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Highly Sensitive Smart Cushion Embedded with SMS Structure for Contactless Vital Signs and Activity Monitoring

Shuying Han[a,**], Wei Xu[b,c,**], Shanhong You[a,*], Bo Dong[b,c,d], Changyuan Yu[e], Wei Zhao[b,c,d], Yishan Wang[b,c,d]

[a]School of Electronic & Information Engineering, Soochow University 215006, China. [b]State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China. [c]University of Chinese Academy of Sciences, Beijing 100049, China. [d]Collaborative Innovation Center of Extreme Optics Shanxi University, Taiyuan 030006, China. [e]Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, HongKong, China.

**These authors contributed equally to this work.

*Corresponding author: shyou@suda.edu.cn

ABSTRACT

A smart cushion based on single-mode-fiber-multimode-fiber-single-mode-fiber (SMS) with core-offset splicing, which can simultaneously realize human vital signs monitoring and activity monitoring, is proposed and experimentally demonstrated. The SMS structure is sandwiched between a piece of fiberglass mesh and a polyvinyl chloride (PVC) layer and then embedded in a common home or office cushion, which is the component of the proposed cushion. When people sit on the cushion placed on a chair, micro-strain induced by human activity including respiration, heartbeat and body movement will change the output light intensity of the fiber structure. By signal processing algorithms including filtering, fast Fourier transform (FFT) and feature extraction, the respiration rate (RR) and heartbeat rate (HR) can be obtained and human activity state on the cushion including nobody state, movement state and normal state can be judged. Furthermore, the performances of two memory foam cushions with different thicknesses are compared and proven to be both available. Such a smart portable cushion can realize real-time, noninvasive and highly sensitive monitoring of vital signs and activities within the accuracy of one second, especially for the elderly in nursing homes and office workers.

Keywords: smart cushion, optical fiber sensors, vital signs, activity monitoring

1. INTRODUCTION

With the rapid development of science and technology, people pay more attention to their own health and their demand for portable health monitor devices enhances unceasingly. Health monitor devices should implement two kinds of expected primary functions, referring to vital signs and activity monitoring. Respiratory rate (RR) and heartbeat rate (HR) are the two most important parameters of vital signs, which is the pillar of maintaining the normal physiological activities of the body. No matter which parameter is abnormally changed, it will lead to serious disease and worse outcome. On the other hand, real-time activity monitoring can record users' activities and furthermore acquire the frequency of body movement. Combining the both, health monitor will help users keep abreast of the health condition of themselves including cardiac activities and lung function, effectively preventing and diagnosing cardiopulmonary diseases, as well as evaluate the degree of fatigue, assisting users to reduce the hidden troubles.

Nowadays, health monitor devices on market emerge in an endless stream, commonly divided into noninvasive and invasive monitoring. Invasive devices including smart bands, face masks, photoplethysmography (PPG) sensors, need to be worn on a certain part of the body, increasing the discomfort to users. Optical fiber sensors have been widely applied to noninvasive health monitoring field relying on their distinct advantages, such as low cost, compact structure, fast response, capability of electrical insulation and electromagnetic interference resistance. In terms of vital signs monitoring, Yu et al[1-2] proposed a health monitoring mattress embedded with Mach–Zehnder interferometer (MZI) which could detect the breath and heartbeat of subjects in sleeping position. Wang et al[3] demonstrated a non-invasive Mach-Zehnder modal interferometer based on dual-up-taper structure for monitoring people's RR when lying on it. A sensing

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mattress system based on polarization maintaining fiber (PMF) and Sagnac interferometer (SI) was presented by Qu et al[4], and a twin-core fiber-based sensor was proposed by Tan et al[5] for non-invasive vital sign monitoring, including RR and HR, which was fabricated by sandwiching single-mode fiber (SMF) on both ends and attached under a mattress.

As for activity monitoring, a MZI based activity monitoring in sleeping position using Recursive least square (RLS) algorithm was proposed by Wang et al[6]. Han et al[7] proposed an effective activity monitoring algorithm based on principle component analysis (PCA) and random forest (RF) and Zeng et al[8] developed an accurate non-wearable method using MZI installed in the mattress and a deep bidirectional long short-term memory (Bi-LSTM) network model to monitor three kinds of activities. The above research results are mostly based on mattress systems while cushion based systems are rarely mentioned.

