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Activity Monitoring and Energy Expenditure in COPD Patients: A Validation Study

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Abstract

There is increasing interest in the objective measurement of physical activity in chronic obstructive pulmonary disease (COPD) patients due to the close relationship between physical activity level, health, disability and mortality. We aimed to (a) determine the validity and reproducibility of an activity monitor that integrates accelerometry with multiple physiologic sensors in the determination of energy expenditure in COPD subjects and (b) to document the independent contribution of the additional physiologic sensors to accelerometry measures in improving true energy expenditure determination. Eight subjects (4 male, FEV₁ 56.4 ± 14.1%, RV 145.0 ± 75.7%) performed 2 separate 6-minute walk and 2 incremental shuttle walk exercise tests. Energy expenditure was calculated during each exercise test using the physiologic activity monitor and compared to a validated exhaled breath metabolic system. Test-retest reproducibility of physiologic activity monitor during the walking tests was comparable to an exhaled breath metabolic system. Physiologic sensor data significantly improved the explained variance in energy expenditure determination ($r^2 = 0.88$) compared to accelerometry data alone ($r^2 = 0.68$). This physiologic activity monitor provides a valid and reproducible estimate of energy expenditure during slow to moderate paced walking in a laboratory setting and represents an objective method to assess activity in COPD subjects.

Keywords

Energy Expenditure; COPD; Ambulatory Monitoring; Exercise Test; Activities Of Daily Living

INTRODUCTION

Research interest in therapeutics for chronic obstructive pulmonary disease (COPD) is reflected by a plethora of new pharmacologic and device interventions stimulated by a growing understanding of the pathophysiology of the disease (1). Unfortunately, these therapeutic advances are hindered by a lack of consensus on the best outcome measure to use in trials of such therapies (2). Traditional physiologic variables, such as FEV₁, only modestly account for the variability in maximal exercise oxygen consumption (3), explain less than 10% of the variance in the quality of life (4) and are poor predictors of survival. Further, the impact of interventions, such as new disease modifying biologicals, which may decrease exacerbation frequency or other systemic disease manifestations, may not be

reflected in simple measures of expiratory flow. Indeed, recent studies support the superiority of multidimensional tools in assessing long-term outcome (5). For patients, the impairment in daily functional performance is one of the most significant aspects of COPD.

As such, there is increasing interest in the use of both subjective and objective measures of this “free-living” functional performance (6, 7). For example, the 6-minute walk (8) is a popular objective surrogate because of its simplicity, correlation with dyspnea, functional status (9) and quality of life (10), and its responsiveness to a wide variety of interventions (11). However, even laboratory-based exercise tests are only indirect surrogates of “free-living” functional performance and only capture limited aspects of the disease’s overall impact (5).

As a result, there is growing interest in functional performance assessment by direct, objective measurement of “free-living” physical activity. Several methods have been described which are cumbersome, inaccurate or expensive. The gold-standard, a radio-isotope methodology, is costly, technically difficult and only determines cumulative energy expenditure (EE) over a 1–2 week period and cannot assess patterns of physical activity. Conversely, the simplest method, pedometers, though reasonably accurate in normal subjects (12), can suffer from the inability to accurately measure body movement during non-walking activities or slow walking (13), particularly relevant in debilitated COPD patients.

Recently, multi-axis accelerometers have gained acceptance as reproducible (14) and valid measures of EE in the laboratory setting in normal (15), elderly (16) and COPD subjects (17). They have also been validated in the “free-living” setting compared to activity diaries (18), radio-isotope methods (15, 18) and indirect calorimetry (19) in both normal and COPD (17) subjects. However, individual error in EE determination is still significant and has encouraged advances in software modeling (19) and hardware methods [e.g. additional sensors] to improve accuracy (20).

