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Laboratory Validation of Hexoskin Biometric Shirt at Rest, Submaximal Exercise, and Maximal Exercise While Riding a Stationary Bicycle

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Abstract

Objective: Evaluate Hexoskin performance on a stationary bike against ‘gold standard’ laboratory equipment and develop adjustment models for future use in field settings.

Methods: Compared respiratory rate (RR), tidal volume (V_T), minute ventilation (V_E), and heart rate (HR) measured by the Hexoskin shirt to simultaneous spirometry and full 12-lead electrocardiogram during a laboratory based incremental exercise test on a stationary bicycle.

Results: Data from 17 participants demonstrated Hexoskin V_T and V_E had the best agreement in the submaximal exercise level (discrepancies ≤5.3%) with larger discrepancies observed at rest (≤15.3%) and at maximal exercise level (≤11.7%). The discrepancies for HR and RR were lower at all levels (<10%). Adjusting for sex and body weight allowed for a single V_E algorithm across the entire range of effort ($r^2 = 0.89$).

Conclusion: These discrepancies are acceptable for field use in comparison to the ranges typical of bicycle commuting.

Keywords

Biomonitoring; Personal Exposure; Inhalation Exposure; Minute Ventilation; Validation

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Conflict of Interest
All authors report no conflict of interest

Introduction

Given the variability in how much air humans breathe throughout a day, the ability to reliably measure minute ventilation in the field in cohort studies would provide a breakthrough in personal exposure assessment techniques. Advances in wearable technology allow for reliable lower cost field measurements, provided the technology performs well when validated against gold standard equipment in a laboratory setting. The Hexoskin Biometric shirt (Carré Technologies Inc., Montreal, Québec, Canada) is a compression shirt with built-in cardiac and breathing sensors as well as a 3-axis accelerometer. The sensors sit around the thorax and abdomen and continuously measure heart rate (HR), respiratory rate (RR), tidal volume (V_T), and minute ventilation (V_E). The shirt also measures electrocardiography via a five-lead ECG, but this function was not evaluated as part of the current study. Proper validation of the shirt will allow its credible use in health-related field studies.

Minute ventilation, a product of RR (breaths per minute) and V_T (L per inspiration), is the volume of air an individual inhales in one minute (L/min). The ability to measure both V_E and the concentration of air pollutants in the breathing zone (C_Z) continuously during various activities allows for the calculation of potential inhaled dose (D_P) of pollution. This dose is considered ‘potential’ as the actual dose of any particle associated air pollutant is further impacted by physiological defense mechanisms. The ratio of nasal to mouth breathing is also a factor in evaluating actual inhaled dose. Low to moderate activities can elevate V_E by a factor of 2-3 above resting levels and vigorous exercise can increase V_E by more than an order of magnitude.[1] Due to physical activity, D_P can vary more than C_Z and should therefore be a better external exposure metric for dose response studies. This laboratory validation was done as part of our study entitled “Potential Inhaled Dose of Particulates, Biking, and Cardiovascular Indicators”, which aims to test the feasibility of measuring potential inhaled dose in a field setting and explore the association of acute cardiovascular outcomes associated with short-term exposure from riding a bicycle to work in New York City.

In order to directly measure V_E while riding a bicycle outside, an expensive and cumbersome flow meter with a mouth piece or mask is needed. To avoid this burden, three proxy measurements have been suggested for estimating V_E in field settings: accelerometry,[1] heart rate,[2,3] and measurements via dual channel respiratory inductance plethysmography (RIP) sensors.[4,5] Of the three methods, the RIP is considered to be more accurate since it calculates V_E from estimates of RR and V_T.[5] An advantage of the Hexoskin shirt is that it contains built-in sensors for all three methods. The shirt also allows for continuous monitoring periods without disrupting daily life activities, as the shirt is easily worn under clothing.

A prior validation study of the Hexoskin shirt by Villar et al. (2015) was conducted while lying, sitting, standing, and walking,[6] but not for riding a bicycle or other activities that reach peak exercise. Villar et al. (2015) were able to assess good agreement, consistency, and low variability for heart rate and respiratory rate measurements, but were unable to properly validate V_T and V_E measurements as arbitrary units were used. The prior validation effort of Villar et al. (2015) was completed before the shirt's manufacturer developed refined algorithms for unit-based measurements of V_T (liter) and V_E (liters per minute).

A more recent validation of the Hexoskin shirt utilized the refined-unit based algorithms for V_E on ten elite male cyclists.[7] The shirt was found to be valid and reliable for HR and V_E at moderate intensity of exercise (50 and 75% work rate maximum (Watts)) based on the standard error of the estimate and Pearson correlation coefficient.[7] Authors did caution use at higher intensity due to lower validity.[7] Cherif et al found similar results in a maximal exercise test on a treadmill involving 28 healthy participants.[8] HR and RR showed high concordance correlation coefficient, significant intraclass correlation coefficient, and good, tight agreement based on Bland-Altman analysis.[8] However, V_E showed more variability and weaker correlation coefficients and noted difference between males and females likely due to differences between the male and female shirts.[8]

As bicycle are used in cities by commuters and occupational riders (i.e. bicycle messengers and food deliver), there is a growing interest in looking at the potential inhaled dose of pollutants instead of simply concentrations. Having a low-cost wearable shirt to measure minute ventilation and heart rate will be beneficial to numerous field and occupational studies. The purpose of the current study was to evaluate the shirt's performance against a "gold standard" laboratory method at rest and during an incremental exercise test on a stationary bicycle for healthy but non-elite males and females. Additionally, the goal of the study is to evaluate the shirt for field use on healthy, non-elite bicycle commuters and develop potential models both across intensity and at select intensity levels to better fit the data, specifically the V_E data.

