

Review

Assessment of physical activity – a review of methodologies with reference to epidemiological research: a report of the exercise physiology section of the European Association of Cardiovascular Prevention and Rehabilitation

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Physical activity has a fundamental role in the prevention and treatment of chronic disease. The precise measurement of physical activity is key to many surveillance and epidemiological studies investigating trends and associations with disease. Public health initiatives aimed at increasing physical activity rely on the measurement of physical activity to monitor their effectiveness. Physical activity is multidimensional, and a complex behaviour to measure; its various domains are often misunderstood. Inappropriate or crude measures of physical activity have serious implications, and are likely to lead to misleading results and underestimate effect size. In this review, key definitions and theoretical aspects, which underpin the measurement of physical activity, are briefly discussed. Methodologies particularly suited for use in epidemiological research are reviewed, with particular reference to their validity, primary outcome measure and considerations when using each in the field. It is acknowledged that the choice of method may be a compromise between accuracy level and feasibility, but the ultimate choice of tool must suit the stated aim of the research. A framework is presented to guide researchers on the selection of the most suitable tool for use in a specific study. *Eur J Cardiovasc Prev Rehabil* 17:127–139 © 2010 The European Society of Cardiology

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Introduction

There is abundant evidence from both observational and clinical studies that moderate exercise is protective in the development of cardiovascular disease and atherosclerosis and many other chronic diseases [1,2]. Increasing

physical activity is a key component of recommendations to decrease morbidity and mortality [3]. Monitoring physical activity levels is important for surveillance and for assessing the effectiveness of interventions or public health initiatives aimed at increasing physical activity. Investigation of the dose–response relationship between physical activity and health outcomes is dependent on a reliable and valid responsive assessment of physical activity [4]. Assessing physical activity is fraught with difficulties as it is multidimensional, and no single method can capture all subcomponents and domains in

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the activity of interest. Crude measures of physical activity may have led to inconsistent and false-negative results for the association of physical activity (or inactivity) and disease risk in epidemiological studies [5]. Apart from improved measurement techniques, a number of issues would help to improve the assessment of physical activity, these include: well thought out research questions, an understanding of the dimensions of physical activity and related terminology, and the selection of the most appropriate tool(s) to measure the subcomponent(s) of interest. The aim of this study was to address these issues and provide researchers and clinicians with a framework when selecting a method to measure physical activity. From the outset it is acknowledged that the perfect assessment method does not exist; selection of a method must be based on careful consideration of its pros and cons, indications for use and the evidence to support it. In this review, special emphasis will be given to methodologies suitable for epidemiological studies and related theoretical issues (reliability and validity) will also be introduced. Finally, we will provide recommendations on different assessment methods for different types of studies.

Definitions

Physical activity and fitness

Physical activity is a different concept to physical fitness [6], although the two are often related. Physical activity has been defined as 'any bodily movement produced by skeletal muscles that results in caloric expenditure' [7]. Therefore, physical activity is commonly described by the following four dimensions: (i) frequency – 'the number of events of physical activity during a specific time period'; (ii) duration – 'time of participation in a single bout of physical activity'; (iii) intensity – 'physiological effort associated with participating in a special type of physical activity'; and (iv) type of activity [7]. Any assessment of physical activity should ideally measure all of these dimensions and account for day-to-day variation [8]. Three of these dimensions (i.e. intensity, frequency and duration) of physical activity are fundamental because their assessments provide the ability to calculate energy expenditure (EE) associated with physical activity.

It is assumed that in healthy normal-weight individuals at rest, the body oxygen consumption is approximately 3.5 ml/kg per min which equates to approximately 1 kilocalorie (kcal)/kg/h as 1 l of O₂ has an energy cost of approximately 5 kcal. This basal rate of oxygen consumption and associated calorie cost is said to be 1 metabolic equivalent (or 1 MET) and other activities can be expressed as multiples of 1 MET: in healthy adults, activities in the range of 1.8–2.9 MET are considered low intensity; 3.0–5.9 MET moderate intensity and ≥ 6.0 MET considered as vigorous intensity. A compendium of physical activities and their associated MET values

has been published for adults and recently for children and they are frequently used to ascribe intensities in the analysis of self-report measures of physical activity [9,10]. The assumptions underlying METs are not valid for children as they have a higher oxygen consumption relative to body mass at rest [11], and it does not hold for other groups such as obese people in which oxygen consumption expressed in relation to body weight is lower than in normal-weight individuals [12], and elderly people in which the basal metabolic rate is usually lower [13,14].

When assessing physical activity, the day-to-day and seasonal variability need consideration as they may influence on the number of days measured. Finally, researchers might be interested in which domain activity takes place. The domains of activity are usually defined as the household or domestic domain, the occupational domain, the transportation domain and the leisure time domain.

Exercise (or exercise training) is a component of leisure time physical activity, and is where planned, structured and repetitive bodily movements are performed to improve or maintain one or more components of physical fitness [7,15].