In this paper, a smart cushion based on SMS with core-offset splicing is proposed and experimentally demonstrated. The SMS structure is sandwiched between a piece of fiberglass mesh and a polyvinyl chloride (PVC) layer and then embedded in a common home or office cushion. To verify its feasibility, two kinds of memory foam cushions with different thicknesses are applied in our experiment. By signal processing algorithms, the respiration rate (RR) and heartbeat rate (HR) can be obtained and human activity state on the cushion including nobody state, movement state and normal state can be judged as well when someone sits on the proposed smart cushion.

2. PRINCIPLE OF OPERATION

2.1 Sensing principle

The SMS structure is fabricated by splicing a segment of MMF between a leading-in SMF and a leading-out SMF and there is a slight core-offset at each splicing point, as shown in Fig. 1.

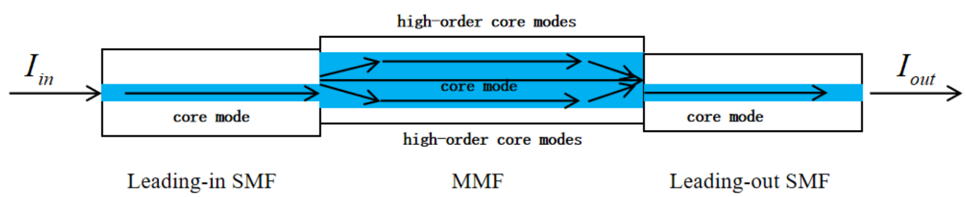

Figure 1. Schematic diagram of the SMS structure.

The incident light firstly propagates along the leading-in SMF, and only LP_{01} mode exists. When reaching at the first splicing point, due to core diameter mismatch, the light is coupled into the MMF segment and the high-order core modes of MMF are excited. Then all the modes propagate along the MMF and will interfere with each other at the second splicing point and be coupled back into the leading-out SMF. The output light intensity I_{out} can be expressed as[9]:

$$I_{out} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\varphi) \tag{1}$$

where I_1 and I_2 are the light intensity of two dominate modes participating in the interference, φ is the phase difference between these two modes and can be expressed as[9]:

$$\varphi = \frac{2\pi}{\lambda}(n_1 - n_2)\ L \tag{2}$$

where λ is the central wavelength, n_1 and n_2 represent the effective refractive indices of two modes respectively, and L is the interference length. When people sit on the proposed cushion placed on the chair, micro-strain induced by human body activity including respiration, heartbeat and body movement will be exerted on the SMS structure, changing the phase difference φ, and then the output light intensity will change accordingly.

Owing to the insufficient sensitivity of only a single SMS structure, the sensing unit of the proposed cushion is fabricated by sandwiching the SMS structure between a piece of fiberglass mesh and a PVC layer as shown in Fig.2. The three layers are stuck together with glue and the fiberglass mesh is arranged at the top layer. Fig. 3. shows the transverse section of the sandwich structure, and the fiberglass mesh tightly covering the SMS structure will cause the fiber micro bending and deformed, further increasing the sensitivity of the cushion.

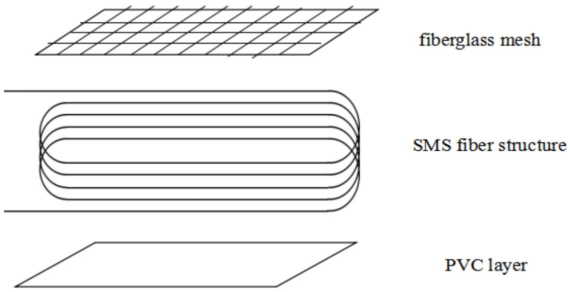

Figure 2. Schematic diagram of the SMS structure.

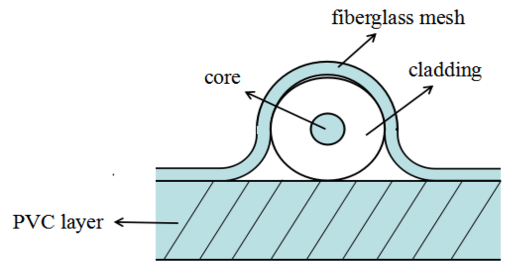

Figure 3. The transverse section of the sandwich structure.

