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# Novel Flexible Material-based Unobtrusive and Wearable Body Sensor Networks for Vital Sign Monitoring

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***Abstract*—The increased prevalence of chronic disease in aging population entails health risks and imposes significant economic and social burden. It is essential to provide comfortable, cost-effective, easy-to-use unobtrusive and wearable systems for personal well-being and healthcare. Novel flexible material-based non-invasive and wearable sensors offer an efficient and cost-effective solution which enables the continuous and real-time monitoring of important physiological signs of the human-beings, the assessment of personal health conditions and provides feedback from remote and home monitoring. In this paper, novel flexible material-based wearable sensors, devised into body sensor networks to capture and monitor vital bio-signals including, Electroencephalography (EEG), Electrocardiography (ECG) and respiratory, are proposed. Silver nanowires (Ag NWs) and polydimethylsiloxane (PDMS) composite material, carbon foam and graphene-based fiber are used to sense the EEG, ECG and respiratory respectively. With different flexible materials, the smart hat and smart jacket are designed to affix the sensors which enable long-term health monitoring of vital signals seamlessly. Meanwhile, the corresponding acquisition circuits are developed and mounted with the proposed electrodes on the garments. More importantly, a comprehensive protocol is designed to validate the performance of the proposed system while some standard sensors and commercial devices are used for comparison. The evaluation results demonstrate the proposed system presents a comparable performance with the existing system. In summary, the proposed sensing system offers an unobtrusive, detachable, expandable, user-friendly and comfortable solution for physiological signal monitoring. It can be expected to use for the remote healthcare monitoring and provide personalized information of health, fitness, and diseases.**

***Index Terms*—Novel flexible materials, Vital Bio-signal measurements, Body sensor networks**

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## I. INTRODUCTION

THE aging population combined with the increased prevalence of chronic disease are becoming significant socioeconomic burdens for present-day society. Besides this, the accompanying costs are increased rapidly in terms of the prescription drugs, medical instruments, hospital care and so on [1], [2]. Thus, seeking for the innovative solutions and new technologies to improve the quality of healthcare services and to provide the early detection/intervention at an affordable price is extremely important. The emerging technology Body Sensor Networks (BSNs) provides long-term monitoring of physiological signals without interrupting the human's normal activities. It combines the intelligent, flexible, light in weight novel sensors with the human body and offers a comprehensive solution to providing a detailed information regarding the personalized health and fitness, tracking the personal wellbeing, detecting the health risk, facilitating timely intervention to acute events such as stroke, epilepsy and heart attack and so on [3], [4]. Physiological signs such as EEG, ECG, and respiration play a vital role in healthcare monitoring. Specifically, EEG can provide high temporal resolutions and reflect the dynamics of brain activities for neurobiological disorders diagnosis; ECG and respiration signals can furthermore provide a comprehensive cardiopulmonary, respiration and physical actives information for daily actives analysis and disease analysis like arrhythmias, ischemia, sleep apnea, etc. As an indispensable part of the remote healthcare monitoring, EEG, ECG, and respiration sensing systems attracted the attention of many researchers and entrepreneurs in recent years.

The sensing systems/devices have evolved from bench-top, and portable devices, to the recent garment and small gadgets based wearable devices. Wearable devices have grown rapidly in popularity recently. Until now, several various commercial wearable devices are available on the market like BioStampRC® by mc10, USA [5], Wearable biosensor by Philips [6], HUAWEI WATCH by Huawei, China [7], Apple Watch by Apple, USA [8], Hexoskin Smart Shirts by Hexoskin Wearable Body Metrics, Canada [9], etc. Most of existing commercial products are presented or manufactured in the form of watch or adhesive sticker. It may integrate ECG electrodes, accelerometer and gyroscope to monitor the heart rate and motion like the number of steps, climbing, and running. But the concerns and doubts about the achievable signal quality obtained by these devices remain controversial. And other bio-signals like EEG and respiration rate were scarcely considered in existing wearable devices.

Apart from commercial wearable devices, a variety of wearable sensors/systems based on novel materials have been reported in the literature. As for the EEG signal measurement, Ng et al. [10] proposed a vacuum casting method to fabricate the micro-spike EEG electrode and characterized the sensing performance in terms of the impedance level and stability. Lin et al. [11] designed a novel dry foam-based EEG electrode, which was fabricated by electrically conductive polymer foam covered with a conductive fabric. Recently, Fiedler et al. [12] designed a polymer-based multipin dry EEG electrode, which used a multi-phase chemical coating method to coat polyurethane electrode with the silver. These proposed novel dry EEG electrodes have overcome the limitations of conventional wet electrodes such as skin preparation, and conductive gel requirements. However, the micro-spike electrode and polymer-based multipin electrode may cause the discomfort due to their rigid pin design and polymer foam seems more suitable for collecting the EEG signals originating from the area without hair by simply affix the designed electrodes pad to the skin with adhesive tapes.

Regarding other physiologic signals monitoring, like ECG, several studies have also reported their developments. Pandian et al. [13] proposed a customized ECG sensor using silicon rubber with pure silver fillings, which was fabricated in the form of a belt to acquire ECG signal. Yamamoto et al. [14] presented a gel-less sticky ECG electrode that mixed multiwall carbon nanotubes (CNT) with the adhesive ethoxylated polyethyleneimine-polydimethylsiloxane (PEIE-PDMS). Pani et al. [15] proposed a novel textile electrode based on woven fabrics treated with PEDOT:PSS. Castrillón et al. [16] made a comparative study on textile electrodes involving PEDOT:PSS treated fabrics based on cotton, cotton–polyester, lycra and polyester in terms of the contact impedance, electrode polarization, noise, and long-term performance. The novel ECG sensors and systems are developed to overcome the main limitations of the widely used silver/silver chloride (Ag/AgCl) disposable ECG electrodes. However, there also have some drawbacks, like, the textile electrodes may result in a high contact impedance due to the materials and belt-based ECG may cause discomfort and not suitable for long-term monitoring.

For measuring respiration signal, a textile capacitive respiration sensor (TCRS) [17] and a fiber-optic deformation sensor [18] were explored. The TCRS is fabricated with conductive textile and polyester, and the respiration is derived from the distance changes between two textile plates in the TCRS, which measures the force from the abdominal diameter changes caused by the respiratory movement. In [18], the fiber-optic deformation sensor measures bending deformation directly. Two fiber-optic sensors are bonded to an elastic belt and a differential system for respiratory measurement is established. Mostly, the prototypes of respiration monitoring systems are designed as belt form. These proposed systems can avoid the limitations of traditional pressure transducer or thermocouple-based respiratory systems which need to be fitted in or near the nostrils.

