Footfalls & Heartbeats

Knitted Band for Continuous Respiration Monitoring

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Abstract
Respiration monitoring is a key metric that is largely unused within day-to-day monitoring. Footfalls and Heartbeats (Footfalls) have developed a first-of-its-kind textile respiration monitoring band, unlocking access to patient adoption and compliance not possible until now. It's textile nature removes the barriers to traditional monitoring systems, whilst providing accuracy of up to 97.4%.

Keywords
Respiration, Textile, Validation, Monitoring

Introduction

Despite significant interest and evidence supporting the use of respiration monitoring, it is yet to find widespread adoption within sport or remote monitoring healthcare applications. This white paper outlines the role of respiration in the human body, and why it is such a useful physiological marker. The uses and applications within a multitude of health and fitness scenarios are discussed. Further note is made of the current technologies used in the sectors above.

It goes on to outline and validate a textile Respiration Band, offering all the comfort of a textile alongside the robust and reliable signal quality required to access the information needed.

Two protocols are outlined to assess the systems performance: the first takes place with participants sitting still whilst the second requires participants to adopt common sleeping positions. The results validate the capability of the sensor to sense and recognize the wearers respiration in these conditions.

Scientific Background

The Role of Respiration

Respiration is one of the core processes in the body, responsible for delivering oxygen to the lungs via continuous inhalation and exhalation. The first half of the respiration process is where oxygen is inhaled into the lungs and diffused into the blood. This oxygenated blood is then delivered to the respiring tissues where oxygen enters and is used in energy production. As a waste product of this process, carbon dioxide is produced and must be expelled from the body before it builds up. A consequence of this build up is the blood turning acidic and damaging cells and tissues. The second half of the respiration cycle involves the blood transporting the carbon dioxide back to the lungs, where it is diffused back and expelled via exhalation [1].

The way an individual breathes, along with how their breathing changes, are fundamental indicators for a multitude of physiological conditions and stresses. Early detection of conditions or frequent overstressing can lead to early interventions, reducing the speed and severity of corresponding health issues. This is becoming an increasingly prominent issue, with the National Health Service (NHS) reporting that respiratory diseases together are the third largest cause of death in England [2].

Biomechanics of Respiration

The biomechanics of respiration describes how the thoracic cavity, the area in which the lungs occupy, expands and relaxes. As the cavity expands the lungs are opened and air rushes in to fill the new empty space, and as they relax the air is forced back out again [3].

At rest and during periods of low physical activity there are two main drivers of respiration: the diaphragm which sits below the cavity, and the external intercostal muscles which sit around the lungs, attached to the rib cage [4]. The diaphragm expands the cavity by pulling it down, whilst the external intercostal muscles expand it by pulling it up and out [3] [5]; this in-turn increases the volume of the lungs, drastically decreasing the pressure and causing the air to rush in [5]. To release the air these muscles relax to allow the natural elasticity of the rib cage to compress the lungs, forcing air back out.

During periods of exercise or respiratory distress, the body requires more energy to be created and so a larger amount of oxygen is required to meet this need. To achieve this, the thoracic cavity has a variety of other 'accessory' muscles such as the sternoclemastoid and the internal intercostals which are all designed to help expand the lungs further and faster. Additionally they can assist in maintaining this increased rate for longer [5]. The variables that the body has to play with here are how frequently this respiration process takes place, known as respiration rate, and how much air is taken in per breath, known as the breathing volume.

Respiration Rate

The metric used in determining how much a person is breathing is their respiration rate, which is defined most commonly as the average number of breaths per minute (RR). Whilst baseline breathing rates differ from person to person, there are general healthy respiration rate windows for any given demographic ($\sim$10-15 breaths per minute whilst at rest for adults aged 18-65) [6]. A respiration rate outside of these can indicate potential respiratory health issues. Generally, healthy respiration takes the form of relatively consistent respiration rates over time, along with consistent rate changes depending on activities and levels physical exertion. A strong indicator of respiratory health issues can also be sporadic breathing and fluctuating respiration rates, especially during consistent periods of low effort.

Respiration and Wellbeing

The importance of respiration in human life means that it has crucial links, and dependencies upon, a huge variety of human conditions. It acts as a vital indicator not only to respiratory system health, but also to bodily oxygen requirements and hence its ability to perform physical tasks of varying exertion levels. Robust respiration monitoring therefore open up insights into large areas of human health.