Methods

Study Population

We conducted a pilot trial of 19 participants recruited from New York City to test the Hexoskin Biometric Shirt against the spirometry and 12-lead electrocardiogram (ECG) in the Human Performance Laboratory at Columbia University Medical Center. This study was part of a larger feasibility study on potential inhaled dose and cardiovascular indicators (NIEHS R21 ES024734) and participants were recruited based on its criteria. Participants were eligible if their regular bicycle commute to work was at least 30 minutes one-way, they were not a current smoker, and they were not on any blood pressure related medication. Participants signed an informed consent in accordance with the Columbia University Human Subjects Review Board. Participants were dropped from the study if resting hemodynamic or cardiovascular instability was seen at any time during the procedure.[9]

Hexoskin Biometric Shirt

The compression shirt contains cardiac and respiratory sensors in their built-in thoracic and abdominal bands (Figure 1). The shirt is commercially sold and each sensor does not require nor allow calibration. There are slight differences in the women's and men's shirt. The thoracic band in the women's shirt is built into the lower band of the built-in sports bra and the abdominal band is built right into the main fabric. For the men's shirt, both thoracic and abdominal bands are built into the main fabric. The cardiac sensors are analog ECG recording at 256 Hz and the respiratory sensors are dual channel respiratory inductance plethysmography (RIP) sensors recording at 128 Hz. The shirts' data logger module includes a 3-axis accelerometer recording at 64 Hz. Measurements of HR, RR, V_T, and V_E were used for analysis. HR was detected from the ECG and recorded every second in units of beats per minute (bpm). The RR was recorded every second in units of breaths per minutes (bpm). The measured inspiration and expiration values were used to derive the V_T (L). Average V_T, respiratory rate, and the individual's body weight were used to derive V_E (L/min), but the company's proprietary algorithm was not released to the public (including researchers).

Procedure

Participants were first trained on the equipment and overall protocol for the field portion of the study. During the training, participants were initially fitted for the Hexoskin shirt based on the sizing chart provided by the manufacturer, and then study staff checked the fit. The physiology laboratory metabolic cart and ECG (Vmax Encore Metabolic Cart, Care Fusion, Palm Springs, CA) were used to compare the sensors at rest and during incremental exercise on a stationary bicycle. A Care fusion breath-by-breath flow sensor was used to measure RR, V_T, V_E and 12-lead ECG recorded HR (Cardiosoft v 6.7, GE healthcare, Fairfield, CT). The VMAX encore metabolic system measures breath-by-breath data via a low-resistance mass thermal flow meter. Dual flow and gas calibration were performed prior to each test. The system estimates ventilatory variables by temperature and pressure differentials and flow rate across the coils of the flow meter. The 12-lead ECG calculates heart rate from the R-R interval. Manual blood pressures were also taken every 1-2 minutes to monitor participant for safety during testing (Welch Allen, Skaneateles Falls, NY).

The exercise protocol started with five minutes of rest, while seated on the stationary bicycle, followed by three minutes of warm-up at a self-selected cadence level. Women performed a 20-30 watt ramp protocol and men performed a 30-50 watt ramp protocol. Ramping was based on normal predicted values and self-reported physical activity (i.e. people who were also recreational athletes had a steeper ramp than those who only bike commuted at a leisurely pace), with the goal of achieving a peak VO_2 within 8-12 mins from the onset of exercise.[10] The workload increased until volition or peak HR was achieved. Good effort was determined by a respiratory exchange ratio of > 1.0, peak HR > 85%, plateau of oxygen utilization <2.1 ml/kg/min and perceived exertion level of >7 by modified borg 0-10 scale. Exercise was followed by a three minute of cool down and five minutes of rest.

Equipment was matched based on timestamp for analysis. Each monitor was synchronized to time.is prior to the exercise test (https://time.is).

Data Analysis

To evaluate the Hexoskin sensors, Hexoskin data and Vmax data were compared on the basis of slopes, r^2, root mean square error (RMSE), percent discrepancy, Bland-Altman analysis, and coefficient of variation (CV). The one-second recordings from the Hexoskin shirt were matched to the corresponding breath recordings from the Vmax system based on the second of exhalation. Once matched, one minute averages for the Hexoskin shirt and Vmax system were analyzed across all levels of effort to determine best fit linear regressions for males and females. Processing was identical between Vmax and Hexoskin with the exception of variable names and the need to convert Hexoskin V_E from mL to L.

A model was developed to illustrate how adjustments could be made for Hexoskin data collected in the field for participants not measured in the laboratory, based on the slopes and intercepts of one-minutes averages from the laboratory validation across all levels of effort. The model was based on simple linear regression and adjusted for body weight (kg) and sex (Male = 1; Female = 0), as they were the significant covariates.

$$Vmax\, V_E = \beta_0 + \beta_1(hexoskin\, V_E) + \beta_2(Weight) + \beta_3(Sex) + \varepsilon \quad \text{(Equation 1)}$$

Initial analysis of Pearson correlation was measured for each metric at rest, at submaximal exercise, and at maximal exercise. Resting analysis utilized the 3rd and 4th minutes of the beginning resting period to ensure proper acclimation time to the equipment. Sub maximum (SM) was defined as the minute before reaching the anaerobic threshold as most bike commuter will not reach their anaerobic threshold during their commute.[2] Individual anaerobic threshold was identified based on 75% of the maximal heart rate.[11] Maximal (M) exercise was analyzed based on the last minute of exercise to ensure analysis for a full spectrum of exercise.

