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Benchtop Characterization of Wearable Respiratory Monitors for Assessing Feasibility of Measuring Lung Volume

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Objective: This study characterizes three commercially available wearable respiratory monitors (WRMs): (1) Hexoskin Smart Garment, (2) Smartex WWS, and (3) Equivital EQ02 LifeMonitor, each with a unique chest motion sensor technology: respiratory inductance plethysmography, piezoresistor, and strain gauge, respectively. WRMs comprise of a body garment with embedded sensors that measure ambulatory chest motion in real-time. Once calibrated, chest motion waveforms from WRMs can be converted to lung volume waveform, which is then used to derive respiratory topography. The aim of this study is to assess and compare these WRMs in terms of: (i) their response signal to chest motion linearity, which is necessary for successful calibration, and (ii) their ability to measure breath-hold, which is a parameter of interest for lung deposition modeling. Methods: A benchtop test setup was built to simulate chest motion in a controlled way to facilitate comparison across the three devices. A staircase square-wave chest motion profile was used to simultaneously assess both signal linearity and ability to measure breath-hold. The respiratory response from the sensors was compared to the simulated chest motion. Results: The Hexoskin showed the best performance in both metrics, whereas the Equivital had the worst performance in both. The Smartex showed moderate ability to measure breath-hold but poor signal linearity. Conclusion: Of the three WRMs tested, the Hexoskin appears to be the best choice for ambulatory lung volume measurement. Significance: This study demonstrates the feasibility of adapting current technology to observe respiratory behavior valuable in many research domains, including tobacco research.
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Keywords: inhalation topography, lung volume, respiratory topography, smart garment, wearable respiratory monitor, sensing, monitoring, and diagnostics, wearable technologies

1 Introduction

Commercially available wearable respiratory monitors (WRMs) can be adapted for observing natural environment ambulatory respiratory topography parameters, including inhalation and exhalation flowrates, volumes, and durations, as well as breath-hold duration. These parameters provide the necessary boundary conditions for the numerical modeling of particle deposition in the lungs [1]. Additionally, these parameters provide a quantitative measure of tobacco use behavior [2], including inhalation patterns associated with puffing (i.e., mouth-to-lung [3] versus direct-to-lung [4]) and provide a means to quantify and assess compensatory behavior [5].

A WRM is a device, comprised of a sensorized garment and data logger, and is able to measure a number of biosignals including respiratory rate (RR), heart rate, and heart rate variability. WRMs are used in a variety of applications including fitness and sports [6], at-home health monitoring [7], sleep studies [8], and military personnel monitoring [9].

Of specific interest in this paper is the WRM's embedded respiratory sensors that measure the chest motion waveform, i.e., expansion and contraction of the chest wall due to inhalation and exhalation as a function of time. The WRM uses this waveform to derive RR. However, the raw chest motion waveform can also be used to calculate the lung volume waveform via calibration according to the model introduced by Konno and Mead [10]. Once the volume waveform is obtained, the respiratory parameters of interest can be derived [2].

A previous paper qualitatively assessed different off-the-shelf WRMs in terms of six attributes based on identified key product characteristics [11]. There were some product characteristics, highlighted in the paper that could not be assessed without directly testing the WRM. Two of which are the WRM's (i) linearity of respiratory sensor response to chest motion and (ii) ability to measure breath-hold. No information was found on these characteristics in the manufacturer's product literature. The signal linearity is an important characteristic because a linear relationship must exist between chest motion and the observed WRM's sensor response for it to be possible for calibration. The ability to measure breath-hold is

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an important characteristic because breath-hold is one of the factors that may affect particle deposition [12].

The WRMs that were previously identified differed in many product characteristics but the key factor that is believed to drive the difference in terms of signal linearity and ability to measure breath-hold is the respiratory sensor technology. No information was provided in the product literature of any of the WRMs regarding signal linearity or whether they were able to measure breath-hold. Of the WRMs identified, the three primary respiratory sensor technologies were: strain gauge, piezoresistor, and respiratory inductance plethysmography (RIP). To assess the difference between these sensor technologies, three off-the-shelf WRMs were chosen, each equipped with one of the sensor types.

