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Recent Advances in Free-Living Physical Activity Monitoring: A Review

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Abstract

It has become clear recently that the epidemic of type 2 diabetes sweeping the globe is associated with decreased levels of physical activity and an increase in obesity. Incorporating appropriate and sufficient physical activity into one's life is an essential component of achieving and maintaining a healthy weight and overall health, especially for those with type II diabetes mellitus. Regular physical activity can have a positive impact by lowering blood glucose, helping the body to be more efficient at using insulin. There are other substantial benefits for patients with diabetes, including prevention of cardiovascular disease, hyperlipidemia, hypertension, and obesity. Several complications of utilizing a self-care treatment methodology involving exercise include (1) patients may not know how much activity that they engage in and (2) health-care providers do not have objective measurements of how much activity their patients perform. However, several technological advances have brought a variety of activity monitoring devices to the market that can address these concerns. Ranging from simple pedometers to multisensor devices, the different technologies offer varying levels of accuracy, comfort, and reliability. The key notion is that by providing feedback to the patient, motivation can be increased and targets can be set and aimed toward. Although these devices are not specific to the treatment of diabetes, the importance of physical activity in treating the disease makes an understanding of these devices important. This article reviews these physical activity monitors and describes the advantages and disadvantages of each.

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Abbreviations: (DLW) doubly labeled water, (GPS) global positioning system, (HR) heart rate, (SWA) SenseWear armband, (TEE) total energy expenditure

Keywords: accelerometers, energy expenditure, physical activity, physical activity monitors

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Introduction

Increased metabolic physical activity, along with the achievement and maintenance of energy balance, has emerged as an important personal health goal for the 21st century. It is well understood by health professionals that many leading health problems are caused or aggravated by physical inactivity and the consequences of consuming more calories than are burnt. For many diseases and medical conditions, increasing physical activity can improve recovery rates, delay recurrence rates, and generally improve outcomes. This is true for individuals with type 2 diabetes mellitus. Physical activity has been shown to enhance insulin sensitivity and improve glucose tolerance in individuals with type 2 diabetes.[1–3]

Several different technologies are available for the measurement and assessment of physical activity and energy expenditure. These methodologies range from expensive and objective laboratory procedures such as doubly labeled water (DLW)[4] to subjective measures such as 24-hour recall. In between are techniques such as indirect calorimetry, pedometers, accelerometry, devices measuring heart rate (HR), and multisensor devices. In general, most of these methodologies suffer from one of several characteristic flaws: expense, difficulty of use, inaccuracy, or being only suitable to measure a small range of activities. Although all of these techniques have their place, there is still a need for an inexpensive, accurate, comfortable, and durable device that can assess metabolic physical activity and energy expenditure outside the laboratory in a free-living environment. From the behavior change literature,[5–8] it is well recognized that regular and accurate self-monitoring in the free-living environment can provide important feedback, which increases self-awareness—the prerequisite for healthy decision making and long-term lifestyle change.

As microprocessors, wireless technology, statistical methods, and the Internet have advanced, so have the opportunities to develop personalized body monitoring devices that allow individuals to accurately track and analyze daily activities. A recent trend in physical activity monitoring is toward devices with multiple sensors that achieve much higher accuracies than single sensors while preserving low cost and ease of wear.

This article reviews physical activity monitoring devices and evaluates each type on the dimensions of cost, accuracy, wearability, ease of use, durability, and quality of the supporting software. Not every physical activity monitor is covered; however, representative examples from each class are considered.

Comparison of Physical Activity Assessment Devices

The number of calories a person burns is an important and actionable parameter for many applications and disease conditions. These include metabolic disorders, weight control (loss, gain, or maintenance), sports performance, and body composition changes. True total energy expenditure (TEE) is very difficult to measure, and nearly all techniques make use of approximations of one kind or another, as discussed later.