A recently engineered, portable physiologic activity monitor (PAM), the SenseWear Pro Armband, (BodyMedia Inc., Pittsburgh, PA) was designed to improve EE prediction by integrating accelerometry with multiple physiologic sensors including galvanic skin resistance, heat flux, body temperature and near-body ambient temperature. Because the device is so unobtrusive, it holds promise as a practical measure of “free-living” EE. Indeed, preliminary studies of normal subjects (21) and diabetics (22) suggest this device reproducibly and accurately predicts resting and active EE. However, before the device can be reliably used in the field, it needs to be studied under controlled conditions in COPD subjects who are generally more impaired than the subjects previously studied, and who may demonstrate a disproportionate contribution of respiratory muscles to EE that may not be captured by accelerometers. Finally, the degree to which the physiologic sensors augment the accuracy of this device compared to accelerometry alone is unknown.

Thus, in this report, we have (a) documented the validity and reproducibility of the physiologic activity monitor (PAM) in the determination of energy expenditure (EE) in COPD subjects and (b) determined the independent contribution of the additional physiologic sensors to accelerometry measures in improving true EE determination.

METHODS

Subjects and study design

Eight subjects with stable, non-oxygen requiring COPD were recruited from the Emphysema Research Registry at the University of Pittsburgh. The protocol was approved

by the institutional review board of the University of Pittsburgh and written informed consent was obtained from all subjects. Subjects completed pulmonary function testing (23), two 6-minute walk (6 MW) tests, and two incremental shuttle walk (ISW) tests (30 minutes apart) on 2 days in random order within 10 days.

Walk testing

The 6 MW was performed on a straight track (150 feet/lap) in accordance to American Thoracic Society guidelines (8). The ISW was performed on a 10 m oval course according to published guidelines (24). In this test, an audio signal guides the subject's walking pace which linearly increases each minute. Subjects continue without encouragement until they are no longer able to maintain the required pace.

EE was measured during all walk tests simultaneously using the PAM and a portable exhaled breath (EE-BXB) metabolic device.

EE using the physiologic activity monitor (EE-PAM)

The PAM used in this study (SenseWear Pro ArmBand, BodyMedia Inc., Pittsburgh, PA) is an advanced, lightweight (82 grams) microprocessor-based device that is worn over the right triceps which records data from a 2-axis micro-electromechanical accelerometer, a galvanic skin resistance sensor, a heat flux sensor, a skin temperature sensor and a near-body ambient temperature sensor. The device was allowed to equilibrate to body temperature for at least 20 minutes prior to all walk tests.

The data from the device was later downloaded to a dedicated software package (InnerView Research Software v.2.2, BodyMedia Inc.), which uses a proprietary multiple non-linear regression equation to predict minute-by-minute EE from the accelerometry data, physiologic sensors and demographic information. In order to assess the relative contribution of the accelerometer and the physiologic sensors, we extracted the accelerometry channel output (longitudinal (x) and transverse (y) axis) to calculate the cumulative vector magnitude units (VMU) using the following formula: $VMU = \sqrt{x^2 + y^2}$.

EE using standard exhaled breath metabolic system (EE-BXB)

We used a lightweight, validated (25), portable telemetric system to collect metabolic data on a breath-by-breath (BxB) basis during all tests (V_{MAXST} , Sensormedics Corp.). This system utilizes a turbine digital volume transducer, an electrochemical O_2 -analyzer and an infrared CO_2 -analyzer. Two-point gas calibration and volume calibration were completed prior to each walk test.

Data collected during the walk tests included oxygen consumption (VO_2), carbon dioxide production (VCO_2), heart rate, respiratory rate and tidal volume. Data were averaged over 1 minute interval. EE-BXB was derived using the included metabolic data software package (Metasoft v.1.11.2, Cortex Biophysik), which utilizes Weir's abbreviated equation ($3.94 * VO_2 + 1.11 * VCO_2$) (26).

Statistical analysis

Baseline data are summarized as mean $\pm$ standard deviation (SD). Reproducibility was assessed using the intra-class correlation coefficient. Comparison of cumulative EE measurements between methods was made using Pearson's correlation coefficient. Differences in cumulative and minute-by-minute EE measurements between PAM and BXB methods were tested using a mixed model approach with subject effects as random. A Bland and Altman analysis was used to identify the differences between EE-PAM and EE-BXB at

different levels of EE. All data were analyzed using a commercial software package (STATA v.8; Stata Corp., College Station, TX).

