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Bodies in motion: Monitoring daily activity and exercise with motion sensors in people with chronic pulmonary disease

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Abstract—A primary goal of pulmonary rehabilitation is to improve health and life quality by encouraging participants to engage in exercise and to increase daily physical activity. The recent advent of motion sensors, including digital pedometers and accelerometers that measure motion as a continuous variable, have added precision to the measurement of free-living daily activity. Daily activity and exercise are variables of keen interest to proponents of the national health agenda, epidemiologists, clinical researchers, and rehabilitation interventionists. This paper summarizes issues related to conceptualizing and monitoring activity in the rehabilitation setting; reviews motion sensor methodology; compares motion-sensing devices; presents analysis issues and current and potential applications to the pulmonary rehabilitation setting; and gives practical applications and limitations.

Key words: accelerometer, daily activity, exercise, pedometer, pulmonary disease, pulmonary rehabilitation.

INTRODUCTION

In chronic pulmonary disease, dyspnea and deconditioning profoundly constrain physical activity and are known to produce, over time, spiraling losses in global functioning and life quality. Pulmonary rehabilitation, which includes graded exercise, strength and flexibility training, and collaborative self-management education, improves physical functioning and life quality and is now considered an integral component of optimal care for persons with severe lung disease [1,2]. It is likely that the most salient benefits of pulmonary rehabilitation come through program-related improvement in the ability to carry out daily physical activities, and in particular, to undertake the ubiquitous behavior of walking. The measurement of free-living physical activity and walking has recently been found to be particularly suited to devices that measure motion, such as accelerometers, which can objectively quantify even low levels of physical activity as a continuous variable and can detect subtle incremental changes as a result of intervention [3]. This article provides an overview of the potential utility of motion sensors to measure physical activity in persons with chronic pulmonary disease in the setting of pulmonary rehabilitation. We address the conceptualization of activity, exercise rehabilitation, motion sensing, comparison of motion sensors, methodological and analysis issues, applications to pulmonary rehabilitation, and practical considerations and limitations.

Abbreviations: COPD = chronic obstructive pulmonary disease, ICC = intraclass correlation coefficient, VMU = vector magnitude units.

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CONCEPTUAL DISTINCTIONS

For purposes of clarity, a number of conceptual distinctions should be made. First, exercise, such as those activities undertaken in a pulmonary rehabilitation program, is defined as the planned, structured, and repetitive bodily movement carried out to improve or maintain one or more aspects of physical fitness [4]. Daily physical activity, a variable only recently quantifiable, is the totality of voluntary movement, produced by skeletal muscles during everyday functioning [4]. Daily physical activity includes exercise. Because daily physical activity is both voluntary and community-based, the additional descriptor of "free-living" daily activity is often used. Tudor-Locke conceptualizes physical inactivity as a human behavior characterized by lack of participation in vigorous activities and minimal physical movement [5]. Persons who experience daily, incapacitating dyspnea due to chronic pulmonary illness fall readily into this group.

According to Webster's Dictionary [6], motion is defined as the act of moving the body or any of its parts; motion sensing is therefore the measurement of movement of the body, or in selected instances, depending on the location of the device, the movement of a body part, such as the arm or leg. While devices that measure motion of the body in toto or in one of its parts would seem to have strong face validity for characterizing daily physical activity measurement, this issue is less than clear, particularly in persons with very low levels of activity. For example, the issue of sensing extraneous motion that is not associated with voluntary movement and energy expenditure (arm movement without movement of the body, pendulous abdomen movement, and movement associated with car trips) may be responsible for considerable error variance.

MEASURING PHYSICAL ACTIVITY WITH MOTION SENSORS

Overview

Motion sensors in current use include pedometers and accelerometers. These devices may be used for purposes of surveillance, clinical, research, and program evaluation [7].

Surveillance

Motion sensors have been used to characterize population-based activity levels for the purposes of monitoring national physical activity levels and evaluating the attainment of physical activity recommendations, both at an individual and a population level [8,9].

Clinical Settings

Clinical uses of motion sensors include measurement of the processes and outcomes of programs in which exercise enhancement and increased daily activity are variables of interest [10]. Much work has been conducted with pedometers as a means to motivate clinical groups to exercise, including people with diabetes, obesity, and congestive heart failure [11–13].

Research and Program Evaluation

Apart from the research substantiating the validity, reliability, and stability of these devices in specific groups and settings, motion sensors have been used to measure adherence to experimental exercise protocols and relationships between free-living physical activity and other key variables, such as functional capacity, self-efficacy for walking, and health status [14,15]. Accelerometers are particularly useful in providing objective feedback of ambulatory activity (dose quantification) to investigators and to study participants in exercise adherence research. This is especially important for pulmonary patients, for whom precise quantification of walking during daily living is essential because small improvements due to effective treatment can often produce large gains in overall functioning. Motion sensor technology may also be used to evaluate and improve the quality of rehabilitation programs and program changes.

Motion Sensor Methodology

Traditional methods for measuring daily, free-living physical activity are imprecise and suffer from a number of problems. For example, methods that rely on self-report of activity and exercise, such as diaries and questionnaires, are both time-consuming and unreliable, especially for the elderly because they depend on memory [16,17]. Direct observation is time-intensive and intrusive. Other more reliable methods, such as radioisotope techniques using doubly labeled water, are technologically complex and expensive [18].

A wide array of motion sensors exists that has the potential to more precisely measure free-living daily physical activity in rehabilitation and other settings. The **Table** contains an overview of the types of devices, ranging from the simplest (least complex) to the most complex, with a

Table.
Comparison of activity monitors available in United States.

