Respiration Monitoring using a Motion Tape Chest Band and Portable Wireless Sensing Node

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ABSTRACT

The measurement of vital signs (such as respiration rate, body temperature, pulse, and blood pressure), especially during strenuous activities, is essential for physical performance and health monitoring. A variety of wearable chest band sensors have been developed, commercialized, and widely used in consumer and healthcare settings. The plethora of technology choices also means that each unique chest band sensor may require different data acquisition hardware and software systems, and data may not be transferable between platforms. Therefore, the objective of this work was to develop a low-cost, disposable, respiration sensor that could be attached onto any elastic chest band. The approach was to spray-coat graphene nanosheet (GNS)-based thin films onto unidirectionally stretchable elastic fabric to form a piezoresistive material. Snap buttons were incorporated at the ends of the fabric so that they could be attached onto any chest band, removed at any time, and replaced for a new data collection event. The resistive nature of the nanocomposite sensor means that they can be easily interfaced (*e.g.*, using a voltage divider) with any existing data acquisition (DAQ) module while adding respiration monitoring capabilities. To facilitate testing of these nanocomposite respiration sensors, a miniature DAQ module with four sensing channels was also prototyped. Then, tests were performed with human subjects wearing a nanocomposite chest band and a reference commercial respiration monitoring chest band. Simultaneous measurements of subject respiration verified the respiration monitoring performance of these low-cost, disposable, nanocomposite fabric sensors.

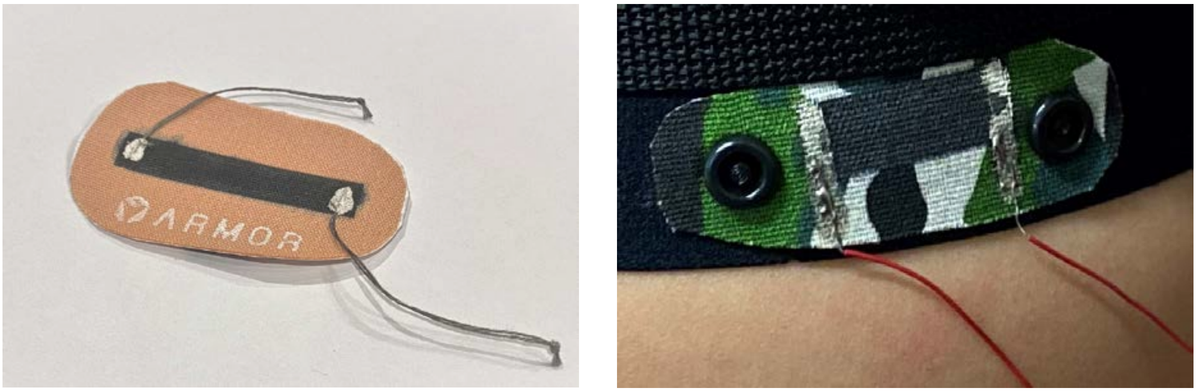
INTRODUCTION

The measurement of vital signs (such as respiration rate, body temperature, pulse, and diastolic and systolic blood pressure), especially during strenuous activities, is essential for physical performance and health monitoring. In addition, changes in vital signs may be indicative of deteriorating health or serious underlying medical issues [1]. Currently, a common practice to acquire vital signs, whether in a hospital, community, or home setting, is to take periodic manual measurements [2]. For instance, temperature and blood pressure can be measured using analog or digital thermometers and blood pressure cuffs, respectively. However, pulse and respiration rate are frequently measured by manual counting over a fixed timeframe. Not only does this result in infrequent vital sign measurements, but it has also been reported that manual respiratory rate measurements may be prone to inaccuracies and error, even if they are taken by nurses and in a hospital setting [3]. In a study that involved two trained observers and 140 patients, significant interobserver variability of vital sign measurements were found [4]. In addition, some vital signs, such as respiratory rate, are more likely to be undocumented than others [5].

An alternative to manual vital sign measurements is to employ a continuous electronic patient monitoring strategy, which entails the use of (1) transducers that sense relevant physiological parameters, (2) signal analysis and interpretation, and (3) user or caregiver feedback [2]. Recent advancements in wearable sensors and Internet-of-Things (IoT) technologies have demonstrated specific use cases for adult patients [6], chronic disease patients and the elderly [7], and infants and newborns [8]. Another major advantage of these wearable sensors is their application beyond the hospital setting including community, in-home, and even challenging field environments. For example, wearable heart rate sensors based on technologies such as camera-based photoplethysmography, reflectance pulse oximetry, laser Doppler, capacitive, piezoelectric, and electromyography sensing mechanisms, have been reported [8].