Although WRMs with these sensors have been used in prior studies, no work has been found that directly characterized these respiratory sensors, in particular for signal linearity and ability to measure breath-hold. This is presently a gap in the literature that this investigation hopes to address.

To quantitatively characterize and compare the three WRMs, this study used a benchtop test apparatus to simulate chest motion in a controlled manner. The aims of this study are (i) to characterize each WRM in terms of its signal linearity and ability to measure breath-hold, and (ii) to identify the WRM most suitable for measuring ambulatory lung volume.

2 Methods

2.1 Wearable Respiratory Monitors. The three WRMs selected for benchtop testing were (i) Hexoskin Smart Garment (Carré Technologies Inc., Montréal, PQ, Canada) which has the RIP sensor, (ii) Smartex Wearable Wellness System (WWS) (Smartex s.r.l., Pisa area, Italy) which has the piezoresistor sensor, and (iii) Equivital EQ02 LifeMonitor (Hidalgo Inc., Swavesey, UK) which has the strain gauge sensor. The specific features and capabilities of each WRM have been previously described [11].

Each of these WRMs has different form factors: The Hexoskin and the Smartex are both full torso shirts, whereas the Equivital is a chest strap with two shoulder straps. All three can be worn in conjunction with or instead of an undergarment. The sensors are embedded into the fabric and they each come with a detachable proprietary data logger that powers the sensors and stores the sampled data.

Both the strain gauge and piezoresistor sensors function similarly in that their electrical resistance changes in response to the mechanical deformation (i.e., stretching and contracting) of the substrate they are attached to. In the case of the smart garments, these sensors are embedded in the fabric and produce a signal response due to the lateral stretching and contracting of the garment while the user is breathing. The RIP sensor is comprised of a loop of coiled wire, embedded into the garment around the torso, which generates a magnetic field when alternating current is passed through. This magnetic field fluctuates with the changes in the circumference of the wire, e.g., during breathing. The fluctuating magnetic field and the corresponding induced current are proportional to and are used to infer chest motion.

These WRMs were obtained from their respective vendors and were not modified in any way. The original software packages that came with each monitor were used to communicate with and download data from the device.

2.2 Benchtop Test Setup. A computer-programmable benchtop chest expansion simulator (CBTS) was built to characterize the selected WRMs. The CBTS (shown in Fig. 1) is comprised of a motorized linear actuator, a linear actuator controller (LAC) a sliding rail, and two C-brackets. The linear actuator has a stroke length of 100 mm and has a precision of ±0.3 mm. The linear actuator can resist a force of 100 N at full stroke length. Both the linear actuator and LAC were purchased from Actuonix Inc. (Saanichton, British Columbia, Canada). It was determined from preliminary investigations that when the Equivital is stretched by 100 mm, the compressive force is around 75 N. Hence, a linear actuator that can resist greater than 75 N of force was chosen. The supporting structures and sliding rail were obtained from an online retailer.

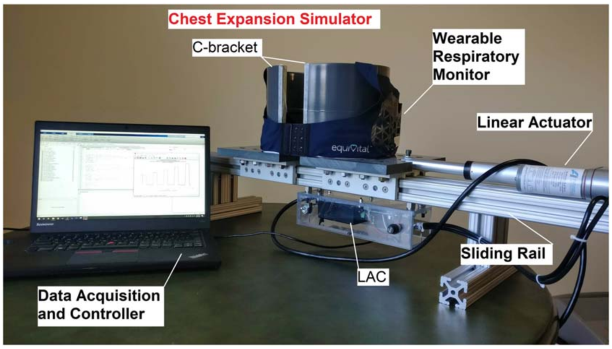

Fig. 1 Computer programmable benchtop test setup for characterizing WRM signal response to simulated chest motion

One C-bracket was fixed in place whereas the other was connected to the linear actuator and free to slide along the rail. Together, the two C-brackets mimicked the lateral sides of the human torso. When actuated, the translation of the C-brackets relative to each other mimics chest motion. By extending the linear actuator from the resting position, the motion of inhalation is mimicked. By holding the linear actuator at the extended position, breath-hold is mimicked. By contracting the linear actuator back to the rest position, exhalation is mimicked.