Type	Brand/ Manufacturers/ Price	Characteristics and Features	Physical Placement of Device	Strengths	Limitations	Populations Used in Validation Studies
Pedometer/ Step Counter	Yamax Digiwalker® (Yamax Inc., Tokyo, Japan; New Lifestyles, Inc., Kansas City, MO) (most often used in research) $20–$30 Many other brands, including Freestyle Pacer®, Eddie Bauer®, and Accusplit® $19–$30	Measures vertical accelerations at hip to count steps taken. Smaller than a pager, extremely light. LCD screen display. 4 models with variable programmable functions: steps, distance, calories, time. Uses photo/electronic battery with life up to 3 years. Has safety strap to prevent loss.	Waist	Displays cumulative data continuously. Useful as a motivational tool. Easy to use and unobtrusive. Least cost of any option. Good measure of walking activity.	Must remain vertical. Wearer must record output if daily activity data required.	Healthy adults
	StepWatch® (Prosthetics Research Study, Seattle, WA) $3300 for monitor, computer interface dock, and communication software	Measures step counts via a custom accelerometer with programmable filtering parameters adjusted for cadence and motion. Requires Mac computer, reader interface unit, and proprietary software. Pager-sized.	Ankle	Displays walking activity as time series. Allows long-term continuous recording of ambulatory function.	Expensive.	Adults with amputations Adults with chronic conditions affecting mobility
Uniaxial Accelerometers	Caltrac® (Muscle Dynamics, Torrance, CA, $70–$90	Measures vertical accelerations. Pager-sized. LCD screen display with updates every 2 min. Energy expenditure estimated by entering age, height, weight, and gender of wearer. Programmable modes for cycling and weight lifting. Runs on two AAA batteries.	Waist	Displays cumulative data continuously. Useful as a motivational tool. Low cost.	No time-series data, cannot show patterns of activity. Wearer must record output if daily activity data required.	Healthy adults Older adults Children
	Actigraph® (formerly CSA Actigraph) (MTI Health Services, Fort Walton Beach, FL) $1500 for monitor, interface unit, and software	Measures vertical accelerations. Analog filters reject frequencies outside range of normal human movement. Slightly smaller than pager. Programmable; requires PC, reader interface unit, and proprietary software. Memory up to 256 k. Data collection up to 22 days. Uses coin cell battery. Mainly used in research.	Waist Wrist Ankle	Collects time-series data; shows activity patterns. Output can be either activity counts or step counts. Count ranges for light, moderate, hard and very hard have been established. Calibration device available. Water resistant.	Discriminates change in speed but not grade. Higher cost. No feedback to wearer.	Healthy adults Adults who use wheelchairs

Table. (Continued)
Comparison of activity monitors available in United States.

Type	Brand/ Manufacturers/ Price	Characteristics and Features	Physical Placement of Device	Strengths	Limitations	Populations Used in Validation Studies
Multiaxial Accelerometers	RT3® Triaxial Research Tracker (replaced Tritrac®) (StayHealthy, Inc., Monrovia, CA) $500 for monitor and docking station CTI® Personal Calorie Tracker (available for personal/clinical use) $150	Measures 3 planes (vertical, horizontal, and sagittal); records as vector magnitude units. Pager size. Requires PC, docking station, and proprietary software that is downloadable through web site. Data collection up to 21 days. Reports activity units and energy expenditure. Has event marker. Uses two AAA batteries.	Waist	Sensitive to low levels of activity. Reflects intensity & frequency of activity. Collects time-series data; shows activity patterns. Output available as *x*, *y*, *z* axis plots, as well as a triaxial vector plot over time. Moderate cost.	Possible vibration artifact. No feedback to wearer.	No studies using RT3. Tritrac: Young adults Older adults Adults with multiple sclerosis Adults with COPD Children
	Mini-Motion Logger Actigraphs® (Ambulatory Monitoring, Ardsley, NY) $500–$2000/unit +$1200–$2600 for interface unit and software	Measures 3 planes. Analog filters reject frequencies outside range of normal human movement. Multiple models available from micro-mini (wristwatch size, less than 1 oz) to basic-mini (4×3 cm, 1.7 oz). Light sensor available. Multiple programmable parameters. Requires PC, reader interface unit and proprietary software. Memory size 32 to 128 k. Software programs for motor activity, sleep, and circadian rhythms. Data collection 16–30 days, depending on model. Lithium battery.	Wrist	Sensitive to low activity levels. Collects time-series data; shows activity patterns. Validated sleep estimation algorithm. Wrist placement is convenient and familiar.	Possible vibration artifact. Expensive. No feedback to wearer.	Healthy adults Women following coronary bypass surgery Older adults
	Actiwatch® (MiniMitter Company, Inc., Bend, OR) $1075 per unit + $1850 for reader and software	Measures 3 planes (“omnidirectional”). Watch size, 17 g wt. Programmable epoch length. Requires PC, reader interface unit, and proprietary software. Memory size 16 to 64 k. Software programs for motor activity, sleep, and circadian rhythms. Downloaded data can be displayed both graphically as actograms and numerically as activity counts. Data collection up to 44 days. Lithium battery.	Wrist	Sensitive to low activity levels. Collects time-series data, shows activity patterns. Validated sleep estimation algorithm. Very small and light. Wrist placement is convenient and familiar. Waterproof.	Possible vibration artifact. Expensive. No feedback to wearer.	Adults with Alzheimer’s disease Adults with cancer Children and infants

similar continuum from the least to the most expensive. They also vary on continuums of sensitivity to motion and degree of information available to participants. Selection of a motion sensor requires consideration of the strengths and features of the motion sensing device and the amount and type of data required. Practical issues include cost of the device, comfort and ease of wearing the device, and the need for computers or other accessories.