In general, both existing commercial devices and novel wearable sensing systems proposed in the literature have shown the dramatical improvement of the healthcare monitoring systems. Despite its significant contributions in remote healthcare monitoring systems, several issues still remain challenging. 1) For long-term healthcare monitoring, the wearable sensors should satisfy the ergonomic requirements, e.g. they should be flexible and comfortable to wear; easy to set-up and remove. 2) Regarding the bio-compatibility, the wearable device should be hypo-allergenic and nontoxic to the human body. 3) The wearable devices should ensure the measurement accuracy while considering the cost and efficiency, e.g. they should be easy to fabricate at low cost and high efficiency. 4) The bio-signal sensing systems are susceptible to the motion artifacts, thus flexible electrodes which have smaller skin-electrode impedance and better tolerance on motion artifacts are required to overcome the limited sensitivity and reliability of the existing systems. A robust healthcare system should be able to address these issues and to enable continuous and uninterrupted monitoring. Thus, a novel flexible material-based unobtrusive and wearable vital bio-signal sensing system is proposed in this paper.

In this paper, a novel flexible Ag NWs/PDMS composite material is proposed to measure the EEG signal. It is an ideal material for sensing EEG signal due to its low impedance, high safety, high conductivity, and good resistance stability. In the existing work, two fabrication methods were widely used to produce this kind of silicon rubber-based materials. One is coating conductive layer on the silicon substrate by magnetron sputtering or multi-phase chemical coating process. This fabrication process has been used in some EEG electrodes design [12], [19]. However, due to its inherent stiff character, these metal coatings may cause cracks easily under bending or twisting states, which makes these EEG sensors are not suitable for long-term wearing. Another method is combining silicon rubber and conductive additives to generate a conductive composite [20], [21]. The conductive additives are usually metal particles or flakes, these structures are difficult to form conductive networks in composite, therefore, these composite electrodes usually have high impedance and poor resistance stability. In this paper, we use one-dimensional Ag NWs as conductive additives rather than the structures of particles or flakes [22], [23]. The Ag NWs/PDMS composite has high conductivity and good resistance stability due to the forming of wonderful Ag NWs conductive networks in silicon rubber. This conductive composite electrode is more suitable for long-term EEG measurement. For sensing the ECG signal, a novel material proposed in [24] is used. This material has widely used in electromagnetic shielding application [25] and sensing pressure [26]. Due to its good conductivity and excellent elasticity characteristics, it was first attempted to acquire the ECG signal in this paper. As for sensing respiratory signal, the graphene-based fiber material is applied. The material applies the structure of the double covered yarn of the fiber substrate endows the fiber an incorporation of ultrahigh sensitivity to tensile strain deformation and wide maximal sensing range, which shows superior strain-sensing performance compared with other stretchable electronics [27]. Besides, conventional flexible sensors [28], [29] that based on metal, which restricted by their rigidity and may not fit properly with human bodies. As a two-dimensional conductive nanomaterial, graphene exhibits high conductivity and excellent combination with the substrate. The fiber is light and flexible enough to conform to arbitrary curved surfaces, indicating its conformability in the robust and flexible wearable electronics. With the flexible and stretchable Ag NWs/PDMS composite material, carbon foam, and graphene-based fiber material, different sensor prototypes for measuring EEG, ECG, and respiration signal are designed by mounting the EEG sensors on the hat and embedded the ECG and respiration sensors in the garment.

The rest of this paper is organized as follows: Section II gives the overall requirements and design of the vital bio-signal sensing system. Section III presents a brief description of the novel flexible materials and electrodes prototypes proposed in our system. Followed by a details explanation of the proposed prototype of the sensing system in Section IV. Evaluations of the proposed sensing system are presented in Section V. At last, the brief discussion and conclusion are shown in Section VI and VII, respectively.

## II. Vital Bio-Signal Sensing System

The main objective of the proposed sensing system is to enable continuous monitoring of physiological signals, which involves the sensing and monitoring of EEG, ECG, and respiratory. Fig. 1 presents a conceptual architecture of the proposed BSN for the remote healthcare monitoring, which mainly involves the sensing system, local process unit for monitoring and displaying the signals, cloud computing for the further data analysis and medical intervention. Thus, we proposed the following requirements based on the need-finding.

- Continuously and long-term monitoring the EEG, ECG and respiration signals simultaneously: all the components are unobtrusive, detachable and user-friendly.
- All the components are comfortable to wear: all the sensors are flexible, small in dimensions, light in weight and hypo-allergenic and nontoxic to the human body.
- A reasonable layout of the sensors to avoid the signal interruption between different sensors.
- All the sensors conform well with the ergonomic requirements which provide a good conductivity between the skin and the electrodes.
- A comfortable base (for example, clothes, hat) for embedding or mounting the sensors to avoid the motion artifacts.
- The acquisition modules can be expandable to add more monitoring functions if needed.

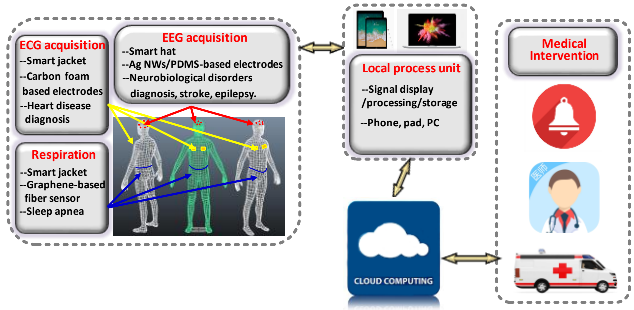


Fig 1. Conceptual architecture of the proposed BSN for remote healthcare monitoring

To fulfill the requirements of the sensing system mentioned above, novel flexible materials are explored to obtain the physiological signals unobtrusively. Different sensors prototypes are presented due to the flexible material properties and ergonomic requirements. Meanwhile, to provide a flexible solution for embedding and mounting the proposed electrodes, two modules namely the smart hat and smart jacket which includes the different acquisition systems for monitoring EEG, ECG, and EMG are designed. These two modules are detachable, expandable, user-friendly for measuring the EEG, ECG, and respiration simultaneously. Moreover, the detailed evaluations of the proposed sensing system are also provided to verify the signal quality recorded by the proposed system in comparison to different commercial devices.

## III. Novel Flexible Materials and Sensing Methods

In this section, novel materials for sensing the EEG, ECG, and respiration signal were briefly introduced, more details about these materials can be found in our recent publications [30], [31], and [32] respectively. Based on these materials, the corresponding sensing methods are also proposed.