Indirect Calorimetry

Metabolic carts (indirect calorimetry) measure the oxygen and carbon dioxide that a person inhales and exhales and, from this, indirectly compute the calories burned during the period of measurement. This method is normally done under laboratory conditions. With this technique one can accurately measure the oxygen consumption (and carbon dioxide production) of an individual; therefore, one can get a good estimate of energy expenditure. This technique of measurement is currently very widely accepted in the research community as a standard. Based on a survey of the literature, devices of this category differ from one another by 5–10% and differ even on repeated measurements of the same activity by around 5–10%.[9–12] Most metabolic carts are rather large and bulky and are not suited for monitoring outside the laboratory setting. These devices are expensive, costing well upward of $20,000 for a basic system.[13]

Recently, portable metabolic carts have become available. These devices require wearing analyzer modules strapped on the chest or on the back and breathing through a mouthpiece or mask and are able to monitor a wider set of activities for a reasonably short period of time. However, these portable devices have higher error rates than stationary metabolic carts[14–20] and show significant differences from metabolic carts.[18,19] For both stationary and portable metabolic carts, use of the mask limits the set of individuals and activities that can be studied. Software for both portable and stationary metabolic carts allows the viewing of both values through time and session totals.

Doubly Labeled Water

The DLW stable isotope method is considered the gold standard for measuring TEE during free living.[21] This method is based on the principle that in a loading dose of $^{2}H_2{}^{18}O$, ^{18}O is eliminated as CO_2 and water, while deuterium is eliminated from the body as water. The rate of CO_2 production, and, thus, energy expenditure, is calculated from the difference of the two elimination rates. The only requirements of subjects are to give urine and saliva specimens before and after drinking an initial dose of $^{2}H_2{}^{18}O$ and then return in 1 to 2 weeks to give a final urine specimen. During the period between initial and final samplings, subjects are free to carry out their normal activities. This is a safe procedure, as the isotopes are stable and emit no radiation. Limitations of the DLW method include a high cost (~$1500/person), the need for specialized equipment and expertise to implement the techniques, and the fact that the method can only be used to measure expenditure over a long period of time (e.g., 10–14 days). Doubly labeled water has an error rate of about 5% over a 2-week period because of starting and ending conditions.[21]

Self-Report Techniques

Self-report methods include questionnaires, interviews, and activity diaries. There are some advantages to using self-reports or 24-hour recalls.[22] These tools can be used to assess large populations because they are very inexpensive and easy to administer. They can capture both qualitative and quantitative information. The biggest disadvantages are the questionable validity, repeatability, and reliability of these tools[23–27] because of their subjective nature. Estimating duration and energy expenditure with these tools has been problematic,[28] and these tools only provide a rough estimate of activity level.[29] Individuals often overestimate their activity levels; differences between self-report and DLW may be as high as 30 ± 9.9%.[23]

Pedometers

Pedometers, by definition, measure footfalls. The clear advantage of pedometers is the low cost, ranging from $15 to $300.[30] Pedometers can be found in almost any store. Some of the more popular manufactures are DigiWalker, Omron, Acumen, Freestyle, and Accusplit. In general, pedometers are not accurate when used for activities that do not involve footfalls (e.g., weight lifting, biking, household activities).[31,32] Even for ambulatory activities, pedometers have been found to be inaccurate at both counting steps and assessing distance walked.[31] In most cases, pedometers (at the higher end) can be accurate at counting steps, although they are much less accurate at predicting energy expenditure, even during walking, with error rates of ±30%.[33] A pedometer can be used as a coaching or self-monitoring tool[34] to help people set goals.[31] As a result, pedometers are reasonable tools for helping individuals increase their physical activity levels. The main drawback to pedometers is that they do not measure the intensity, duration, or frequency of physical activity.[32]