RESULTS

Subject characteristics

Subject characteristics are summarized in Table 1. We studied 8 subjects (4 male) with mild-to-severe COPD.

Reproducibility

Test-retest reproducibility of EE-PAM between the 1st and 2nd ISW tests (intra-class $r = 0.84$) and the 1st and 2nd 6 MW tests (intra-class $r = 0.86$) was very good and comparable to the reproducibility of the BXB system (intra-class $r = 0.90$).

Validity

Cumulative EE and minute-by-minute EE were compared. Cumulative EE-PAM during the 2nd 6 MW and 2nd ISW was highly correlated with cumulative EE-BXB ($r = 0.93$, $p < 0.001$) (Figure 1). However, EE-PAM underestimated EE as measured by the BXB system by 9.4% (-2.8 ± 4.3 kcal, $p = 0.03$). The underestimation was greater for the 6 MW tests (-15.5% , -4.6 ± 4.7 kcal, $p = 0.03$) than for the ISW tests (-4.7% , -1.4 ± 3.6 kcal, $p = 0.34$). The minute-by-minute EE measurements were compared using data from both the 1st and 2nd walks. This revealed that the PAM generally tracked EE during both the ISW and 6 MW (Figure 2).

This underestimation of EE by the PAM was most evident at an EE-BXB > 5 kcal/min, corresponding to a walking speed of approximately 4.5 feet/sec. Throughout the 6 MW, subjects maintained an average walking speed close to this (4.22 ± 0.09 feet/second). Conversely, during the ISW, subjects only reached or exceeded 4.5 feet/second after the first 6 minutes of the test.

The difference between EE-PAM and EE-BXB compared to the EE-BXB revealed underestimation of EE using the EE-PAM at higher levels of EE when measured on a minute-by-minute basis (slope coefficient = -0.29 , $p < 0.001$) (Figure 3) or on a cumulative basis (slope coefficient = -0.20 , $p = 0.03$).

Predictive value of additional physiologic sensors

The accelerometer data was extracted from the EE-PAM data channels and converted to cumulative vector magnitude units. This information accounted for significantly less (F test, $p = 0.08$) of the variability in cumulative EE-BXB ($r^2 = 0.66$) as compared to the EE derived from the PAM software, which integrates accelerometer data with the physiologic sensor data ($r^2 = 0.86$) (Figure 1).

DISCUSSION

This study, previously reported in abstract form (27), demonstrates that an activity monitor incorporating multiple physiologic sensors with accelerometry provides highly reproducible estimates of EE during walking tests in subjects with COPD. Further, we found these measurements to be valid compared to a standard exhaled breath metabolic system at walking speeds expected during the daily activities of subjects with COPD.

We measured within-day reproducibility using two walk tests performed 30 minutes apart. As a result, the reported reproducibility estimates (based upon serial tests) are likely

conservatively low, since they also incorporate biological variability and variation due to the learning effect of serial walk tests (24, 28, 29), in addition to measurement error. Thus, the measurement error due to the PAM is best indicated by comparing the reproducibility of EE-PAM to that of the EE-BXB. Indeed, we show that the PAM was highly reproducible compared to the BXB system.

We assessed the validity of EE determination using cumulative and minute-by-minute measurements. The PAM underestimated cumulative EE by 9.4% compared to the BXB system. The minute-by-minute measurements revealed that this bias was attributable to EE underestimation at greater metabolic levels (Figure 3). In particular, EE-PAM underestimated EE-BXB by 13.6% at levels above 5 kcal/min but only by 1.3% at levels below 5 kcal/min. This conditional underestimation explains the difference in accuracy of cumulative EE during 6 MW compared to the ISW: During the 6 MW, subjects maintained a constant walk speed and had a metabolic demand above 5 kcal/min for two-thirds of the test (from minutes 3–6); in contrast, the ISW, due to its incremental nature, only elicited that metabolic demand for one-quarter of the test (7th and 8th minutes). However, since 5 kcal/min corresponded to a brisk walking speed of approximately 2.9 miles/hr, not typically encountered during daily activities, the PAM should be very accurate at walking speeds expected during normal daily activities of COPD patients.

