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Review of physical activity measurement using accelerometers in older adults: Considerations for research design and conduct

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Abstract

Objective.—Accelerometers are being increasingly used in studies of physical activity (PA) among older adults, however the use of these monitors requires some specialized knowledge and up-to-date information on technological innovations. The purpose of this review article is to provide researchers with a guide to some commonly-used accelerometers in order to better design and conduct PA research with older adults.

Methods.—A literature search was conducted to obtain all available literature on commonly-used accelerometers in older adult samples with specific attention to articles discussing research design.

Results.—The use of accelerometers in older adults requires a basic understanding of the type being used, rationale for their placement, and attention to calibration when needed. The updated technology in some monitors should make study conduct less difficult, however comparison studies of the newer versus the older generation models will be needed.

Conclusions.—Careful considerations for design and conduct of accelerometer research as outlined in this review should help to enhance the quality and comparability of future research studies.

Keywords

Physical activity; Measurement; Review

Engagement in physical activity (PA) is a health behavior that can positively impact the severity and course of chronic diseases. The health benefits include decreased mortality rates; lower incidence of developing diseases; maintenance of conditions such as hypertension, diabetes, and obesity; reduction of fall risk; improvement in mood and well-being; and the lessening of functional decline (Pate et al., 1995; Taylor et al., 2004; Kahn et al., 2002; Karmisholt et al., 2005). Physical activity is also particularly beneficial to people with osteoarthritis, a leading cause of disability among older adults (Centers for Disease and Prevention, 2001). Studies have shown that PA of different intensities can

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prevent or forestall disability in people with osteoarthritis (Dunlop et al., 2005; Feinglass et al., 2005; Penninx et al., 2001). Even participation in low intensity activities has been found to be protective against the development of difficulty in activities of daily living such as stair climbing, walking, and bathing over a 2 year period.(Feinglass et al., 2005).

Physical activity measurement

Physical activity is often assessed using self-report measures. These measures are easy to administer and can provide information on the types of activities performed, but may not capture activity patterns throughout the day (Davis and Fox, 2007). Some measures also include calculations to estimate energy expenditure based on the duration and frequency of reported activity participation (Dipietro et al., 1993; Stewart et al., 2001). However, there are some disadvantages to using self-report measures such as recall bias, and in older adults in particular, self-report may also be influenced by fluctuations in health status and mood, depression, anxiety, or cognitive ability (Rikli, 2000). In addition, self-report PA measures designed for younger adults have been shown to be inaccurate when given to older adult samples, particularly underestimating the performance of light and moderate intensity activities (Washburn, 2000).

Objective PA measures have been increasingly used to overcome limitations of self-report measures. Accelerometry, in particular, provides information on the amount, frequency, and duration of PA (Plasqui and Westerterp, 2007). Data can be obtained about daytime and nighttime activity patterns and activity intensity (including estimates of energy expenditure) as they occur in people's daily lives. Although accelerometry provides only crude information on the types of activity in which people participate, Crouter et al. (2006) devised a statistical method using variability of estimates, specifically the coefficient of variation, to differentiate “free-living” activities (i.e. those that occur in a non-structured way during daily routines) from activities such as walking and running.

Objective PA measurement techniques can assess free-living activity which, similar to structured exercise, has been shown to have health benefits. It was recently shown that participation in nonexercise PA (such as housework and climbing stairs) improves mortality risk (Matthews et al., 2007). Other interventions that are designed to build PA (such as walking and stair climbing) into daily routines have shown effects of improved physical fitness in obese women (Andersen et al., 1999) and improved physical function and pain in recent breast cancer survivors (Basen-Engquist et al., 2006). Incorporating free-living activity into the daily routines of older adults is one potential way to promote long-term adoption of PA engagement.

Energy expenditure is often of interest to measure in studies when the outcome is activity intensity. Doubly-labeled water is considered the gold standard to measure energy expenditure over time. It is a method of indirect calorimetry in which carbon dioxide production is tracked from metabolism of specific isotopes in the labeled water. The technique is expensive and requires specific expertise, therefore it is not feasible in many clinical studies or in larger field and epidemiological studies.

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This paper will focus on the use of accelerometers which are now often preferred in clinical studies due to their feasibility and general ease of use. Despite the frequent use of these monitors, there is no concise guide for researchers when using them in older adult populations.

