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A Battery-Free Breathing Monitoring System for Post-COVID Education

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1. Introduction

The COVID-19 pandemic has significantly impacted education globally, with remote learning being adopted as an emergency measure to students, faculty, support staff, and administrators [1, 2]. However, is has also brought about several challenges such as difficulty in interaction and need of education method innovation, especially in practical/laboratory sessions [3]. The intervention is crucial in ensuring education quality, and more monitoring methods are needed to aid the intervention [4]. Additionally, face masks, which have become a norm, pose a problem in the interaction between teachers and students [5]. Without real touch or visual surveillance, how to get more interaction and evaluate the efficiency of the class becomes a problem need to be concerned [6]. More monitoring methods are needed to help the intervention [7, 8]. Additionally, even without COVID, monitoring of students can give more information to the educators, which also provide the opportunities for the future education development as well.

The use of wearable sensing devices has shown promise in monitoring human behaviour and can be used in various areas [9]. Piezoelectric devices are widely used due to their ability to measure pressure and harvest the energy for electronic devices [10]. Because of material science development, new materials with advanced mechanical properties and better sensitivities can be fabricated [11, 12]. More and more piezoelectric devices have been designed to be fit the applications in sports, healthcare, and Internet of Things (IoT) systems, etc [13]. However, the report of its application in education is still lack.

The analysis of breathing signal begins in ancient Greeks, which gives many useful information about human status, so as to might be helpful to the interaction between teachers and students [14, 15] However, most of the past reaches about piezoelectric devices only contains the measurement of force/pressure in a plane with distribution of sensors in every target area, or merely mechanical design but shows fewer results about the real application analysis, which needs more concerns in reality [16]. Here, we do the analysis of the measured signal from the wearable system as well as the learning efficiency obtained from empirical questionnaire [17]. The combination of them aims to help the future education.

To make the device more wearable, piezoelectric sensors are integrated into the system in specially designed positions with a comb-like structure. Piezoelectric devices contain a soft piezoelectric pressure sensor and four series collected hard piezoelectric patches as the energy source of the system. The measured pressure information on soft sensor can be transmitted out by the sensing circuit powered by the energy collected by hard patches and managed by the energy management circuit. The device is used in the real learning and after the learning, a memory test is set to quantify the learning efficiency [18]. After that, we did a correlation analysis to investigate the connection between breathing and studying efficiency. This study is the first to combine the piezoelectric sensor with education research, showcasing the future possibility of wearable devices in improving education quality.

2. Demonstration and design of beathing monitoring

The structure of the piezoelectric sensing system and its application is elucidated in Fig. 1, a. The system can be used in the real class application wearing on students' chest, which can capture the breathing signal by the pressure on it and send the information to the personal computer. The piezoelectric sensing module is mounted using a belt with a buckle to fix it. The insert picture shows the structure to place the piezoelectric devices, which are fabricated by 3D-printing technology. The ends of the comb are stuck together with the belt. The whole comb structure has a length

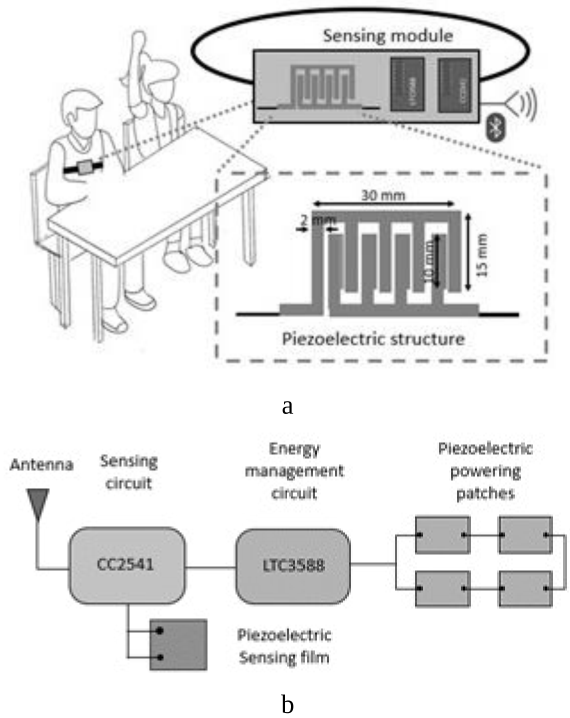
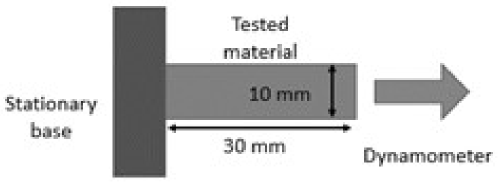
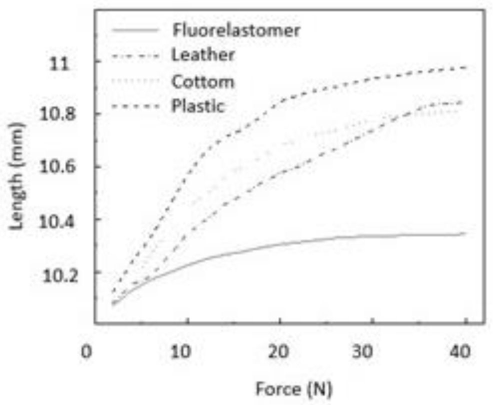