Among the various vital signs, respiration is particularly important because of its relevance to not only the diagnosis of respiratory diseases but also for ensuring work safety, evaluating human emotions, monitoring athletic performance, and assessing warfighter health [9]. Several contact-based respiratory rate sensing mechanisms were identified by Massaroni *et al.* [10] and AL-Khalidi *et al.* [11], including acoustic, airflow, air temperature, air humidity, and chest movements. For the monitoring of chest movements during respiration, one approach is to rely on chest bands with integrated smart materials, such as electro-resistive bands [12], piezoresistive carbon nanotube fabrics [13], and triboelectric metallic yarns [14]. It should also be mentioned that many commercial chest band respiration sensors are also available in the market, such as the Dymedix PerfectFit Effort Belt Chest Sensor, Vernier Go Direct Respiration Belt, and Biosignalsplux Respiration Biometric Sensor, among many others. Many of these commercialized and research-based chest band sensors also aim to measure various vital signs, while some do not have the capability to measure respiration.

Given the diversity of wearable chest-band-based sensors available in the market and under development, the objective of this study is to develop a versatile, low-profile, and conformable sensor that can be coupled with practically any chest band to provide respiration monitoring capabilities. The research approach is to develop piezoresistive nanocomposite fabric sensors that can be attached onto chest bands through the use of snap buttons. Thin films based on graphene nanosheets (GNS) were fabricated and integrated with unidirectionally stretchable fabric to create the low-cost, low-profile, strain sensor that exhibited high sensitivity and linearity. In addition, a portable wireless data acquisition (DAQ) sensing node was also prototyped to facilitate data capture and human subjects testing. This paper begins with a description of the nanocomposite fabric sensor fabrication process and their electromechanical properties, followed by the design of the DAQ sensing node. Tests were performed to verify respiration monitoring using the nanocomposite fabric sensor by comparing them to simultaneous respiration effort data acquired using a commercial chest strap.



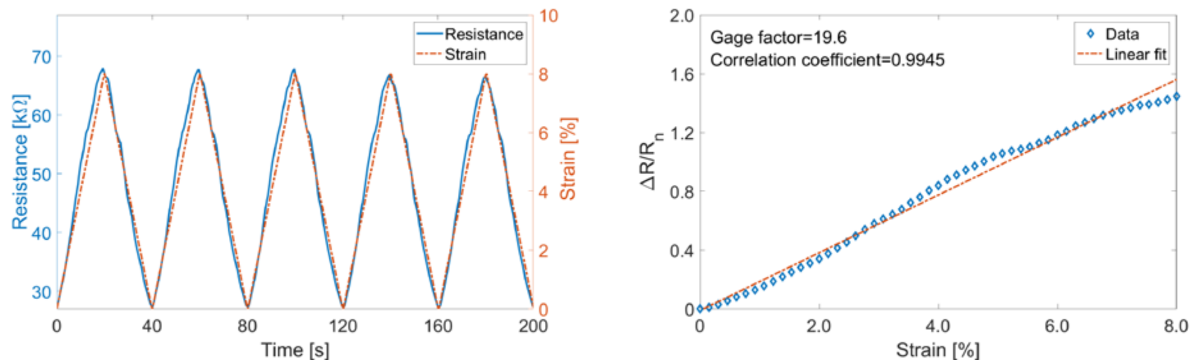
(a) (b)

Figure 1: (a) Motion Tape with piezoresistive GNS-EC sensing element and (b) with snap buttons mounted at opposite ends

NANOCOMPOSITE FABRIC SENSOR

Nanocomposite strain sensing fabrics that compatible with different commercial elastic chest bands were fabricated for respiration monitoring. In short, graphene nanosheets, which were synthesized using a water-assisted liquid phase exfoliation process, were dispersed in ethyl cellulose (EC) and spray-coated onto unidirectionally stretchable elastic fabric. Preparation and spray-coating of the GNS-EC sprayable ink followed the "Motion Tape" fabrication procedure described by Lin *et al.* [15, 16]. A total of three film layers were spray-coated, pausing ~ 2 min between each spraying to allow the film to dry. Upon complete drying of the GNS-EC film after ~ 5 min, flexible conductive silver trace was deposited at opposite ends of the rectangular film (40×10 mm^2), which were then cured at 100 °C for 5 h to form the electrodes. Multi-strand wires or conductive threads were soldered to each electrode to facilitate data collection (Figure 1). In addition, snap buttons were also incorporated at opposite ends of each Motion Tape designed for use with elastic chest bands for respiration monitoring as shown in Figure 1(b).