Older adults and physical activity

There are several issues concerning physical activity measurement that are unique to the older adult population. First, older adults differ from younger adults and children in the type and intensity of activities in which they engage. Compared to the other age groups, older adults spend a higher percentage of their day performing low intensity activities and a lower percentage performing high intensity activities (Westerterp, 2008). These patterns may be due to age-related changes which include loss of flexibility, decreased bone and muscle mass, and decreased ability of the cardiac and respiratory systems to adapt to more intense physical activity (Skinner, 2006). Second, age-related declines in basal metabolic rate and decreased fat free mass may contribute to errors in energy expenditure calculations that were developed using younger adult samples. Third, chronic conditions increase in prevalence with aging and can affect physical activity levels. Fourth, problems with memory and recall among older adults may affect compliance of wearing monitors over a series of days.

This review paper seeks to provide some necessary information when designing and conducting a study using an accelerometer in older adult samples and will also focus on recently updated technology. A literature search was conducted to obtain all available literature from 1998–present on commonly-used accelerometers in older adult samples with specific attention to articles discussing research design. The literature search only spanned the last 10 years because this was thought to be best reflective of technology that still may be in use. A variety of search strategies were used to identify relevant articles. Using the electronic databases MEDLINE and CINAHL, search terms were: physical activity, physical activity measurement, energy expenditure, accelerometers, accelerometry, actiwatch, actigraph, review, validity, reliability, adults, older adults, and elderly. In addition, the author's own bibliographic records were searched as well as a search of the reference lists of research articles and review articles. After all literature was retrieved, it was organized for this review around main considerations of using an accelerometer, information about the different types and new technology, and other aspects of choosing a monitor for older adult samples.

Accelerometer types

The most commonly used accelerometers have piezo-electric sensors. Piezo-electric sensors measure acceleration due to movement and there are two main types, the cantilever beam and the integrated circuit (IC) chip. A thorough explanation of these sensors can be found in Chen and Bassett, 2005 and Mathie et al., 2004. Because the type of sensor in an accelerometer impacts the design and protocol of studies, some basic information will be presented here. The cantilever beam technology is named for the beam that is attached to a support at one side that contains a piezoelectric element and a seismic mass. When acceleration is detected by the seismic mass, it causes the piezoelectric element in the beam

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to bend and record a voltage signal (Chen and Bassett, 2005). The amplitude of the voltage signal is in proportion to the acceleration detected (Mathie et al., 2004).

The IC chip technology is in many of the newer generations of activity monitors. It also has a piezoelectric element and seismic mass that detects acceleration, but the sensor is fully enclosed in a package that is directly affixed on an electronic circuit board. This is advantageous in particular because it enhances durability and repeatability of the monitors. Among these newer generation accelerometers, some have a rechargeable battery as opposed to coin cell batteries which may reduce supply costs for researchers. Another important enhancement among some of the newer generation accelerometers (such as the Actiwatch Spectrum) is a skin conductance feature that can help researchers distinguish sedentary activity from not wearing the monitor. Given that older adults generally engage in many sedentary activities, this feature will increase the accuracy of overall physical activity estimates.

Table 1 shows some common accelerometer brands by the type of technology and identifies the newer generation brands where possible. One advantage of using accelerometers with the cantilever beam technology is that there is a body of literature on validity and reliability of these monitors (see Table 2). Most literature on daytime physical activity using accelerometry involves the use of the Actigraph (Actigraph LLC) brand monitors, where most literature on nighttime activity and sleep patterns involves the use of the Actiwatch (Mini Mitter Co) brand. The main disadvantage of using accelerometers with the cantilever beam technology is the need to be attentive to their calibration. Most companies test each monitor for its ability to sample data in a similar way before shipping. However, the cantilever beam accelerometers have the potential to break or become less reliable over time (Jack McKenzie, Director of Clinical Affairs, Mini Mitter Company, personal communication). Some manufacturers suggest preventive checks on monitors periodically which require them to be sent back to the company for recalibration. When using a cantilever beam accelerometer, it is recommended that researchers have a calibration protocol in place, especially when using the monitors over time in intervention studies and to check the monitors before and after their use in the field (Welk, 2005). In a large population-based study in which participants ranged from children to adults (Troiano et al., 2008), 5% of the accelerometers provided to participants for a week long wearing period were no longer within the calibration specifications set by the manufacturer when returned and the data were excluded. Although calibration may be more of an issue in studies involving children because their activity patterns involve sporadic bouts of vigorous activity (Welk et al., 2000), the reliability of accelerometers used in studies of older adults is still not clear. Researchers may use calibration tools developed by the manufacturers themselves or use a laboratory shaker to check that the monitors are functioning within an acceptable range of error, often represented by the coefficient of variability (Ward et al., 2005). Other suggestions to control for variability among monitors is to randomize them across participants in a study or consider adding the monitor worn as a variable in analysis to remove the error due to differences between monitors (Welk, 2005).