This underestimation is not surprising given that some subjects with moderate to severe COPD have been demonstrated to have increased resting and total daily EE and a greater oxygen consumption for a given workload compared to normal subjects (30). This can be attributed to reductions in skeletal muscle efficiency (31) and a higher work of breathing at a given level of ventilation likely not captured by accelerometers. The difficulty in capturing the activity of the respiratory muscles by accelerometers in order to predict EE was also suggested in a previous report in a COPD population (17). The latter supports the finding of lower explanation of the variance of EE with respect to the accelerometer of the PAM ($R^2 = 0.66$) compared to previous reports in non-COPD populations (adolescents and children) in which the R^2 were in the range of 0.72–0.82 (32, 33). Thus, incorporation of disease-specific prediction models into the analysis software may be necessary to reduce error in EE determination, particularly at higher metabolic workloads. Indeed, a similar approach improved EE prediction using this PAM in patients with cardiac disease (34).

The current gold-standard for measuring EE uses a radioisotope methodology which *directly* captures cumulative EE over a 1–2 week period but is unable to assess patterns and intensity of physical activity (35). In contrast, measures of physical movement per se, such as pedometers and accelerometers, can measure patterns and intensity of physical activity, but only *indirectly* reflect EE through device-specific regression equations (14). Indeed, this leads to significant errors in individual determination of “free-living” EE even in normal (36) and healthy elderly subjects (37).

This error is due to a number of factors: (a) individual variability in mechanical and metabolic efficiency, (b) non-linearity in the relationship of acceleration and EE (36), (c) creation of a single prediction equation in a pooled manner across diverse types of activities (21), and (d) the inability to estimate EE during activities which are poorly reflected solely by accelerometer activity, such as walking on an incline or cycling (36). As such, investigators have used advanced software approaches, such as non-linear (19), patient-specific (38) and activity-specific prediction equations (21), or hardware approaches, such as additional physiologic sensors, to improve EE determination (20, 39, 40). The SenseWear Pro Armband PAM incorporates both a non-linear modeling approach as well as multiple physiologic sensors to improve EE measurement.

The PAM in this study has previously been validated in normal subjects (21, 41, 42) and we have additionally documented its reproducibility and accuracy in COPD subjects. However, we further demonstrated that either the PAM proprietary software modeling or (most likely) the additional sensors improved significantly the explained variance in EE determination compared to the accelerometer data alone, from 68% to 88%. Indeed, the responsibility of the additional sensors for the improved EE variance is biologically plausible since the galvanic skin resistance (43), heat flux (44) and body temperature sensors (43) reflect physiologic surrogates of EE which are independent of bodily movement. However, no prior publication has suggested that the data collected by the physiologic sensors significantly may reduce the error in EE compared to accelerometry alone, in either normal or diseased subjects. This improvement in measurement accuracy likely due to the additional sensors may account for previous reports of improved accuracy of the PAM over a broader range of exercise intensities (42) and during activities such as upper arm exercise and cycling (21, 41), which are reported to be less accurately measured using accelerometers alone (36).

The current study, by validating the accuracy and reproducibility of the PAM in a controlled laboratory setting, is an essential first step prior to applying this technology to the assessment of “free-living” EE measurement in COPD patients. Finally, we recognize that this group of moderate-to-severe COPD patients may not represent the entire spectrum of disease severity, particularly with respect to the very disabled or the very mild patients. Given the emerging interest in the use of activity monitoring in the assessment of outcome across the broad spectrum of disease, there will be a need for larger studies to confirm these findings in patient subgroups. Also, we recognize that the use of the doubly labeled water (DLW) method, the gold standard for EE measurement, would have been ideal, but was not be feasible in this study. The relatively high price of the oxygen-18 water, the need for mass spectrometer instrumentation, and the high level of technical expertise required has limited its widespread application in clinical research.