Fig. 1 a) Schematic illustration of the piezoelectric breathing sensing system. This non-battery system can realize the sensing of breast movement while breathing and transmit the signal to personal computer, which can be used in the real classes; b) circuit structure of the sensing, powering, and in-formation transmission module of 30 mm and a height of 15 mm and the thickness of the wall is set as 2 mm, which is enough to support the structure.

Details of the structure and parameters can be viewed in the zoom in picture of Fig. 1, a. As the human is breathing, the chest cavity will enlarge and the space between two comb-like structures will be minimized. As they touch each other and the force still exists, pressure will be added to the sensors. This comb-like structure is used to improve the energy harvesting efficiency in two manners. Firstly, the structure provides a flat and big enough place to put the patches and sensors, which is not easy for this stretching manner. The structure can also transform the stretching force on the belt to the press on the device, which can make the force more evenly distributed. Secondly, the multi-layer structure can improve the collected power [19]. As the working manner of piezoelectric effect, kinetic pressure can change the structure of material and hence an electric potential will generate. As the N-layer of the piezoelectric material is added, it decreases the voltage a bit because the pressure on each layer is not as high as single layer but increases the current N times [19]. As a result, the communication circuit can be driven by enough electrical energy transformed from kinetic energy [20]. As the pressure on the sensor is changed inspired by the breast movement, this information can be recorded for future analysis.



a



b

Fig. 2 a) The measurement setup of material elongation property; b) measurement results of the different materials

For the working of the system, the mechanical property of the belt connecting the 3D-printed structure plays a very important role [21]. Here, we measured the elongation property of different materials to choose the most proper material, which can be shown in Fig. 2. The planks of different material are cut into thin strips with a width of 10 mm, length of 30 mm, and thickness of 1mm. As one end of the strip is held on the wall, the other end is fixed to the dynamometer with a designed force to stretch the strip. The results of the stretching force and the corresponding length of the strips are shown in Fig. 2, b. Four different but usually used materials, fluoroelastomer, leather, cotton, and plastic strip are tested. In the measurement, the elongation of the strip will also absorb the force and limit the piezoelectric energy harvest. As a result, a material with less change with added force is desirable. As shown in Fig. 2, b, both these four materials have the non-linear property and the fluoroelastomer material shows the smaller deformation, which is used in real belt fabrication.

In the experiment, two circuit chips are used to build the breathing sensing system. The commercial multichannel energy harvesting chip (LTC3588) is used in harvesting electric energy and another Blue-tooth low-energy chip (CC2541) can transmit the breathing signal to the laptop. An antenna has also been integrated into the transmitting circuit. The four series-connected hard piezoelectric pads are connected to the energy harvest module and the soft sensor is connected to the Bluetooth module. As a human is breathing, the chest cavity will enlarge and cause pressure on the sensors. For the piezoelectric devices, it is easy to understand that the electric voltage is proportional to the pressure on the sensors from the breathing caused breast enlargement. This signal can be captured by the system and different pressure will cause the different signal intensities.