In contrast, physical fitness comprises cardiorespiratory endurance (assessed by either measured or estimated VO_{2max}), muscle endurance and muscle strength, both of which are specific to a muscle group and must therefore be measured individually. Flexibility, balance, agility and coordination are additional components of physical fitness [6,16]. An important distinction between physical activity and fitness is the intraindividual day-to-day variability; physical activity will undoubtedly vary on a daily basis, whereas fitness will remain relatively static, taking time to change. It is physical activity rather than physical fitness that is the subject of this review.

Reliability, validity and responsiveness

Three key concepts must be understood when considering the accuracy and precision of any measurement technique, that is, reliability, validity and responsiveness. One aspect of reliability is the reproducibility of a method, that is, the same results are obtained when the method is used by different independent assessors. Reliability is a prerequisite to validity. Validity refers to the ability of a measure to measure what it is supposed to measure. Criterion validity is when a method is validated against an objective method or gold standard method; the relationship is frequently reported as a correlation coefficient (Pearson or Spearman). Absolute validity is when the absolute outcome, for example EE or time spent in activity, is compared with the same result obtained by an objective instrument. Relative validity is when an instrument is validated against a similar

instrument. An example of relative validity is when a questionnaire is compared with another self-report instrument. Relative validity may be misleading, as a high correlation between two self-report instruments does not mean either method is valid as they may be subject to correlated error. The name of these different validities may differ between papers, but these definitions of the concepts are universal. Ideally, validity should be reported as the degree of agreement between methods [17], because correlation coefficients may be misleading [18]. A reliable questionnaire that overestimates physical activity to a large extent may correlate highly with an objective physical activity; these two measurements correlate but disagree. This questionnaire is considered valid to rank individuals (validity at the population level) but is not valid to measure physical activity with an absolute score (lack of validity at the individual level). Usually, self-reported instruments such as questionnaires show moderate to good reliability, poor to moderate criterion validity (i.e. correlation coefficients of about $r = 0.30$ to 0.40), whereas absolute validity is often poor.

Responsiveness (sometimes called sensitivity) refers to the ability of an instrument to detect change over time. Reliability and validity are requirements for responsiveness. A commonly used index of responsiveness is the effect size for paired differences. For example, a reliable and valid instrument that aims only to categorize people into broad categories of physical activity, for example low, moderate or high, may not be considered a sensitive instrument to detect subtle changes in activity over time.

Physical activity and energy expenditure

Physical activity energy expenditure (PAEE) is the most variable component of total energy expenditure (TEE), typically accounting for 15–30% of TEE. However, in extremely active individuals, PAEE may constitute 60–70% of TEE. As mentioned above, physical activity is undertaken in several domains all of which contribute to an individual's overall level of activity. It is widely accepted, although not empirically shown, that modern advances in technology, labour-saving devices and transport have resulted in a decrease in EE in all aspects of life [19]. It is not clear as to which domain contributes most to PAEE, and for many in the developed world, occupational physical activity is minimal [20]. If TEE is measured by doubly labelled water (DLW) or through direct or indirect calorimetry, the actual contribution of physical activity to EE can be calculated by subtracting resting metabolic rate from TEE. The accuracy of this is enhanced if a measure of resting metabolic rate is made rather than relying on estimates using standard equations. Indirect calorimetry measures oxygen consumption and provides an accurate measure of EE during rest and physical activities of varying intensities.

Overview of methods

The methods of assessing free-living physical activity or related EE can be summarized as:

- (1) Self-report – questionnaires; diaries; logs; recalls.
- (2) Objective measures – motion sensors: accelerometers and pedometers; heart rate (HR) monitoring; direct observation; and DLW.

These methods vary in the measured variables and therefore in their primary outcomes. However, it is possible to estimate EE from most of these methods either as the primary or secondary outcome (Table 1). These methods have been substantially reviewed elsewhere [21–24].

Roughly, the cost of an assessment method is inversely proportional to its accuracy; for example, self-report methods are the least expensive methods to administer and the least accurate, in contrast to, for example, room calorimetry, which is a highly accurate method of measuring EE in a controlled setting but expensive and bothersome. All methods should have a standard operating procedure that covers device initialization (if appropriate), subject administration or instruction, measures to ensure compliance and data handling. This review will focus on methods that can be applied in large scale, population-based studies and include self-report, and body motion sensing by accelerometry, HR monitoring and pedometry.

Self-reports

Self-report instruments are the most widely used tools to assess physical activity and include self or interviewer-administered (face-to-face or by phone) questionnaires, recalls and activity diaries [25]. Self-report method is the cheapest and easiest way to collect physical activity data from a large number of people in a short time. There are numerous limitations to self-reported methods, which include: difficulties in ascertaining the frequency, duration and intensity of physical activity, capturing all domains of physical activity, social desirability bias and the cognitive demands of recall [25]. The sequential cognitive processes underlying the storage of memories have been described [26] along with models explaining their retrieval [27], illustrating the complexity of the task especially to report durations. These issues along with problems with reliability, validity and sensitivity have been comprehensively summarized [28]. However, structured questionnaires provide an assessment of physical activity by domains, which is not obtained when using objective measurement of physical activity and may have the potential to provide valid estimates of PAEE and time spent at different intensity levels on group level.