### A. *Novel Flexible Materials*

**Ag NWs/PDMS Composite Material:** In this paper, a conductive and stretchable Ag NWs/PDMS composite material is applied for sensing the EEG signal. Fig. 2a illustrates the fabrication process, firstly, the prepared Ag NWs ink is screen printed on a glass substrate, and then the printed Ag NWs pattern is dried in a vacuum oven to form a uniform and conductive film of Ag NWs network. Next, fresh PDMS liquid is cast on top of the printed Ag NWs film, followed by curing at 80 °C for 4 h. When peeled off the substrate, the Ag NWs film is bonded to the cured PDMS and form the Ag NWs/PDMS composite electrode. The Ag NWs film is actually buried just below the PDMS surface, as shown in the scanning electron microscopy (SEM) image of Fig. 2b. Before curing at high temperature, the liquid PDMS penetrates into the pores of the three-dimensional (3D) Ag NWs network. After curing, the

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PDMS becomes highly cross-linked, and all the Ag NWs are randomly buried into the PDMS surface without any voids. Fig. 2c demonstrates the cross-sectional SEM images of the composite electrode. It's obvious that the composite electrode has a double layer structure, the first layer is a composite layer of Ag NWs and PDMS with a thickness of about 7μm, which forms the conductive and stretchable layer, and the second layer is pure cured PDMS, which acts as the stretchable substrate. The produced composite electrode has excellent flexibility and stretchability as shown in Fig. 2d, which means the electrode can attach to the surface of the skin comfortably. Owing to the network structure of Ag NWs, the composite electrode has a high conductivity of 6912 S/cm. Because of the flexibility and high conductivity, the Ag NWs/PDMS composite material can be an ideal candidate for sensing the EEG signal.

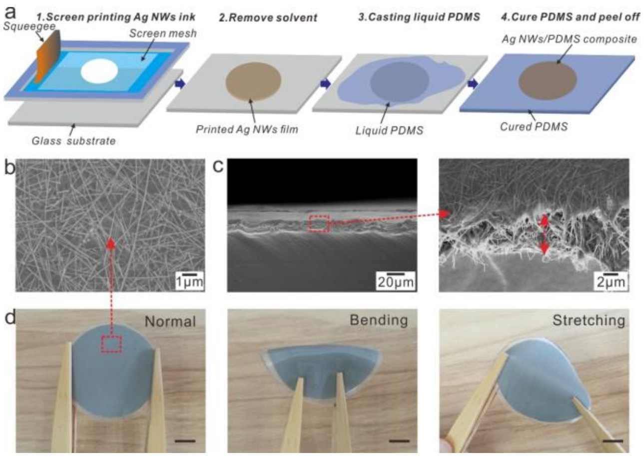


Fig 2. (a) Schematic illustration of the fabrication process of Ag NWs/PDMS composite electrode; SEM images of the surface morphology (b) and the cross-section of the composite electrode (c); (d) Photographs of the obtained Ag NWs/PDMS composite electrode, under bending and stretching state.

**Carbon Foam Material:** The carbon foam material has excellent flexibility as shown in Fig. 3, which can provide comfortable attachment. For Ag NWs material, it has high conductivity due to the network structure of Ag NWs, which make it be an ideal candidate for the Bio-potential recording electrode. Compared to Ag NWs/PDMS composite materials, carbon foam has weaker electrical conductivity, but it can still effectively collect signals such as ECG. In addition, it has been verified that carbon foam has good motion artifacts resistance capabilities, which will be given in the following evaluation section. To produce the carbon foam material, the melamine-based polymer was pyrolyzed at 800 ºC - 900 ºC in a quartz reactor under N2 flow (600 mL min-1) for about for 1-3 h. The heating rate of 20 ºC/min. After temperature cooling down, the as-prepared carbon foam was produced and the SEM image of carbon foam is shown in Fig. 3.

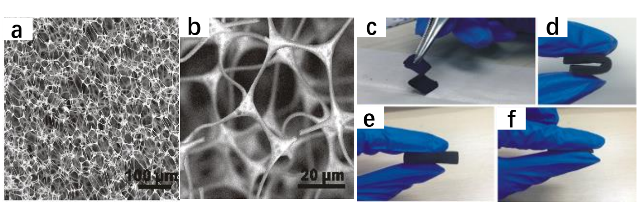


Fig 3. (a)(b) SEM image of carbon foam; (c) The obtained carbon foam; (d) Carbon foam under bending; (e) A 1.0 cm thick carbon foam before being compressed; (f) A 1.0 cm thick carbon foam compressed to around 0.3 cm under the applied forces.

**Graphene-based Fiber Material:** In the process of breathing, the body's chest and abdomen will have regular ups and downs with the expansion and retraction of the lungs which causes the changes in the circumference of abdomen cyclical. Usually, when inhaled, the circumference of the abdomen is as short as three to five centimeters when exhaled. Based on this feature, a graphene-based fiber proposed in [32] was used for sensing the respiration signal. Fig. 4. shows the schematic illustration of the fabrication strategy of the fiber sensor and the SEM images of the fiber sample during the whole process.

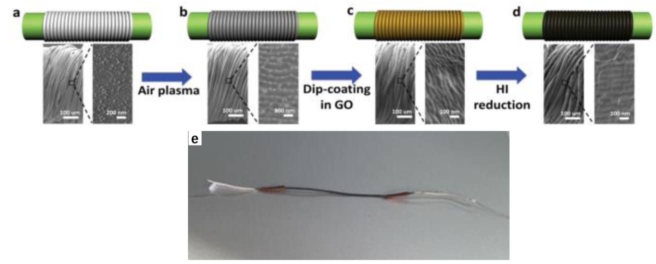


Fig 4. (a–d) Schematic illustration of the fabrication process and the characterization of the graphene-based fiber; (e) The graphene-based fiber.

*B. Sensing Methods*

**Ag NWs/PDMS Composite Material-based EEG Electrode:** The structure and prototype of the novel flexible dry electrode are shown in Fig. 5. It consists of the Ag NWs/PDMS composite material (D) and a support case (A, B, C, E, F) printed by a 3D printer. The composite material is monolayer conductive and tailored to the shape in Fig. 6, including the circular shape contact portion and a rectangle shape wire lead-out tail. The support case includes Electrode Lead (A), Electrodes External Retaining Nut (B), Wire Retaining Clip (C), Electrode Material Support Base (E) and Electrode External Retaining Base (F).

As the prototype shown in Fig. 5, the two-layer electrode support base design integrates the ease of electrode assembling and the good electrodes conductivity. A weld-free method by conducting the Ag NWs/PDMS composite material with the electrode lead which makes the proposed electrodes reusable by easily changing the composite material is presented. Furthermore, the dome at the bottom of the electrode material support base keeps the Ag NWs/PDMS composite material above the bottom surface of the electrode external retaining base. It would make the Ag NWs/PDMS composite material contact with the skin properly when using the novel EEG electrode.