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Placement of monitors

In addition to monitor reliability, protocol decisions made by researchers may affect the validity of the output. The output of an accelerometer depends on the position at which it is placed, its orientation, posture, and activity being performed (Mathie et al., 2004. Because of this, different acceleration signals are recorded depending on placement.

Monitors record acceleration in different axes or planes of movement. These monitors are often described as uniaxial, biaxial, or triaxial for the axis or plane (e.g. vertical, anteroposterior, lateral) in which the monitor is most sensitive at detecting acceleration. Most commonly used cantilever beam monitors are usually referred to as "uniaxial" because they are most sensitive in the axis of bending (vertical). Some monitors have been described as "omni-directional" because the configuration of the cantilever also allows the piezoelectric element to bend in other directions; however, the contribution of these added directions are not distinguishable (Chen and Bassett, 2005). Some monitors may have more than one piezoelectric sensor to sample additional planes of movement. Table 2 has information about the specifications of some commonly-used monitors and provides some updated information from a previous review article (Trost et al., 2005).

In a clinical study, the type of monitor or monitors chosen depends on the motion of interest and the investigator's primary outcome variables. Whole body movement can be measured by a three dimensional monitor or by multiple monitors. Often one monitor is placed near the center of mass to approximate whole body movement and energy expenditure. However, the output of monitors depends on placement and is activity-specific. For example, upper extremity movement of stroke survivors has been assessed using a wrist-worn monitor (Green, 2007). Gait and balance have been assessed using hip or trunk worn accelerometers and a combination of monitors have been used to distinguish sit to stand movements in the clinic (Culhane et al., 2005). In addition, sleep and wake patterns are often measured using wrist-worn activity monitors (Morgenthaler et al., 2007); however, wrist worn accelerometers are not recommended to approximate energy expenditure (Trost et al., 2005).

When measuring energy expenditure, the hip or waist is the most common site to wear an accelerometer. The manufacturers have different instructions for how to don the monitors and may recommend wearing the monitor over one hip or anywhere on the waist. There is a lack of detailed information about positioning monitors in some common user manuals and positioning protocols may not be reported in research studies using the monitors. However, the positioning of monitors appears to be one potential source of error in studies. Welk (2002) found that a uniaxial monitor (the Actigraph) had significantly different results depending on which of three positions it was worn about the hip; however, no significant differences were seen on these three positions for the Biotrainer or Tritrac. In addition, which hip the monitor is worn on is also a consideration. In a recent study, the RT3 triaxial monitor worn on the left or right hips generated significantly different activity counts depending on its position during the performance of lab-based functional tasks for older adult participants (Sumukadas et al., 2008). Positioning of the monitor can also be an issue when data are collected over a series of days (Welk, 2005) because of less supervision and guidance on wearing it appropriately. Having a snug fit between the monitor and the

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person has been recommended to limit extraneous movement (Actigraph, 2008). It is not clear whether different options of wearing the device (for example having the monitor on a belt clip versus on a waist belt) contributes to significant differences in activity counts. In the future, more studies are needed to examine the variability of the actual placement of monitors in field-based studies among older adult participants and whether this affects physical activity estimates.