Accelerometers

Accelerometers operate by measuring acceleration along a given axis, using any of a number of technologies, including piezoelectric, micromechanical springs, and changes in capacitance.[35] Often, multiple axis measurements are bundled into a single package, allowing two and three axis accelerometers. The major function of accelerometers is that the sensor converts movements into electrical signals that are proportional to the muscular force producing motion.[36] Some common accelerometers include the wrist-worn one-dimensional Actiwatch (Mini Mitter, Bend, OR), the waist-worn BioTrainer (IM Systems, Inc., Baltimore, MD), the RT3 (TriTrac, StayHealthy, Monrovia, CA), and the foot pod-based Nike+ iPod (Apple/Nike, Cupertino, CA). Most accelerometers compute energy expenditure by first rectifying the accelerometer signal and then integrating to compute accelerometer *counts.* Typically, these counts are then multiplied by a constant and added to a separate constant to compute energy expenditure.[33,35]

Moreover, accelerometer equations have been developed for specific activities (e.g., walking and running, sometimes rest) and do not estimate other activities accurately (e.g., stationary biking, elliptical trainer). Additionally, accelerometers are subject to motion artifacts from activities such as driving in a car or riding on a train. The consensus appears to be that for activities composed entirely of flat-ground ambulation and rest, accelerometers can provide objective measures of activity. Advantages of these types of activity monitors are that they are low to moderate in cost ($50 to more than $1000) and are typically relatively easy to use. Because of the complex nature of some of these devices, as well as the size, subject compliance can sometimes become an issue.[35,37]

Typically, accelerometers either provide feedback directly on the device (e.g., RT3 TriTrac) or allow the user to upload data to a PC-based software package. Some have the ability to upload to Web sites as well (e.g., Nike+

iPod). To our knowledge, none of these devices has the ability to allow a health-care provider access to data other than via email or sharing of passwords.

Recent work in the field is heading toward utilizing more complex equations for estimating energy expenditure from counts.[33] In these methods, the coefficient of variation of the accelerometry signal is utilized to select an appropriate regression equation, which works because the coefficient of variation of regular walking activity is lower than for free-living activities such as house cleaning. Essentially this idea utilizes two aspects of a signal: first to classify and then to predict. This is a one-dimensional version sharing some advantages of the multisensor monitors described next.

Heart Rate Monitors

Heart rate is one of the fundamental vital signs and is related to the level of physical exertion. Especially for moderate to strenuous activity, a person's heart rate increases linearly with oxygen consumption.[34] Heart rate monitoring is quite common and is often used as part of an exercise prescription.[35] Furthermore, most HR monitor companies have released software for converting HR data into an estimate of energy expenditure (e.g., Polar, Kempele, Finland). Several studies[35–37] have found that calibration is required to create a curve between the subject's heart rate and estimated energy expenditure, involving a submaximal stress test at moderate activity levels.[34,38,39] Furthermore, heart rate monitors also are only accurate for moderate to vigorous activities, as in lower-intensity activities, confounds such as stress, emotions, caffeine intake, ambient temperature, or illness[29,38] are significant.

Chest-strap heart rate monitors can be a burden to participants because of the constriction required across the chest to maintain good skin contact. Electrode-based heart monitors are difficult to wear, as placement, skin treatment, and irritation can be significant issues and detriments to long-term wear. Subjects have shown poor compliance at wearing heart rate monitors in free-living trials.[40] Finally, many HR monitors receive interference from electrical equipment, thus signal transmission is prone to interference.[41]

Global Positioning System (GPS) Monitors

Several devices based on GPS [e.g., Garmin's (Olathe, KS) Forerunner and Edge products] have been introduced that compute speed and distance traveled and, from that information, estimate calories expended for a particular activity (e.g., walking/running, road biking). The accuracy of these products is only beginning to be assessed adequately. Even for outdoor activity, where the GPS signal is strongest, some research indicates that these products may overestimate energy expenditure except for fast walking.[42] Although GPS receivers have become quite wearable for short durations, long-term wear may be uncomfortable. Furthermore, because the monitors only work outdoors and for activities involving true translational motion, these devices have significant challenges with respect to being a suitable free-living monitor of energy expenditure. In terms of software, most devices report either on the device itself or to a personal computer. Garmin's Forerunner product line offers the use of motionbased.com, a Web site providing additional analysis.