3. Figures and tables

The used devices, final system, and experiment setup can be viewed in Fig. 3. Fig. 3, a–b displays the soft PVDF piezoelectric thin film (LDT0-028K, provided by Shenzhen Weijingyi Electronics Co. Ltd) and hard PZT piezoelectric pad (purchased from Wuxi Hui Feng Electronics Co. Ltd), respectively. They are both cut as the rectangle with width of 1 cm and length of 1.5 cm. To protect the more sensitive soft sensor, cardboard is used as the background. And all the sensors are cut in rectangle form to make them easy to be inserted into the 3D-printed buckled structure. As the sensors are placed at the designed positions, two ends of the structures are tied with the belt and an interface circuit is connecting the sensors, which can be viewed in Fig. 3, c. While in the experiment measurement, the system is tied on the chest as shown in Fig. 3, d and when the test volunteer is breathing, causing an enlargement of the chest and a relative movement will appear among the two comb-like structures and the pressure on the device will be transformed into electric energy. This pressure will not only provide an electric signal that needs to be captured but also give a driving voltage to the circuit. After the system continuously harvests the energy, there is enough energy for the chip's low-power mode to actively sense the input transducer signals.

The system is then used in the real breathing volunteer for monitoring. Some results are shown in Fig. 4. Because the frequency and intensity of the breath play very important roles in the analysis of breath, we use different breathing statuses in the experiment. For the result shown in Fig. 4, a, the breathing speed is relatively slow, which is 0.9 Hz and becomes relatively higher in Fig. 4, b to 2.3 Hz. The measured result combining the high-frequency breath and low-frequency breath is shown in Fig. 4, c. Between the quick speed breathing, the volunteer also reaches at a slow speed. All the breathing results measured and shown in Fig. 4 show a good capture of the breathing frequency and depth in the real application. The choice of belt material, structure to embed the sensors, and design of the circuit will both make an influence on the sensing precision.

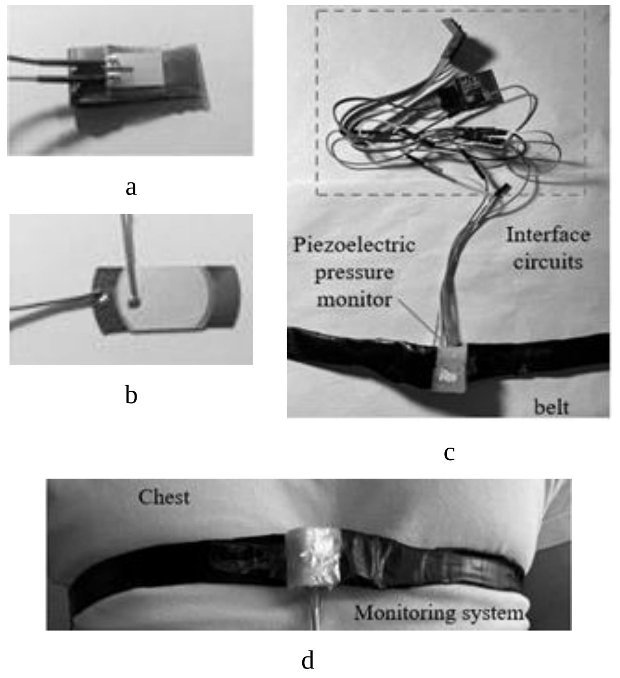


Fig. 3 a) The used soft PVDF sensor to capture the pressure change; b) Hard PZT piezoelectric patch for harvesting the electrical energy and provide the energy for circuits; c) The demonstration of the used breathing monitoring system; d) Experiment setup for the real volunteer. The monitoring system is tied to the chest