2.2 Vital signs analysis

The respiratory rate (RR) and heartbeat rate (HR) of normal individuals are 12~20 times and 60~100 times per minute, respectively, corresponding to the frequency range of 0.2~0.33 Hz and 1~1.67 Hz. Take a section of raw signals of a 34-year-old male collected from the proposed cushion system as an example, as illustrated in Fig. 4.

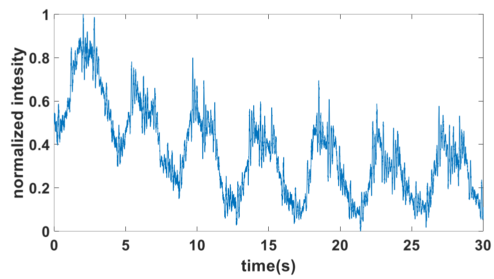

Figure 4. A section of raw signals with duration of 30 seconds.

The respiration waveform can be extracted by dint of wavelet transform. As for heartbeat signals, by adopting band pass filtering, low-frequency respiratory signal interference of the original signals will be removed and the characteristic peak of every single heartbeat, namely, J-peak, will be detected by extracting those locations that exceed their immediate neighboring values by at least the value of a specified threshold (a minimum height difference between a peak and its neighbors), thus obtaining the J-J interval between two neighboring heartbeats. The R-peak of each respiratory waveform can be extracted in the same way as shown in Fig. 5, furthermore, RR and HR can be calculated, which can be given as:

$$RR = \frac{60}{R\text{-}R\text{-interval}} \times 1000,\ HR = \frac{60}{J\text{-}J\text{-interval}} \times 1000 \tag{3}$$

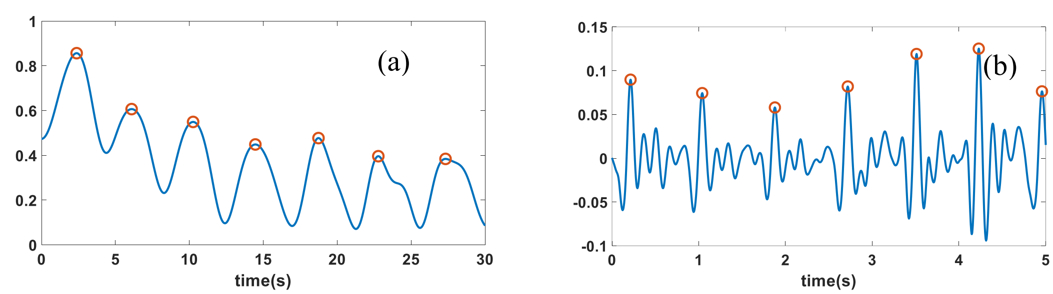

Figure. 5. (a)The extracted respiratory waveform; (b)The extracted heartbeat waveform.

2.3 Activity monitoring

Human activity state can be classified into three kinds: normal state (someone sitting still on the smart cushion), movement state (someone moving on the cushion), nobody state (nobody on the cushion), as Fig. 6 shows. The signals corresponding to the three activity states differ greatly in frequency domain characteristics, as illustrated in Fig. 7. Hence, by carrying on fast Fourier transform (FFT) and then calculating the frequency spectrum energy (FSE) over a range of frequencies, expressed by formula (3), the activity state can be distinguished.

$$FSE = \int_{6Hz}^{7Hz} FFT(rawdata)df \quad (3)$$

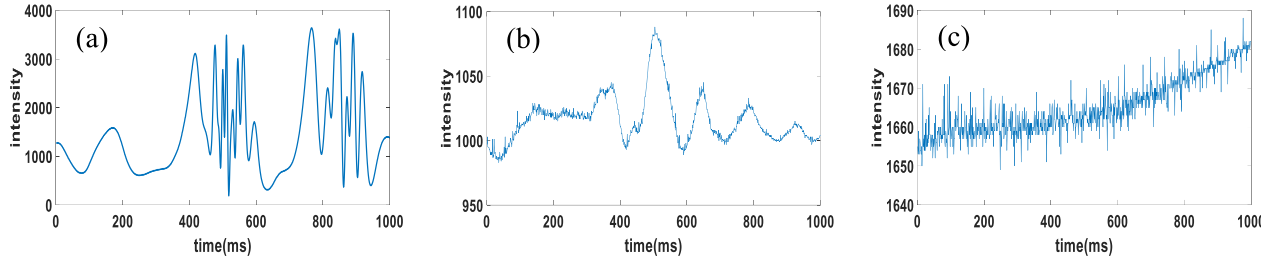

Figure. 6. Waveforms of original (a) movement; (b) normal; (c) nobody signals.