Sleep

Sleep plays a crucial role in maintaining good health [7] [8]. High quality sleep lowers the risk of various health problems such as heart disease, and diabetes, whilst aiding recovery following exercise, reducing stress levels and increasing mental well-being. To maintain and fuel high quality sleep, a constant and consistent supply of oxygen is needed [7] [8].

During sleep, respiration rate decreases due to a lower demand for oxygen [6] [9]. As an individual falls deeper into sleep, their respiration rate falls further, and can drop to as low as $\sim$7RR [6] [9]. Healthy individuals will experience mostly predictable and continuous respiration throughout the night [10]. However, individuals with sleep disorders are more likely to suffer from respiration irregularities and may suffer from periods of reduced, or no, breathing (>10 seconds); also known as an apnoea event [10] [11]. Additionally, these individuals may also suffer from prolonged periods of shallow and rapid breathing. Both of which can be identified by monitoring a wearers' breathing pattern and respiration rate.

COPD

Chronic obstructive pulmonary disease (COPD) is the term assigned to a group of lung conditions and diseases which can cause difficulties whilst breathing. This is typically caused by damage or restrictions to the lungs or the airways, reducing the body's ability to effectively take in oxygen [12]. A key symptom of COPD is a shortness of breath, leading to a disproportionately large increase in respiration rate compared to a normative rate for a given task [12] [13]. Although COPD is not curable, early detection and appropriate treatment regimens can minimise and potentially delay the effect it has on an individual's day-to-day life [13].

Exercise

As a key driver of energy synthesis, healthy respiration is critical for optimal physical and athletic performance. During periods of exercise the body requires more energy, and so requires more oxygen and produces more carbon dioxide needing removal [1]. The main ways it achieves this is by increasing respiration rate from an average of approximately 15 breaths a minute to $\sim$40-60 times a minute, and by increasing the volume of air inhaled per breath. Together these can increase the total volume of air being inhaled per minute from $\sim$12 liters to up to $\sim$100 litres, depending on the level of exertion.

A person's fitness will determine the strength of their respiration muscles. Stronger muscles mean the thoracic cavity can be expanded further, increasing the volume of air entering the lungs. Also the expansion can be done much faster, increasing the respiration rate. Additionally, stronger muscles are then able to maintain these higher rates for longer periods.

Respiration rate monitoring can also serve as a developmental tool, whereby individuals can specifically train the appropriate tissues, to be able to increase their RR and reach larger lung volumes [9].

Existing Respiration Monitoring Techniques

To address the demand for robust respiration monitoring, a wide range of techniques and devices have been created. These methods can be split into two distinct categories: contact, and non-contact monitoring.

Contact Monitoring: requires physical contact with the patient, and includes techniques such as blood oxygen monitoring, heart-rate inference, accelerometer based or conventional strain sensing. The main benefits of these solutions are accuracy, as they can be placed wherever they are needed, and in some cases portability [9] [14]. The large drawback here though is comfort. Often it requires the wearers to wear a solid piece of uncomfortable and heavy electronics, making it difficult if not impossible to go unnoticed by the user. This can make it extremely difficult to get people to wear it even in a healthcare setting. If it also be visible if worn outside of a healthcare environment then studies show this can lead to high levels of stigma for the wearer, further reducing the likelihood of the device being worn [14].

Non-Contact Monitoring: avoids making contact with the patient and so avoids the issue of poor user comfort. These can include techniques such as radar monitoring, video analysis and camera analysis. These can provide great options for single patients, but often fail if multiple people are in the capture zone. Systems also tend to be expensive making them inaccessible to the public and impractical for widespread home use, whilst the fact that they are not portable means they cannot be used for monitoring whilst the patient is active.

Monitoring Techniques

What is required for widespread and easy to access respiration monitoring is a solution which is both cheap and robust. It must be portable such that it can be worn throughout day-to-day life, and comfortable enough for the wearer to forget that it is being worn. Additionally, it should be as discrete as possible so that the wearer doesn't risk embarrassment or attention being drawn to their health conditions.