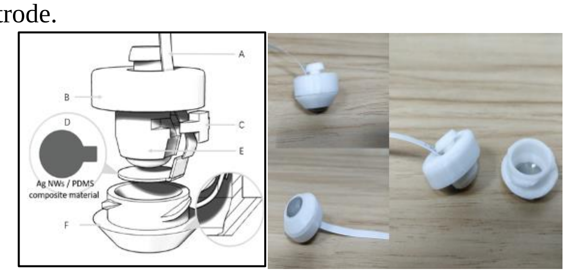


Fig 5. The structure and prototype of the novel EEG electrode. (A) electrode lead; (B) electrodes external retaining nut; (C) wire retaining clip; (D) Ag

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NWs/PDMS composite material; (E) electrode material support base; and (F) electrode external retaining base.

**Carbon Foam Material-based ECG Electrode:** Fig. 6 shows the structure of the novel ECG electrode. The electrode consists of four parts, carbon foam (A), electret gel layer (B), non-woven fabric (C) and metal lead button (D). Carbon foam is connected to the metal lead button. The nonwoven fabric is sandwiched between the electret gel layer and the metal lead button as a protective layer. An electret gel layer serves as a paste layer surrounding the carbon foam. The prototype the proposed ECG electrode is presented in Fig. 6. The thickness of the carbon foam is made higher than the thickness of the surrounding electret gel layer. When the electrode is pasted on the skin, the carbon foam tends to be compressed and provide a high conductivity. This characteristic increases the stability of the contact between the electrode and the skin automatically and enhances the quality of the acquired signal during movements.

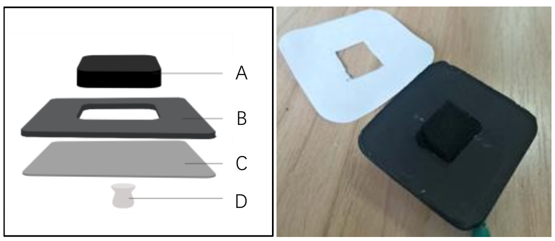


Fig 6. The structure and prototype of the novel ECG electrode. (A) carbon foam; (B) electret gel layer; (C) non-woven fabric; and (D) metal lead button.

**Graphene-based Fiber Material-based Respiration Sensor:** Fig. 7 presents the graphene-based fiber material-based respiration sensor which is composed of a graphene-based fiber material (A) and an elastic belt (B). The graphene-based fiber is attached to the elastic belt and the belt is with the size of 2.0 cm wide. When the fiber undergoes tensile deformation, bending, and twisting, the mechanical structure will change, resulting in a change in the resistance of the material. Therefore, the mechanical deformation of the subject can be reflected by the changes in electrical resistance, such as the changes of the circumference of abdomen cyclical.

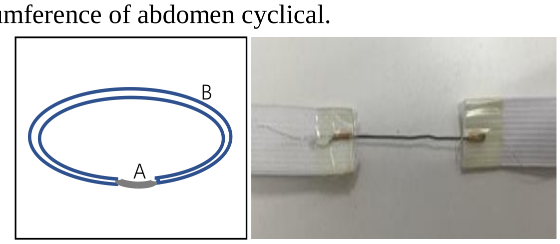


Fig 7. The structure and prototype of the novel respiration sensor. (A) graphene-based fiber material and (B) an elastic belt.

## IV. Prototype of the Vital Bio-signal Sensing System

After the design of sensing sensors, the prototype of the vital bio-signal sensing system is explored, which mainly includes a smart hat and smart jacket.

### A. *Smart Hat*

To mount the proposed novel EEG electrodes, a smart hat is designed. It combines the proposed EEG electrodes and the elastic fabric material belts, as shown in Fig. 8. The layout of the fabric belts and the electrode placement positions on these belts strictly obey the 10-20 international standard system. EEG electrodes can be attached to the electrode position on the belts and easily set-up and remove from the belts. The number of electrodes can be increased or decreased according to the specific requirements of the recording. With the disposable and changeable EEG electrodes and the design of the adjustable belt, the smart hat can provide a flexible, extensible solution for the long-term EEG monitoring.


Fig 8. The structure and prototype of the smart hat

### B. *Smart Jacket*

The smart jacket is designed for embedding the ECG electrodes and respiration sensor. As best electrode locations for a bipolar ECG acquisition suggested in [33], the proposed ECG sensors were embedded in the jacket around the chest position, specifically, the fourth intercostal space on the right sternum (V1) and fourth intercostal space at the left sternum (V2), as shown in Fig. 9. Meanwhile, the proposed respiration sensor is attached to the elastic belt and sewn on the jacket around the chest.

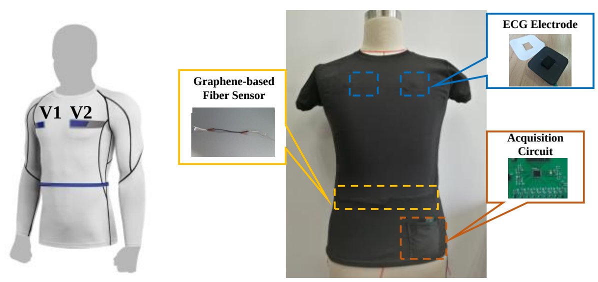


Fig 9. The structure and prototype of the smart jacket

### C. *Bio-signal Acquisition System*

To monitor EEG, ECG and respiration signal, the corresponding acquisition systems are developed in Fig. 10.

For sensing and recording the EEG signal, it combines the aforementioned flexible EEG electrodes and the acquisition circuit. The flexible electrodes are used for sensing the electrical brain activation patterns. As for the EEG acquisition, a portable, function-rich, configuration-flexible, low power-consumption, and comfortable EEG acquisition system is developed. It involves a pre-processing circuit for denoising; an analog front end (AFE) for multi-stage signal amplification, analog-to-digital (AD) conversion, and filtering; a microcontroller unit (MCU) to control the data acquisition process; and a wireless data transmission unit for sending the EEG signal to the local process unit like, PC, phone or pad. An integrated 8 channel AFE ADS 1299 is used for EEG acquisition and it can also be extended to 32-channel. Moreover, the proposed system can be reconfigured by adjusting the sampling rate and gain for different application scenario with the help of programmable devices and multiplexers in the

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circuit structure. The sampling frequency can be adjusted from 250 Hz to 16 kHz.

The ECG signals are acquired by using flexible carbon foam electrode combined with an integrated analog front end ADS1292 which performs amplification, AD conversion, and filtering. ADS1292 is specially designed for ECG signal acquisition at a relatively lower cost, while ADS 1299 is specially designed for EEG signal acquisition. The frequency of the ECG acquisition circuit can be adjusted from 125 Hz to 8 kHz. In addition, the graphene-based fiber was implanted into an elastic fabric belt for respiratory signal acquisition. Meanwhile, the MCU is used to control the ECG and respiration data acquisition process and the processed ECG and respiration data will be sent to the local process unit through the Bluetooth.