Mean HR, RR, V_T, and V_E at each stage were analyzed using simple linear regression (t-test) on a significance level 5% with limits of two standard deviations. Discrepancy percentage was calculated by the percent difference between the Hexoskin shirt and Vmax system. Coefficient of variation (CV = (SD/mean) × 100) was analyzed to assess the within-participant variability of the measurements. A Bland-Altman test with alpha = 0.05 was used to assess agreement[12] between the Hexoskin shirt and the gold standard laboratory data.

In an effort to decrease discrepancy, additional analysis was conducted to develop a predictive model for Vmax system V_T and V_E recordings based on collected Hexoskin and Vmax data at each level. The model was based on simple linear regression and adjusted for body weight (kg).

$$Vmax\, V_T = \beta_0 + \beta_1(hexoskin\, V_T) + \beta_2(Weight) + \varepsilon \quad \text{(Equation 2)}$$

$$Vmax\, V_E = \beta_0 + \beta_1(hexoskin\, V_E) + \beta_2(Weight) + \varepsilon \quad \text{(Equation 3)}$$

Statistical analysis was performed using R (version 3.3.2).

Results

Participants

Nineteen participants (13 males and 6 females) were trained and tested in the physiology laboratory (Table 1). Excluded based on cardiovascular status or equipment failure result in a sample size of 17 for RR, V_T, and V_E. See supplement for details.

The occasional failure of the shirt to properly record heart rate is visibly evident when plotting heart rate over time. Supplemental Digital Content Figure S1a provides an example of a proper heart rate recording, and figure S1b is an example of a faulty heart rate recording warranting exclusion. Failure to record respiratory data is evident by continuous zero recordings for RR, V_T, and V_E, indicating a broken RIP sensor.

Minute Ventilation

To visualize the linear regression line for each individual, one minute averages of minute ventilation recordings for all effort levels were plotted (Figure 2). Individual R^2 ranged from 0.60 to 0.99, with more variability observed for females (0.60 – 0.99) than males (0.80 – 0.99). Mean slope for females and male were similar (1.07 and 1.03, respectively), but females observed a wider range (0.73 – 1.54) than males (0.84 – 1.19). A simple linear regression model was developed based on these one minute averages and adjusted for body weight and sex (Equation 1). Root mean square error of the predictive model was 9.8. The Vmax system and Hexoskin observed ranges for each effort level are presented in Table 2. Percent discrepancies for the unadjusted RIP sensors and the adjusted model (Equation 1) can be found in Table 3.

Hexoskin to Vmax correlation for V_E was highest at maximal effort ($R= 0.85$, $p<0.01$), followed by submaximal effort ($R= 0.81$, $p<0.01$), and rest ($R= 0.49$, $p=0.048$) (Figure 3). When stratified by sex, only males at rest were significantly different on a level of significance of 5% ($p = 0.05$). The discrepancy was highest at rest and lowest at SM (Table 2).

The Bland-Altman agreement between the Hexoskin shirt and Vmax system was 1.97± 4.18 L/min at rest, 2.3± 14.6 L/min at submaximal, and 11.6 ± 31.6 L/min at maximal efforts (Figure 3). The coefficient of variation for Hexoskin minute ventilation recordings is less than Vmax at rest and submaximal exercise (Table 2).

Linear models (Equation 3) were also used to predict V_E Vmax measurements using Hexoskin measurements and adjusting for body weight at both rest and maximal levels. The predictive values generated from the model resulted in mean discrepancy less than 1%. At rest, discrepancy was −0.74% ± 8.4%, and at maximal, discrepancy was −0.52% ± 8.71%. Root mean square error was 1.09 L/min at rest and 8.16 L/min at maximal. Average maximal V_E measured by the Vmax system was 99.35 L/min (range 66.7 – 145.6 L/min).

Times series plots were created for each participant spanning the duration of the test. Select plots comparing times series of Hexoskin V_E, Vmax V_E, and predictive V_E (equation 1) can be found in the supplemental digital content figure S2. Notable differences can be seen in two female participants (BIKE2002 and BIKE2004) for minute ventilation with the differences growing over time. As previously mentioned, these participants likely had poor agreement due to ill-fitting shirts. On the other hand, some participants such as these two males (BIKE1009 and BIKE1010) appear to have near prefect alignment through the duration of the test.

Heart Rate

Heart rate was initially analyzed with all participants (n=18). At all effort levels, the Hexoskin had moderate correlation with lab data (rest R= 0.41, p<0.01; SM R= 0.55, p<0.01; M R= 0.62, p<0.01) and weak coefficient of determinations (rest R^2 0.17; SM R^2= 0.31; M R^2= 0.39).

Analysis was then conducted excluding three participants with visibly irregular recordings (Supplemental Digital Content Figure 1b). Once exclusions were made, correlation coefficient improved across all three levels (rest R= 0.99, R^2 = 0.98, p<0.01; SM R=0.91, R^2= 0.83, p<0.01; M R= 0.90, R^2= 0.80, p<0.01) (Supplemental Digital Content Figure S3). The exclusion of those three resulted in good agreement at all three levels (rest: 1± 3 bpm, SM: 4± 8 bpm, and M: 4± 17 bpm) (Supplemental Digital Content Figure S3).

For student's t-test, heart rate measured by the Hexoskin shirt was only significantly different in men at rest (p = 0.017) and SM (p = 0.004). Discrepancy for HR was highest at submaximal effort and lowest at rest (Table 2). Coefficients of variation were lower for the Hexoskin compared to Vmax at rest and submaximal levels (Table 2).

Respiratory Rate

Correlations of participant level data was best at the submaximal level (R=0.95, p<0.01), followed by max (R=0.88, p<0.01) and resting (R=0.84, p<0.01) (Supplemental Digital Content Figure S4). The coefficient of determination for resting (R^2= 0.71), submaximal (R^2= 0.91), and max (R^2= 0.78) were strong as well (Supplemental Digital Content Figure S4). The coefficient of variation was lower for Hexoskin measurement compared to Vmax measurements at all three levels (Table 2).