Electromechanical tests using a Test Resources 100R load frame were performed to characterize the strain sensing properties of the GNS-EC fabric. Multiple cycles of tensile cyclic loads to a peak strain of 8% were applied to the Motion Tape specimen (similar to Figure 1a), while the electrical resistance of Motion Tape was recorded using a Keysight 34465A digital multimeter sampling at ~ 1.5 Hz. A representative overlay of the applied strain pattern and the Motion Tape time history response is shown in Figure 2(a). Figure 2(a) confirms that its electrical resistance changes in tandem with applied tensile strains, consistent with previous findings. Its resistance increased in response to tensile strains and decreased in compression [15, 16]. Figure 2(b) plots the normalized change in resistance with respect to applied strains during one of the loading cycles. A linear least-squares regression line was also fitted to the data and overlaid. The overall fit confirmed the strong linearity of the sensor, while the slope of the regression line is 19.6 and is equivalent to the strain sensitivity (or gage factor) of this Motion Tape specimen tested. Previous work showed that the sensitivity of Motion Tape could be designed to be higher or lower depending on the GNS-EC ink formulation and other fabrication parameters [15-17].



(a) (b)

Figure 2: (a) Motion Tape resistance time history response overlaid with applied tensile cyclic strain pattern; (b) normalized change in resistance versus applied strains for one loading cycle

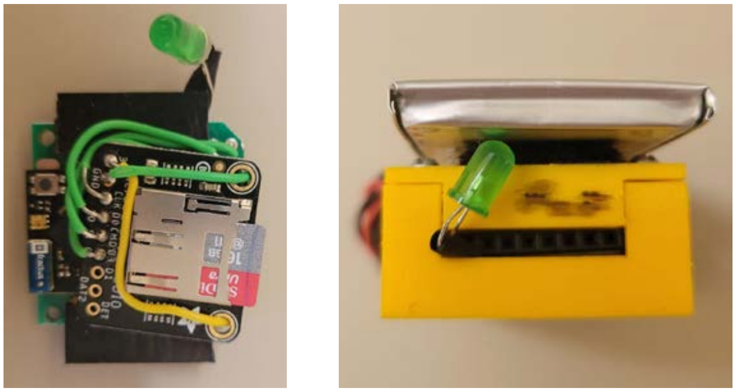
PORTABLE DATA ACQUISITION MODULE

A portable DAQ sensing node based on a TinyPICO – ESP32 Development Board was designed to interface with and to acquire Motion Tape respiration monitoring data (Figure 3). The 18×32 mm^2 TinyPICO board includes a ESP32 microcontroller unit with a 32-bit dual core 240 MHz processor. Other key features of this board include a 4 MB serial peripheral interface (SPI), 4 MB pseudo-static random-access memory (PSRAM), universal serial bus (USB) for programming, Bluetooth BLE 4.2, and a 12-bit analog-to-digital converter (ADC). The board is programmable through Arduino IDE.

Two other circuit boards, as well as a 1,200 or 2,000 mAh 3.7 V lithium polymer (LiPo) battery, were also stacked on top of the TinyPICO board. First, a sensing interface board with four voltage divider circuits was designed and prototyped. Each voltage divider circuit corresponded to a unique sensing channel, with one resistor being Motion Tape and the other a reference resistor. The analog voltage output reading was connected to the input/output (I/O) pin on the TinyPICO board. On the other hand, two sets of eight female header pin connectors were used to connect to Motion Tape and the reference resistors. Second, a microSD card circuit board was also employed for storing all Motion Tape data locally on the DAQ node. The microSD board interacts with TinyPICO through the SPI. A 16 GB microSD card was used for all tests, and all sensing streams were saved in CSV format. Figure 3(a) shows a picture of the assembled stacked boards, along with an on/off light emitting diode (LED). Figure 3(b) shows the portable DAQ sensing node with its 3D-printed polylactic acid (PLA) outer case and its external 2,000 mAh LiPo battery. It should be mentioned that the DAQ node can also be powered using two coin-cell batteries. A summary of the performance specifications of the portable wireless DAQ node is presented in Table 1.

RESPIRATION MONITORING TESTS AND RESULTS

Respiration monitoring chest bands were formed by attaching a Motion Tape fabric strain sensor to each Polar Pro chest strap as shown in Figure 4 [17]. This chest strap was selected because it is designed for use with other Polar wearable sensors and is deemed suitable for demonstrating the ease of adding respiration monitoring capabilities to an existing commercial product. First, two snap buttons were installed on the chest strap using a button snap fastener plier. Second, each subject wore



(a) (b)

Figure 3: (a) A stacked circuit board design was employed for the compact DAQ sensing node, and (b) they were encased in a PLA shell with an external LiPo battery.