Moreover, the primary analysis results obtained from the local process unit can be uploaded to the cloud for further data interpretation.

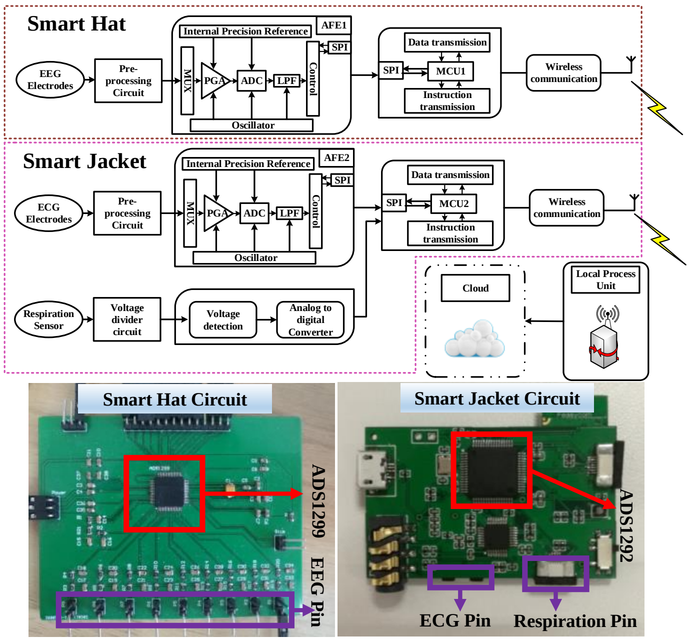


Fig 10. The architecture and prototype of the signal acqusition system

## V. Evaluations of the Vital Bio-Signal Sensing System

In the section, a comprehensive evaluation of the vital bio-signal sensing system is performed. It mainly includes the electrodes evaluation and the signal acquisition system performance evaluation.

The electrodes evaluation includes the electrical characterization test of the novel material and the performance comparisons of the proposed electrodes with the traditional electrodes using the standard commercial equipment. The signal acquisition system evaluation is used to assess the signal quality by combining the proposed sensors with the designed acquisition circuits in comparison to the commercial devices.

### *A. Participants and Experimental Procedure*

Five healthy volunteers (2 females, 3 males, mean age 25.40 ± 2.88, range 22–30 years) participated in this study. All participants had no history of neurological or psychiatric disorders. Meanwhile, to avoid alcohol and or caffeine effects on the experiment, participants were asked to refrain from drinking alcohol and caffeine for 12 hours before the experiment. Furthermore, detailed written and verbal information on the experiments was given to all participants and all five participants gave their written informed consent before the experiment. Then the experiment was performed in a claim laboratory, the participants were asked to wear the proposed system and commercial devices simultaneously for the further evaluation of the proposed electrodes and system.

### *B. Novel Flexible Material-based Electrodes Evaluation*

In this section, only the evaluations of EEG and ECG electrodes are performed, the detailed evaluation of respiration sensor material (e.g. the characterization and the strain sensing properties of the graphene-based fiber) can be found in [32].

#### 1) EEG Electrodes

In the clinical test, the Ag/AgCl electrode widely used for signal acquisition in Fp area and the Gold Cup electrode used for signal acquisition in the hair-covered area. Therefore, a comprehensive test protocol to evaluate and compare proposed EEG electrodes with Gold Cup electrode and Ag/AgCl electrode is designed.

**Electrical characterization test:** The skin-to-electrode is a good measure to characterize the performance of the electrodes. The smaller skin-to-electrode interface impedance can achieve high-fidelity signals acquisition, and large skin-to-electrode interface impedance may result in significant attenuation of the input signal amplitude of the post-stage amplifier was observed in [34]. Thus, the skin-to-electrode interface impedance of different electrodes is measured by the electrochemical workstation (ZAHNER - Zennium). The frequency of input signal sweeps from 0.1 Hz to 200 kHz. In the experiment, the electrodes were put on the different brain area for the test, namely, the Fp1 and F3 according to the international 10-20 system.

Fig. 11 gives the electrical impendence-frequency curves (Z-f curves) which characterize the skin-to-electrode interface of PDMS electrode (the proposed electrode), Gold Cup electrode and Ag/AgCl electrode (Covidien, H124SG) from Fp1 and F3 area. Since the human body can be equivalent to a circuit consisting of resistors and capacitors, the equivalent impedance will decrease as the frequency increases [35].

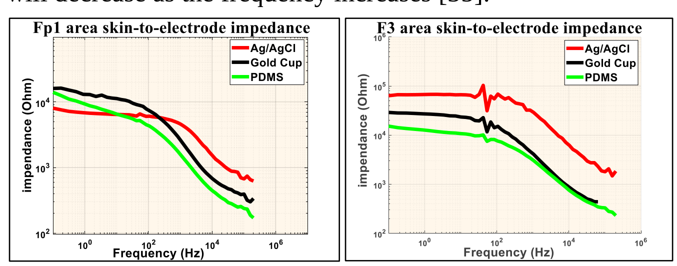


Fig 11. Fp1 and F3 area skin-to-electrodes interface impedance test

The experimental results exhibit that the proposed electrode and Gold Cup electrode have the same trend between 0.1 Hz to 200 kHz frequency band and the proposed electrode has a smaller skin-to-electrode interface impedance than Gold Cup electrode for both Fp1 and F3 area. Although the Ag/AgCl electrode achieves a slightly better performance than the proposed electrode within 210 Hz for Fp1 area, the performance of the Ag/AgCl electrode sharply decreases in F3 area. To acquire the EEG signal from the hairy and non-hairy area, it is well known that the largest obstacles are the influence of the hair and different thickness of stratum corneum, which act as barriers to ionic current and thus significantly increases the impedance. Meanwhile, the electrical nature of the interface between the biopotential electrodes and scalp also plays a vital role in impedance. Even the skin preparation will be performed before applying the Ag/AgCl electrodes, some hair will still adhere to the surface of the conductive gels which will significantly influence the conductivity between the electrodes and scalp. Hence, in practice, the Ag/AgCl electrode is only used in the frontal brain area without the influence of hair instead of other areas of the brain. In comparison to Ag/AgCl electrodes, the conductive medium of the proposed PDMS electrodes is Ag NWs conductive networks rather than the ion medium of the conductive gels, which ensures the conductivity between the electrodes and the scalp. Moreover, with the flexibility of the proposed electrodes, it would also potentially ensure the good conductive and thus decrease the impedance.

**Electrode signal quality test:** After evaluating the EEG electrodes characterization, the signal quality obtained by these electrodes were also investigated. To ensure the same signal conditioning environment for comparing the signal sensing ability, the electrodes are connected to the same device, Compumedics Grael Polysomnography (Grael PSG).