Reliability and validity of physical activity monitors are specific to the device, the population, and the activity behavior being studied. Accuracy/precision depends on how the device is constructed, as well as how it is used. Concurrent validity is most often established by assessing the degree of correlation with other activity measures (calorimetry, self-report, observation) or with indicators of known outcomes of activity (fitness, functional capacity, heart rate, VO_{2max}). Characteristics of the population under study may affect the accuracy of motion sensors. For example, older adults with limited mobility may move so slowly that the motion is not detected by the sensor. Finally, the specific activity behaviors of the individuals being monitored will affect the validity of activity measurement. Energy expenditure during static work (work done without movement) will not be measured by motion sensing technology.

As a measure of steps taken, electronic pedometers have demonstrated reasonable validity and high reliability. All pedometers tend to underestimate distance or steps for very slow walking [19,20]. This inaccuracy results from vertical movements at the hip being less pronounced at slow speeds and the sensor commonly failing to register some of them. A comparison of the accuracy of five electronic pedometers (Freestyle, Pacer, Eddie Bauer, Yamax, and Accusplit) for measuring distance walked found significant differences among models; the Yamax, Pacer, and Accusplit demonstrated the greatest accuracy [19]. The effects of walking speed were also examined, and the Yamax was found to be significantly more accurate than the Pacer and Eddie Bauer models at slow to moderate speeds. No significant differences were found at the fastest speed. We also assessed inter-unit reliability and found only the Yamax to be consistent between units. Other investigators have found similar variability among units due to differences in spring tension [20]. Step counts measured by the Yamax pedometer correlated only modestly with self-reported energy expenditure (r = 0.34–0.49) [20].

Studies exploring the validity of both uniaxial and multiaxial accelerometers as a measure of energy expenditure have substantiated significant correlations between the two (0.66–0.96) [20–22]. A major issue in the use of accelerometry for physical activity measurement is that the unit of measure (activity count, or vector magnitude units [VMU]) is not standardized, and no direct translation into energy expended exists. Several of the instruments include programs based on regression equations to calculate caloric expenditure; but differences in the accuracy of the calibration equations, rather than differences in the monitors themselves, have been shown to contribute to differences in recorded energy expenditure [23]. For research purposes, we recommend that motion sensor data be analyzed as counts [20].

Because uniaxial sensors track motion in the vertical plane only, they are not accurate for activities with static trunk movement, such as cycling and rowing [20]. The specific activities being performed also affect the accuracy of accelerometry for measuring energy expenditure. For example, the Tritrac accelerometer has been shown to overestimate the energy expenditure of walking and jogging and to underestimate the energy expenditure of stair climbing, stationary cycling, and arm ergometry [24]. Similarly, another study comparing three accelerometers and a pedometer for prediction of energy expenditure during moderate intensity activity suggested that all four motion sensing devices overpredicted energy expenditure during walking, but underpredicted energy expenditure in activities that included arm movement and static work [25].

A major advantage of a triaxial sensor over a uniaxial sensor is that the instrument is more sensitive to light activities, such as slow walking. A disadvantage, however, related to this greater sensitivity is that the device also becomes sensitive to vibrational artifact, recording background vibration (especially that related to being in a vehicle) as movement. Some manufacturers claim to set the device at a frequency response capable of capturing the range of human movement but to filter out rapid vibrations. These claims require researcher evaluation and can be tested by determining if measures obtained during vehicular transportation as a passenger differ significantly from measures obtained during quiet sitting [26].

Accelerometers have been shown to be more sensitive in detecting activity differences in inactive populations and more sensitive at detecting short activity periods than recall measures [14,27–29]. Field evaluation studies comparing accelerometers to self-reported activity have usually suggested that accelerometers underestimate the amount of vigorous activity and energy expended in activity [30,31]. However, it is well known that self-report of activity is subject to recall bias. Multiple assessment devices (accelerometers and self-report measures) can be used together to improve the accuracy of activity profiles [25,32].

Like waist-mounted triaxial accelerometers, wrist-worn accelerometers have been shown to differentiate light, moderate, and heavy activity levels, as well as to record differences in sedentary activities. They can more accurately represent activities that are underrated by waist-mounted devices, such as cycling and rowing, but may overrate activities requiring rapid hand movements (especially typing) [33].

Several recent studies have compared the relative accuracy and validity of various motion sensing devices. Tudor-Locke and colleagues [34] compared CSA uniaxial accelerometer counts to Yamax pedometer steps and found the two to be highly correlated (r = 0.74–0.86), but because of the CSA's greater sensitivity, it tended to record more steps than the Yamax pedometer. Leenders et al. [31] compared a pedometer (Yamax) with a uniaxial (CSA) and a triaxial (RT3) accelerometer and found all three to be highly correlated (r = 0.84–0.93), with the highest correlations between the two accelerometers. The authors concluded that the accelerometers were comparable for assessing the amount and intensity of activity. They also suggested that the high correlations between the accelerometers and step count indicated that a large portion of physical activity was determined simply by measuring the number of steps taken each day.

Welk and colleagues [23] evaluated the absolute and relative validity of three accelerometers (CSA, Tritrac, and Biotrainer) during choreographed lifestyle activities and treadmill activity. Correlations among the three devices were high for both treadmill (r = 0.86) and lifestyle activities (r = 0.70). Kochersberger et al. [35] similarly compared the Tritrac and Mini-Motion Logger Actigraph. Again, correlations between the two were high and significant (r = 0.77, p = 0.001).

Individual physical activity is known to vary based on day of the week due to differences in work and leisure activity profiles. This variability may be less important in those who do not work a typical work week. Matthews et al. [36] measured day of the week effects in a large sample of healthy adults using an accelerometer (CSA) and found that, to guarantee 80 percent reliability for measuring activity counts and time spent in moderate to vigorous activity, at least 3 to 4 days of monitoring were required, with at least 1 weekend day included. To reliably measure inactivity, these same authors recommend at least 7 days of monitoring.