Technology Background

Footfalls and Heartbeats

Footfalls and Heartbeats are an SME, comprised of smart textile experts, based in Nottingham, UK. Footfalls wants to change the way healthcare is delivered in the 21st century, to make personalised, proactive health technology affordable and available to all. The culture is encapsulated by ”be bold, be brave, have fun and change the world”.

Knitted Sensors

Footfalls' patented knitted technology consists of substituting sections of the non-conductive yarns within knitted textiles and replacing these with conductive yarn, resulting in electrically conductive areas. As these area's move or stretch so their electrical output also changes, allowing us to gain an insight into the movement that causes these deformations.

The type and ratio of stitches (stitch pattern) used within the sensor has a huge impact on the quantitative quality of the sensor reading. Footfalls' patented sensor designs allow for the creation of sensors with all the physical properties of a knitted textile whilst maintaining the output signal quality required for robust signal processing and feature detection.

Footfalls' Respiration Band

Footfalls have developed a band strap containing proprietary strain sensing technology to monitor a wearers' breathing. It is placed on the wearer just below their chest, proximal to the xiphoid process (Figure 1), with its design meaning it can be worn over or under any garment and used for any application.

As a result of this placement the respiration band expands and contracts with the chest wall, resulting in an output waveform which contains the human respiration pattern. Footfalls' proprietary algorithms process these waveforms to recognise and count the breaths. These metrics can then be analysed to find irregularities in a person's breathing, periods of low to no breathing, and combined with time to give their respiration rate.

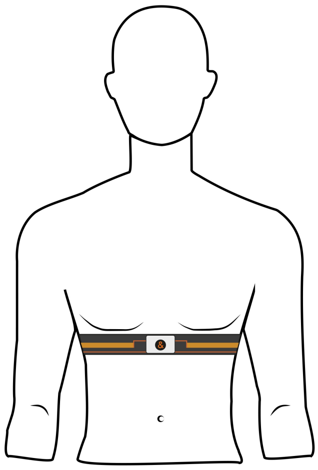

Figure 1. Optimal placement of the Footfalls Respiration Band

Study Design

Equipment and Construction

The system used in this study is a Footfalls Respiration Band. Footfalls have created a custom sizing for the band ranging from XS to 3XL, with the selected size depending upon the chest size of the individual. Sizes S to XL were used within this study.

For wireless data acquisition and transmission, Footfalls' custom electronics unit was used.

Participants

This study involved 5 participants, all of whom were volunteers from the current staff at Footfalls.

Anthropometric data displayed in Table 1. Participants were selected solely based upon their availability during the trial dates, with no consideration of physical properties. All participants were fit and healthy at the time of testing and had no respiratory illness/diseases present that may alter their breathing mechanics.

ID	Height (cm)	Chest Size (cm)
68_Sm1	159	80
76_5_Sm1	183	90
76_5_Sm2	174	90
78_2_Sm1	184	92
91_1_Sm1	183	106

Table 1. Anthropometric data from the participants

Protocols

Two test protocols were performed as part of this study. One to gauge basic sensor functionality and the second to assess performance within a sleep setting. Each participant used the same band across all tests and throughout each protocol.

During both protocols, the breath count was measured by two devices: the Footfalls Respiration Band, and a smartphone camera. Participants wore a clear face mask, with paper trails attached across the vents (Figure 2) allowing the movement of air to be easily visible by the smartphone. This video was used as the reference data during data analysis.

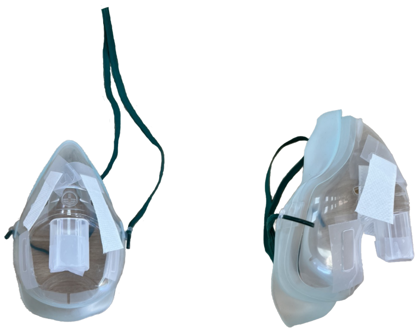

Figure 2. Face masks that were used to display RR.

Protocol A - Sitting Tests: was designed to replicate one of the most common scenarios a user may experience. It required the participants to sit upright in an office chair whilst leaning against the chair back. For the sake of realism, exact replication of the posture between participants was avoided by instructing them to adjust themselves until they felt comfortable. This protocol was performed three times per participant.