CONCLUSION

This activity monitor is a reproducible and accurate measure of EE during slow-to-moderate paced walking in a laboratory setting in subjects with COPD and moderate functional limitation. This PAM has potential as a meaningful outcome assessment tool for clinical trials of established and novel therapeutic interventions aiming to improve functional performance in COPD subjects.

References

1. Barnes PJ. New treatments for COPD. *Nature Rev Drug Discov.* 2002; 1(6):437–446. [PubMed: 12119745]
2. Croxton TL, Weinmann GG, Senior RM, Hoidal JR. Future research directions in chronic obstructive pulmonary disease. *Amer J Respir Crit Care Med.* 2002; 165(6):838–844.
3. Mahler DA, Harver A. Prediction of peak oxygen consumption in obstructive airway disease. *Med Sci Sports Exer.* 1988; 20(6):574–578.
4. Jones PW, Quirk FH, Baveystock CM, Littlejohns P. A self-complete measure of health status for chronic airflow limitation. *St George's Respir Question Amer Rev Respir Dis.* 1992; 145(6):1321–1327.
5. Celli BR, Cote CG, Marin JM, et al. The body-mass index, air-flow obstruction, dyspnea, and exercise capacity index in chronic obstructive pulmonary disease. *New Engl J Med.* 2004; 350(10): 1005–1012. see comment. [PubMed: 14999112]
6. Patel SA, Sciurba FC. Emerging concepts in outcome assessment for COPD clinical trials. *Sem Respir Crit Care Med.* 2005; 26(2):253–262.

7. Pitta F, Troosters T, Probst VS, Spruit MA, Decramer M, Gosselink R. Quantifying physical activity in daily life with questionnaires and motion sensors in COPD. *Eur Respir J*. 2006; 27(5):1040–1055. [PubMed: 16707399]
8. ATS statement. Guidelines for the six-minute walk test. *Amer J Respir Crit Care Med*. 2002; 166(1): 111–117. [PubMed: 12091180]
9. Carter R, Holiday DB, Grothues C, Nwasuruba C, Stocks J, Tjep B. Criterion validity of the Duke Activity Status Index for assessing functional capacity in patients with chronic obstructive pulmonary disease. *J Cardiopul Rehab*. 2002; 22(4):298–308.
10. Guyatt GH, Thompson PJ, Berman LB, et al. How should we measure function in patients with chronic heart and lung disease? *J Chron Dis*. 1985; 38(6):517–524. [PubMed: 4008592]
11. Solway S, Brooks D, Lacasse Y, Thomas S. A qualitative systematic overview of the measurement properties of functional walk tests used in the cardiorespiratory domain. *Chest*. 2001; 119(1):256–270. [PubMed: 11157613]
12. Tudor-Locke C, Ainsworth BE, Thompson RW, Matthews CE. Comparison of pedometer and accelerometer measures of free-living physical activity. *Med Sci Sports Exer*. 2002; 34(12):2045–2051.
13. Le Masurier GC, Tudor-Locke C. Comparison of pedometer and accelerometer accuracy under controlled conditions. *Med Sci Sports Exer*. 2003; 35(5):867–871.
14. Bouten CV, Westerterp KR, Verduin M, Janssen JD. Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Med Sci Sports Exer*. 1994; 26(12):1516–1523.
15. Bouten CV, Verboeket-van de Venne WP, Westerterp KR, Verduin M, Janssen JD. Daily physical activity assessment: comparison between movement registration and doubly labeled water. *J Appl Physiol*. 1996; 81(2):1019–1026. [PubMed: 8872675]
16. Kochersberger G, McConnell E, Kuchibhatla MN, Pieper C. The reliability, validity, and stability of a measure of physical activity in the elderly. *Arch Phys Med Rehabil*. 1996; 77(8):793–795. [PubMed: 8702373]
17. Steele BG, Holt L, Belza B, Ferris S, Lakshminaryan S, Buchner DM. Quantitating physical activity in COPD using a triaxial accelerometer. *Chest*. 2000; 117(5):1359–1367. [PubMed: 10807823]
18. Starling RD, Matthews DE, Ades PA, Poehlman ET. Assessment of physical activity in older individuals: a doubly labeled water study. *J Appl Physiol*. 1999; 86(6):2090–2096. erratum appears in *J Appl Physiol* 2001 May;90(5):following table of contents. [PubMed: 10368377]
19. Chen KY, Sun M. Improving energy expenditure estimation by using a triaxial accelerometer. *J Appl Physiol*. 1997; 83(6):2112–2122. [PubMed: 9390989]
20. Moon JK, Butte NF. Combined heart rate and activity improve estimates of oxygen consumption and carbon dioxide production rates. *J Appl Physiol*. 1996; 81(4):1754–1761. [PubMed: 8904596]
21. Jakicic JM, Marcus M, Gallagher KI, et al. Evaluation of the SenseWear Pro Armband to assess energy expenditure during exercise. *Med Sci Sports Exer*. 2004; 36(5):897–904.
22. Mignault D, St-Onge M, Karelis AD, Allison DB, Rabasa-Lhoret R. Evaluation of the Portable HealthWear Armband: a device to measure total daily energy expenditure in free-living type 2 diabetic individuals. *Diabetes Care*. 2005; 28(1):225–227. [PubMed: 15616258]
23. Standardization of Spirometry, 1994 Update. American Thoracic Society. *American Journal of Respiratory & Critical Care Medicine*. 1995; 152(3):1107–1136. [PubMed: 7663792]
24. Singh SJ, Morgan MD, Scott S, Walters D, Hardman AE. Development of a shuttle walking test of disability in patients with chronic airways obstruction. *Thorax*. 1992; 47(12):1019–1024. [PubMed: 1494764]
25. Schulz H, Helle S, Heck H. The validity of the telemetric system CORTEX X1 in the ventilatory and gas exchange measurement during exercise. *Intern J Sports Med*. 1997; 18(6):454–457.
26. Weir JB. New methods for calculating metabolic rate with special reference to protein metabolism. 1949. *Nutrition*. 1990; 6(3):213–221. [PubMed: 2136000]
27. Patel SA, Sciruba FC. Validation of a wearable body monitoring device in COPD. *Am J Respir Crit Care Med*. 2004; 169:A771.