The WRMs were placed on the CBTS such that the full circumference of the garment wrapped around both C-brackets. The starting resting position was chosen to be one that provided a snug fit to the garment. In the case of the Hexoskin, only the abdominal respiratory sensor was placed around the C-brackets.

A MATLAB script was written to control the linear actuator by sending specific commands to the LAC. The two main movement controls are speed and distance. The LAC has a built-in proportional-integral-derivative (PID) controller to regulate the distance. By controlling the distance as a function of time, the chest expansion waveform was simulated. The LAC has a built-in potentiometer-based feedback sensor that reports the current displacement in real-time. This *observed* displacement, and not the *command* displacement, was used for comparison with the respiratory response from the WRM sensors.

2.3 Simulated Chest Motion Waveform. To assess the ability of the WRM to measure breath-hold, the garment needed to be stretched and held in place before being released back to its resting position. To assess the linearity of the WRM's respiratory response to chest motion, the sensor needed to be subjected to a range of expansion distances. To assess both of these at once, a staircase square-wave chest motion waveform was simulated using the CBTS. The command square wave started at a magnitude of 15 mm and reached 35 mm in increments of 5 mm. The breath-hold duration at each step was 5 s.

2.4 Data Analysis. Respiratory data collected from the WRMs were transferred to the computer using the software provided by the manufacturers. First, the respiratory waveform from each was plotted side by side with the CBTS observed displacement waveform. This allowed for a visual assessment of the ability of each WRM to measure breath-hold. Next, the respiratory waveform was plotted against the CBTS observed displacement waveform. This allowed for visual assessment of the response signal to chest motion linearity. In assessing repeatability, linear regression was used to derive a linear equation to fit data from each trial. All data analysis and plotting were done in MATLAB.

The magnitudes of the raw sensor data from the WRMs are considered to have an arbitrary unit, represented herein as (count), as it is unknown what the exact configuration of circuitry and data processing is done within each data logger. Each WRM comes with its own proprietary data logger and software that measures, interprets, and exports out the raw data, as such it is not expected that the magnitude of (count) is the same across each WRM. In order to obtain quantitative and comparative measurements of respiratory parameters in engineering units (i.e., (ml)), the WRM must be calibrated against known volumes. Calibrating these WRMs is beyond the scope of this investigation. Here, the raw data obtained from each WRM's software are used for qualitative analysis.

3 Results

3.1 Breath-Hold. A significant factor related to the ability of each WRM to measure breath-hold is the degree to which the respiratory signal decays during the period of breath-hold, with the smallest decay rate being best for measuring breath-hold. Figure 2(*c*) shows that the Hexoskin showed virtually no decay, while the Smartex (Fig. 2(*b*)) showed some decay and the Equivital (Fig. 2(*a*)) showed the most significant decay during breath-hold. In both the Smartex and the Equivital, the decay began immediately after the onset of breath-hold and persisted until the end of the breath-hold. For the given breath-hold duration, only the Equivital has shown complete signal decay. It is unclear if the signal from Smartex would decay completely after a certain amount of time.

In addition to the signal decay, the Equivital also demonstrated an unexpected reversal in signal response during exhalation (i.e., during the trailing edge of the square waveform). Starting at the onset of exhalation, the signal response magnitude increases in the negative count direction until the exhalation stops. At this point, the signal began to decay back to baseline, similar to its behavior during breath-hold after inhalation.

3.2 Signal Linearity. Figure 3 shows the relationship between the simulated chest expansion and the WRM respiratory response waveform at each sampled point. Out of the three WRMs tested, the Hexoskin (Fig. 3(*c*)) showed the most linear relationship, whereas the Smartex (Fig. 3(*b*)) showed poorer linearity and the Equivital (Fig. 3(*a*)) showed the least linear relationship.

To further confirm the linearity of Hexoskin's respiratory response to chest motion, repeated trials ($n = 5$) were performed with the result shown in Fig. 4. Linear regression was used to determine a line of fit to the scatter points from each trial and from that it was found that the signal response from the Hexoskin is both linear and repeatable, with a mean regression slope of 0.141 ± 0.004 (mm/count).

