MONITORING VITAL SIGNS OF RESPIRATION AND HEART BEAT SIMULTANEOUSLY VIA A SINGLE FLEXIBLE PIEZOELECTRET SENSOR
Yao Chu1,2, Huiliang Liu1,2, Junwen Zhong2, Ying Dong3, Xiaohao Wang1,3, and Liwei Lin1,2
1Tsinghua-Berkeley Shenzhen Institute, Tsinghua University, CHINA
2Berkeley Sensor and Actuator Center & Mechanical Engineering Department, UC Berkeley, USA
3Graduate School at Shenzhen, Tsinghua University, CHINA

ABSTRACT
This work reports a self-powered, flexible piezoelectret sensor with honeycomb structures for monitoring vital signs. Compared with the state-of-art technologies, three distinctive advancements have been achieved: (1) a self-powered and flexible pressure sensor using laser-patterned honeycomb piezoelectret structures for high sensitivity; (2) the capability to record both respiration and heart beat at the same chest location simultaneously via a single device; (3) successful extraction and separation of respiration and heart beat signals for practical applications. As such, this piezoelectret sensor could enable various health diagnostics such as asthma and cardiopulmonary arrest as well as observing the physical activity intensity levels for the training of athletes.

INTRODUCTION
With the rapid development of wearable devices, we have witnessed its widespread application in daily health monitoring. One of the vital signs monitored mostly is the heart rate. As shown in Table 1, several sensing technologies have been developed for heart rate detection including photoplethysmogram, electrocardiogram and the pressure pulse. However, the existing sensors are usually targeted to monitor only one body function by checking one vital sign, for example, the breath rate. When compared with the exponentially developed devices for the heart rate, the respiration (breath) rate sensors attract less attention. Respiration rate is an important physiological signal especially for the training athletes and the care elder people. This parameter can help monitor the status of the athlete during training in order to maximize their potential and the effect of training and to minimize the underlying risk and athletic injuries. Respiration frequency is also a valuable measurement for the early detection of respiratory diseases such as asthma. Some researchers design a resistive sensor which is sensitive to humidity and embedded in the mask to monitor the respiration rate via the humidity change during the inhale and exhale process. Another method adopted for breath rate monitoring is to measure the diaphragm wall motion by an ultrasound sensor. However, such sensors are not perfect for embedding in clothing considering the power consumption and flexibility. This work utilizes the principle of piezoelectret transducers [1, 2] with an improved design based on the honeycomb structure for high sensitivity in order to measure both breath rate and pulse rate simultaneously. Furthermore, the flexible sensor has been successfully demonstrated for common application scenarios in daily life usages without the requirement of well-controlled setups as described in previous works.

DESIGN
Figure 1a shows the conceptual schematic of using the wearable patch to monitor the vibration of the chest wall of the human body to extract both respiration signals and heart beats at the same time. A flexible patch is attached on the chest where both the vibration of the chest wall and the heart beat can be extracted. Afterwards, the coupled physiological signal is separated into the respiration and heart beat signals, respectively, according to their different amplitude and frequency. The working mechanism in one period of pressing and releasing of the piezoelectret sensor is shown in Figure 1b. When the sensor is pressed (i to ii), the distance between the top and bottom electrodes decreases and the inductive charges on both electrodes decrease, which results in the output current in the external circuit. When the applied force is released (iii to i), the distance between the electrodes recovers and the inductive charges on both electrodes increase, which results in the outputs current in the opposite direction in the external circuit. The current is pre-amplified and filtered by a low noise current preamplifier (Stanford Research Systems, SR570), and then sampled by a DAQ (National Instruments, PCI-6259) for further analyses.

Figure 2 illustrates the structure of the laser-patterned honeycomb piezoelectret film, which has great flexibility and skin conformality for wearable applications. The Ecoflex layer patterned with the honeycomb structure is sandwiched in between two layers of fluorinated ethylene propylene (FEP) with electrodes.

![Figure 1](image-url) (a) The conceptual schematic of attaching the flexible patch based on the cellular piezoelectret transducer on the chest for mobile health monitoring where the sensor outputs (green line) are extracted and separated for the respiration signals (red line) and heart beat signals (blue line). (b) The working mechanism of the piezoelectret-based pressure sensor in short-circuit mode in one period of pressing (i to ii) and releasing (iii to i).
Table 1. Comparison of Different Types of Wearable Sensors for Heart Rate and Respiration.

