Physical Therapy Reviews

Physical Therapy Reviews, Volume 15, Issue 3 (2010)

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011 | Volume 15, 2010 | Vol 14, 2009 | Vol 13, 2008

Objective Monitoring of Physical Activity in Clinical Populations

Guest editorial

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Use of pedometers and accelerometers in clinical populations: validity and reliability issues

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Background: Pedometers and accelerometers are often used in clinical research studies, and have the potential to provide valid and objective information on physical activity.
Objectives: The purposes of this review are to introduce clinicians to various activity monitors that are commercially available, and to discuss their strengths and limitations. Scientific articles over the past 20 years were reviewed, and the most common types of physical activity monitors were identified. Emphasis was placed on devices with established validity and reliability, which were acceptable to participants and did not interfere with their activities. Ease-of-use from the investigator's standpoint was also considered.
Major findings: A number of activity monitors were identified, including four pedometers (Yamax SW digi-walker, New Lifestyles NL-2000, Omron HJ-720 ITC, and StepWatch), three accelerometer-based activity monitors (ActiGraph, Actical, and RT3), and a multisensor device (Sensewear Armband). Validity and reliability of these devices is discussed.
Conclusions: Pedometers and accelerometers are useful for tracking ambulatory physical activity in clinical populations, and those that display steps and/or calories are useful in motivating patients to increase their activity levels.

Keywords: Motion sensor, Walking, Ambulation, Physical activity, Energy expenditure

Introduction

There are many reasons why researchers are interested in obtaining accurate and objective measures of physical activity. These include: (i) determining the percentage of people who are meeting the national physical activity guidelines; (ii) tracking temporal trends in physical activity; (iii) comparing the physical activity levels of different groups; and (iv) quantifying the amount of activity performed in longitudinal studies of exercise training.[1] In addition, some studies have used physical activity as an outcome variable in studies designed to test efficacy of medications, surgical procedures, and prosthetic limbs.

Pedometers and accelerometers can provide objective measures of physical activity, and they are seeing increasing use in research studies. One advantage of these devices over the traditional self-report instruments such as physical activity logs, diaries, and questionnaires is that pedometers and accelerometers are less subjective. They do not depend upon a person's recall ability, whereas self-report instruments rely heavily on a person's ability to judge the frequency, intensity, and duration of activity bouts. With increases in the memory capacity of computer chips, activity monitors can now store data on a minute-by-minute basis. Thus, these devices can provide information on the total accumulated quantity of activity performed, as well as the pattern of activity over the course of the day.

A new finding in the past decade is that pedometers and accelerometers are not only useful as measurement tools, but they can also motivate sedentary people to increase their activity level.[2] For instance, numerous studies have shown that physical activity programs consisting of a pedometer, a daily step goal, and a step diary will increase physical activity levels by an average of approximately 2500 steps, compared to a sedentary control group.[3] Pedometers and accelerometers provide useful feedback to people on their current level of physical activity, and most people will respond when encouraged to increase their activity level.[4] However, 'accountability' is necessary to enhance compliance with these programs.

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DOI 10.1179/1743288X10Y.0000000004

Figure 1 Yamax pedometer, model SW-200.

Figure 2 New Lifestyles pedometer, model NL-2000.

Physical activity monitors have evolved over the years, and have become more sophisticated. Thus, the purpose of this review is to introduce clinicians to the current generation of activity monitors that are commercially available, as well as to discuss their strengths and limitations.

Articles from the scientific literature over the past 20 years were reviewed, and the most common types of physical activity monitors were identified. Emphasis was placed on devices with established validity and reliability, which did not hinder the participants' activities. Ease-of-use from the investigator's standpoint was a major consideration in selecting devices.

Major Findings

Several objective physical activity monitors were identified that have been widely used in research studies.

Yamax SW digi-walker

The Yamax SW digi-walker is a waist-mounted device and is the most widely used pedometer in research studies (Fig. 1). Previous studies comparing 10 or more pedometer models identified it as one of the most accurate and reliable electronic pedometers available.[5–7] The Yamax SW-200 pedometer ($24) is a simple step counter with a single button that resets it to zero. Other models in the SW series allow stride length and body mass to be entered for the purpose of estimating distance and calories. The internal mechanism in the Yamax digi-walker is a spring-suspended horizontal lever arm that bobs up-and-down with each step, opening and closing an electrical circuit. An electronic step counter accumulates the steps, and displays them digitally on a liquid crystal display (LCD). Battery life is approximately 2–3 years.