Multilocation Devices

Given that some of the problems of predicting energy expenditure from motion come from an activity that utilizes a part of the body not being measured (e.g., stationary biking), one solution is to utilize accelerometers on multiple parts of the body. Two devices, the DynaPort (McRoberts, BV, The Hague, The Netherlands) and the IDEEA monitor (MiniSun, Fresno, CA), utilize this technique. The IDEEA monitor classifies more than 30 activities, with high reported accuracy,[43] and utilizes five accelerometers attached via medical tape to the chest, the underside of each foot, and the front of each thigh. Wires connect the accelerometers to a belt-worn recorder. The accuracy of the device appears to be good, as they are reported to be accurate to within 10% for energy expenditure for some activities.[43] In general, these devices tend to be expensive (more than $1000) and have a significant ease-of-use problem. Convincing users to wear a single-location device can be difficult, let alone convincing them to wear something involving taping multiple electrodes to locations only accessible when disrobed.

Multisensor Devices

Most of the single-sensor based systems that are appropriate for free-living activities involve surrogates for energy expenditure. Measuring steps, motion, heart rate, location on the planet, or even expired oxygen are only indirect measures of energy expenditure.

Take the case of accelerometry. Low motion might indicate rest or it might indicate physical activity using a part of the body far from the accelerometer. Moderate motion might indicate physical activity or it might indicate riding in a moving vehicle on a rough road. By adding another variable, such as heart rate, these different contexts can be disambiguated. Riding in a car will typically induce lower heart rates than moderate physical activity; subjects at rest will typically have lower heart rates than those performing low-motion physical activity. By taking advantage of the science of data fusion, multisensor systems typically achieve higher accuracies than single sensor systems while typically keeping overall costs moderate.

The Actiheart is a two sensor device combining an electrocardiogram monitor and an accelerometer. It takes advantage of the flex-HR technique,[44,45] which utilizes four different "contexts" and equations and results in accuracies with approximately 5% error on ambulatory activities.[45,46] The Actiheart is worn on the chest and is attached to regular adhesive electrodes. The Actiheart weighs only 10 grams and has an internal replaceable battery and memory that lasts for at least 10 days. Advantages include high accuracy and relative simplicity of use. Disadvantages include the use of adhesive electrodes and a two-component wired system. Additionally, the best results appear to be obtained only utilizing per-subject calibrations; utilizing group calibrations results in R^2 values for walking as low as 0.54.[47]

Another multisensor system is the Garmin Forerunner, which utilizes GPS, heart rate, and optional foot pod and biking cadence/speed sensors to fill in when the GPS signal drops out. As mentioned earlier, the result from this combination of sensors does not yet seem to have much published validation research, although the motionbased.com Web site is also usable with this product.

Another multisensor monitor is the SenseWear® Pro3 (BodyMedia Inc., Pittsburgh, PA). The SenseWear armband (SWA) is a small, wireless, and wearable body monitor worn on the back of the upper right arm. The SWA utilizes a unique combination of sensors. A proprietary heat-flux sensor measures the amount of heat being dissipated by the body by measuring the heat loss along a thermally conductive path between the skin and a vent on the side of the armband. Skin temperature and near-armband temperature are also measured by sensitive thermistors. The armband also measures galvanic skin response (the conductivity of the wearer's skin), which varies as a consequence of physical and emotional stimuli. A two-axis accelerometer tracks the movement of the upper arm and provides information about body position.[48] Additionally, a wireless display device is available that can be worn as a watch or clipped to clothing that displays the calories burned, steps taken, and minutes spent in moderate and vigorous physical activity for today, yesterday, and from the time a trip button was pressed.