The Hexoskin respiratory rate recordings were in agreement with the Vmax system at rest, submaximal, and maximal exercise levels. The mean difference was 2 breaths or less for each level (1 ± 3 breaths during rest, 1± 3 breaths during submaximal, and 2±7 breaths during maximal exercise) (Supplemental Digital Content Figure S4).

For student's t-test, respiratory rate measured by the Hexoskin shirt was only significantly different in men at rest (p < 0.01) compared to the Vmax system. Discrepancy percentage was highest at rest and lowest at SM (Table 2).

Tidal Volume

Correlation for V_T was highest at SM (R=0.92 p <0.01), followed by M (R=0.82 p<0.01), and rest (R=0.69 p < 0.01) (Supplemental Digital Content Figure S5). For both females and males, the differences between Hexoskin V_T measurements and Vmax V_T measurements was not statistically different during any level at a significance level of 5%. For V_T the discrepancy was highest at maximal and lowest at submaximal effort (Table 2).

Based on Bland Altman analysis, average difference at rest was 0.049 ±0.391 L, at SM 0.139 ±0.784 L, and at M 0.313 ±0.960 L (Supplemental Digital Content Figure S5). The CV for tidal volume was higher for Hexoskin compared to Vmax at all three levels (Table 2).

A linear model to predict Vmax measurements was developed using Hexoskin measurements and adjusting for body weight. Models were developed using Equation 2 for both rest and maximal levels. Predictive values generated from the level specific models resulted in mean discrepancy less than 1%. At rest, discrepancy was −0.24% ± 10.9%, and at M, discrepancy was −0.81% ± 10.7%. Root mean square error was 0.091 at rest and 0.322 at M. Models at submaximal effort were not needed as no covariate yielded a significant model.

To observe the linear regression of each individual over the duration of the test, one minute averages of tidal volume recordings were compared on an individual basis (Supplemental Digital Content Figure S6). Except for one participant, all participants had high coefficients of determinations with $R^2 > 0.69$ (Supplemental Digital Content Table S2). We are unable to explain why one participant had anomalous data but suspect the shirt moved during one part of the test.

Discussion

Hexoskin vs Vmax system

Comparing individual participants (6 females and 11 males) across all effort levels showed the range in individual V_E slopes for females to be nearly twice as large as males, primarily due to shirts fitting men better. Adjusting for sex and body weight allowed for a single regression across all effort levels ($r^2 = 0.89$) with a RMSE of 9.8 L/min.

Comparing across subjects allowed us to evaluate sensor performance as a function of effort. The discrepancy between the Hexoskin and Vmax system for RR and HR was less than 10% at all three levels, which indicates similarity between the Hexoskin shirt and the Vmax system. These findings support previous validation studies.[6,7,8] For V_T, discrepancy at rest and sub maximal effort (SM) was less than 10% and discrepancy at M was 11.2%. Discrepancy for V_E was less than 10% at SM, and 11.7% at M and 15.3% at rest. These findings demonstrate resting data has the greatest level of discrepancy and submaximal exercise the lowest. While possible, it is unlikely for bicycle commuters to reach maximal exercise during their ride and, by definition, they cannot maintain it for an extended period of time. Additionally, based on a Dutch study,[2] a majority of bicycle commuters do not treat their commutes as an intense workout, but rather as a simple means of transportation. Therefore, minute ventilation during bicycle commuting is likely to fall within the submaximal level, when the Hexoskin shirt agreed best with the laboratory measurements. Additionally, the application of correction factors and cleaning the raw data to remove obviously erroneous data artifacts greatly improved the agreement between measurements.

The agreements between the gold standard measurements and the Hexoskin shirt for minute ventilation and tidal volume were greater than 10% at rest and maximal effort. However, the application of the effort level-specific correction factor reduced the discrepancy to < 1% (equation 3). A discrepancy of ≤3% between two measures of volume is considered acceptable.[13] To further decrease discrepancy for V_T and V_E, linear predictive models were developed to predict Vmax measurements based on Hexoskin measurement and body weight. Using these models to predict V_T and V_E may improve accuracy of Hexoskin measurements, bearing in mind model was based on 17 participants. If effort in the field cannot be specifically categorized, but is in a submaximal to maximal effort range, a linear predictive model across all effort levels should be used to adjust Hexoskin values (equation 1). Adjustments based on equation 1 lowered the percent discrepancies at the 50, 75, and 90% quantile of measured V_E (Table 3). Observed V_E in those quantiles ranged from 37.1 to 86.3 L/min, which is an expected range of V_E experienced during bicycle commuting[2,3,14]. Applying this adjustment model to bicycle commuting activities, or other activities within said range, will yield more accurate values. Improving the overall fit of the shirt on an individual may also improve measurements.

The CV for both Hexoskin and Vmax systems for HR recordings were similar and low. For RR, V_T, and V_E there was more variation. The differences in the CV between Hexoskin and Vmax reflect the different modes of measuring ventilation. The breath-by-breath measurement of data by the Vmax captures smaller breathes or swallows that the Hexoskin is less likely to register. These coughs, swallows or small breathes lend way to greater CV, particularly in the RR. Likewise, the Hexoskin mistakes shifts in the shirt for tidal volume changes which would cause a greater CV. As V_E is a product of these factors, it also influences the CV.