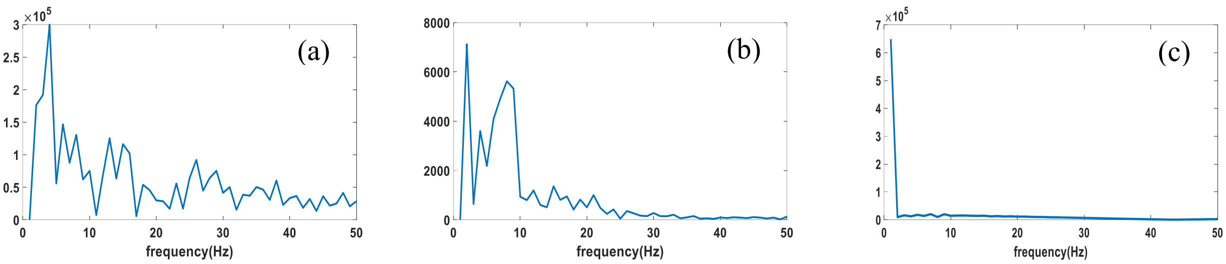

Figure. 7. Frequency spectrums corresponding to (a) movement; (b) normal; (c) nobody signals.

3. EXPERIMENT AND DISCUSSIONS

3.1 Experimental setup and fabrication

The whole cushion system consists of a laser source, a photodetector (PD) and a sensing unit fabricated by sandwiching the SMS structure between a piece of fiberglass mesh and a PVC layer with the same size of 27cm*38cm, and the thickness of PVC layer is 2mm. The concrete connection scheme is demonstrated in Fig. 8. The SMS structure is fabricated by a commercial fiber splicer (Furukawa Fitel-S179), splicing a 15-meter-long MMF between two standard SMFs with the core-offset of 4μm at each splice point. The SMF is of the standard size 8.2/125μm, and the core/cladding diameters of the step index fiber MMF is 62.5/125μm. The sandwich structure is embedded in a common home or office cushion, in this experiment, two different size of the cushions made of polyurethane memory sponge are used for performance comparisons: one is 40cm*40cm*3cm (Cushion 1) and the other is 43cm*43cm*9cm (Cushion 2), as shown in Fig. 5. Firstly, an optical spectrum analyzer (OSA) is used to find the appropriate operating wavelength and monitor the transmission spectrum of the SMS structure as shown in Fig. 9.

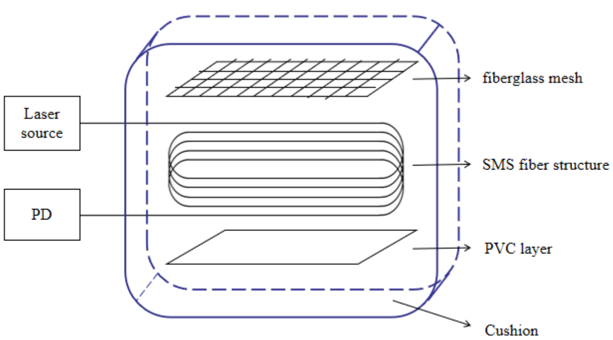

Figure. 8. Schematic diagram of the experimental setup.

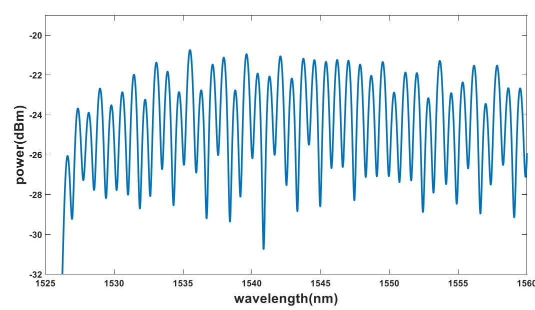

Fig. 9. Transmission spectrum of the SMS structure.