Table 1: Summary of portable DAQ Sensing Node specifications

- Sensing channels: 4
- ADC resolution: 12 bits
- Maximum sampling rate: 66 Hz
- Local data storage: 16 or 32 GB microSD card
- Wireless communications: Bluetooth
- Battery life: ~ 90 min on 2,000 mAh LiPo battery

the Polar Pro chest strap and positioned the strap so that it rests over the sternum. Then, a Motion Tape with pre-installed snap buttons were attached to the chest strap. Data from Motion Tape were acquired using the portable DAQ sensing node mentioned earlier.

Reference respiration measurements were also obtained simultaneously using a Vernier Go Direct® Respiration Belt. The Vernier chest belt features an adjustable nylon strap and measures respiration effort or force. Although respiration force may be different than the localized strains measured by the Motion Tape chest band, the respiration waveforms should be comparable. That said, the subject also wore the Vernier Go Direct® Respiration Belt and positioned the sensor adjacent to the Motion Tape chest band as shown in Figure 4. Data from the chest belt was acquired wirelessly (via Bluetooth) using the *Vernier Graphical Analysis Pro* software running on a Microsoft laptop.

Engineering tests were performed to assess the sensing performance of the Motion Tape chest band during slow, steady breathing in a static pose. Each subject wore both the Motion Tape chest band and Vernier Go Direct® Respiration Belt. A representative result is shown in Figure 5, where the Motion Tape chest band strain measurements (in terms of voltage) are overlaid with the Vernier chest strap respiration effort data. First, it can be observed that both time history signals exhibit similar trends. When breathing in, the chest expanded, which led to an increase in both strain (*i.e.*, Motion Tape chest band) and respiration force (*i.e.*, Vernier chest strap). The opposite was true during exhalation. Figure 5 also shows that the respiration rate appeared to be similar, with the peaks and troughs of both signals aligning well during the nine respiration cycles shown. Second, the Motion Tape chest band also outputted high signal-to-noise ratio response, which is in part because of the high strain sensitivity of Motion Tape as shown in Figure 2. Overall, these preliminary results confirm that Motion Tape chest bands can be used for respiration monitoring.

The Motion Tape raw data obtained and shown in Figure 5 can be further processed to reveal insights about respiration. A fast Fourier transform (FFT) was applied to the Motion Tape time history data, and the results are shown in Figure 6(a). A dominant frequency of ~0.073 Hz can be clearly observed, which corresponds to approximately 4.4 breaths per minute (bpm). This respiration rate can be confirmed by counting the number of respiration cycles in the data of Figure 5, where roughly 4.5 breaths occurred in the first 60 s; this is the case for both Motion Tape and Vernier force measurements.

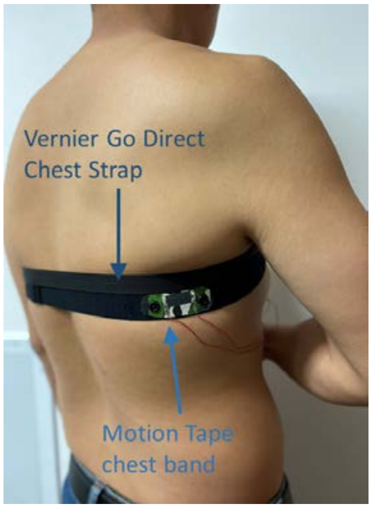


Figure 4: Respiration testing with Motion Tape chest band and Vernier chest strap as the reference

