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A Low-Cost Lung Monitoring Point-of-Care Device Based on a Flexible Piezoresistive Flow Sensor

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Abstract—This work presents the development of a piezoresistive flow sensor-based low-cost point-of-care lung monitoring device. The objective of the study is to find an affordable and accessible solution for pulmonary health diagnosis and monitoring. The proposed biomedical device consists of an ergonomically designed cylindrical mouthpiece, a flexible piezoresistive sensor, and an electronics unit for detection, signal processing, and transmission of the derived signal. The flexible piezoresistive sensor acts as a transducer for the device by exhibiting a change in resistance when subjected to the airflow from the user's breath. Preliminary tests for lung monitoring such as peak expiratory flow rate test and breathing frequency tests were conducted using the device developed in the current study in order to identify its detection, health monitoring and telemedicine capabilities.

Keywords—flexible sensor; piezoresistivity; graphene; point-of-care testing; lung monitoring; mobile health; telemedicine

I. INTRODUCTION

Regular and accurate monitoring of health parameters can drastically improve life expectancy by early diagnosis of many potentially aggravating health disorders at very early stages. To this end, low-cost and portable point-of-care testing (POCT) devices have enabled a large section of the society to monitor health with accurate diagnostics [1]. Lungs being one of the most critical physiological organs in humans, pulmonary function tests are important to measure the fitness of the lungs [2]. Pulmonary disorders like asthma and chronic obstructive pulmonary diseases (COPD) are all potentially lethal [3], claiming more than 4 million lives every year and leaving another 1 billion people under the burden [3]. Underdiagnoses and under-treatments are rampant [3] even as required medication or services may not be accessible or affordable in most of the low-income countries. Till date, peak flow meters [4] and spirometers [5] have been two of the most widely used diagnostic tools for pulmonary function tests (PFTs). A peak flow meter usually works by measuring the maximum flow rate when a person forcefully exhales after a deep full inhalation [4]. Presently, flow meters based on kinematic mechanisms (e.g. spring-piston or torsion-spring) or stator-rotor pairs are the sensory systems implemented in mechanical and digital peak flow meters [6]. Spirometers

work by measuring the values of important lung volume parameters such as forced vital capacity (FVC) and forced expiratory volume in the 1st second (FEV1) [5]. Pneumotachometer [5] type sensory arrangements are commonly used for spirometers. In addition, many attempts have been made to commercially build some POCT forms of peak flow meters and spirometers [7]. These systems demand the requirement of clinical specialists for activity and examination making them expensive and often not accurate [2]. Crucially, such facilities are only incorporated at diagnostic centers or specialty hospitals, access to which is limited for people from lower strata of society [1]. The monitoring device proposed here aims to fill the significant gap present in the current healthcare delivery and approach to the management of COPD and other lung diseases.

II. MATERIALS AND METHODS

Figure 1. Flexible piezoresistive sensor (a) process of fabrication (b) illustration of sensor (c) photograph of the sensor.

A. Sensor fabrication

Piezoresistive sensors have long been used for biomedical sensing applications and mobile health systems [8]. Fig. 1a shows the schematic representation of the process steps

involved in the fabrication of the flow sensor. A thin polydimethylsiloxane (PDMS) layer of thickness 200 μm is spin-coated on a silicon wafer and heat-cured. Copper contacts are placed on the PDMS layer before dispersion of a 220 μm thick graphene strip layer on top. Another thin PDMS layer of thickness 200 μm is spin-coated and heat-cured on top in order to form a sandwich-like sensor configuration which can be clearly understood from the illustration in Fig. 1b. Fig. 1c shows the photograph of the flow sensor fabricated using the above methodology. The sensor changes its resistance when subjected to mechanical strain, due to the piezoresistive behavior of the graphene dispersion layer [9]. The thin and flexible PDMS strip enables large bending strains for airflow stimuli [10] while protecting the graphene layer from external factors.

Figure 2. 3D Design of the device: (a) design and components of the proposed device (b) x-ray vision model of prototype

B. Device design

The proposed lung monitoring device design, created using the Autodesk TinkerCAD 2019 platform, is shown in Fig. 2a. It consists of a flexible piezoresistive sensor mounted on a cylindrical body and sealed with an adhesive ring. The circuit box of the design houses the electronic circuits, with control buttons on top of a closed panel. Fig. 2b shows the X-ray view of the stage-one prototype model. The cylindrical body forms the airflow channel with dimensions of length 15 cm and an inner diameter of 2.5 cm. The top end of the device was designed with a 1.2 cm wide rectangular edge indentation for mounting the sensor. The honeycomb filter, aligned in the direction of flow as shown, was added as it reduces turbulence in the airflow [11] due to a very small pressure drop through the honeycomb structure. The two main constraints [11] for designing the honeycomb filter given by

$$6 < L/D < 8 \quad (1)$$

$$B > 0.8 \quad (2)$$

were satisfied using a honeycomb length (L) of 38.5 cm, cell hydraulic diameter (D) of 5.3 cm and porosity (B) of 0.985.