MOTION SENSORS IN PULMONARY REHABILITATION

For most adults, the health benefits of an exercise program are believed to be dependent on the dose of physical activity undertaken. Dose is characterized by the frequency, duration, intensity, and type of activity. Although less is known about specific dose-response relationships, a positive association between training intensity and maximal oxygen consumption, muscle strength, and other exercise outcomes has been reported in the literature [37,38]. Motion sensors have the potential to document more accurately the actual dose of a prescribed exercise regimen. They are especially useful because in most outpatient or home-based programs, only a small part of the program is supervised by program staff, who assess and record the quantity of exercise and the responses of participants. Since there are greater risks of injury and other health emergencies associated with higher intensity exercise, it is important to identify the optimal level of activity that produces the greatest health and immediate outcomes benefits while minimizing potential risks [39].

More recently, digital pedometers and accelerometers have shown promise as adjuncts to reinforce exercise adherence by allowing self-monitoring, and as process and outcome measures for physical conditioning programs [23,28,35,40]. A number of studies support the validity, reliability, feasibility and clinical utility of accelerometers in the care of people with chronic respiratory disease. Preusser and Winningham first used a Caltrac accelerometer to measure four days of home activity in a group of 17 patients with chronic obstructive pulmonary disease (COPD) and found significant correlations with inspiratory muscle strength (r = 0.66; p = 0.004) and inspiratory muscle endurance (r = 0.71; p = 0.001) [41]. In a study of 47 outpatients who had COPD as they entered a pulmonary rehabilitation program, we determined that a triaxial accelerometer, the Tritrac R3D, had excellent test-retest reliability during three standardized 6 min walk tests (intraclass correlation coefficient, r_{ICC} = 0.84). Pearson correlations between accelerometer-measured movement during walking compared to walking distance varied from 0.84 to 0.95. During measurement periods of free-living activity over three days at home, the device had an r_{ICC} of 0.69, implying good stability over longer periods of meas-urement. These data support the use of this device in meas-uring daily activity, even in very inactive populations [14].

To determine concurrent validity of accelerometer measurement of daily activity under free-living conditions, we measured daily activity over three full days at home in 63 outpatients with COPD who did not exercise regularly. We found significant correlations between accelerometer-measured daily activity and exercise capacity (maximal 6 min walk, $r = 0.60$; $p < 0.001$), level of obstructive pulmonary disease (percentage of predicted forced expiratory volume in 1 s, $r = 0.37$; $p < 0.01$), dyspnea (Functional Status and Dyspnea Questionnaire, $r = -0.29$; $p < 0.05$) and activity self-efficacy (Activity Self-Efficacy Questionnaire, $r = 0.27$; $p < 0.05$) and physical health status (SF-36, Physical Functioning Subscale, $r = 0.40$; $p < 0.01$). Multivariate analysis demonstrated that the only predictor of physical activity was the 6 min walk test. Like other studies, physical activity measured by accelerometer was not associated in this sample with self-report of functional status [15]. These findings indicate that the accelerometer has good concurrent validity with other indicators of function and above all, represents with precision walking behavior in chronic respiratory disease.

The greater accuracy of accelerometer technology has excellent potential in documenting pulmonary rehabilitation outcomes [2]. Walking is a key indicator of improvement in pulmonary rehabilitation programs and similar regimens aimed at reducing the consequences of physical inactivity. Although these devices poorly represent strength training activities that do not involve much bodily movement, they can capture improvements in endurance and exercise capacity. We have found that the Tritrac R3D is a sensitive process measure of physical activity undertaken during a pulmonary rehabilitation program. In a study of 41 men and women with COPD enrolled in an 8 week outpatient pulmonary rehabilitation program, subjects underwent 5 days of daily activity measurement using the Tritrac R3D accelerometer. Physical activity, measured in vector magnitude units (VMU) per minute, was 87.4 + 38.8 (mean, standard deviation) before the start of the program; VMU per minute increased to 115.2, standard deviation + 59.4, during the final weeks of the program ($p < 0.01$) [10]. **Figure 1** demonstrates differences between a patient's daily physical activity measured in VMU before starting a pulmonary rehabilitation program and on the same days of the week while attending the program. Significant differences are evident between exercise and nonexercise days.

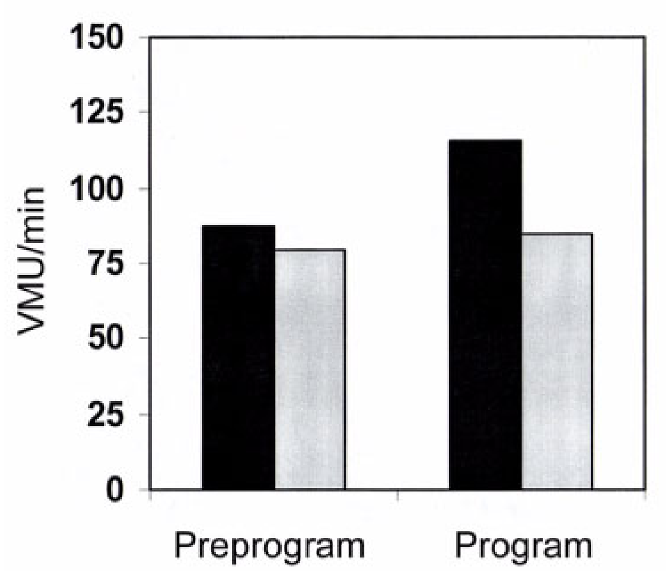

Figure 1.
Average daily activity (VMU/min) for 2 days before beginning pulmonary rehabilitation program (PRP) (preprogram) and 2 days while participating in PRP (program). Solid bars = Thursdays (exercise day); shaded bars = Fridays (nonexercise day).