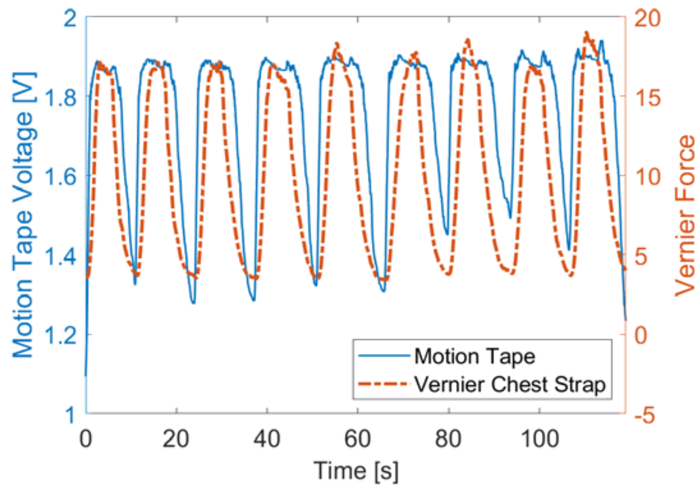
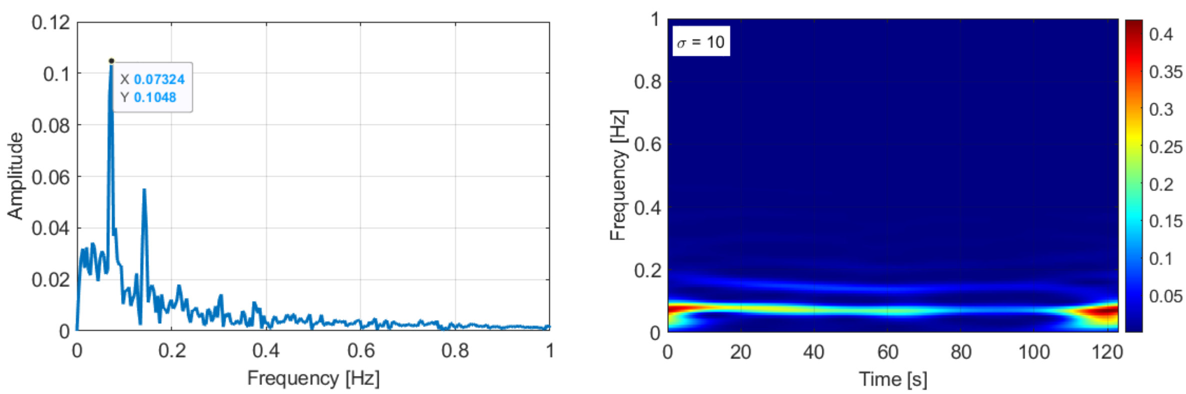


Figure 5: Motion tape chest band strain (voltage) measurements overlaid with Vernier Go Direct respiration effort (force) data during slow, steady, breathing



(a) (b)

Figure 6: (a) Fourier spectrum of Motion Tape test data shows dominant frequency at ~0.073Hz; (b) the time-frequency plot can be used to track respiration rate over time

While the engineering tests performed in this study required the subjects to breathe at a steady (constant) rate, normal respiration rate can vary, for example if the individual is performing physical activities or has an underlying health condition that may alter respiratory rate (e.g., anxiety). To help visualize respiration rate and how respiration rate varies over time, a time-frequency representation of the raw data in Figure 5 can be plotted, as is shown in Figure 6(b). To create the time-frequency plot in Figure 6(b), the time history data was processed using wavelet transform using a Modified Complex Morlet Wavelet and a 10-s Gaussian moving window (σ) [18, 19]. The light-colored features in the time-frequency plot of Figure 6(b) identifies how the dominant frequency (*i.e.*, in this case respiration rate) varies over the entire duration of testing. In this study, respiration rate was controlled, so the time-frequency plot does not show significant dominant frequency variations. Future tests will consider measuring subject respiration in more varied and physically intense environments so that changes in respiration rate can be observed. The goal of this preliminary study was only to demonstrate the respiration measurements are possible using a Motion Tape chest band coupled with a prototype portable data acquisition node.

CONCLUSIONS

In conclusion, the objective of this study was to develop a low-cost, disposable, nanocomposite strain sensor that could be attached onto any elastic chest band for respiration monitoring. The approach was to spray-coat graphene nanosheet thin films onto unidirectionally stretchable elastic fabric to form the sensing element. Snap buttons were integrated at opposite ends of the nanocomposite fabric sensor so that they can be attached onto practically any elastic chest band. In addition, a portable, wireless, data acquisition sensing node was designed and prototype to facilitate testing and remote data collection. The DAQ node was based on the TinyPICO development board and was programmed using Arduino IDE. The system features four sensing channels, a 12-bit analog-to-digital converter, onboard microSD card for data storage, and Bluetooth wireless communications capabilities. Then, the nanocomposite fabric sensors were attached to commercial Polar Pro elastic chest bands for respiration monitoring tests, which involved having each subject conduct repeated slow and steady breaths. In addition, reference respiration measurements were also acquired simultaneously using a Vernier Direct Go chest strap. Overall, the test results confirmed the ability of the nanocomposite sensor and elastic chest band for respiration and respirate rate monitoring. The findings presented in this work brings this nanocomposite fabric-based respiration sensor closer to commercialization. The piezoresistive nature of this sensor means that they can be easily interfaced and integrated with different commercially available data collection modules, where this technology can be used as an add-on for existing wearable sensing systems. Future work will investigate the possibility of using self-adhesive elastic fabric sensors for respiration monitoring so as to achieve greater versatility and broader use cases.

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