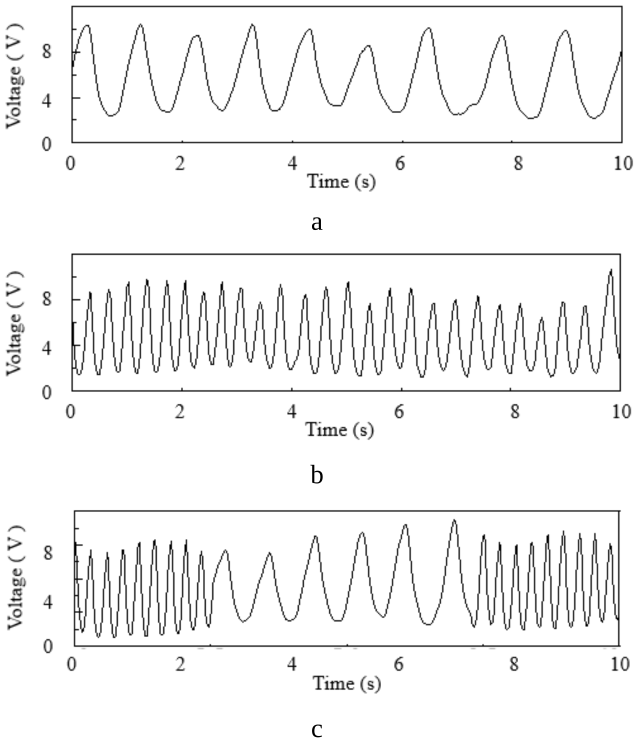


Fig. 4 Measured breathing voltage signal when: a) the tested volunteer is breathing in a low speed; b) the tested volunteer is breathing in a quick rhythm; c) volunteer is controlling the breath as first in a quick speed and then slow speed for six times and then quick speed again

4. Application and analysis

After the design, fabrication, and measurement of the piezoelectric device, we also show that the device is very useful in daily class education, which can be in the real teaching, especially for the analysis of the students. We used the statistic module to do a cross-sectional investigation about whether breathing has an influence on student study efficiency, involving 50 learners with a learning procedure and a test. This study is useful to help teachers get well known the student status and improve teaching efficiency. Furthermore, the other status of the students can also be captured in future analysis, which will broaden the application of wearable devices.

Table 1

Features of the testers

Variable	Category (input to module)	Percentage
Gender	Male (1)	52%
	Female (2)	48%
Age	12-15 (1)	18%
	15-18 (2)	24%
	18-22 (3)	36%
	22-25 (4)	22%
Race	Asian (1)	30%
	White (2)	26%
	Black/African descent (3)	24%
	Latino (4)	20%

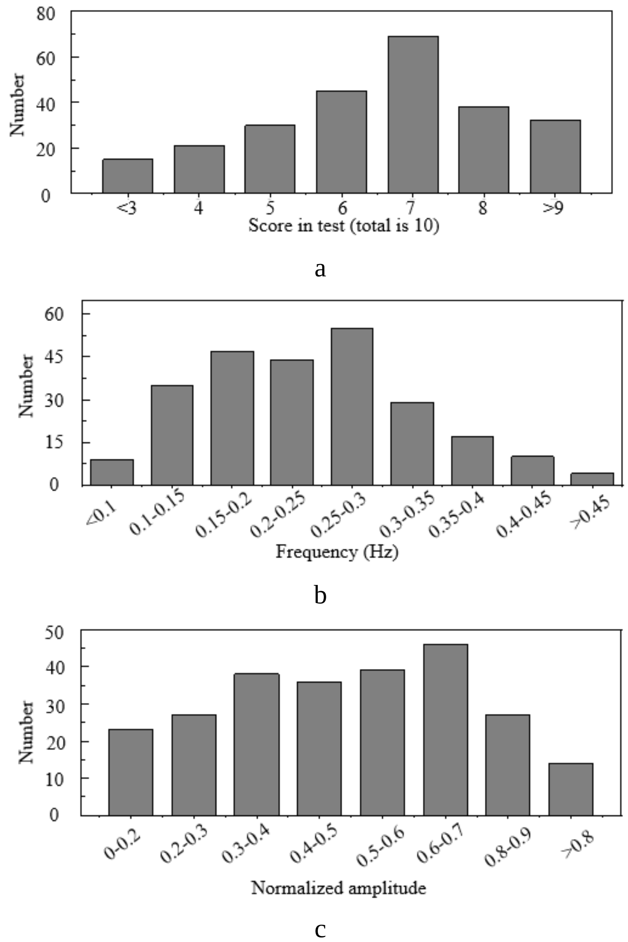


Fig. 5 Distribution of a) test score; b) breathing frequency; c) breathing amplitude in this work

In the experiment, the students in the test wear the breathing measurement device to measure the breathing signal and save it on the laptop. Two K-12 memory experiments, a picture memory test, and a face memory test are implemented by these volunteers 5 times, which are designed by a researcher from the University of Washington

[22]. The data is measured from all 50 healthy volunteers, which have around average distribution about sex, age (18-30), educational background, and race (the distribution is listed in Table 1). To obtain the results with the different breathing signals, proper exercise including walking, jumping, running, and squatting is encouraged between the two tests. Every test is lasting 3 minutes, and the total score is 10. The test score of the memory test is used as the output of the memory test and input data in the correlation analysis. At the same time, the breathing signal E is recorded for analysis. Two features of breathing are extracted for the other inputs of the statics analysis. The first is breathing frequency f, which can be calculated by the Discrete Fourier Transform of the measured signal. Another feature is the breathing intensity I, which can be calculated by the equation:

$$I = \left(E_{max} - E_{min}\right)/C, \tag{1}$$

where: E_{max} and E_{min} are the maximum and minimum of the measured signal E. To minimize the influence of individual difference, we also measured the maximal vital capacity C and use it in the normalization (dividing the breathing signal by the maximal vital capacity) of the test. The total number of E is 250, which is same with the number of scores. Each measurements result is recorded using the ordinal number for the correlation analysis.