In addition to providing information about group performance, accelerometer measurement of daily physical activity provides a more precise indicator of individual performance during unsupervised exercise than previously possible. **Figure 2** includes individual tracings of free-living daily activity of one pulmonary rehabilitation participant and clearly differentiates walking behavior during his two 6 min walk tests, sitting activity, and free-living walking to his vehicle, as well as the movement contributed by riding home in his car. Physical activity measured during an observed pulmonary rehabilitation exercise session is represented in **Figure 3** and includes VMU measurement while patients used the treadmill, a seated stepper (NuStep®), an arm ergometer, and free weights. Static exercise (free weights, seated stepper, and arm ergometer) is generally less well represented than moderately paced walking on the treadmill. **Figure 4** reflects two full days of activity accelerometer monitoring of one participant, comparing a day when he attended his pulmonary rehabilitation program with a day when he

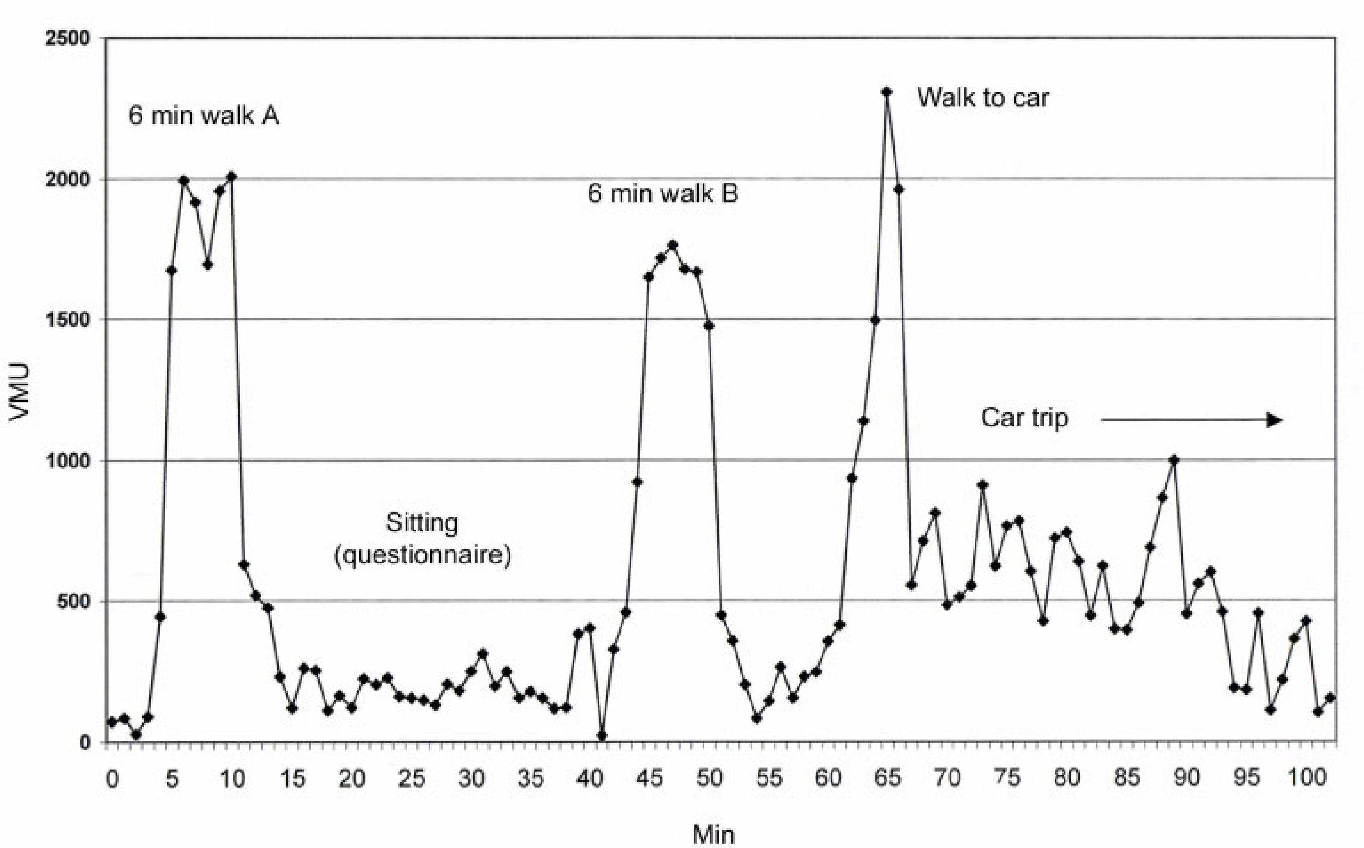

Figure 2.
Vector magnitude unit (VMU) measurements of minute-by-minute tracings for pulmonary rehabilitation program patient in defined activities: performing 6 min walk tests, sitting while completing written questionnaire, walking to vehicle, and driving home following appointment.

did not attend. The graphical display demonstrates more activity (in VMU) on the day he attended the exercise session.

CHOOSING A MOTION SENSOR FOR PULMONARY REHABILITATION

Accelerometer technology, with its relatively complex data collection and management methodology to study daily activity, begs the question of why a digital pedometer would not suffice for this purpose. Certainly, in most circumstances with healthy individuals, step-counting will readily document walking activity and, as noted earlier, is useful as an adjunct to reinforce walking behavior and other exercise. A number of reasons support the use of accelerometer technology for persons with chronic pulmonary disease and others with diminished physical functioning. First, even the most reliable digital pedometers are unable to accurately measure slow walking speeds under 2 mph, because of less-pronounced accelerations at the hip [19]. For this reason, pedometers will underrepresent much of the walking activity of these groups. For the same reason, pedometers will be less sensitive to small improvements in walking activity in inactive individuals. Field-monitoring of exercise and daily activity over time is also better undertaken with an accelerometer because of its longer memory and its lack of dependence on having subjects record a daily value or otherwise keep a separate record of the pedometer data. This may be particularly true in persons with chronic pulmonary disease because of their high, preexisting burden of self-management and other considerations relating to their severe, chronic illness. Finally, the capability to document both the duration and relative intensity of movement, e.g., during walking, provides a unique quantitative index of the vigor with which exercise or