Fig. 12 presents the EEG signals and the corresponding spectrum obtained from Fp1 and F3 area using the proposed flexible EEG electrode, Ag/AgCl electrode, and Gold Cup electrode. In Fp1 area, eye blink signals are clearly observed and the signals collected by the three electrodes have high consistency. Due to the different sensing ability of the electrodes, there are some differences in signal amplitude, but the frequency components are the same. While, in F3 area, the Ag/AgCl electrode fails to obtain the EEG signal because of the hair. However, the proposed flexible EEG electrode and the Gold Cup electrode can still achieve favorable signal quality.

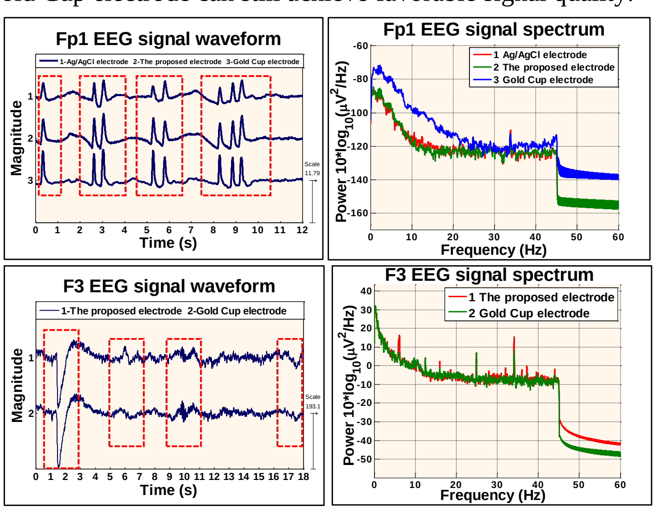


Fig 12. EEG signal and spectrum of Fp1 and F3 area

Electrodes signal quality evaluation results have proved that the proposed electrodes are suitable for EEG signal acquisition and can achieve comparable performance with the wet electrodes like the Gold Cup and Ag/AgCl electrodes.

### 2) ECG Electrodes

For evaluating the performance and applicability of the proposed carbon foam-based ECG electrode, a comparison of the proposed ECG electrode and Ag/AgCl electrode is presented. In the clinical test, the wet electrode Ag/AgCl electrode is widely used. Thus, for ECG electrodes evaluation, only Ag/AgCl electrode is involved and tested for the comparison.

**Electrical characterization test:** Using ZAHNER-Zennium with the same experiment condition aforementioned for the EEG test, the skin-to-electrode interface impedance of the proposed ECG electrode and the Ag/AgCl electrode are measured. Fig. 13 demonstrates that the impedance corresponding to the proposed Carbon Foam (CF) electrode is slightly larger than that of the Ag/AgCl electrode. The impedance of the Ag/AgCl electrode is nearly 566 kOhm in near dc range, while for the carbon foam-based electrode is about 675 kOhm. This is mainly because before using the Ag/AgCl electrode, the skin preparation is performed by removing the epidermal stratum corneum and applying conductive gels. This preparation would potentially facilitate the transduction of the ionic currents into electric current and provide a low impedance path for signal transduction, therefore, lower the skin-electrode impedance. While before applying carbon foam electrode, there is no requirement for any skin preparation.

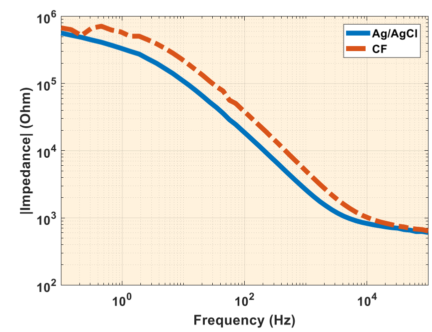


Fig 13. Skin-electrode impedance of ECG electrodes

**Electrode signal quality test:** To evaluate the signal quality obtained by the proposed ECG electrodes, we connect the proposed ECG electrode and Ag/AgCl electrode to a commercial device Shimmer-3. Fig. 14 shows that the proposed ECG electrode can acquire comparable signal quality with respect to Ag/AgCl electrode. The shapes of both signals have high similarity and R peaks of both signals can be easily detected. To measure the similarity between the ECG signal obtained by the proposed ECG electrodes and the ECG signal acquired by the Ag/AgCl electrode, the Pearson cross-correlation coefficient is calculated. For the Pearson cross-correlation coefficient, it lies between −1 to +1, where 1 is the total positive correlation, 0 is no correlation, and −1 is the total negative correlation. If the cross-correlation coefficient is close to +1, then it indicates that there is a strong linear positive correlation. In this paper, a high Pearson cross-correlation coefficient between both signals is obtained, which can reach 0.9568. It indicates that is a strong linear positive correlation between these two signals, which also indicates that there is a high similarity in terms of morphological attributes between these two signals.

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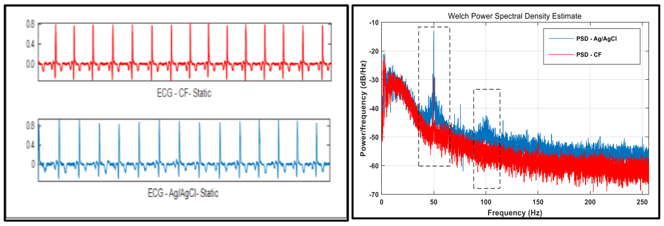


Fig 14. ECG signal and spectrum obtained by Ag/AgCl eletrodes and carbon foam electrodes

The proposed carbon foam electrode and Ag/AgCl electrode are both connected to a commercial device Shimmer-3 simultaneously without any filter strategy, which ensures the signal obtained by two different types of electrodes are acquired at the same condition. Then Power Spectral Densities of two signals are estimated and presented in Fig. 14. Owing to the improvement of resistance loss, dielectric loss, and magnetic loss of the carbon foam material [25], [36]–[38], the electromagnetic interference (EMI) shielding characteristics of carbon foam material has been immensely improved. Meanwhile, due to the features of the power line interference, which have the large concentration of energy and large noise amplitude, it would be more efficient in the process of noise energy attenuation when the noises couples into carbon foam material. Finally, as can be seen from Fig.14, the results of the experiment reveal that less power line interference is contained in the signal acquired by the proposed carbon foam-based electrodes, which is consistent with the theoretical inference. Therefore, carbon foam-based electrodes can be considered as a good candidate material for the acquisition of the ECG signal.

### *C. Bio-signal Acquisition System Evaluation*

After the evaluation of the proposed electrodes, a detailed evaluation of the sensing system in comparison with commercial devices is provided.