28. Sciruba F, Criner GJ, Lee SM, et al. Six-minute walk distance in chronic obstructive pulmonary disease: reproducibility and effect of walking course layout and length. *Am J Respir Crit Care Med.* 2003; 167(11):1522–1527. [PubMed: 12615634]
29. Singh S, Morgan MD. Activity monitors can detect brisk walking in patients with chronic obstructive pulmonary disease. *J Cardiopul Rehab.* 2001; 21(3):143–148.
30. Creutzberg EC, Schols AM, Bothmer-Quaedvlieg FC, Wouters EF. Prevalence of an elevated resting energy expenditure in patients with chronic obstructive pulmonary disease in relation to body composition and lung function. *Eur J Clin Nutr.* 1998; 52(6):396–401. [PubMed: 9683390]
31. Skeletal muscle dysfunction in chronic obstructive pulmonary disease. A statement of the American Thoracic Society and European Respiratory Society. *Am J Respir Crit Care Med.* 1999; 159(4 Pt 2):S1–40. [PubMed: 10194189]
32. Puyau MR, Adolph AL, Vohra FA, Zakeri I, Butte NF. Prediction of activity energy expenditure using accelerometers in children. *Med Sci Sports Exer.* 2004; 36(9):1625–1631.
33. Freedson PS, Melanson E, Sirard J. Calibration of the Computer Science and Applications, Inc. accelerometer. *Med Sci Sports Exer.* 1998; 30(5):777–781.
34. Cole PJ, LeMura LM, Klinger TA, Strohecker K, McConnell TR. Measuring energy expenditure in cardiac patients using the Body Media Armband versus indirect calorimetry. A validation study. *J Sports Med Phys Fitness.* 2004; 44(3):262–271. [PubMed: 15756165]
35. Schoeller DA, van Santen E. Measurement of energy expenditure in humans by doubly labeled water method. *J Appl Physiol Respir Environ Exer Physiol.* 1982; 53(4):955–959.
36. Jakicic JM, Winters C, Lagally K, Ho J, Robertson RJ, Wing RR. The accuracy of the TriTrac-R3D accelerometer to estimate energy expenditure. *Med Sci Sports Exer.* 1999; 31(5):747–754. see comment.
37. Fehling PC, Smith DL, Warner SE, Dalsky GP. Comparison of accelerometers with oxygen consumption in older adults during exercise. *Med Sci Sports Exer.* 1999; 31(1):171–175.
38. Levine J, Melanson EL, Westerterp KR, Hill JO. Tracmor system for measuring walking energy expenditure. *Eur J Clin Nutr.* 2003; 57(9):1176–1180. [PubMed: 12947439]
39. Luke A, Maki KC, Barkey N, Cooper R, McGee D. Simultaneous monitoring of heart rate and motion to assess energy expenditure. *Med Sci Sports Exer.* 1997; 29(1):144–148.
40. Eston RG, Rowlands AV, Ingledew DK. Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. *J Appl Physiol.* 1998; 84(1):362–371. [PubMed: 9451658]
41. Fruin ML, Rankin JW. Validity of a multi-sensor armband in estimating rest and exercise energy expenditure. *Med Sci Sports Exer.* 2004; 36(6):1063–1069.
42. King GA, Torres N, Potter C, Brooks TJ, Coleman KJ. Comparison of activity monitors to estimate energy cost of treadmill exercise. *Med Sci Sports Exer.* 2004; 36(7):1244–1251.
43. Saltin B, Gagge AP, Stolwijk JA. Body temperatures and sweating during thermal transients caused by exercise. *J Appl Physiol.* 1970; 28(3):318–327. [PubMed: 5414764]
44. Layton RP, Mints WH Jr, Annis JF, Rack MJ, Webb P. Calorimetry with heat flux transducers: comparison with a suit calorimeter. *J Appl Physiol Respir Environ Exer Physiol.* 1983; 54(5): 1361–1367.