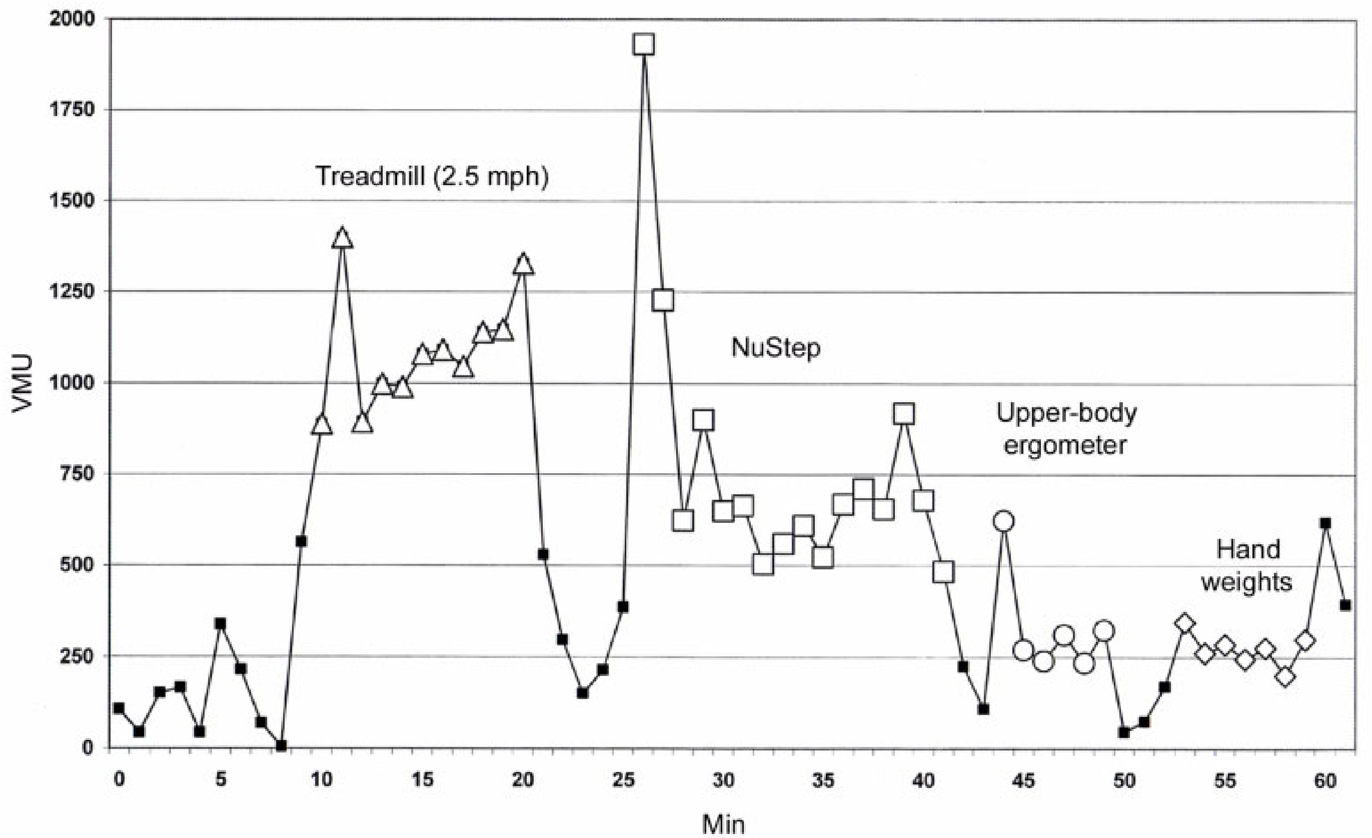

Figure 3.
Vector magnitude unit (VMU) measurements of minute-by-minute tracings for patient in pulmonary rehabilitation program: Δ—treadmill (2.5 mph), □—NuStep®, ○—upper-body ergometer, ◇—upper-body strengthening with handheld weights (seated). (■—periods of rest between identified activities).

activity is undertaken. Process and outcome measures that include these fundamental exercise elements can provide much more precise and valuable information to both program staff and participants.

DATA ANALYSIS AND PRACTICAL CONSIDERATIONS OF USING MOTION SENSORS IN PULMONARY PATIENTS

Data Analysis Concerns with Pedometers

Step counters or pedometers are simple, lightweight, and inexpensive devices, useful in the documentation of ambulatory activities. They rely on the patient to simply wear it and record the daily steps. Because of the necessity of gravity's action on the mechanical arm to record the step, the physical orientation is key to accurate counting. We have found in more obese patients that "abdominal overlap" prohibits this vertical orientation when attached at the waist, thus reducing the number of steps. Also, step counters, while correlating moderately well with accelerometer information, are unable to distinguish the intensity and the temporal distribution of activity. Finally, some devices, such as the Digiwalker®, will not accurately measure steps in individuals who walk under 2 mph, a major concern in severely functionally impaired patients.