#### 1) Smart Hat

In this test, EEG signals in Fp1 area are simultaneously acquired by using the proposed sensing system and a commercial device Brian Product (BP), Germany. The EEG signal is sampled at 250 Hz for both systems. The pulse signal in Fig. 15 corresponds to the eye blink, which shows that the signals collected by the two systems have high consistency and proves the effectiveness of the proposed system. Meanwhile, the spectrogram analysis also indicates that the two systems have the same spectral components, which demonstrates the proposed system can achieve comparable signal quality in comparison to the commercial device. While in the Fp1 area, even the obtained signals have high similarity, most of the EEG signals were submerged by the eye movement traces, which may not that persuasive for the EEG measurement. To further validate the performance of the proposed system in the different brain area, an eyes-open and eyes-closed task and a steady-state visual evoked potentials task are performed.

Eyes-open and eyes-closed task: Alpha rhythm, as the neural oscillations in the frequency range of 7.5 to 12.5 Hz, predominantly originates from the occipital lobe during wakeful relaxation with closed eyes. Quantities studies have revealed that alpha rhythm reduces when the eyes open. To verify the performance of the proposed system, an eyes-open and eyes-closed task is performed. In this task, subjects were comfortably seated in a dimly lit and sound attenuated room, while EEG signals were acquired in the C3 area by using the proposed system. Fig. 16 demonstrates the EEG spectrum of eyes open and eyes closed states. A clear difference of the EEG spectrum between these two states can be observed. In Fig. 16, alpha rhythm act as dominant components in the eyes closed state, which also proved that the proposed system can efficiently record the EEG signal in two different states.

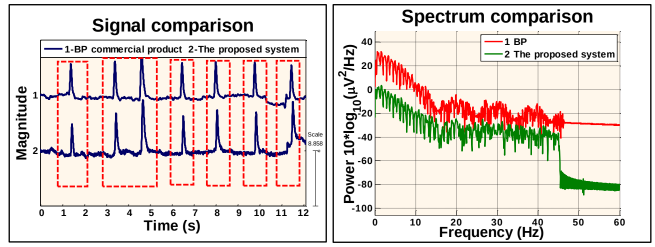


Fig 15. Fp1 area signal obtained by BP commeicial product and the proposed syetem

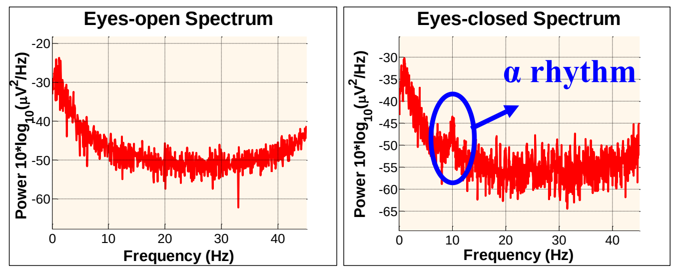


Fig 16. EEG spectrum of eyes-open and eyes-closed task

**Steady-State Visual Evoked Potentials (SSVEP) task:** SSVEPs are signals which appear in the visual cortex of the brain as the natural response to a visual stimulus. When the retina is excited by a visual stimulus, the brain generates electrical activity at the same (or multiples of) frequency of the visual stimulus [39]. To validate the performance of the proposed system, a SSVEP task is performed. The aforementioned five healthy volunteers participated in this task. All of them had normal or corrected to normal vision. The signal was collected using the proposed system at a sampling frequency of 250 Hz. The proposed electrodes were placed at the area near the Oz position, and the reference and ground electrodes were placed on the earlobes (A1 and A2 position, respectively). The task consisted of two sessions. For the first session, a flickering of LED that alters at 20 Hz was used as the visual stimulus. For the second session, a flickering of LED of 30 Hz was used as the visual stimulus. Each session contained three trials for each subject. For each trial, the visual stimulus lasted for 10 s followed by a rest for 5 s. Thus, a total of 30 trials was performed of these five subjects. In each trial, subjects were asked to gaze at a flickering stimulus. For these two sessions, the corresponding averaged SSVEP response frequencies for all the trials are 19.96 Hz and 29.97 Hz with the standard deviations of 0.02 Hz and 0.01 Hz, respectively. Fig. 17 shows the averaged EEG spectrum at 20 Hz and 30 Hz collected using the proposed system. The dominant frequencies of the EEG spectrum are 19.96 Hz and 29.97 Hz, which correspond to the visual stimulus of the two sessions. These results are consistent with the characteristics of the SSVEP response and prove the stability and reliability of the proposed system in collecting EEG signals.

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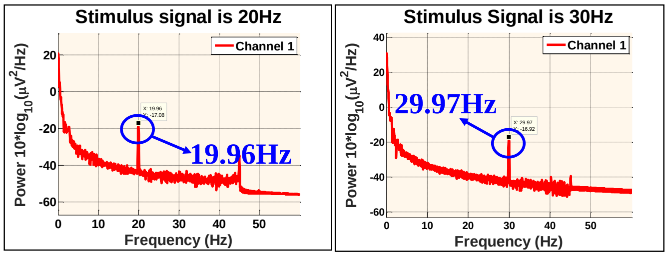


Fig 17. EEG spectrum of SSVEP task

### 2) Smart Jacket

For the smart jacket module, we used the proposed sensing system to acquire ECG and respiration signals. Comparisons were performed for ECG and respiration using the Grael PSG and Shimmer-3 respectively.

**ECG Signal:** The ECG signals are recorded at V1-V2 lead at a sampling frequency of 250 Hz by the proposed system and a commercial instrument Shimmer-3. Fig. 18 presents the ECG signal acquired by the proposed sensing system and the Shimmer-3 during a motion condition. Meanwhile, the acceleration signal which indicates the motion condition (Acc) is recorded by IMU of Shimmer-3 is also presented in Fig. 18. It reveals that the proposed sensing system represents even better tolerance on motion artifacts due to the mechanical properties of the material. This is mainly due to the mechanical properties of carbon foam. In the motion state, the conductive deterioration of the skin-to-electrode interface and unstable conditions of material properties may significantly influence the obtained signal quality. While for the carbon foam electrode, it can be compressed by 50% (ε=50%) and recovered to its original shape. To further verify the mechanical properties of the carbon foam, repeated compression and recovery process of 1, 3, 10, 50, 100 cycles loading-unloading to ε=50% tasks were performed. From the compressive stress-strain curves in Fig. 19, the carbon foam manifests no stress decrease required to deform it, which reveals that the carbon foam is intact after 100 compress and release cycles. All these demonstrated that the carbon foam is competent to maintain its framework under deformation. Moreover, with the high flexibility, conductivity and the structural stability of the material, it makes the carbon foam electrode to be an ideal candidate for ECG signal acquisition even in motion state.