Comparison to EPA Reference Values

In the absence of field V_E measurements, reference values have been used.[15,16,17] The EPA reference values for estimated V_E are based on the average adult male weighing 70 kg.[14] Reference value for cycling at submaximal exercise is estimated at 40 L/min, and cycling at maximal exercise is estimated at 85 L/min. For comparison, average submaximal V_E measured by the Vmax system was 45.3 L/min (range 28.5 – 65.2 L/min) and maximal V_E was 99.35 L/min (range 66.7 – 145.6 L/min). If EPA reference values for submaximal and maximal exercise were used in the cross-activity level predictive model (equation 1), the RMSE would increase from 9.8 to 22.1 L/min. If EPA reference values were to be used in the predictive model for minute ventilation at maximal exercise (equation 3), the RMSE would increase from 8.16 to 26.0 L/min. We therefore conclude that the Hexoskin approach substantially outperforms standard reference values.

Issues with HR data and Shirt Fit

The failure to properly record heart rate throughout exercise may be related to improperly fitting shirts causing the sensors to be further away from the skin than needed. The cardiac sensors are covered with textile electrodes that need to be in direct contact with skin to properly record heart rate. Those excluded for improper heart rate measurements were still able to obtain reasonable RR, V_T, and V_E recordings due to utilization of different sensors.

The shirt contains three cardiac sensors as highlighted in blue in Figure 1a. The respiratory sensors are two continuous bands across the thorax and abdominal as highlighted in Figure 1b. The circumferential bands may be less prone to improperly fitting shirts or shirt movement as recordings do not rely on direct contact with textile electrodes. The textile electrodes are visible on the inside of the Hexoskin where they cover the three cardiac sensors (Figure 1c and d).

Improvements are needed in fitting the shirts to women's figures. The greatest variability in agreement between measures were seen in women. Only two of the six females had discrepancy less than 10%. The lower agreement in women may be due to varying thorax to navel proportions, making it more difficult for the shirt to fit properly. Women's thorax to navel ratio tends to vary greater than man, and larger differences between the thorax and navel may result in more error. Improvement in shirt fit was seen when the study personnel selected the appropriate sized shirt, rather than allowing the participant to self-select as they might select a larger size if they prefer to wear looser clothing. It is important the shirt is snug throughout the torso, but not too tight to overstress the RIP bands. Using a dot of glycerin-based cream on the cardiac textile electrodes is recommended by Hexoskin to improve the conductivity of the textile electrodes thereby decreasing the noise seen on the ECG.

Potential Adjustments and Calibrations

The Hexoskin shirt has overall low variability. This is evident by low CV and high individual R^2 values (Table 2) when one minute averages are compared over the duration of the test. The Hexoskin shirt is sufficient in tracking the temporal patterns as the minute ventilation recordings increase and decrease over time in regards to changing activity. The discrepancies are driven by inaccurately measuring the magnitude of the recordings, especially at rest and maximal efforts. Given the low variability, Hexoskin values have the potential of being more valid if adjusted by a factor involving the ratio between navel and thorax measurement or using the models previously stated (Equation 1, 2, & 3).

Calibration of the Hexoskin shirt with a spirometer may also be useful in improving results. LifeShirt, another wearable data recording textile, found agreement to improve when a spirometer was used for calibration.[18] Ventilation results from the LifeShirt were considered acceptable for a constant low-level work rate and an incremental exercise test as the greatest mean difference was 9.5%.[18] An increase in difference was also noted as exercise intensity increased, and the shirt's performance at higher exercise intensities was questioned.[18] As shown in Table 2, the Hexoskin shirt also experiences an increase in difference as exercise intensity increased. Unlike the Hexoskin shirt, the LifeShirt has been described as difficult and confusing to use.[19] Goodrich and Orr (2009), doubted the successful use of the LifeShirt at home without the help of trained technicians due to its difficulty. The easy use of the Hexoskin shirt provides an improvement over the LifeShirt in field studies. As both shirts utilize a respiratory inductive plethysmography, calibration with a spirometer may also be useful in improving Hexoskin agreement.

Calculating V_E from HR

In addition to the Hexoskin shirt's wearability, the presence of the dual channel RIP sensors, cardiac sensors, and accelerometer, allow for three V_E metrics. If the dual channel RIP sensors fail to record data, as seen in one participant during the laboratory validation, V_E can be estimated based on heart rate recordings or accelerometer activity. More information on this attribute of the Hexoskin shirt will be provided in another paper focusing on the field data in our commuter feasibility pilot.

While V_E can be calculated from the HR recordings, use of the dual channel RIP is preferred as it provides the lowest mean discrepancy from the 'gold standard' Vmax system and lowest RMSE (Table 3). A calculated V_E derived from an algorithm based on HR introduces an extra layer of generalization and error. Based on collected data, we derived an algorithm to calculate V_E across all activity levels from HR for use when the dual channel RIP sensors fail (Equation 4).

$$Predicted\ V_E = 3.1 + -0.088(hexoskin\ HR) + 0.0034(hexoskin\ HR)^2 \quad \text{(Equation 4)}$$

An overall equation is used for field settings due to the rapid changes in physical exertion while biking in the city. The laboratory setting allowed for a smooth transition from rest to submax to max but biking in a city involves more stopping and going due to traffic lights and stop signs.

Given the small sample size consisting of healthy bicycle commuters, external validity is limited. Sample size was majority male with there being twice as many as females. The small sample size is also a weakness in fitting models and deriving a correction factor.