The Yamax pedometer is widely used in research, and this has made it possible to compare descriptive data (steps per day) for specific age groups, cultures, and clinical populations. Tudor-Locke and Bassett[8] have proposed step indices based on data collected with the Yamax digi-walker:

Steps per day	Classification
<5000	Sedentary
5000–7499	Low active
7500–9999	Somewhat active
10 000+	Physically active

The Yamax SW-200 pedometer has a plastic cover that can be secured shut (with a plastic zip-tie) to prevent resetting, and also to minimize pedometer 'reactivity'. Reactivity refers to a change in physical activity that results when an individual is allowed to view his/her activity data on an LCD display,[9] and is considered undesirable when collecting baseline or descriptive epidemiological data.

There are several threats to the validity of the Yamax pedometer. Slow walking, obesity, and pregnancy can lead to undercounting of steps when using spring-lever pedometers. At 1.5 miles/hour (mph) it records 75% of actual steps, and at 2.0 mph it records 88% of actual steps.[5,10] The Yamax digi-walker undercounts steps to a greater degree in obese populations.[11,12] This limitation is due to decreased sensitivity as the pedometer is tilted away from the vertical axis.[11] In addition, the Yamax undercounts in pregnant women during the second and third trimesters, and hence it is not recommended for use in that population.[13] Overcounting errors are rare, but can occur when driving motor vehicles. The Yamax digi-walker records 6–10 erroneous steps while driving a distance of 10 miles.[14] Although some pedometers are susceptible to double-counting steps during brisk walking or running, the Yamax digi-walker is designed to avoid this error.

New Lifestyles NL-2000 pedometer

The New Lifestyles NL-2000 ($70) is a small pedometer worn on the waist (Fig. 2). It contains a piezoelectric accelerometer. An accelerometer is a mechanism that measures accelerations of the trunk or limbs during human movement. The number of steps can be determined by counting peaks or zero crossings of the acceleration versus time curve. One difference between the accelerometer and the spring-lever mechanisms is that an accelerometer can

Figure 3 Omron pedometer, model HJ-720 ITC.

determine the precise magnitude of the vertical accelerations that occur during walking and running, whereas the spring-lever mechanism exhibits an 'all-or-none' response.

The NL-2000 allows the user characteristics (age, height, weight, and gender) to be entered, and it uses these data to compute the resting metabolic rate. The output data include steps, activity calories, and total calories (resting + activity). One advantage of the NL-2000 is that it correctly estimates about 120 kcal to run a mile, and 80 kcal to walk a mile for a 70 kg person, even though it requires about 1000 steps to run a mile, and 2000 steps to walk a mile. This is due to the device's ability to detect the increased impact force of running steps, as opposed to walking steps. The NL-2000 can store activity data over 8 days, in 1-day epochs. Battery life is approximately 10 months.

The NL-2000 yields highly accurate step counts at walking speeds of 3.0 mph and faster, but it under-counts to a similar degree as the Yamax SW-701 at slower speeds.[10] In normal-weight individuals, it measures a similar number of steps per day as the Yamax SW-200.[7] The NL-2000 is not affected by adiposity, and has similar accuracy in lean, over-weight, and obese individuals.[11] The NL-2000 has a cover that can be secured shut to reduce reactivity. Due to the 7-day memory capacity of the NL-2000, researchers can collect a week's worth of data in 1-day epochs, and then retrieve it by scrolling through the data.

Omron HJ-720 ITC pedometer

The Omron HJ-720 ITC ($35) is a pedometer that can be worn in a pocket, around the neck, or on a belt clip (Fig. 3). It uses two accelerometers mounted at 90° to each other, so the orientation of the pedometer within the pocket does not matter (i.e., it can be rotated 360°) as long as front side of the pedometer is within 30° of vertical. The Omron HJ-720 ITC uses the acceleration versus time curves to determine step counts.

The Omron HJ-720 ITC allows user characteristics (age, height, weight, and gender) to be entered. The output includes steps, aerobic steps (accumulated in continuous bouts of 10 minutes or longer), minutes for aerobic steps, amount of fat and calories burned, and distance. Up to 41 days of activity data can be stored in memory (the most recent 7 days are displayed and can be retrieved by scrolling through them). Battery life is approximately 6 months.