<table>
<thead>
<tr>
<th>Type of Vital Signals</th>
<th>Type of Sensors</th>
<th>Source of Signals</th>
<th>Flexibility</th>
<th>Power Consumption</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate</td>
<td>Optical</td>
<td>Variation of blood volume in the skin</td>
<td>No</td>
<td>600 μW</td>
<td>[3]</td>
</tr>
<tr>
<td></td>
<td>Electrocardiogram</td>
<td>Electrical changes on the skin</td>
<td>Yes</td>
<td>NA</td>
<td>[4]</td>
</tr>
<tr>
<td></td>
<td>Triboelectric</td>
<td>Pulse on the wrist</td>
<td>Yes</td>
<td>Self-powered</td>
<td>[5]</td>
</tr>
<tr>
<td>Respiration</td>
<td>Resistive</td>
<td>Humidity change</td>
<td>Yes</td>
<td>~ 5 nW</td>
<td>[6]</td>
</tr>
<tr>
<td></td>
<td>Ultrasound</td>
<td>Diaphragm wall motion</td>
<td>No</td>
<td>~ 50 mW</td>
<td>[7]</td>
</tr>
<tr>
<td>Heart beat + Respiration</td>
<td>Resistive</td>
<td>Epidermal strain change</td>
<td>Yes</td>
<td>NA</td>
<td>[8]*</td>
</tr>
<tr>
<td></td>
<td>Triboelectric</td>
<td>Vibration of chest wall</td>
<td>Yes</td>
<td>Self-powered</td>
<td>[9]</td>
</tr>
<tr>
<td></td>
<td>Piezoelectret</td>
<td>Motion underneath the chest when lying down</td>
<td>Yes</td>
<td>Self-powered</td>
<td>[10]</td>
</tr>
</tbody>
</table>

*Can measure heart beat and respiration signals at the wrist and on a mask respectively, but not the coupled signal.

FABRICATION

The fabrication process is shown in Figure 3. Firstly, Ecoflex is spin-coated (400 rpm, 1 min) and cured to form a 150 μm-thick layer. Secondly, the designed honeycomb pattern is engraved on the layer by a laser cutter (Universal, VLS 6.60). Thirdly, both sides of the patterned Ecoflex layer and one side of FEP films are treated by oxygen plasma to form –OH group on the surface. Then, the Ecoflex layer is further modified by soaking into 3-aminopropyltriethoxysilane (APTES, 99% purity, Sigma–Aldrich) solution. The Ecoflex and FEP are chemically bonded together by a uniform press at 40°C and then one electrode is deposited as the ground electrode for corona charging, where a high voltage (~18 kV) is used to break down the air within the honeycomb structure. Finally, the other electrode is applied on the sandwich structure.

Table 2. Detailed geometric parameters.

<table>
<thead>
<tr>
<th>Schematic Description</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-to-side diameter (d)</td>
<td>4 mm</td>
</tr>
<tr>
<td>Gap (g)</td>
<td>1 mm</td>
</tr>
<tr>
<td>Void ratio of honeycomb</td>
<td>64%</td>
</tr>
<tr>
<td>Thickness of Ecoflex</td>
<td>150 μm</td>
</tr>
<tr>
<td>Thickness of FEP</td>
<td>25 μm</td>
</tr>
<tr>
<td>Thickness of electrode</td>
<td>50 nm</td>
</tr>
</tbody>
</table>

Figure 2: (a) The schematic illustration of the transducer where Ecoflex (blue) is sandwiched in two piezoelectret films (red) with the top and bottom electrodes (yellow). (b, c) Optical photos showing the flexibility of the sensor and the honeycomb structure.

Figure 3: The fabrication process. i. spin coating Ecoflex on a glass substrate; ii. laser cutting honeycomb structures; iii & v. oxygen plasma treatment; iv. soaking the Ecoflex film in APTES solution; vii. bonding, electrode deposition and corona charging; viii. electrode deposition.