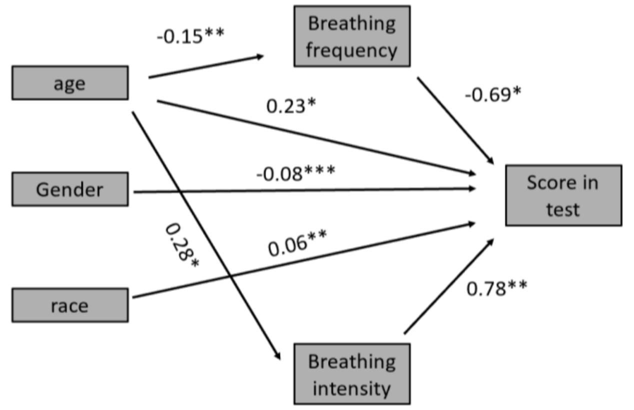


Fig. 6 Final structural equation modelling (SEM) model describing the direct effects between variables. Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

The distribution of the score, E and C are shown in Fig. 5. It can be viewed that the results both have a normal distribution where the test score has a peak number of 7; the breathing frequency has a peak of about 0.25-0.3 Hz but the data is more concentrated on the low-frequency area; the amplitude distribution is more average around the amplitude apart from extreme value. Then the correlation analysis is done and a structural analysis can be plotted, which is shown in Fig. 6. The correlation coefficients demonstrate the strength of the linear relationship between two variables and compare their association, where a bigger coefficient means a stronger correlation between the two variables. It can be viewed that breathing has an apparent influence on the test score. For a high breathing frequency volunteer, he/she will show a much lower test score with a probability p value larger than 0.9. And if the volunteer has deep breathing, they will also likely have a higher score. Generally speaking, a peaceful, slow, and deep breathing will make the tester have a higher score and the other variables have no apparent influence on the results.

5. Conclusions

In conclusion, a battery-free pressure sensing system for breathing monitoring is designed, manufactured, experimentally fabricated, and used in the analysis of learning efficiency. The sensing system has a sensing part to measure breathing and a power harvest part to provide power, both based on piezoelectric devices. The breathing monitoring system will be fixed using a belt on the breast, which has a breathing-caused movement to stretch the belt. The system has a comb-like structure that the piezoelectric energy harvesting devices can embed into them and improve the working efficiency. And the belt material is artfully chosen to fulfil both the soft and non-stretchable requirements. After the experimental validation of the system, it is used to explore the relationship between breathing and learning efficiency. The memory test is used to represent learning efficiency and the correlation coefficient between breathing frequency, amplitude, testing score, and other parameters in the test are calculated, which shows that breathing has a strong influence on learning. This interdisciplinary work shows the broad future application of wearable sensing system in different research areas.

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A BATTERY-FREE BREATHING MONITORING SYSTEM FOR POST-COVID EDUCATION

S u m m a r y

Embedded systems have more and more designs and applications in wearable health monitoring and the Internet of Things (IoT) recently. In this work, a battery-free human breathing monitoring system based on soft polyvinylidene fluoride (PVDF) piezoelectric thin film for pressure sensing and solid lead zirconate titanate (PZT) pads for powering energy harvest is designed and fabricated. Proper material and structure are chosen by mechanical analysis to fabricate the systems. Then the device is used to measure the real breathing signal while studying (the memory test is used to represent the study procedure). The breathing frequency and intensity data are extracted and used in correction analysis with the testing score. And the results show that peaceful, slow, and deep breathing will have a positive influence on the testing score. This study opens the mind to combine engineering designed devices with educational research, showing the broad application of mechanical and electronic systems.

Keywords: piezoelectric monitoring system, mechanical property analysis, memory test in study, correction analysis.

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