The SWA utilizes pattern detection algorithms[48,49] that utilize the physiologic signals from all the sensors to first detect the wearer's context and then apply an appropriate formula to estimate energy expenditure from the sensor values. The armband can recognize many basic activities, such as weight lifting, walking, running, biking, resting, and riding in a car, bus, or train. Other activities are classified into combinations of these basic activities; for example, baseball could be broken down into a combination of mostly near-restful activity and running. Key to the armband's utility is that it can be worn comfortably during a person's normal life[50] and does not require any time in the laboratory for uncomfortable measurements. Laboratory tests indicate that the device is accurate across a broad range of activities[49,51,52] and performs well when compared to doubly labeled water in diabetic and obese subjects[53] with only an 8% average error.

The SWA can be utilized with both desktop and Web-based software. In Web-based software, a user's health-care provider can be granted permission to view user's data, enabling remote care and objective feedback to aid in the behavior modification process.

Discussion

Table 1 lists the various devices discussed in this review article. For highest accuracies, doubly labeled water appears as the only real choice for assessing free-living individuals. For an inexpensive but approximate metric, pedometers and the less expensive accelerometers appear to offer a good option for large-scale studies. For good accuracies across the spectrum of free-living activities, multisensor devices such as the SenseWear Pro3 and the Actiheart offer the best option. For ease of use in behavioral modification work for both research and clinical applications, the SenseWear product line offers good accuracies, moderate pricing, and software ready to be used with subjects and patients.

The trend in health care seems clear. The role of lifestyle in both treating and understanding diseases seems only to be increasing. Easy-to-wear monitors that provide both the patient and the health-care providers with objective information about the wearer's lifestyle offer many possibilities to improve the treatment and management of diseases, including diabetes. As devices become smaller

Table 1.
A comparison of physical activity monitors[a]

Device/technology	Approximate cost	Laboratory error	Free-living error	Wearability	Real-Time display	PC software	Web site software	Shared Web interface	Comments
DLW	$1500/dose	N/A	~5%[4]	Very high	No	No	No	No	
Indirect calorimetry	$20,000–$40,000	~3–10%[10]	N/A	Very low	Yes	Yes	No	No	
Portable IC	$20,000–$30,000	~5–10%[9]	N/A	Very low	No	Yes	No	No	
SenseWear Pro3	$999	~10–15%[51]	~8%, R = 0.86[53]	High	Yes	Yes	Yes	Yes	
Actiheart	$900	~5% ambulatory[44,45]	N/A	Low	No	Yes	No	No	
IDEEA	~$1000? Software?	~5–10%[43]	N/A	Low	No	Yes	No	No	
Dynaport	$6500[49]	Good[57,b]	N/A	Low	No	Yes	No	No	
Polar	$50–$500	~16.9–20%[35]	N/A	Medium	Yes	Yes	No	No	
Garmin Forerunner 305	$375	N/A	N/A	Medium	Yes	Yes	Yes	No	
Garmin Forerunner 302	$215	N/A	N/A	Medium	Yes	Yes	Yes	No	
Nike+	$200–$500	N/A	N/A	High	Yes	Yes	Yes	No	
RT3/TriTrac	$300–$500	19–28%[55]	42–67%[49]	Medium	Yes	Yes	No	No	
BioTrainer	$100–$500	R = 0.89 treadmill[49]	42–67% R = 0.55[49]	Medium	Yes	Yes	No	No	
Actiwatch	$500–$3000	14%[56]	N/A	Medium	Yes	Yes	No	No	
DigiWalker	$20–$450	~30%[33]	N/A	Medium	Yes	No	No	No	
Accusplit	$20–$40	~30%[33]	N/A	Medium	Yes	No	No	No	
Self-report	Inexpensive	N/A	~30%[23]	Very high	No	No	No	No	

[a] Costs and laboratory accuracies were found online on company Web pages in March 2007 if not otherwise cited. Prices cited are with software.
[b] Study showed correlations of 0.999 to walking time and 0.750 to lying down time.

and incorporate more sensors, the estimates will become more accurate for a wider subset of the population. Validations on free-living subjects are needed for most of these devices.

Disclosure:

Both authors, David Andre and Donna Wolf, are currently employed at BodyMedia Inc.

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