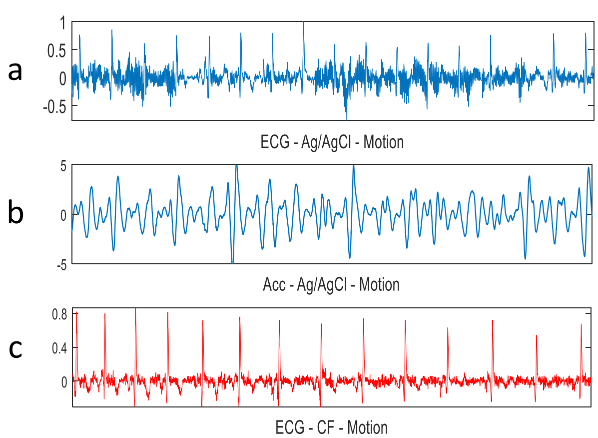


Fig 18. (a) ECG signal obtained by Shimmer-3 in motion state; (b) Simultaneous accelerations signal obtained by Shimmer-3; (c) ECG signal obtained by the proposed system in same motion state.

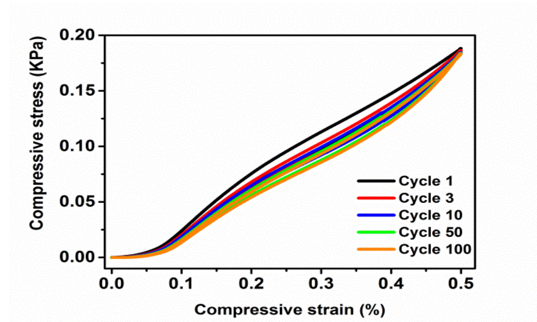


Fig 19. Stress-strain curves of carbon foam for 100 cycles

**Respiration Signal:** The respiratory signals are recorded using the proposed sensing system and thorax belt of the Grael PSG device simultaneously with the sampling rate of 32 Hz. Fig. 20 demonstrates that the trend of the signal obtained by the proposed system is consistent with the signal acquired by the thorax belt of the Grael PSG device. It shows that the peaks and troughs of the signals collected by the two systems are in good consistency. Meanwhile, the proposed system can achieve the same respiratory rate as the Grael PSG device, which proves the effectiveness of the proposed sensing system.

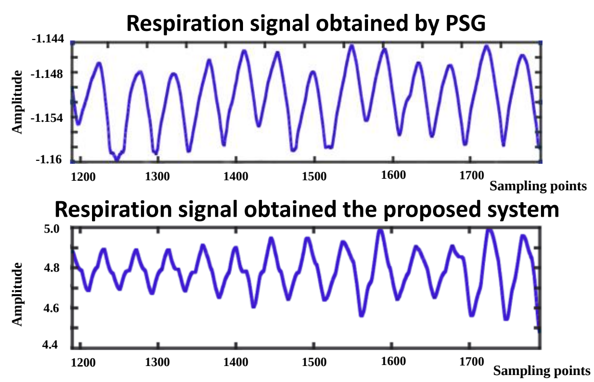


Fig 20. Respiration signal obtained by PSG and the proposed system

## VI. Discussion and Applications

With the development of sensing materials and technologies, novel sensors have dramatically enhanced the capability of sensors to acquire data efficiently and comfortably. Nowadays, multiple sensors are expected to collect different signals simultaneously and to provide a more detailed information of the individual's health status. In this paper, a vital bio-signal sensing system based on novel sensing materials is proposed. The conductive and stretchable Ag NWs/PDMS composite material is proposed and fabricated for sensing the EEG signal. To sense the ECG and respiration signals, carbon foam material and graphene-based fiber material are used. Followed by the specific EEG, ECG, and respiration signal acquisition circuits. The novel EEG electrodes and the EEG acquisition circuit are mounted on a hat, while the ECG electrodes, the respiration sensor, and the corresponding acquisition systems are embedded in a jacket. The proposed sensing system offers a long-term unobtrusive monitoring of physiological signals at a low-cost and high-efficiency way. Meanwhile, the proposed sensing system is detachable, expandable and user-friendly.

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Experimental results show that the sensing system can monitor the EEG, ECG, and respiration rate simultaneously with a high performance. The signals obtained by the proposed system achieves favorable results in terms of the signal quality in comparison to the existing commercial products. Meanwhile, it can be extended to monitor 32-channel EEG signal with an adjustable sampling frequency of 250 Hz to 16 kHz. For ECG signal monitoring, the sampling frequency can be adjusted from 125 Hz to 8 kHz. Moreover, a lower powerline interference is observed from the ECG signal acquired by using the carbon foam material-based electrode, which may due to the reticular microstructure of carbon foam.

With the sensing ability of EEG, ECG, and respiration signal, the proposed system can be explored to various applications in long-term health management. The possible applications are introduced as follows. 1) Safety Alarm. In case of any sudden health issues like heart failure, an alarm module can be integrated with the proposed system to raise an alarm and notify the persons concerned or the healthcare services. An immediate medical intervention can be initiated in case of a sudden issue. 2) Early Detection and Prediction. The proposed system allows the detection of some potential health risks like stroke, epileptic seizures. It can be extended and used in early detection of trends in an individual's health status towards an exacerbation event. 3) Rehabilitation. Tracking the change in conditions of exercise functions can be utilized as a feedback means to guide appropriate rehabilitation processes. With the physiological signals like ECG, personalized health status can be estimated and monitored for guiding the rehabilitation process. 4) Clinical Assessment. Assessing the treatment efficacy is essential to assist the clinical diagnosis and treatment. With the proposed system, it may help to assist the clinical diagnosis and treatment in the foreseeable future.

To improve and extend the capabilities of the proposed sensing system, the following points will be involved in our future work. 1) More sensors and systems based on flexible materials to obtain physiological signals like, blood oxygen saturation, blood pressure, temperature, etc. will be explored and added to our existing system. 2) To provide a meaningful conclusion for assisting clinical diagnosis and treatment or tracking the personal wellbeing or detecting the health risk, data fusion that fuses heterogeneous data and generates a comprehensive conclusion from multi-signals will be investigated.

## VII. CONCLUSION

In this paper, novel materials for sensing the EEG, ECG, and respiration signal were investigated and fabricated. According to the material properties and ergonomic requirements, different flexible electrodes were developed. It provided a flexible and long-term monitoring solution that can overcome the limitations of traditional electrodes. Meanwhile, a smart hat and jacket were designed to mount and affix the proposed electrodes and acquisition systems. The proposed sensing system offered an efficient and cost-effective solution that allows monitoring the important physiological signs of the human-beings in real time. Experimental results showed that the proposed sensing system achieves comparable signal quality in comparison with the existing commercial devices. For the further work, more flexible sensors and acquisition circuits will be added and the interpretation of recorded physiological signals will be involved for providing a comprehensive evaluation of personalized health, fitness, and clinical diagnosis for remote healthcare monitoring.

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