When the subject sit on the cushion placed on the chair, body activity including respiration, heartbeat and body movement will result in different forces exerted on the SMS structure which bend and deform the fiber, and hence the spectral response will change accordingly and be collected by PD. Furthermore, a photoelectric pulse wave flow sensor (HKG-07B) is used as HR reference and the reference RR can be monitored by direct observation of breath counts.

3.2 Vital signs monitoring

The measurement results according to Cushion 1 and Cushion 2 are shown in Fig. 10. It's make sense that the sensitivity of Cushion 2 are lower that of Cushion 1 as Fig. 10.(a) and Fig. 10.(d) show, for Cushion 2 (9 cm thick) is thicker than Cushion 1 (3cm thick). From Fig. 10.(b) and Fig. 10.(c), it can be seen that the RR of the subject measured from Cushion 1 is from 11 to 17 bpm and the HR is from 64 to 85 bpm with the max error of 1 bpm and 2 bpm respectively, which are closed to the reference values. As for Cushion 2, the results of RR and HR obtained are in good agreement with the certified values as well, where the max errors of HR and RR are respectively 2 bpm and 1 bpm. Thus, these two smart cushions with different thicknesses differ in sensitivity but prove to be both available for vital signs monitoring.

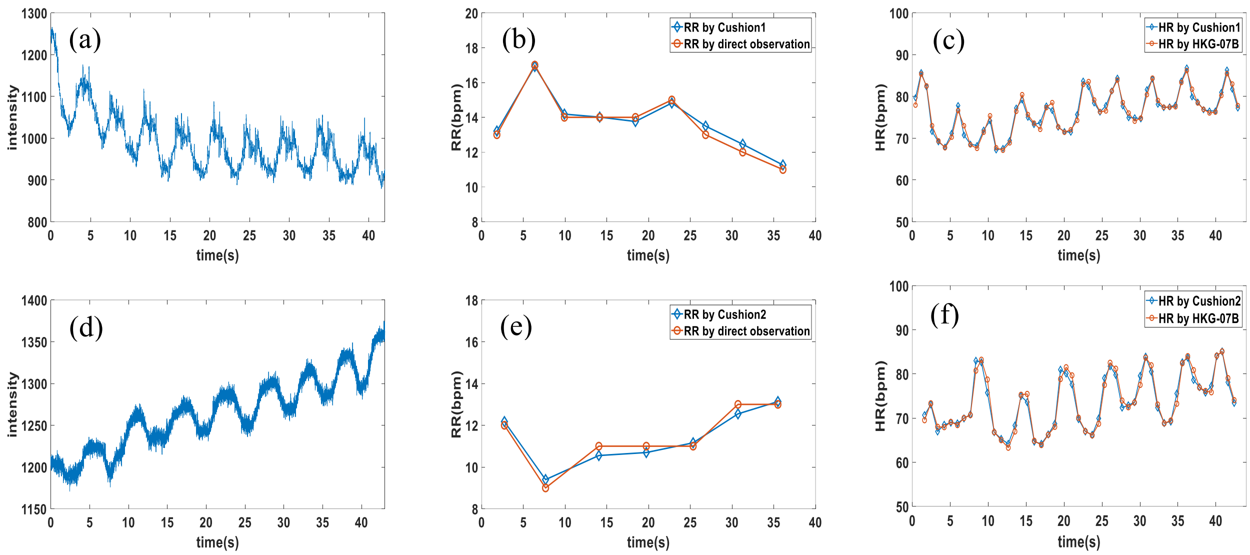

Figure. 10. Measurement results and reference values corresponding to Cushion1 and Cushion2.