Figure 1. (Left) Cumulative EE (kcal/min) during ISW (●) and 6 MW (□) tests measured by a physiologic activity monitor (EE-PAM) compared to an exhaled breath metabolic system (EE-BXB) ($r^2 = 0.86$, $p < 0.001$). (Right) Relationship of the accelerometry only data without physiologic sensors (VMU: vector magnitude units) from the physiologic activity monitor to exhaled breath metabolic system ($r^2 = 0.68$, $p < 0.001$).

Figure 2.

EE (kcal/min) measured by a physiologic activity monitor (—■—) vs. an exhaled breath metabolic system (—◆—) during ISW (*left panel*) and 6 MW tests (*right panel*). Bars represent standard errors. Walk speed (feet/second) (—) and accelerometer “only” output (vector magnitude units) (—■—).

Figure 3.

Kilocalorie difference between physiologic activity monitor (EE-PAM) compared to an exhaled breath metabolic system (EE-BXB). Data points are minute-by-minute values for both the 1st and 2nd ISW (●) and 1st and 2nd 6 MW (□) tests for all subjects.

Table 1**Subject characteristics (n = 8)**

Age (years)	61.5 ± 4.3
Weight (kilograms)	84.0 ± 19
Body mass index (kg/m ²)	30.2 ± 5.8
FEV ₁ (L) (range)	1.49 ± 0.37 (1.17–2.36)
FEV ₁ % predicted (range)	56.4 ± 14.1 (35–69)
FVC (L)	2.86 ± 0.72
FVC % predicted	79.8 ± 19.1
FEV ₁ /FVC	0.53 ± 0.12
RV (L)	2.93 ± 1.60
RV % predicted	145.0 ± 75.7
RV/TLC	0.48 ± 0.15
6 MW (meters) (range)	458.7 ± 73.1 (377–528)
ISW (meters) (range)	401.1 ± 121.2 (210–540)

FEV₁–forced expired volume in 1 second, FVC–forced vital capacity, RV–residual volume, TLC–total lung capacity, 6 MW–6-minute walk, ISW–incremental shuttle walk.