Number of days worn

Another consideration for using accelerometers is the length of time they are worn. Trost et al. 2005 outlines a commonly-used technique (variance partitioning) in which researchers determine the number of days needed to be measured to achieve a desired level of reliability based on the expected between and within subject variance. The number of days sampled depends on the outcome of interest (i.e. habitual physical activity, time spent in moderate intensity activity, inactivity) although typically the sampling period is between 3 and 7 days (Trost et al., 2005). If nighttime activity, such as sleep patterns, is of interest, recent practice parameters recommend at least 3 days of monitor wear (Morgenthaler et al., 2007). Gretebeck and Montoye (1992) suggested that both weekend and weekdays should be sampled, although it is not yet clear from studies if there is sufficient variability between these types of days for older adults.

Compliance and periods of missing data

Compliance by participants wearing accelerometers may also be inconsistently reported in the research literature. Several different approaches can be undertaken by researchers to promote compliance including a daily monitoring log filled out by participants, reminder phone calls, adequate education about the monitor and its proper wear, and identification of potential barriers to wearing with each participant (Trost et al., 2005). Concrete instructions about compliance may be particularly important to provide for older adults given issues with memory and recall. Based on personal experience using accelerometers with older adults, the daily logs are a fundamental tool for data analysis to determine times when the watch was not worn and have been consistently completed by participants. We also include compliance instructions in the daily logs. Because missing data periods can bias the results, imputation strategies are recommended (Catellier et al., 2005; Ward et al., 2005). There are no universal guidelines for data manipulation in the accelerometer literature, however, for study comparability, it is important that researchers clearly state their protocol for monitor wear and their decision rules for handling missing and spurious data (Masse et al., 2005). Consistency in using one monitor in studies of older adults could help build the evidence base along with standard protocols; however, the choice of monitor should depend on the outcome of interest and other factors discussed later in the paper.

Limitations of accelerometers

Accelerometers can be used to approximate energy expenditure, however, they do not capture the full energy cost of certain activities, such as walking while carrying a load or walking uphill, because acceleration patterns do not change under these conditions (Welk, 2002). Physical activity may also be underestimated depending upon the placement of the monitor. Other limitations include the financial cost of monitors, staff time to process and analyze data, and problems with monitor placement when data are collected over a number of days (Dale, Welk, and Matthews, 2002). In addition, although raw activity counts are frequently reported in studies, they are not easily interpretable.

Other methods of assessment

There are other methods of assessment that may be of interest to researchers to assess physical activity. Pedometers are inexpensive compared to methods such as doubly-labeled water or accelerometry. They are easy to use and can provide participants with feedback about their performance which may be an appealing feature for use in physical activity intervention studies. The main physical activity outcome using pedometers is step counts. The disadvantages of pedometers include inaccuracy in measurement of daily energy expenditure (Bassett et al., 2000) and lack of ability to measure physical activity patterns. For frail older adults, pedometers may not be an optimal method for assessment as accuracy is reduced at slow speeds (Cyarto et al., 2004; Le Masurier and Tudor-Locke, 2003). Pedometer accuracy is also reduced for people who have variable gait patterns (Cyarto et al., 2004) and for obese individuals (McClung et al., 2000). Some pedometers have piezoelectric components and have improved accuracy at slow speeds over traditional pedometers (Foster et al., 2005). For example, the Stepwatch-3 activity monitor is an ankle-worn pedometer with a piezoelectric component that also can measure physical activity patterns and is more accurate than other pedometers at slow speeds (Karabulut et al., 2005; Foster et al., 2005). However, it is also more expensive and requires a docking station and software.

Heart rate monitoring is another method of PA assessment, particularly for approximating energy expenditure. These monitors are inexpensive and can also provide information about activity duration and intensity; however, energy expenditure estimates can be confounded by other factors that increase heart rate such as caffeine or stress (Melanson and Freedson, 1996). The SenseWear WMS armband is a monitor that combines accelerometry with other physiologic measures (e.g. heart rate, galvanic skin response); however, limited information is available on the field-use of this device. Some preliminary support for validity and reliability of energy expenditure estimates has been established from lab-based studies in adults (Fruin and Rankin, 2004; Jakicic et al., 2004).

