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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

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