Protocol B - Lying Tests: was designed to understand system performance in a sleep setting. Participants were instructed to adopt four common sleeping positions (left-side, right-side, front, back) to understand how the respiration band works in varying conditions. This protocol was performed once per participant.

Methodology

All trials across both protocols were captured following the same methodology. Participants did no strenuous activity or exercise at least one hour prior to the trials to ensure there was a true resting respiration rate. All participants wore the Respiration Band in the desired location (Figure 1) to ensure that participants' respiration rate was as repeatable as possible. To begin, participants entered the required position and time was given to get comfortable. The clear respiration mask was then fitted, with the strap pulled tight to achieve a seal across the face and ensure all air passed through the modified vents.

Once both recording devices were ready, the data capture began for 30 seconds before the participant was instructed to take an exaggerated deep breath in, which was held for 1 second. This was to be used during data analysis to mark the beginning of the relevant data period. Once completed, the respiration monitoring began and lasted for a period of 3-minutes. During this period, participants watched a video to distract them from focusing on their breathing [15]. After the 3-minutes had elapsed, participants took a second exaggerated deep breath in to identify the end of the period. Data collection continued for an additional 30-seconds to ensure files could be aligned for post-processing.

Data Analysis

Once all trials were complete, videos were reviewed at both 2x, and 1x speed to extract an actual breath count for the trial. If there was a difference between the two counts, the video would be re-watched at 1x speed for an additional check. The raw Band data was passed into custom Footfalls algorithms, which first recognised when a breath took place before finally being counted across the trail. The breath count from the video was taken as the actual respiration rate, and was directly compared to the algorithm breath count from the Respiration Band.

Test Accuracy: Test accuracy is used to understand how well the system performs within an individual test. It is calculated using Equation 1 and it is the percentage of actual breaths that have been correctly recorded. The ideal outcome is a 100% accuracy. A number less than 100% means that the system has under-counted, whilst a value greater than 100% means it has over-counted.

$$Precision = \frac{Counted}{Recorded} * 100 \quad (1)$$

Limits of Agreement (LoA): Limits of Agreement (LoA) will be the methodology used to understand how well the system performs across all tests, by focusing on the difference between the recorded and the actual breath count [16]. The output of this will be an average accuracy (similar to test accuracy) but also a confidence window in which 95% of all data is expected to lie, giving an insight into sensor precision and repeatability. The narrower the confidence window the more repeatable the system performance. The confidence window values are created by multiplying the standard deviation by 1.96, and subtracting this from the bias to get the lower boundary, whilst adding them to get the upper boundary [17] [18]. This standard deviation multiple is also what will be used determining overall system accuracies.

System Accuracy (SA): is the industry standard for gauging how close a systems results are to the expected. It is calculated by multiplying the standard deviation from the dataset by 1.96, this gives the window in which 95% of all data is expected to fall within [19]. The equation below details how SA is calculated, where stdev is the standard deviation of the dataset (Equation 2).

$$SystemAccuracy = 100 - (stdev * 1.96) \tag{2}$$

Results and Discussion

Protocol A - Sitting Tests

A total of 15 tests were performed across all participants. The average test accuracy for each participant was calculated and can be seen in Table 2. The average test accuracy across all participants was 100.56 ± 1.32%. Of the five participants, two recorded 100% for every test with the overall accuracy being brought down by a single participant: participant 4 with a 101.55% accuracy. Here too it was one case affecting the accuracy with a miscount of 2 breaths whilst the other tests scored 100%.

P1	P2	P3	P4	P5	Overall
100.72 ±1.25	100 ±0.00	100 ±0.00	101.55 ±2.68	100.55 ±0.95	100.56 ±1.32

Table 2. Test accuracy per participant, and overall, for Protocol A.

All participant data was then combined into a single dataset for the LoA analysis, giving a result for Protocol A as a whole. The previous paragraph established average accuracy as 100.56%, with LoA calculating that 95% of all data fell within the window (Figure 3). The total system accuracy for this protocol was calculated to be 97.36%, showing the sensors ability to detect the respiration of the wearer whilst sitting.

Protocol B - Lying Tests

A total of 60 trials were performed across all participants. The average test accuracy for each participant can be found in Table 3, giving an average accuracy across all participants as 98.6 ± 2.90%.