4 Discussion

4.1 Potential Reasons for Signal Decay During Period of No Motion. Unlike the Hexoskin, the respiratory signals from the Smartex and the Equivital decayed during the period of no motion (i.e., breath-hold), with the Equivital showing a greater rate of signal decay than the Smartex. One possible explanation for the difference in behavior across the three WRMs may be in

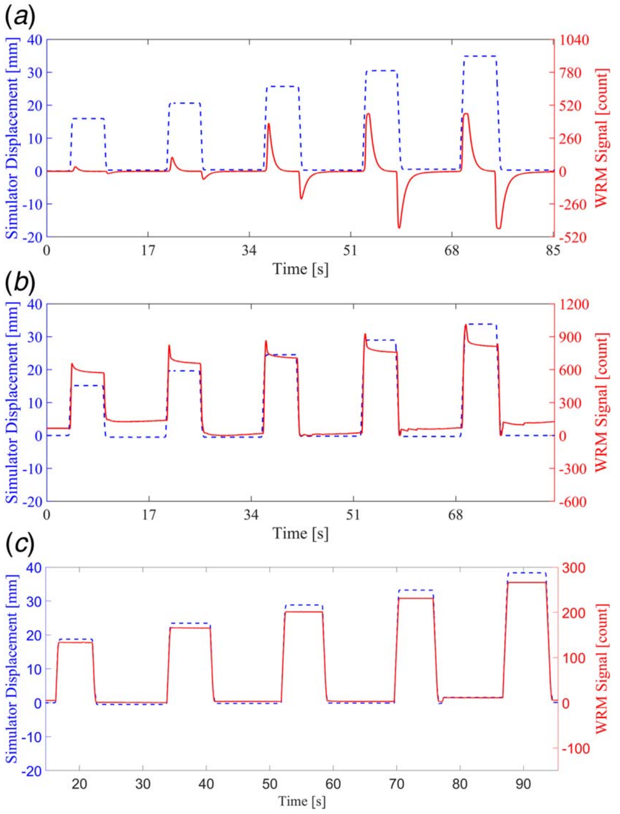

Fig. 2 Linear actuator displacement waveform simulating chest motion (dashed line) and the resultant normalized respiratory waveform (solid line) from the (*a*) Equivital, (*b*) Smartex, and (*c*) Hexoskin. The leading and the trailing edges of the simulated chest expansion square wave represent inhalation and exhalation, respectively. Each WRM's ability to measure breath-hold is demonstrated by the degree to which the respiratory signal decays during that period.

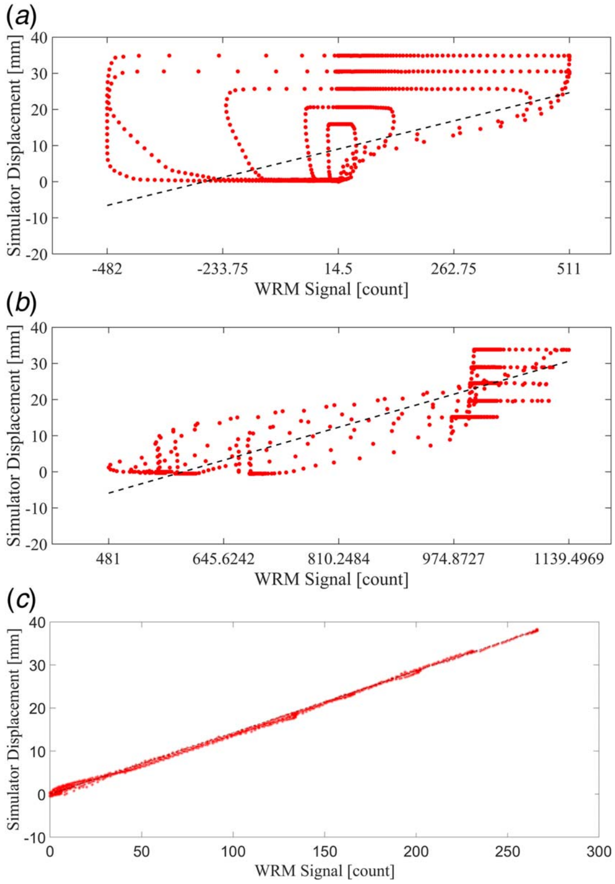

Fig. 3 WRM respiratory waveform response (count) versus simulated chest motion (mm) for the (*a*) Equivital, (*b*) Smartex, and (*c*) Hexoskin. The dashed line is the linear regression line. Each WRM's signal linearity is represented by how close the scatter points are to the linear regression line.