The Omron HJ-720-ITC comes with a USB cable and software for installation on a personal computer. A researcher can set up a user account for each subject, connect the pedometer to the computer with the USB cable, and click a button to download the activity data. All data for a single user are combined in a single account, which can be viewed in any number of ways: by hour of the day, by day of the month, or by month of the year. The ability to view the number of steps taken during each hour of the day is a major advantage because it allows researchers to assess pedometer 'wear time'. Any hour during which steps are taken will have a blue horizontal line above it, and adding up the number of lines tells you the daily wear time. (This is helpful in ensuring compliance with instructions to wear the pedometer during all waking hours of the day.) The Omron pedometer greatly simplifies data management; for instance, it pieces together the early and late parts of a day if it is downloaded in the middle of a day, and it automatically reports the total steps for that day.

The Omron HJ720 ITC pedometer is reported to be extremely accurate during laboratory and track walking, at moderate and brisk speeds.[15] Like the Yamax SW-200 and NL-2000, it fails to detect all of the steps taken at slow walking speeds. The Omron HJ720 ITC is unaffected by body mass index.[16] However, one feature of this pedometer is that it has a 4-second filter, meaning that it only records steps taken in walking bouts of 4 seconds or longer.[17] If a person walks for 3 seconds and stops, these steps are 'lost' and will not be recorded. For this reason, the Omron is likely to record fewer steps during activities of daily living than other pedometers. Nevertheless, the Omron is highly accurate for detecting steps taken during continuous walking bouts[15,18] regardless of body mass index, so it is well suited to walking interventions in overweight/obese individuals.

The Omron pedometer has been used in various clinical settings. Richardson *et al.*[19] used the Omron HJ-720 ITC in an Internet-based physical activity intervention with diabetic patients recruited from a medical centre. Participants all wore the Omron pedometer, and they were randomized into two groups targeting different goal setting strategies: (i) lifestyle goals targeting total daily steps; and (ii) structured goals targeting walking bouts of 10 minutes or longer, at a stepping rate of at least 60 steps/minute. Over 6 weeks, both groups achieved similar

Figure 4 StepWatch 3 pedometer, worn on the ankle.

Figure 5 ActiGraph accelerometer-based activity monitor.

increases in daily step counts, and study completers increased their bout steps by 1921 ± 2729 steps per day (mean $\pm$ SD). However, goals that emphasized total daily steps were more acceptable to participants.

StepWatch 3 pedometer

The StepWatch 3 ($525 + $1400 for docking station and software) is an ankle-mounted pedometer that is worn on an elastic band secured around the ankle with Velcro (Fig. 4). It is a small ($70 \times 50 \times 20$ mm; 38 g) unit that records the number of strides taken every minute for up to 2 months between downloads. With continual use, the estimated StepWatch 3 battery life is 7 years. Unlike the three devices described above, the StepWatch 3 has no display screen to provide immediate feedback to the user. Hence, it is primarily intended to be a measurement instrument, rather than a motivational device.

The principals of operation for the StepWatch 3 pedometer are proprietary information that the company has not disclosed. There is a moving device inside that feels and sounds much like a spring-levered pedometer, but it also contains a custom sensor that is not a traditional accelerometer. User characteristics (age, height, weight, and stepping speed) are input into the software during the initialization procedure, and are used to 'tune' the sensitivity of the device. A researcher can quickly determine whether the StepWatch 3 is detecting strides, by verifying that a test light on the device blinks each time a stride is taken. (One stride equals two steps.)

The StepWatch 3 is placed in a docking station connected to a computer, and the data are then downloaded. The output includes steps, and the software allows a researcher to determine the percentage of steps taken at slow (<30 steps/minute), medium (30–80 steps/minute), and fast (>80 steps/minute) stepping rates. These cut-points were determined by the company based on empirical observations on a couple of hundred subjects, but users also have the option to select other cut-points. The StepWatch 3 stores data in user-defined epochs ranging from 3 to 180 seconds.