P1	P2	P3	P4	P5	Overall
98.79 ±2.82	100.18 ±2.63	98.69 ±2.67	98.84 ±2.12	96.51 ±2.98	98.60 ±2.90

Table 3. Test accuracy per participant, and overall, for Protocol B.

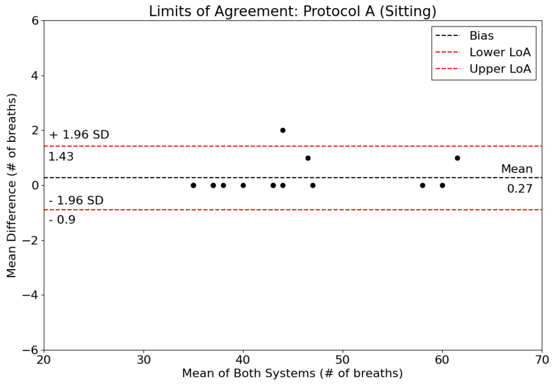

Figure 3. Limits of Agreement: Protocol A.

Left	Right	Front	Back
98.89 ±3.16	99.26 ±1.97	97.37 ±3.53	98.88 ±2.34

Table 4. Test accuracy per positions (Protocol B).

All Protocol B data was combined into a single dataset so that LoA analysis could carried out (Figure 4. In addition to the accuracy of 98.88% determined previously, it showed the confidence window to be -3.00 to 1.80, leading to a system accuracy for this protocol of 94.20%.

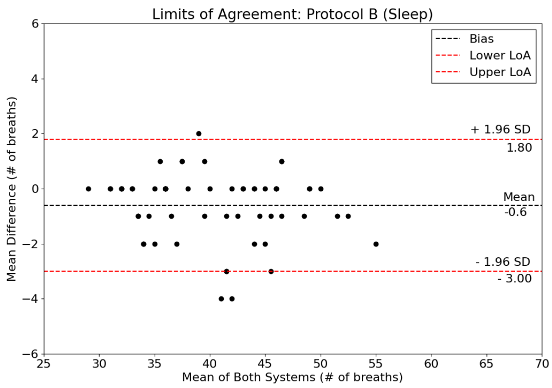

Figure 4. Limits of Agreement: Protocol B

Pose Detection: The opportunity was taken during Protocol B to validate the systems ability to recognise the wearers position. The attached electronics contains a 3-axis IMU from which the direction of gravity can be determined and hence position predicted. The data from this protocol was processed alongside the position of the wearer. The outcome is that all four poses were successfully recognised at 100% thus validating the systems ability to detect pose.

Total System Performance

To get a single number for how the system performed across all tests and participants, all tests from all protocols were combined into a single dataset for complete LoA analysis (Figure 5). Doing so showed a total test accuracy of 100.2 ± 2.91% alongside a confidence window of -2.73 to 1.88, giving an overall system accuracy of 94.30%.

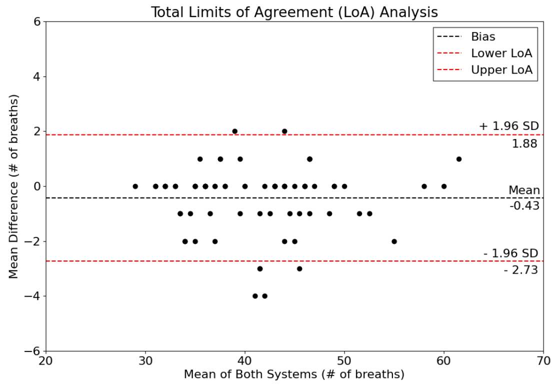

Figure 5. Limits of Agreement: Respiration Band

Conclusions

An individuals respiration offers unparalleled insights, whether that be in the monitoring and improving of their fitness, or for understanding and diagnosing various health conditions. In recent years a wide variety of different respiration monitoring technologies and techniques have been developed to try and gain access to these parameters with varying levels of success and adoption. Despite their ever-increasing use, widespread adoption of respiration monitoring, outside of clinical environments particularly, has not yet been achieved. Footfalls have designed a comfortable textile Respiration Band validated for data collection at home and whilst sleeping. The Band alongside Footfalls' proprietary algorithms have been proven to recognise breaths of the wearer, allowing for the calculation of accurate respiration rate and the reliable recognition of breathing irregularities.

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