Choosing an accelerometer

Table 3 lists some general considerations for choosing an accelerometer for use in studies with older adults. Mathie et al. (2004) state that there are three types of monitoring that researchers may be interested in which affects the choice of monitor: clinical assessment (such as a one-time assessment of a participant in their home environment), event monitoring (such as fall events), and longitudinal monitoring of general or specific movements. In addition, monitors like the Actiwatch-Score have an added feature to allow participants to enter in responses on a scale that can range from 0–10 which has been used to sample within-day symptoms in rheumatic populations (Kop et al., 2005; Murphy et al., 2008a) and to rate the frequency of use of health behaviors (Murphy et al., 2008b). It is important to be aware that although different monitors may measure similar dimensions of PA, the choice of monitor should be guided by what most accurately measures the

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primary outcome of interest with regard to feasibility and reduction of participant burden. Feasibility may include the size of the study, the memory capacity of the monitor, and practical considerations such as equipment, supply costs, and technical support available for data processing. Participant burden is also important to consider when determining whether to use one or more monitors, placement, and length of wear.

Many researchers are interested in approximating PA energy expenditure from accelerometers. This approximation is often done by using regression formulas provided by the accelerometer manufacturers. There is a large body of literature that examines how accelerometers estimate energy expenditure and a thorough review can be found in Chen and Bassett (2005). Recently a two level regression model was developed for both the Actical and Actigraph brand monitors across the same lab-based functional activities and participants in order to enhance comparability across these commonly-used monitors (Crouter and Bassett Jr., 2008, Crouter et al., 2006). This two-level method accounts for different types of activities that may improve the estimation of energy expenditure compared to a single regression model. However, more studies are needed to determine how well these equations estimate free-living PA and how they apply to older adult populations. In addition, the relationship between energy expenditure and PA may not always be linear (Chen et al., 2004; Ward et al., 2005) and nonlinear modeling has been shown to improve energy expenditure estimates in a study using a triaxial monitor (Chen and Sun, 1997). Future studies will be needed to develop population specific formulas to accurately estimate energy expenditure.

Future directions

The newer generation accelerometers offer some practical advantages to researchers and are tested by manufacturers to be equivalent to the older generation models. However, future studies will need to examine the generational comparability under different conditions. It is likely that the older monitors will still be actively used if they are already owned by researchers or generally available. In future publications, it will be important to know some of the measurement differences in these different generations of monitors in order to generalize across studies.

A few comparative studies of different generations of monitors have been published. Rothney and colleagues (2008a,b) found measurement differences among three generations of Actigraph brand accelerometers (the 7164, 71256, and the Actigraph GT1M). Specifically, compared to the older models, the GT1M had improved inter-monitor variability but decreased ability to monitor lower intensity activities. In a study of adolescents, Corder et al. (2007) found that the Actigraph GT1M model data was significantly different from the 7164 data when classifying time spent in light intensity versus sedentary activities.

Summary

The use of accelerometers in physical activity and older adult research has grown substantially in recent years. This article sought to provide a guide to the body of literature outlining use of these devices and update information on the recent technological advances that affect PA measurement. Careful considerations for design and conduct of accelerometer research will enhance the quality and comparability of future research studies.

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Table 1

Types of piezoelectric sensors in accelerometers by brand

Company	Cantilever beam	IC chip
Actigraph LLC, Pensacola, FL	Actigraph 7164 (formerly CSA, MTI)	Actigraph GT1M
	Actigraph 71256	
Mini-Mitter Company, Sun River, OR	Actiwatch-Score	
	Actiwatch-64	Actiwatch 2
	Actiwatch-L	Actiwatch Spectrum
	Actical	
IM Systems, Baltimore, MD	Actitrac	
	Biotrainer	
Stayhealthy Inc., Monrovia, CA	R3D-Tritrac	RT3- Triaxial Research Tracker