In terms of accuracy, the StepWatch 3 is the most accurate pedometer ever designed for walking, and it is capable of detecting the number of actual steps taken to within $\pm 3\%$ for speeds ranging from 1 to 5 mph.[10] It is not affected by adiposity or pregnancy, due to its location on the ankle.[16,20] Thus, three of the major threats to validity of waist-mounted pedometers (slow walking, obesity, and pregnancy) are not a concern with the StepWatch 3. Researchers have examined the effects of other potential sources of error, including car driving, heel tapping, stationary cycling, and leg swinging.[10] Car driving resulted in virtually no erroneous steps being recorded, while heel tapping registered only about 29 erroneous steps, when tapping at a rate of 120 per minute. The StepWatch 3 records bicycle pedal revolutions and leg swinging, but in most Americans these errors would be unlikely to have a large impact on steps per day.[10] In summary, the StepWatch 3 is valid for clinical populations who walk slowly, including frail elderly individuals,[21,22] stroke patients,[23] and youth with cerebral palsy[24] and muscular dystrophy.[25] Some researchers have suggested that the StepWatch is a valuable criterion measure of steps per day for validating other devices.[26]

ActiGraph

The ActiGraph (Pensacola, FL, USA) is one of the most widely used activity monitors in physical activity research, and has been around for over 20 years (Fig. 5). It is usually worn at the waist, and does not have a display screen to provide feedback to the user. Hence, it is intended for measurement of physical activity, not for motivating people to exercise. Vertical accelerations of up to ± 2.00 G are measured in 0.05 G increments, at multiple time points each second. The raw accelerations are converted to a digital signal, filtered, full wave rectified, and integrated to yield 'counts'. The number of counts/minute is typically used to provide an estimate of intensity that roughly corresponds to a rate of energy expenditure (EE). Data can be

downloaded to a computer for subsequent analysis, using the ActiLife website.

There have been several generations of ActiGraphs, starting with those produced by Computer Science and Applications and Manufacturing Technologies Inc. The current company (ActiGraph) began producing the 7164 model, which used a uniaxial cantilever-beam accelerometer, capable of sensing dynamic accelerations. With the introduction of the GT1M model in the early 2000s, the ActiGraph moved to a microelectrical mechanical sensor (MEMS) capacitive accelerometer. There are three major advantages of the MEMS capacitive accelerometers: (i) lower manufacturing cost; (ii) better manufacturing tolerances reduce the variability in output and eliminate the need for individual calibration; and (iii) they are able to measure both static accelerations (due to gravity) and dynamic accelerations (due to movement). The current ActiGraph GT3X ($300) uses a MEMS accelerometer that is capable of measuring acceleration in three planes (vertical, front-to-back, and side-to-side).

The ActiGraph memory capacity has increased over time, and now stands at 16 MB of non-volatile memory, with 20-day battery life. Unlike the devices described thus far, the ActiGraph counts must be translated into meaningful units such as metabolic equivalents (METs), kcal/kg/minute, or the amount of time spent in light, moderate, and vigorous activities. Many researchers have developed and validated single regression models for the ActiGraph accelerometer to convert counts/minute to EE (for review, see Ref. 27). Thus, researchers face the question of which ActiGraph regression equation to use. To date, there has been no consensus as to which of these regressions equations is the best, with the result that there is little consistency across studies in how ActiGraph data are analysed. This hinders comparisons of ActiGraph physical activity data across studies.

The ActiGraph has several other limitations. First, while it does a good job of discriminating between different walking speeds in the range of 2–5 mph, it does a poor job of discriminating between running speeds in the range of 6–12 mph. This has been called the 'plateau phenomenon' whereby as speed increases from 3 to 12 mph, ActiGraph counts level off at around 6 mph and then at faster speeds they even decline slightly. In addition, ActiGraph regressions based on walk/jog activities have been proven to underestimate EE of moderate-intensity lifestyle activities by as much as 50%, and will often misclassify them as light, rather than moderate. This leads to a large underestimation of time spent in moderate activity.[28] ActiGraph regression equations developed on moderate-intensity lifestyle activities (e.g., walking, yard work, housework, shopping, and childcare) are significantly better at predicting the EE of these types of activities, but are not accurate for light and vigorous activities.[27]

Figure 6 Actical accelerometer-based activity monitor.