Conclusions

In conclusion, the Hexoskin biometric shirt is suitable for measuring respiratory rate and heart rate at rest, submaximal exercise, and maximal exercise when excluding improper recordings without adjustment models as discrepancy was below 10%. The shirt is also suitable for measuring tidal volume at rest and submaximal exercise, and minute ventilation at submaximal exercise based on their low mean discrepancies. Our overarching conclusion is the Hexoskin shirt comprises a reasonable tool for measuring minute ventilation, but careful inspection of data is necessary, and some data loss is to be expected. When artifacts were removed, data from all participants demonstrated Hexoskin V_T and V_E had the best agreement in the submaximal exercise level (discrepancies $\leq 5.3\%$) with larger discrepancies observed at rest ($\leq 15.3\%$) and at maximal exercise level ($\leq 11.7\%$). Given effort during biking commuting ranges from the submaximal to maximal effort range and can change rapidly, an overall adjustment equation (equation 1) is recommended to increase accuracy of measured V_E during field measurements. In conclusion, the Hexoskin sensors capture data with errors and precision acceptable for most field studies given the range in minute ventilation observed for healthy recreationally active people.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Rodes CE, Chillrud SN, Haskell WL, Intille SS, Albinali F, Rosenberger ME. Predicting adult pulmonary ventilation volume and wearing compliance by on-board accelerometry during personal level exposure assessments. Atmospheric Environment. 2012; 57: 126–137. [PubMed: 24065872]
2. Zuurbier M, Hoek G, van den Hazel P, Brunekreef B. Minute ventilation of cyclists, car and bus passengers: an experimental study. Environmental Health. 2009; 8: 48. [PubMed: 19860870]
3. Cozza IC, Zanetta DMT, Fernandes FLA, da Rocha FMM, de Andre PA, Garcia MLB et al. An approach to using heart rate monitoring to estimate the ventilation and load of air pollution exposure. Science of the Total Environment. 2015; 520: 160–167 [PubMed: 25813969]
4. Carry PY, Baconnier P, Eberhand A, Cotte P, Benchetrit G. Evaluation of respiratory inductive plethysmography: Accuracy for analysis of respiratory waveforms. Chest. 1997; 111(4): 910–915. [PubMed: 9106568]
5. Fiamma MN, Samara Z, Baconnier P, Similowski T, Straus C. Respiratory inductive plethysmography to assess respiratory variability and complexity in humans. Respiratory Physiology & Neurobiology. 2007; 156(2): 234–239. [PubMed: 17251070]
6. Villar R, Beltrame T, Hughson RL. Validation of the Hexoskin wearable vest during lying, sitting, standing, and walking activities. Applied Physiology, Nutrition, & Metabolism. 2015; 40(10): 1019–1024.
7. Elliot CA, Hamlin MJ, Lizamore CA. Validity and reliability of the Hexoskin wearable biometric vest during maximal aerobic power testing in elite cyclists. Journal of Strength and Conditioning Research. 2017.
8. Cherif NH, Mezghani N, Gaudreault N, Ouakrim Y, Mouzoune I, Boulay P. Physiological Data Validation of the Hexoskin Smart Textile. BIODEVICES. 2018; 1: 150–156.
9. “ATS/ACCP Statement on Cardiopulmonary Exercise Testing.” American Journal of Respiratory and Critical Care Medicine. 2003; 167(2): 211–277. [PubMed: 12524257]
10. Hansen JE, Sue DY, Wasserman K. Predicted values for clinical exercise testing. American Review of Respiratory Disease. 1984; 129(2): S49–S55. [PubMed: 6421218]
11. Soucie LP, Carey C, Woodend AK, Tang ASL. Correlation of the Heart Rate-Minute Ventilation Relationship with Clinical Data: Relevance to Rate-Adaptive Pacing. Pacing and clinical electrophysiology. 1997; 20: 1913–1918. [PubMed: 9272528]
12. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet. 1986; 1(8476): 307–310. [PubMed: 2868172]
13. Wanger J, Clausen JL, Coates A, Pedersen OF, Brusasco V, Burgos F et al. Standardisation of the measurement of lung volumes. European Respiratory Journal. 2005; 26: 511–522. [PubMed: 16135736]
14. U.S. EPA. Exposure Factors Handbook 2011 Edition (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011.
15. de Nazelle A, Rodriguez DA, Crawford-Brown D. The built environment and health: Impacts of pedestrian-friendly designs on air pollution. Science of The Total Environment. 2009; 407(8): 2525–2535. [PubMed: 19201451]
16. Rojas-Rueda D, de Nazelle A, Tainio M, Nieuwenhuijsen MJ. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ. 2011; 343 :d4521. [PubMed: 21816732]

17. Tainio M, de Nazelle AJ, Gotschi T, Kahlmeier S, Rojas-Rueda D, Nieuwenhuijsen et al. Can air pollution negate the health benefits of cycling and walking? Preventive Medicine. 2016; 87: 233–236. [PubMed: 27156248]

18. Kent L, O'Neill B, Davison G, Nevill A, ELborn JS, Bradley JM. Validity and reliability of cardiorespiratory measurements recorded by the LifeShirt during exercise tests. Respiratory Physiology and Neurobiology. 2009; 167(2): 162–167. [PubMed: 19505672]

19. Goodrich S, Orr W. An investigation of the validity of the LifeShirt in comparison to standard polysomnography in the detection of obstructive sleep apnea. Sleep Medicine. 2009; 10(1): 118–122. [PubMed: 18083629]

Figure 1.
a) Cardiac sensors of the Hexoskin shirt; b) respiratory sensors of the Hexoskin shirt; c) Front inside view of the Hexoskin shirt; d) close up of the textile electrodes around the cardiac sensors.