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Table 2

Overview of commonly-used accelerometers

Name	Manufacturer	Type[*]	Size and weight	Cost[†]	Placement	Epoch length	Memory capacity	What it provides	Validity/reliability[‡]
Actigraph Model 7164 [formerly CSA, MTI]	Actigraph LLC Pensacola, FL	Uniaxial	5.1×41×1.5 cm 45.5 g	N/A for purchase	Usually hip, also ankle/ wrist	Records activity in 5 s to 1 min. epochs	Records up to 22 d of data when using 1 min. epochs	Activity counts Energy expenditure	Welk et al., 2000 Welk et al., 2004 Freedson et al., 1998 Hendelman et al., 2000 Crouter et al., 2006 Rothney et al., 2008a,b Moeller et al., 2008 McClain et al., 2007 Esliger and Tremblay, 2006
Actical	Mini-Mitter Sunriver, OR	Uniaxial; Omni-directional	2.8×2.7×1.0 cm 17.5 g	$950 w/ software $450 per unit	Wrist, hip, or ankle	Records epochs from 15 s to 1 min.	Stores up to 45 d of data using 1 min. epochs	Activity counts Step counts Energy expenditure	Welk et al., 2004 Crouter et al., 2006 Rothney et al., 2008a,b Esliger and Tremblay, 2006 Esliger et al., 2007 Heil, 2006 Klippel NJ, 2003
Actiwatch AW16 or AW64	Mini-Mitter Sunriver, OR	Uniaxial; Omni-directional	2.8×2.7×1.0 cm 16 g	$1966 w/ software $985 per unit	Hip or wrist	Records epochs 15 s to 15 min	AW16 records up to 11 d of data using 1 min. epochs; AW64 up to 45 d	Activity counts Sleep quality	Chen et al., 2003 Gironda et al., 2007
Actitrac	IM Systems Baltimore, MD	Biaxial	5.6×3.8×13 cm 34 g	$799 per unit $399 for software $99 for cable	Wrist	Records epochs 2 s to 2 min	Records up to 44 d of data when using 1 min. epochs	Activity counts	Welk et al., 2003
Biotrainer	IM Systems Baltimore, MD	Biaxial	7.6×5×2.2 cm 51.1 g	$199 per unit $199 for software $99 for cable	Hip	Records activity in 15 s to 5 min. epochs	Records up to 22 d of data when using 1 min. epochs	Activity counts Converted into ‘g’ units or kilocalories expended	Welk et al., 2000 Welk et al., 2003
GT1M Actigraph	Actigraph LLC Pensacola, FL	Biaxial	33×3.7×1.8 cm 27 g	$335 per unit $349 for software	Hip or waist	Records activity in epochs of 1 s to several minutes	Records up to 378 d of data when using 1 min. epochs	Activity counts Step counts Energy expenditure Sleep quality	Corder et al., 2007 Rothney et al., 2008a,b
Actiwatch Spectrum	Mini-Mitter Sunriver, OR	Uniaxial; Omni-directional	49×3.7×1.4 cm 29.8 g	$1599 per unit $399 for reader/charger unit	waist	Records activity in 15 s to 1 min. epochs	Records up to 36 d of data when using 1 min. epochs	Activity counts sleep quality	
Actiwatch 2	Mini-Mitter Sunriver, OR	Uniaxial; Omni-directional	4.4×23×1 cm 16.1 g (with band)	$999 per unit $299 reader	waist	Records activity in 15 s to 1 min. epochs	Records up to 30 d of data when using 1 min. epochs	Activity counts Sleep quality	

Name	Manufacturer	Type*	Size and weight	Cost†	Placement	Epoch length	Memory capacity	What it provides	Validity/reliability‡
RT3-Triaxial Research Tracker [formerly R3D]	Stayhealthy Inc. Monrovia, CA	Triaxial	7.1×5.6×2.8 cm 65.2 g	$200 per unit $300 for docking station	Hip or waist	Records activity in 1 s to 1 min. epochs	Records up to 7 d of data when using 1 min. epochs	Activity counts for each plane: vertical, horizontal, mediolateral Energy expenditure	Rothney et al., 2008a,b Esliger and Tremblay, 2006 Powell and Rowlands, 2004

Note. s = seconds; min = minutes, d = days.

*Uniaxial refers to accelerometers which measure acceleration in one plane, usually vertical to the ground. Omni-directional refers to a single beam accelerometer that detects acceleration primarily in one plane but also incidentally in two others. Biaxial and triaxial refer to accelerometers which measure acceleration in two or three planes respectively.

†price quotes as of August, 2008.

‡Adult population articles concerning physical activity only.

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Table 3

Considerations for choosing a monitor

Type of monitoring
Lifestyle PA
Sleep
Exercise
Step counts
Energy expenditure
Optimal for assessing primary outcome variable
Ease of wear for subject
Monitor size
Monitor weight
Comfort of wear
Location of monitor
Clip versus belt
Water-proof
Length of monitor wear needed
Size and scope of study
Cost of monitor
Accessories
Software
Expertise among research team, university, technical support
Amount of data manipulation needed