Despite these limitations, the ActiGraph is the most widely used activity monitor in research studies, and it adequately discriminates between people with varying levels of physical activity (although the data may not be quantitatively accurate). Output variables include EE, and time spent in light, moderate, and vigorous activity. 'Wear time' can be determined by excluding periods of 60 or more consecutive minutes where the accelerometer output=0 counts/minute.[29,30] In addition, researchers have used a threshold of 100 counts/minute to discriminate between sedentary behaviours and light activity, although the validity of using 0–100 counts/minute to identify sitting has not been well established. The MEMS ActiGraph models have a step-count function, which is accurate for walking speeds of 83 and 133 m/minute, although it undercounts steps at 50 m/minute. The daily step values from the ActiGraph 7164 are approximately 12% higher than those obtained with the Yamax digi-walker.[31]

Actical

The Actical accelerometer (Philips Respironics, Bend, OR, USA) is a small omni-directional accelerometer that is typically worn at the waist (Fig. 6). Although omni-directional, the device is most sensitive to accelerations in the vertical axis. The Actical ($327 + $738 for reader and software) records accelerations ranging from 0.05 to 2.0 G. Battery life is 180 days, and up to 44 days of data can be stored in 1-minute epochs.

Similar to the ActiGraph, the Actical converts raw acceleration data into 'counts' that can be stored at 15, 30, or 60-second epochs. The count data are then downloaded to a computer for later analysis. As with other physical activity monitors, numerous regression equations have been developed to translate Actical counts into EE. Several equations have been developed for adults[32–34] and for children.[35–38] (For an overall review of objective monitoring in youth, see Ref. 39.) As noted previously, the use of various

Figure 7 RT3 accelerometer-based activity monitor.

Figure 8 SenseWear Pro3 Armband, worn on the upper arm.

regression equations for converting counts to EE limits the ability to draw comparisons across studies. And while EE estimates may not be quantitatively accurate for estimating EE, the Actical is able to discriminate between individuals who vary in their levels of daily physical activity.

The Actical records fewer counts per day than the ActiGraph, when both are worn simultaneously. Paul *et al.*[40] found that the Actical detected a significantly smaller amount of daily physical activity, compared to the ActiGraph (188 ± 101 counts/minute versus 216 ± 106 counts/minute). The Actical does not show a plateau in counts at higher running speeds, possibly due to the use of a wider band-pass filter than that used by the ActiGraph. However, one study reported that the Actical had the lowest interdevice reliability out of the four devices tested (ActiGraph, Biotrainer Pro, Tritrac-R3D, and Actical).[41] On the other hand, a mechanical shaker study found that Actical had the best intra- and interdevice reliability of three devices (Actical, ActiGraph, and RT3).[42] Despite these possible limitations, the Actical is a widely used accelerometer-based activity monitor, especially in 3- to 5-year-old children.[43]

RT3 activity monitor

The RT3 activity monitor (Stayhealthy, Inc., Monrovia, CA, USA) is a triaxial accelerometer-based device that has gained acceptance in clinical studies (Fig. 7). It replaced the Tritrac R3D device,[44] but the output of the two devices is not identical. The RT3 ($500) fits into a plastic holster that is affixed to the wearer's belt. It uses two AAA batteries and has a battery life of 60 days. The RT3 has an LCD display on top that features a status indicator, full memory alert, and elapsed time. Data can be downloaded to computer via a docking station, and the software then estimates activity EE (METs or kcal/minute) based on counts.

Unlike the ActiGraph and Actical, the RT3 uses proprietary equations to convert acceleration counts to activity EE. This simplifies data reduction for end users, and it also provides more consistency across studies. However, researchers have no knowledge of how EE is being estimated, and must accept the output variables (kcals, and time spent in light, moderate, and vigorous physical activity) at face value. However, some researchers have begun developing their own cut-points for the RT3 in child and adolescent populations.[45]

The limited validity studies performed to date indicate that the RT3 performs in a manner similar to the ActiGraph and Actical. In a validation study using structured activity bouts, the RT3 overestimated activity EE for all activities combined, overestimated TM activities by 9%, and underestimated activities of daily living by 34%, compared to indirect calorimetry.[46] The RT3 underestimates total EE by 539 kJ (4%) and activity EE by 485 kJ (15%), on average.[46] In terms of reliability, the RT3 has been found to have good reliability within RT3 units, but poor reliability among RT3 units.[45,47]

SenseWear Pro Armband

The SenseWear Pro Armband (BodyMedia, Inc., Pittsburgh, PA, USA) is a relatively new type of activity monitor that uses multiple sensors to detect acceleration, skin temperature, skin galvanic response, and heat flux (Fig. 8). It is worn on the upper arm, and it sends a radio signal to a wristwatch. The SenseWear wristwatch displays total daily EE, activity EE, steps, time spent in various intensity zones, and sleep duration.