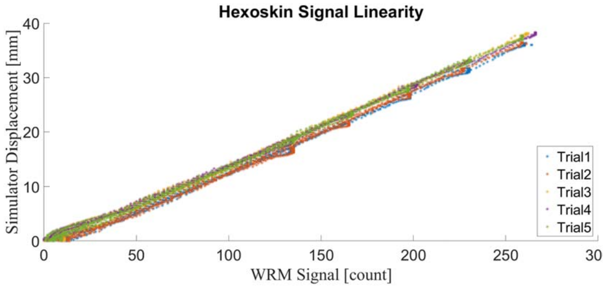

Fig. 4 Hexoskin respiratory waveform response (count) versus simulated chest motion (mm) at each sampled point from five repeated trials

the sensor technology used in each. The behavior of Equivital's respiratory signal seems to suggest that the sensor is measuring strain rate and not strain, contrary to what was suggested by the manufacturer. The Equivital appears to only respond during motion, in the positive count direction during inhale and a negative count direction during exhale. This and the fact that it is not able to maintain a signal during no motion seem to support the notion that it is measuring strain rate.

Another possible cause is in the data logger of the devices. The manufacturers do not disclose the type of data processing that may be done to the raw signal as it is collected. It is possible that the signal decay may be due to the internal data processing.

Since the linear actuator's position is actively controlled by a PID controller and the current position is read back from the controller in real-time, signal decay due to contraction of the linear actuator arm can be ruled out.

4.2 Difference Between Simulation and the Real Scenario. In tidal breathing, the inhale and exhale portions of the respiratory cycle are typically curvilinear. For control simplicity, a linear inhale and exhale were used instead. The benefit of using this idealized respiratory cycle also extends to the ease of comparison and analysis. This method of analysis is suitable for the objectives of characterizing the ability to measure breath-hold and investigating the signal linearity. This approach using the simulator was preferred over an on-person approach because it provided more control over the chest motion and avoided uncertainty introduced by bodily motion of a person. It would not be possible for a human to expand or contract their chest to the same precision as the simulator.

The benchtop test setup only simulates chest expansion in the transverse direction. It does not simulate the expansion in the anterior-posterior direction, which is how the chest moves in real breathing. However, since the sensors measure lateral stretch along the circumference of the garment, for any given change in the circumference, the signal response should be the same regardless of whether the stretch is in the transverse or the anterior-posterior direction.

Despite these limitations, we believe that the knowledge gained through this controlled investigation is still applicable to the natural use environment with an actual subject.

4.3 Expectations of Human Subject Trials. All respiratory responses presented in this paper have arbitrary units of counts. The WRM needs to be calibrated to allow conversion from counts to volume units (e.g., ml). Many calibration techniques have been previously proposed [2,10,13,14]. The signal linearity is a prerequisite for a successful calibration. With good calibration, the WRM would be able to measure the lung volume waveform. It is not expected that calibration done on a person would be generalizable to all persons using the monitor. The calibration curve is dependent on the physiology of the user and the way they breathe.

4.4 State of Research. Although the results of this investigation would save researchers interested in this application both time and money, given the necessary cost of building a test setup and acquiring the WRMs which can range from several hundred dollars to over a thousand dollars each, there presently is still a need to further investigate these and other respiratory sensors so as to extend and corroborate the findings presented here as this investigation is the first to do so, to the knowledge of the authors. Understanding the performance characteristics of the respiratory sensors used in each WRM is a necessary step for quantitative measurement of respiratory parameters using WRMs.

5 Conclusion

Three off-the-shelf WRMs, each with a different sensor technology, were characterized using a benchtop test setup. Of these three WRMs tested, the Hexoskin Smart Garment provided the most satisfactory performance in both its ability to measure breath-hold and its response signal linearity. The Smartex WWS may be suitable for measuring short durations of breath-hold but its signal linearity results indicate likelihood of poor calibration. The Equivital appears to not be suitable for either measuring breath-hold or calibration. The Hexoskin Smart Garment is a good candidate for ambulatory observation of lung volume and respiratory topography in the natural environment.

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Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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