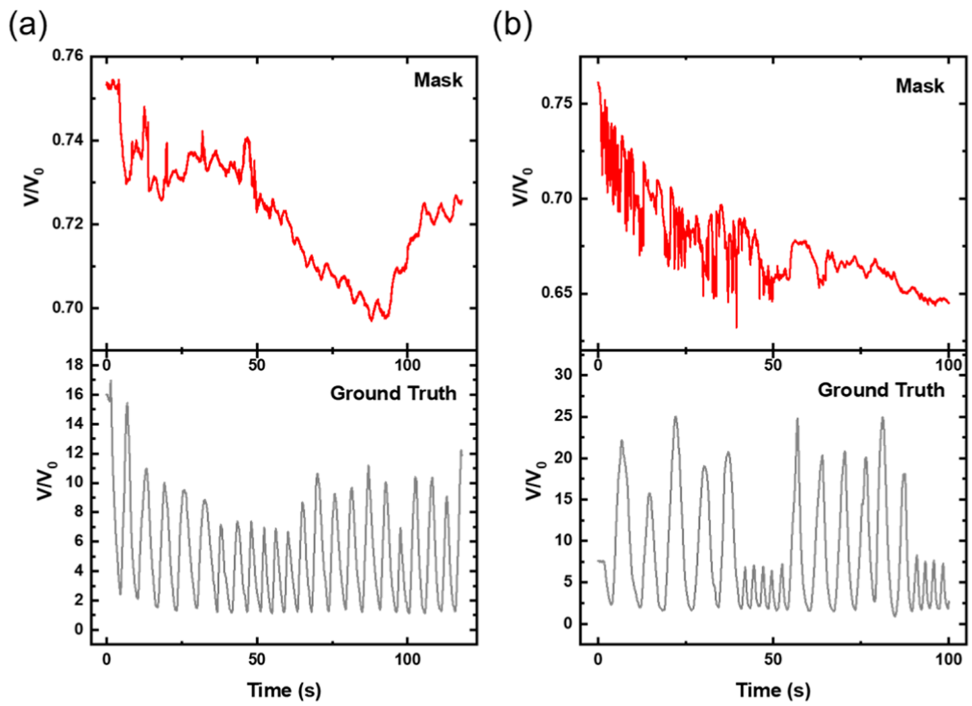

Figure 7. Respiration measured using the PEDOT:PSS sensor mounted in the mask for (a) 1−2 min and (b) 3−4 min.

mask, any changes in respiration need to be easily distinguishable to come to medical conclusions.

To show that the mask can be used for long-term health monitoring, we performed longitudinal respiration monitoring (Figure 6). The participant wore the mask for 4.5 h, and the respiration was recorded every 30 min. We see that the long-term use of the sensors does not result in saturation of the signal. Furthermore, to show the versatility of this sensor design, we mounted the humidity sensor in a fabric mask and recorded a participant taking deep and shallow breaths, the results of which can be found in the Supporting Information (Figures S8 and S9).

We tested a sample of poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) coated on the same cotton as the PEDOT-Cl sensor to compare the sensitivities (Figure 7). We found that the PEDOT:PSS sensors were much more conductive than the PEDOT-Cl sensors, measuring ∼150 Ω. Additionally, the coating procedure was found to be significantly longer as the PEDOT:PSS coatings were nonuniform and multiple coats were needed to cover the entire textile surface. Because of this, the procedure also produced more waste as there was waste associated with each coat, compared to the PEDOT-Cl that requires only one deposition. The PEDOT:PSS sensors showed a respiration signal but were unable to differentiate between deep and shallow breaths. After 2−3 min of breathing on the sensor, we saw the signal decay into noise, suggesting that the sensor had fully saturated. This leads us to believe that the PEDOT-Cl sensors were more sensitive and robust and therefore better for use in this application than the PEDOT:PSS sensors.

■ CONCLUSIONS

We demonstrated a PEDOT-Cl-coated cotton humidity sensor mounted in a face mask for use in respiration monitoring. Through experiments on two different participants, the sensor proved to be sensitive enough to distinguish between deep and shallow breathing, as well as being able to discern talking from

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breathing. The signal quality of measurements taken outdoors was comparable to those taken indoors. We also demonstrated that the breathing signal of a participant taken while walking was insensitive to motion artifacts. The mask proved to be capable of measuring respiration for four consecutive hours without the indication of signal saturation. We additionally demonstrated that the sensor can be integrated and functional within different types of masks by measuring the respiration of a participant using a sensor mounted in a fabric mask. We believe that these findings can lead to a comfortable, functional, and long-term form of respiration monitoring.

MATERIALS AND METHODS

Sensor Fabrication. The humidity sensors were made from PEDOT-Cl-coated cotton using reactive vapor deposition (RVD). The deposition was performed in a custom-built quartz-wall reaction chamber under an applied vacuum. The monomer (3,4-ethylenedioxythiophene, purchased from Sigma-Aldrich), substrate (commercially available cotton), and oxidant (iron(III) chloride (97%), purchased from Sigma-Aldrich) were heated to 95, 110, and 180 °C, respectively, and the polymerization took 30 min at 100 m. The PEDOT-Cl-coated cotton was rinsed with methanol (≥99.8%), purchased from Fisher Scientific, to remove the unreacted oxidant. More details on the deposition conditions can be found in our previous work.[27] The devices were constructed using the coated fabric and silver thread (LessEMF, 66 Yarn 22 + 3ply 110 PET), and the sensor dimensions were measured to be 1 cm × 2 cm.

Sensor Characterization. The hygroresistive properties of PEDOT-CL-coated fabrics were measured using a custom-built 4-point probe. The samples were placed in a sealed testing environment with a humidity probe to monitor the relative humidity (RH) of the testing environment. The humidity was increased by adding a sponge soaked with varying amounts of water into the testing setup, which allowed the RH within the sealed testing chamber to increase over time. Resistance values were recorded approximately every minute to allow the relative humidity within the sealed testing environment to equilibrate to a specific value and to ensure that the conducting polymer coating was subjected to the same local humidity as that indicated by the humidity probe within the test chamber.

Sensing Mask Characterization. The sensors function by translating changes in humidity into changes in resistance of the device. Due to variances in the total charge of local humidity levels inside a mask depending on the unique moisture content of the breath of individual users and the fit of the mask for each user, the humidity levels were not independently measured along with change in the conductivity for the mask measurements. Based on the accurate and repeated measurements of the hygroresistive properties of PEDOT-Cl-coated fabrics, we make the tentative conclusion that changes in the resistance of the final mask platform with users breathing are caused by changes in the local humidity within the face mask as the user inhales/exhales. To convert resistance changes into voltage, we designed an electronic board with a voltage divider by placing a constant resistance (R_1 in Figure 1b) in series with the sensor and capturing the output voltage (V_{press}). A voltage follower is placed to minimize the effect of load on the sensor and to provide a low-impedance output for analog-to-digital converter (ADC).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.1c04616.

Mask outputs for user 2; deep/shallow breathing indoor, deep/shallow breathing outdoors, walking indoors, walking outdoors, and longitudinal measurements for user 2; and pictures of the sensor incorporated into a fabric mask (PDF)

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Author Contributions

⊥L.K.A. and S.R. contributed equally. The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

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Notes

The authors declare no competing financial interest.

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