3.3 Activity monitoring

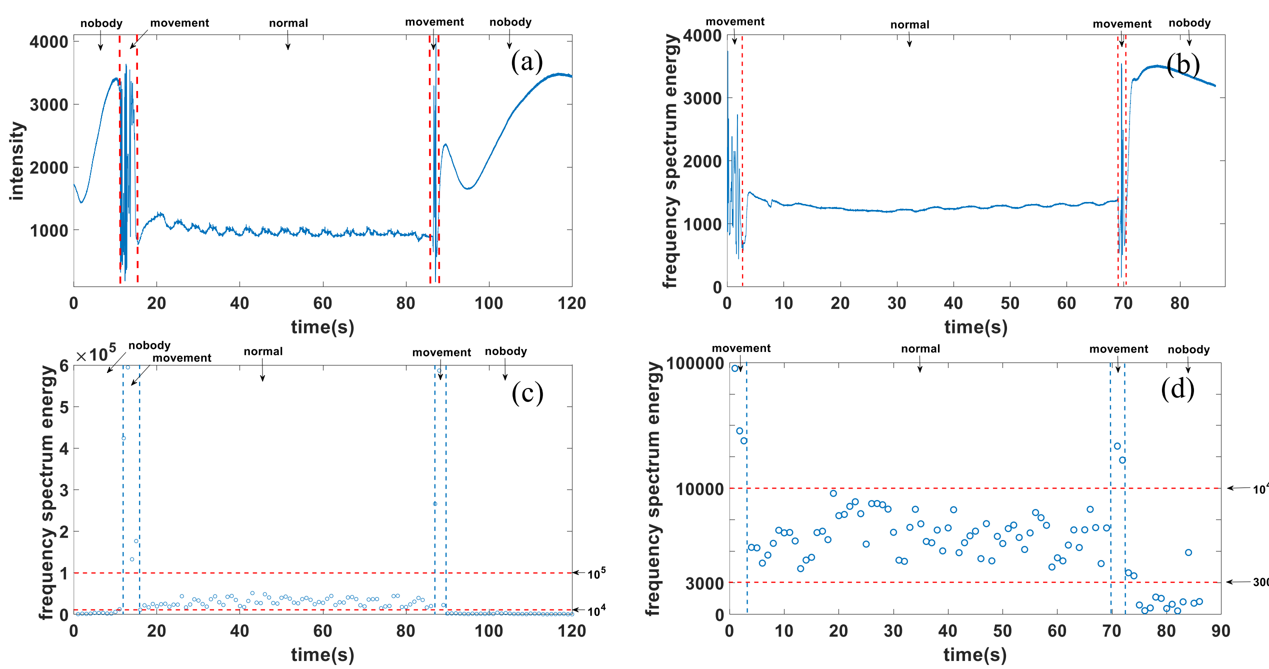

Figure. 11. Raw signals and their corresponding FSE values of Cushion 1 and Cushion 2.

Fig. 11.(a) and Fig. 11.(b) are two sections of raw signals collected from Cushion 1 and Cushion 2 respectively, containing three body activity states including nobody state, normal state and movement state. The frequency spectrum energy of the signals is obtained and depicted in Fig. 11.(c) and Fig. 11.(d). It's obvious that when nobody sits on the cushion, the FSE of the signals will stay at a low level, whose magnitude is in the order of 1000. The subject sitting on the cushion will increase the FSE value, nearly ten times of nobody state. Besides, if the subject move on the cushion, the FSE will rise to a tremendous value, apparently higher than those of another two states. Cushion 1 and Cushion 2 both can be used for activity state monitoring with the accuracy of 98.3% and 96.7%, respectively.

4. CONCLUSION

In conclusion, a smart cushion based on SMS structure with core splicing is proposed and experimentally demonstrated, which can simultaneously realize human vital signs monitoring and activity monitoring. The SMS structure is sandwiched between a piece of fiberglass mesh and a PVC layer and then embedded in a common home or office cushion, which constitutes the basic structure of the proposed smart cushion. The original signals collected by PD are sent to the computer for offline processing including filtering, feature extraction, frequency spectrum analysis. From the results, it can be seen that the HR and RR can be obtained with the accuracy of 1 second and agree well with the reference values with the max errors of 2 bpm and 1 bpm respectively. Three different kinds of human activity states including nobody state, normal state and movement state can be distinguished as well with the accuracy of more than 96%. Besides, the performances of two memory foam cushions with different thickness are compared and proven to be both available for vital signs monitoring and activity monitoring. Such a smart cushion has the advantages of compact structure, simple fabrication, convenient taken-with, high sensitivity and accuracy, and can realize real-time monitoring and ensure uses' comfort, especially suitable for the elderly in nursing homes and office workers.

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