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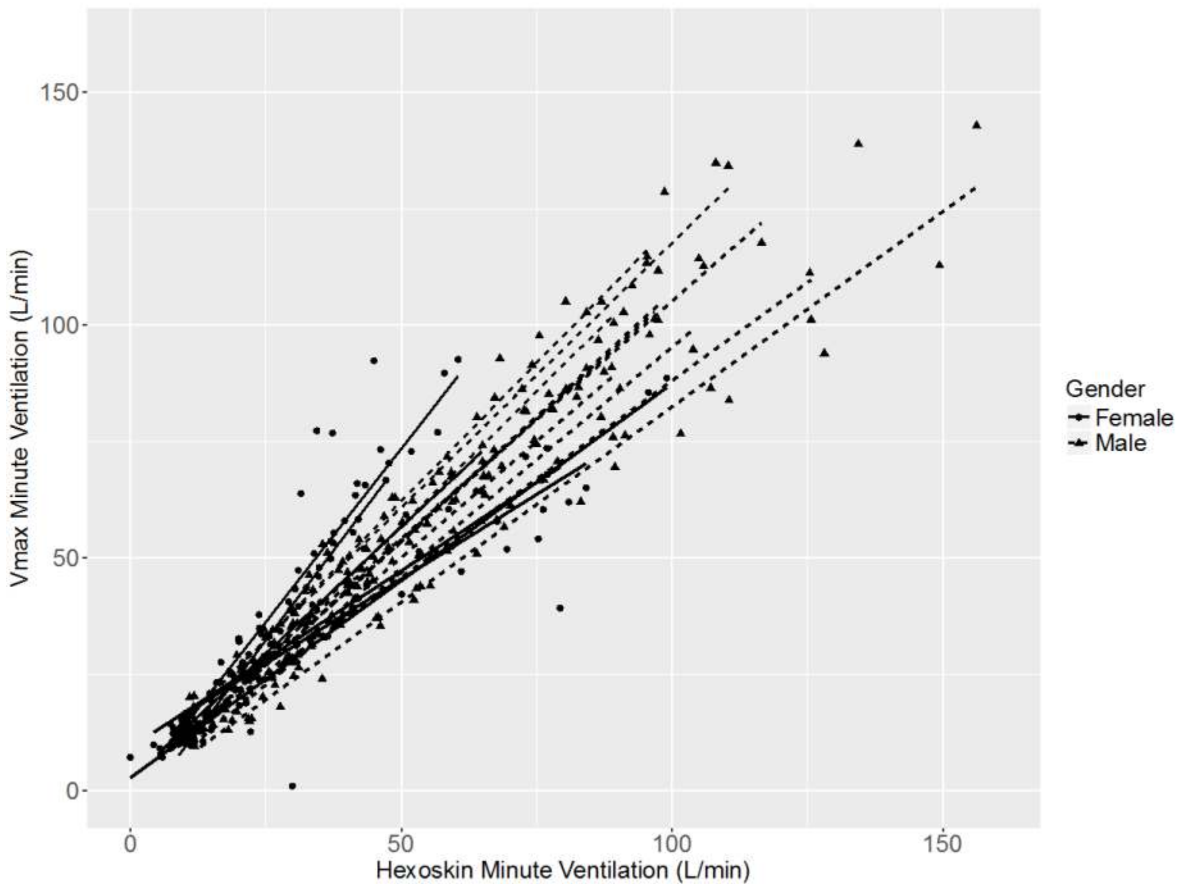

Figure 2.

Scatterplot and linear regression lines of each participant for comparison of Hexoskin V_E recordings to Vmax V_E recordings. Combined $R^2 = 0.88$.