Data Analysis Concerns with Accelerometers

Our present work involves the use of the StayHealthy RT3® triaxial accelerometer (**Figure 5**). We measure activity over 1 min epochs so as to capture brief bouts of activity over longer periods of time (up to 21 days). The intensity of the VMU correlates positively with the velocity of walking, allowing us to examine various levels of activity during daily living, as well as during "exercise

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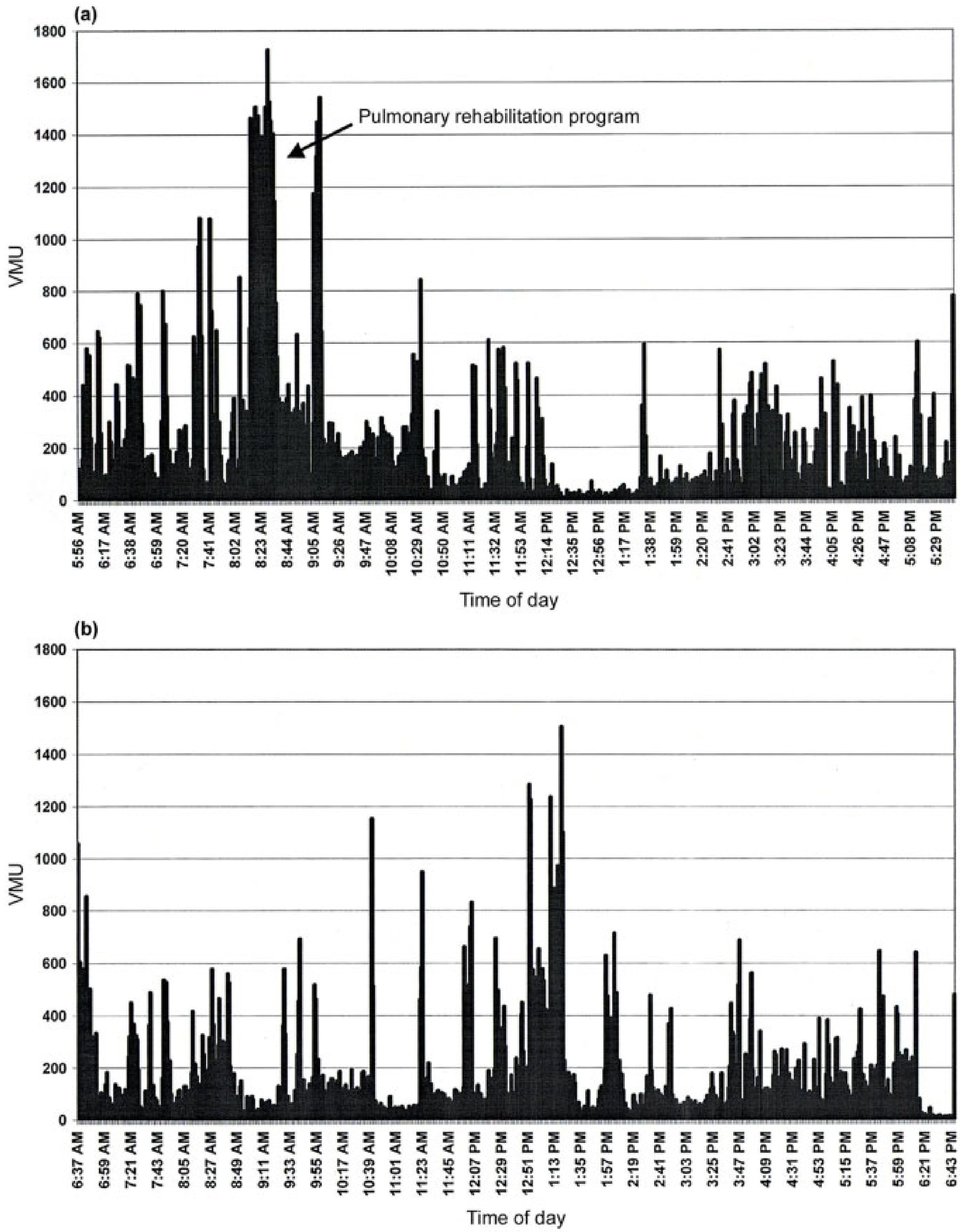

Figure 4.
Full day vector magnitude unit (VMU) measurements: **(a)** day that includes participation in pulmonary rehabilitation program (day 2) and **(b)** day of normal activities (no structured exercise sessions—day 4).

Figure 5.
RT3® accelerometer from StayHealthy®, next to AAA battery to demonstrate scale. Buttons are event markers, useful during analysis for matching vector magnitude units with diary entries.

activities." This accelerometer will provide a large amount of data in the form of VMU "counts," a unitless index of movement (Tritrac R3D® and StayHealthy RT3®). For most uses, it is necessary to analyze these data to come up with one or a few summary measures that characterize the subjects' activity level over the days. There are several issues relating to such analyses, which are discussed in this section.

Sources of Extraneous Variance

Physical Activity Versus Noise Signals. As in **Figure 2**, there is quite a bit of minute-to-minute variability in VMU, with frequent upward spikes punctuating a more low-level base that also varies. Some of this variability represents the type of actual activity that we wish to detect, such as a person getting up off the couch to walk around the house. This activity is easiest to see when it is for a sustained period, as demonstrated by the 6 min walk in **Figure 2**. In our experience with pulmonary rehabilitation patients, it is relatively easy to detect long periods of activity, as are seen when a person is intentionally engaging in exercise.

However, some of the variability in VMU may not actually be major activity, but rather something like a person shifting position on a couch, or just noise in the detection device. In our experience with the RT3, many of the devices record randomly varying, relatively low but nonzero values for VMU when the device is sitting on a table at night while the subject sleeps. For this very inactive population, this type of low-level random noise can be a problem when one is trying to summarize activity level during the day. This may reduce the reliability of activity monitors in very inactive populations.

Variability Between Devices. In our experience with RT3 devices, there is considerable variability from device to device in the VMU readings when the device is sitting on a table. What is not clear is whether these differences in sensitivity across devices represent an additive or a multiplicative effect. If additive (e.g., one device reads 10 VMU higher than another at any given level of activity), it would have some impact at very low levels of activity, but not at high levels. If multiplicative (e.g., one device reads 50% higher than another for any given level of actual movement), then this has serious implications for across-device comparability. This issue needs further investigation. Meanwhile, in our studies we assign the same device for the pre, post, and followup data collection periods for a given subject.