The detailed geometric parameters of the pressure sensor are shown in Table 2. The biomimetic honeycomb structure design help increasing the structural stiffness while providing large areas (with about 64%) of deformable membranes to achieve high sensitivity. Figure 2b shows a photo of the fabricated Ecoflex layer with the honeycomb structure. Figure 2c illustrates the structure with 50 nm-thick Au as the electrode, which is flexible and conforms well to skin.
RESULTS

Figure 4 shows the simultaneously recorded raw data of our sensor and a commercial optical sensor (green LED: Kingbright, AM2520ZGC09; ambient light sensor: Avago, APDS-9008) when taking slow and deep breath intentionally as the sensor is affixed on a volunteer using a chest belt. The respiration signals and heart beat can be extracted and separated from the acquired data in Figure 4a as shown in Figure 5. It is found that the extracted heart rate is the same as the result by using the commercial optical sensor but the further respiratory (breath) information cannot be revealed by the optical sensor. Compared the raw signals in time domain, our sensor is capable to acquire both the respiration, which has a longer period and larger amplitude, and heart beat signal, which has a shorter period and smaller amplitude. With the collected data from our sensor, we can distinguish the respiration and heart beat activity from the acquired data and tell when the inhaling and exhaling happen easily by manual observations. For the optical sensor, however, the respiration activity is not reflected in the collected waveforms. This is reasonable since our sensor measures the change of pressure induced by the physiological activity and respiration and heartbeat both have an effect on it, while the optical sensor monitors the average blood perfusion to the dermis and tissue underneath skin, which is dominated by the cardiac cycle and less influenced by the respiration.

To further demonstrate the capability of our sensor for detecting the physiological signals in daily life, the sensor is affixed on the chest in a more casual and common way - using a sports tape (KT Tape). The signals of holding breath and normal breath are shown in Figures 6a. From the time domain and time-frequency domain analyses (Figure 6b), the heart rate and respiration rate are extracted as 73 and 19 bpm respectively.

In order to derive the frequency information and the location information of the signals at the same time, continuous wavelet transform (CWT) is used rather than Fourier transform where the location in time is missing. During the test of holding breath, the activity of inhaling and exhaling appears as a large and sharp pulse in the time domain and dispersed as shown in the red dotted ellipse in the time-frequency domain. The signals when holding breath is stable with little baseline drift and the main peak and valley of the waveform in each cardiac cycle can be identified clearly. This is also shown in the time-frequency domain analyses in which the series of bright blue-white lines corresponds to the fundamental frequency of heart beat and its harmonics. During the test of normal breath, the acquired signals from our sensor is a superposition of the respiration and heart beat signal. Since the amplitude of respiration is larger than the heartbeat, the respiration feature dominates the data outputs in the normal breath condition, which is also shown as the yellow line (large magnitude) in the time-frequency domain plot. However, the heart beat can still be extracted using the series of bright lines in higher frequency range.

In order to demonstrate the capability of our sensor in breath pattern recognition, the following test are designed. First, the volunteer breathes normally for around 10 times. Secondly, the same volunteer takes short breath for around 20 times. Finally, the volunteer adjust himself to deep breath. From the time-domain (Figure 7a) and time-frequency domain (Figure 7b) results, we can get the following conclusions. The rhythms of normal and deep breaths are similar and much slower than that of short breaths. The magnitude of deep breaths is slightly larger than that of the short breath and around two times larger than that of the normal breath.
The rate and intensity can be used as two features for breath pattern recognition. **Figure 8** shows how these two parameters are changing with time. The sampled scatters are naturally clustered into three clusters, corresponding to the three designed respiration patterns in order. This demonstration shows the potential of our sensor in vital signs monitoring and physical activity recognition, especially for the care of elderly people and the training of athletes.

**CONCLUSIONS**

We have successfully demonstrated a self-powered, flexible piezoelectret sensor with honeycomb structures for monitoring vital signs of respiration and heart beat at the same time. The respiration patterns and the heart beat can be monitored and separated via a single piezoelectret sensor attached on the chest. The simultaneous testing results of a commercial optical sensor and our sensor shows the capability of our sensor in extracting both the respiration and heart beat signals while the optical sensor fails to acquire the respiration information. Breath pattern recognition is also achieved for practical applications. As such, this piezoelectret sensor could contribute to mobile health care especially for some cardiovascular and respiratory problem such as asthma and cardiopulmonary arrest as well as monitoring the physical activity intensity levels for the training of athletes.

**ACKNOWLEDGEMENTS**

This work was supported in part by the Shenzhen Science and Technology Research and Development Funds (JCYJ20160411164305110 and JCYJ20150831192244849). These devices were fabricated at the UC Berkeley Biomolecular Nanotechnology Center (BNC) lab. Yao Chu and Huiliang Liu gratefully acknowledge the financial support from the China Scholarship Council. Prof. Xiaohao Wang and Prof. Liwei Lin are core-principal investigators of Tsinghua-Berkeley Shenzhen Institute (TBSI) and we acknowledge the funding support of TBSI.

**REFERENCES**


**CONTACT**

*Y. Dong, dongy@tsinghua.edu.cn*