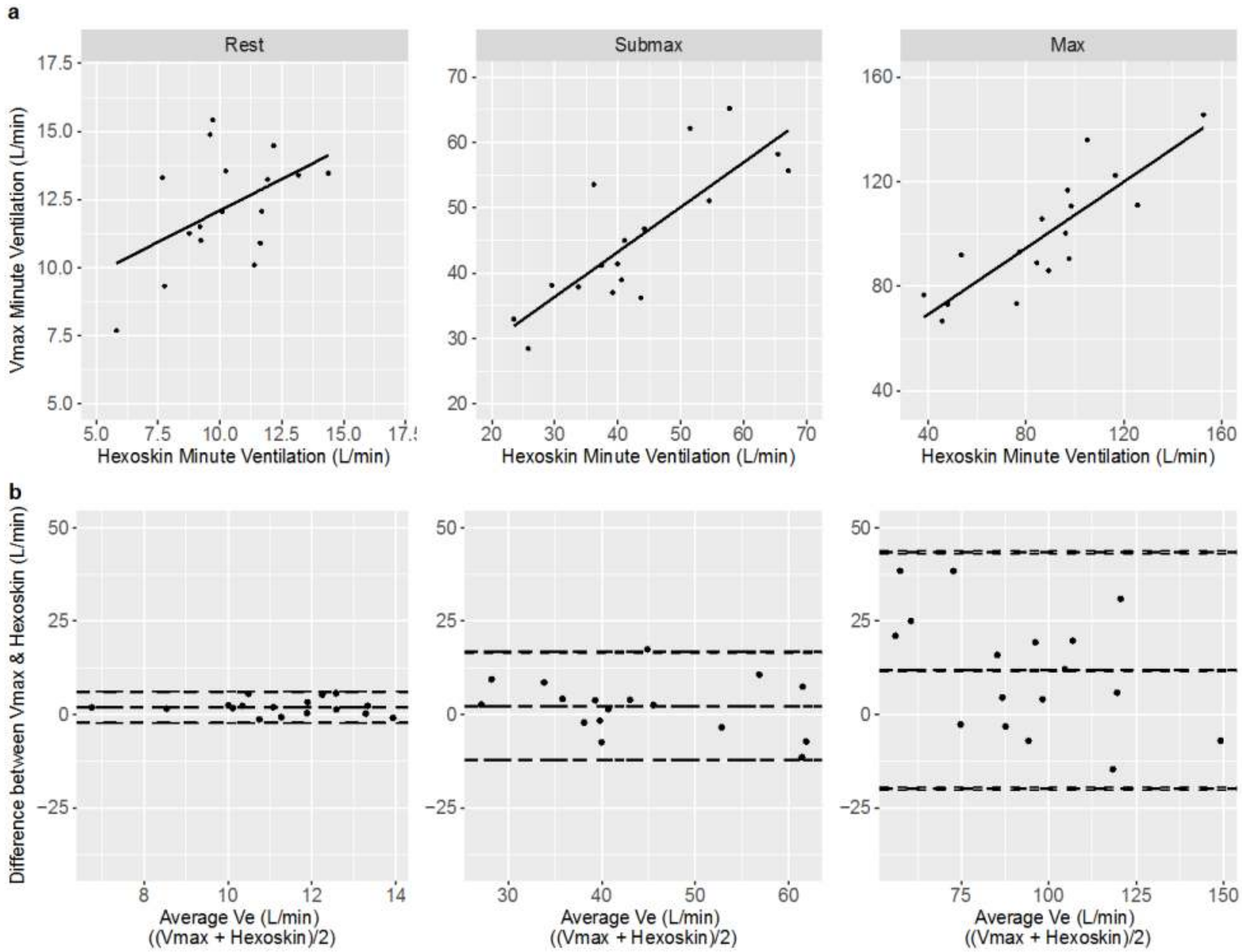

Figure 3.

a) Scatter plot and fitted regression lines for V_E at rest, submaximal, and maximal exercise (n=17). Resting R = 0.49; submaximal R = 0.81; maximal R = 0.85. b) Bland Altman plots of V_E at rest, SM, and M exercise. Resting mean difference = 1.97± 4.2 L/min, SM mean difference = 2.3± 14.6 L/min, and M mean difference 11.6 ± 31.6 L/min.

Table 1.

Participant anthropometrics and demographics

	Height (m)	Body Weight (kg)	BMI (kg/m^2)	Age (years)
Females (n= 6)	1.60	62.1	24	36.2
Males (n=12)	1.79	75.2	23.6	37.2
Total (n= 18)	1.73	70.8	23.7	36.7

Table 2.

Mean, SD, Range, and Coefficient of Variation measured by Vmax and Hexoskin. Correlation and Discrepancy Percentage between Hexoskin and Vmax.

	Vmax Mean	Vmax SD	Vmax Range	Hexoskin Mean	Hexoskin SD	Hexoskin Range	Pearson Correlation r (p – value)	Discrepancy Mean % (SD)	Hexoskin Mean CV	Vmax Mean CV
HR (beats per minute)										
Rest	71	10.1	49 - 83	72	10.0	51 - 84	0.99 (<0.01)	−1.34 (2.0)	4.1	4.2
SM	128	9.9	112 - 150	131	9.0	119 - 150	0.91 (<0.01)	−2.9 (2.4)	2.1	2.5
M	175	12.4	155 - 202	171	18.0	120 - 199	0.90 (<0.01)	2.4 (5.7)	2.3	1.8
RR (breaths per minute)										
Rest	17	2.2	12 - 21	16	2.6	11 - 19	0.84 (<0.01)	8.6 (8.5)	12.5	26
SM	25	5.7	14 - 35	24	5.5	14 - 33	0.95 (<0.01)	3.5 (6.8)	7.3	14
M	38	7.6	28 - 51	36	7.2	25 - 50	0.88 (<0.01)	3.8 (9.3)	9.6	10.2
V_T *(L per inspiration)*										
Rest	0.759	0.179	0.465 - 1.115	0.710	0.274	0.328 – 1.341	0.92 (<0.01)	7.3 (23)	42	38
SM	1.997	0.871	1.004 - 4.838	1.951	0.823	0.897 – 4.261	0.82 (<0.01)	1.63 (18.3)	17.1	15.7
M	2.739	0.821	1.492 - 4.429	2.562	0.793	1.099 – 3.990	0.69 (<0.01)	11.2 (17.6)	14	7.6
V_E *(L per min)*										
Rest	12.2	2.1	7.7 - 15.4	10.3	2.16	5.8 – 14.4	0.49 (0.05)	15.3 (15.6)	12.4	27
SM	45	10.7	29 – 65	43	12.7	24 – 67	0.81 (<0.01)	5.3 (15.5)	7.5	11.4
M	99	22	67 – 146	88	30	38 – 153	0.85 (<0.01)	11.7 (18.3)	10.3	7.5

Abbreviations: HR, Heart Rate; RR, Respiratory Rate; V_T, Tidal Volume; V_E, Minute Ventilation; SM, submaximal exercise; M, maximal exercise; CV, Coefficient of Variation.

Table 3.

Discrepancy and RMSE between Vmax V_E and Hexoskin V_E proxies

Hexoskin V_E proxies	**10% Quantile**	**25% Quantile**	**50% Quantile**	**75% Quantile**	**90% Quantile**	**Mean**	**RMSE**
Dual Band RIP (Discrepancy (%))	−18.7	−3.8	10.6	21.6	31.0	7.8	10.7
Eq. 1 *Model Adjusted Dual Band RIP (Discrepancy (%))*	−35.4	−18.3	−1.4	9.4	19.0	−16	9.8
HR-VE Calculation (Discrepancy (%))	−62.0	−27.7	−0.89	14.7	23.7	−15.8	14.5
For Reference: Vmax V_E (L/min)	11.8	17.5	37.1	62.0	86.3	43.7	-

Abbreviations: RMSE, root-mean-square error; V_E, Minute Ventilation