The SenseWear Pro Armband and wristwatch ($500 + $2400 for software) uses proprietary software to estimate physical activity data. This device uses 'pattern recognition' to predict EE based on numerous inputs. Two studies examined the validity of an early version of the SenseWear Pro Armband. Jakicic *et al.*[48] found that when a generalized proprietary algorithm was applied to the data, the device significantly underestimated the energy cost of walking (by 6.9%), cycle ergometry (by 28.2%), and stair stepping (by 17.7%), and it overestimated the energy cost of arm ergometry (by 29.3%). At the researchers'

request, the company developed exercise-specific algorithms that improved the prediction and resulted in non-significant differences in EE between indirect calorimetry and the SenseWear for these activities. Fruin and Rankin[49] found that the SenseWear Pro Armband was valid and reliable for measuring resting EE, but it overestimated the EE of level treadmill walking and underestimated the EE of treadmill walking up an incline. In addition, another study found that the SenseWear Pro Armband overestimated the EE of level treadmill walking and running.[50]

Subsequently, a SenseWear Pro 2 Armband was developed and improved through the use of 'training data sets'. The SenseWear Pro 2 has been validated in children.[51] The mean per cent errors in EE with the new algorithms were: resting (20.7%), colouring (4.0%), computer games (4.9%), walking at 2 mph (0.9%), walking at 2.5 mph (0.6%), walking at 3.0 mph (3.5%), and biking (25%). A study in children 11–14 years of age found that the SenseWear Pro 2 underestimated the cost of most physical activities, and the underestimation increased with increasing exercise intensity.[52] Since BodyMedia is targeting individuals interested in weight loss, it is important to know if the device is accurate in obese individuals. In a doubly labelled water validation study, the SenseWear Pro 2 with software version 5.1, but not version 6.1, was found to be valid in overweight and obese children.[53] A recent study found that this device had poor accuracy in obese adults during cycle ergometry, stair stepping, and treadmill walking, which led the authors to conclude that there is a need for obesity-specific algorithms.[54]

The SenseWear Pro 3 Armband is the latest version of this device. Dudley *et al.*[55] compared it to simultaneous measurements made by indirect calorimetry, during 18 structured activities. The mean values of EE during nine activities estimated by the SenseWear Armband were within $\pm 16\%$ of the actual values. However, the device underestimated EE during tennis, road running, and track running by 20% or more. Johannsen *et al.*[56] compared the SenseWear Pro 3 Armband and SenseWear Mini (a consumer version) against a criterion method over 14 consecutive days. The average total daily energy expenditure was within 112 kcal per day of the criterion for the SenseWear Pro 3 Armband and within 22 kcal per day of the criterion for the Mini, although the mean absolute percentage error was similar for both monitors (SenseWear Armband: $8.1 \pm 6.8\%$ error; Mini: $8.3 \pm 6.5\%$ error). In general, the SenseWear Pro 2 Armband predicts EE more accurately than a waist-mounted accelerometer. The SenseWear Armband accuracy seems to be improving over time, but researchers should follow the results of validation studies and be aware of which software version they are using.

Conclusions

In summary, devices to monitor physical activity have become more sophisticated and accurate in recent years. While some devices require research participants to record the data each night in an activity log, newer devices have sufficient battery life and memory capacity to store minute-by-minute activity data over several weeks, and download it to a computer. For motivational purposes, a simple, low-cost step counter may suffice, and these are more feasible from a cost standpoint. However, if physical activity EE is a desired outcome variable, more sophisticated accelerometer-based devices have some advantages. Accelerometer-based devices provide several output variables (kilocalories, time spent in moderate and vigorous activity, monitor 'wear time', and steps), but not all of these devices contain a digital display that provides immediate feedback to the user. Physical activity monitors (even those worn on the ankle or arm) are generally well tolerated by clinical populations, including cardiac, pulmonary, kidney, muscular, or neurological diseases. However, further improvements are needed to enhance the accuracy of EE estimates for different types of activities, and assessment of EE in the free-living environment.

Acknowledgements

This work was supported by NIH R21 CA 122430.

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