Car Rides. Another source of noise may be car rides and use of rocking chairs, wheelchairs, and other equipment contributing to movement without skeletal muscle activity. The motions and vibrations of a car cause fairly high VMU readings, when the person is not, in fact, being active. Bouten [18,40] and his investigators deleted data over a certain magnitude which they attributed to automotive transport, but this approach is time-consuming to develop and probably imprecise. We are currently investigating how to deal with this problem. It is probably not practical to identify each car episode and excise these segments from the data. However, if it is known for each individual how many minutes were spent in a car each day, and if we know the average VMU when riding in a car compared to sitting in a chair, then an adjustment can be made. In past studies, we found that there was no significant difference between time spent riding in a car between measurement periods, suggesting that people with chronic lung disease will have similar driving habits over the period of analysis, thus obviating the need to arduously remove the car noise from every driving episode.

Summary Measure Issues. Freedson and Miller [20] have recommended that the summary measure for accelerometers be movement "counts" rather than energy expenditure, which is computed from varied, often undefined formulae, such as the Harris-Benedict equation, which may not be readily applicable to every measurement setting. Nonetheless, temporal factors may add error variance. For example, the devices are usually not worn while sleeping. Therefore, it is important to identify the time period when it is being worn. Data from a 24 hour period can be summarized by either adding up the total VMU over the period in which the device is worn, or taking the average over this period (mean VMU per minute or per hour). The number of hours per day that the device is worn varies across people, so these two methods of summarizing will not be perfectly correlated. For example, on days during which the device was worn only a short period (e.g., 9 hours) because the person forgot to put it on when they first got out of bed, average VMU per minute may be an acceptable measure of daily activity. On the other hand, if someone has only 9 hours of data because they were in bed for 15 hours, then average VMU while it was being worn misses the fact that this person was, in reality, very inactive for most of the day. In this case, total VMU for the day may be a better measure.

Rather than treating VMU as a continuous variable, it may be desirable to define a threshold and compute how often VMU was above this threshold. For example, a threshold of 500 VMU might be good for indicating periods of fairly high activity, so the number of minutes (or percentage of time) during which activity is above 500 may be a good summary measure of activity.

Within and Between Subject Variability. When attached at the waist, the accelerometer measures the various motions of the pelvis during gait, including lateral displacement of the center of gravity, pelvic rotation, and lateral pelvic tilt or drop. These movements vary between individuals and within individuals at different walking speeds, and must be considered when analyzing accelerometer data. While this presents some issues in inter-individual comparisons, the recordings are usually internally consistent within individuals.

Another issue is that there may be differences across people that affect the sensitivity of the device. Such differences may be due to exactly where the device is worn, obesity, or gait differences. This possibility raises the issue of whether VMU values can be interpreted in an absolute sense or need to be somehow normalized to a person. For example, in our study we have VMU measures during a 6 min walk, in which the subject is supposedly walking as fast as possible. We are exploring the use of person-specific thresholds to compute summary measures, e.g., the percentage of time with activity greater than 30 percent of that measured during the 6 min walk. Alternatively, VMU values could be normed to the mean value observed while the person was sitting in a chair filling out a questionnaire, e.g., percentage of time with VMU values more than 3 times as high as this baseline. Finally, handling, bumping, or dropping the unit is an additional source of error variance. To minimize this problem, subjects should be instructed not to handle the devices and to wear the devices in a protective holder that minimizes the possibility of dropping it.

Other practical considerations for the clinical usage of accelerometers include consideration of the participant's cognitive level, certainly necessary for remembering to put the unit on and recording possible interfering activities in a diary. In addition, care in application (more lateral placement often results in breakage of the holder, especially against arms of chairs), and using fresh, fully charged batteries at the beginning of the recording period are also important. The devices require only slight care, although dropping can dislodge the battery, resulting in loss of data.

Underrepresentation of Exercise Behavior

The inability of motion sensing devices to measure static exercise has been discussed previously and remains a major limitation to the use of these devices in pulmonary rehabilitation and other settings, where strength training and other exercise not employing body movement are used. Although walking will usually be accurately represented, accelerometers will not reflect the added work of walking up stairs and inclines. Additionally, motion sensors may not be able to accurately monitor frail older adults with slow gaits [42] or provide similar estimates of the time spent in resting/light, moderate, or hard/very hard physical activity [43].

CURRENT AND FUTURE RESEARCH

Our present research uses accelerometer technology to measure the efficacy of an exercise adherence intervention following a pulmonary rehabilitation program to promote daily physical activity and exercise following program completion. Clearly, as noted earlier, a number of methodological studies need to be undertaken to determine the best ways to limit the signal-to-noise ratio of the devices, particularly when they are used for measuring free-living activity. Motion sensors, particularly accelerometers, have considerable potential for answering questions related to pulmonary rehabilitation. For example, are participants carrying out exercise strategies at home with the same vigor as during supervised exercise sessions? Likewise, is it possible that frail pulmonary rehabilitation participants are reducing daily activity to accommodate their exercise program and are therefore doing less than before? To what degree are weight loss and other negative outcomes associated with a more strenuous program of walking in some individuals?

CONCLUSIONS

The purpose of this article is to provide an overview of the potential utility of motion sensors to measure physical activity in persons with chronic pulmonary disease in the setting of pulmonary rehabilitation. In particular, motion sensors are useful to measure walking behavior, a key outcome of these programs. Walking is also a core activity, fundamental to maintenance of an active and vigorous life in the face of normal aging, as well as the debilitating effects of chronic pulmonary disease. Clearly, the potential use of these devices to measure free-living daily activity, a variable heretofore immeasurable, transcends this limited area to include most domains of rehabilitation care wherein improving bodily movement is a central outcome of interest. It is likely that the future will include broad application of this methodology to clinical, research, and program evaluation venues.

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