III. RESULTS AND DISCUSSION

A. Analysis of pulmonary function tests (PFT)

In order to accurately analyze and monitor the human respiratory system, the developed device was exposed to several PFTs [5]. The sensor was mounted on the device

without any initial tension and was connected to a Wheatstone bridge circuit powered by a 9 volts (V) battery. The voltage drop across the bridge was acquired using the NI-DAQ USB-6003 system and recorded on the NI Signal Express software at a sampling rate of 1 kHz. Fig. 3a displays the signal response of the sensory device when exposed to normal breathing in relaxed condition in a voltage (V) vs time (s) plot. We can also observe the actuation of the piezoresistive flexible sensor mounted on the lung monitoring device when air is exhaled and inhaled respectively from the mouthpiece end which causes the change in its resistance. It must be noted that due to the symmetry of the design, the flow sensor shows the same polarity of change in resistance for both inhalation and exhalation. The frequency of the signal response gives us information about the breathing frequency of the user which is a useful marker for various respiratory disorders [12] while the amplitude of the signal response depends on the magnitude of airflow velocity. Fig. 3b shows the signal response for normal breathing under hyper respiratory conditions such as post exercise situations in a time series plot. The significantly higher breathing frequency was detected successfully by the sensory device, showing promise for possible diagnosis of asthma severity in users [13,14]. Fig. 3c shows the plot for peak expiratory flow-rate (PEFR) signal response of the sensory device when subjected to a forceful expiration after a full forceful inspiration by the user. It is observed that the amplitude of the PEFR signal response voltage peak is significantly greater than the normal breathing signal response. The results indicate that the peak voltage reading in Fig. 3c corresponds to the PEFR, which is the parameter to be quantified. To further analyze the health monitoring capability of the device, a hot wire anemometer (PCE-423, PCE Instruments) was utilized to measure fluid velocities at the position of the mounted sensor, generated by a variable speed direct current (DC) motor mini-fan. Afterwards, standard volume-flow rate equation (Eq. 3) was used to calculate the fluid flow rate as:

$$Q = v \times A \quad (3)$$

where Q is the flow rate in liters per minute (L/min), v is flow velocity and A is the cross-sectional area. The calculated values were plotted to show the variation of sensor output voltage (V) with respect to flow-rate in liters per minute (L/min) in Fig. 3d, which gives a fitted calibration curve for the monitoring instrument. Fig. 3e shows the comparative PEFR signal response analysis for two Asian origin male subjects, of ages 22 – 24 year-old, with heights 173-175 cm. The expected peak flow rate (EPFR) [15] was calculated using standard equations from Knudson [16], and was found to be 616 L/min. The green zone (80 -100% of EPFR), yellow zone (50 -80% of EPFR) and red zone (0 -50% of EPFR) represent the diagnostic and monitoring zones with green indicating normalcy, yellow indicating partially risky situations or warning and red indicating a case of health emergency or severe disorder [17]. When the device output is mapped over these diagnostic zones, the region in which the peaks lie is used as an indicator of the user's lung health. The results obtained in Fig. 3e shows the application of a low-cost flexible piezoresistive sensor in a lung monitoring device.

Figure 3. (a) Normal breathing signal response of the device (under relaxed condition) (b) High frequency breathing signal response of the device (under post-exercise condition) (c) PEFR signal response of the device (d) Physical actuation of the sensor while exhaling (e) Physical actuation of the sensor while inhaling (f) Variation of Flow-rate (L/min) at the sensor end with respect to sensor output Voltage (V) (g) Analysis of PEFR signal response of the device

Figure 4. (a) 3D printed prototype device real image and device in testing (b) Flowchart for telemedicine and mobile health application (c) Lung monitoring smartphone application

B. Mobile health application

Fig. 4a shows the stage-one prototype, 3D printed using the Ultimaker 2+ (Ultimaker BV, the Netherlands) with inexpensive PLA (Polylactic acid) filament. The piezoresistive flow sensing strip was mounted on top without any pretension. An electronic circuit was developed to run a mobile health application configuration [18] as shown in the workflow of Fig. 4b. The flexible piezoresistive sensor mounted on the

device was connected to a voltage divider network. The analog voltage output of the sensor was detected by Arduino UNO Rev3 (microcontroller) and converted to a digital signal. The microcontroller processed the voltage signal before transmitting it to a peripheral smart device/ phone using the ESP 8266 Wi-Fi module. A mobile lung monitoring application was built using Blynk IOT platform and data from the device was wirelessly transmitted to the mobile application [19]. The mobile application demonstrated the ability to display the PEFR of the user and deliver point-of-care diagnosis in three levels using known EPFR as described in Section III. Such a system is expected to be helpful for preventing asthma attacks in adults and children [20,21]. Users would also be able to learn what triggers their asthma attacks, if their treatment plan is on course, if the medication needs to be adjusted according to the progress or seek professional healthcare, all at any given location.

IV. CONCLUSION

In this work, an economical, reliable, convenient, and user friendly lung monitoring point-of-care device was developed using a piezoresistive PDMS-graphene flow sensor. The successful respiratory rate and peak flow measurement results indicate the potential of the device which can pave the way for important early detection analysis, diagnosis and monitoring of health in terms of asthma, COPD and other respiratory infections. Further, a mobile smartphone health application was developed that enables telemedicine capability, thus allowing basic pulmonary healthcare access to all strata of society in developing countries and facilitating home-care in a low-cost manner.

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