Table 1 Overview of methods used to assess physical activity with reference to outcomes, validity and indications for use

Method	Measurement	Primary (1°) and secondary (2°) outcomes	Validity for assessing primary outcome and energy expenditure (EE)	Study sample and resources	Appropriate research aim
Doubly labelled water	CO ₂ production	1° – total energy expenditure	1°– valid	Suitable for all populations Moderate respondent burden Expensive	Precise measure of TEE does not provide information about the intensity, frequency, or duration of PA
Accelerometry	Acceleration of the body or body segments in one or more directions	1°– acceleration 2°– estimates of the intensity, frequency and duration of body movement	1°– valid Validity for measuring PAEE varies between monitors and types of activities. Valid at group level for free-living PAEE estimates	Suitable for all populations Low respondent burden Relative ease of data collection Software packages have improved, simplifying analysis Monitors have become cheaper making them feasible for large-scale studies	An objective measure of overall PA and time spent in activities of varying intensities, and provides an indicator of frequency and duration of activities
Heart rate monitoring	Heart rate i.e. beats per minute	1°– heart rate; intensity, frequency and duration of MVPA–VPA 2°– PAEE estimated using regression equations derived from individual or group calibration	1°– valid Valid at group level for estimating energy expenditure for higher intensity activities, improved by using individual calibration	Suitable for all populations Low respondent burden for short wearing times but may be problematic over longer periods Easy and quick for data collection and analysis Relatively cheap	An objective measure of PAEE and of time spent in different intensities of activity, also provides an indicator of frequency and duration of these activities
Combined heart rate and accelerometer devices	Acceleration of body and heart rate	1°– acceleration and heart rate; PAEE, intensity, frequency and duration of PA	1°– valid Valid for estimating PAEE at group level, evidence for validity in individuals emerging	Suitable for all populations Low respondent burden Relative ease of data collection Data analysis relatively complex Monitors relatively expensive, but are likely to become cheaper and have been used in large-scale studies	An objective measure of time spent in activities of varying intensities, and provides an indicator of frequency and duration of activities Evidence suggests suitable to measure PAEE
Pedometry	Step count	1°– number of steps taken	1°– valid Not valid to estimate EE during free living	Suitable for all populations; children may tamper or alter behaviour in response to readings in an open box monitor Low respondent burden Ease of data collection and analysis Cheap	Suitable to measure steps taken during walking
Direct observation	Categorization of activity	1°– number of bouts and time spent in activities of varying intensity 2°– estimates of energy expenditure by ascribing MET values	1°– valid to estimate PAEE	Traditionally been used in paediatric studies Software programs now available to ease data collection and recording No respondent burden Expensive as labour intensive	Detailed quantitative and qualitative information on PA undertaken for a specific time frame
Self-report	Time spent in different types of activities with varying intensities Time allocated to different domains of activity	1° – number of bouts and time spent in activities of varying intensities 2° – energy expenditure estimated by ascribing METs to reported activities for specified durations	1° – valid Not valid to estimate EE at individual level; varying validity for categorizing individuals into groups; and for ranking of individuals	Suitable for all populations; proxy reporters required for children and possibly the older person Low respondent burden Ease of data collection and analysis Cheap	Provides information on intensity, frequency, duration of activities and the domain(s) of activity Some tools provide qualitative information (types of activities) Surveillance tool

EE, energy expenditure; MET, metabolic equivalent; MVPA, moderate and vigorous physical activity; PA, physical activity; PAEE, physical activity energy expenditure; TEE, total energy expenditure; VPA, vigorous physical activity.

Commonly used self-report measures of physical activity and their associated validation studies were synthesized and published in a comprehensive journal supplement 10 years ago [29]. This collection includes the Baecke Physical Activity Questionnaire, the Godin Shepard Leisure Time Questionnaire, Paffenbarger Physical Activity Questionnaire, Bouchard’s Activity Diary and the recall developed by Sallis [30,31]. Other important

questionnaires have recently been developed which merit particular mention. The first is the International Physical Activity Questionnaire (IPAQ), which is available in a short form for surveillance, and in a longer form when more detailed physical activity information is required, both forms are available in a number of languages. The questionnaire was rigorously tested for reliability and validity [32] and this has been replicated in a number of

countries. In the Netherlands, the Short Questionnaire to Assess Health enhancing physical activity (Squash) was developed and tested for reproducibility and relative validity [33]. The Global Physical Activity Questionnaire (GPAQ) was developed under the auspices of the World Health Organisation and it collects information on participation in physical activity in three domains: activity at work, travel to and from places and recreational activities. Both the IPAQ and the GPAQ were developed for surveillance studies and the GPAQ more specifically for surveillance studies in developing countries. These instruments are not recommended for other purposes. Other questionnaires aiming at measuring the dose of physical activity by domains have been developed for investigative purposes. One of them is the EPIC Physical Activity Questionnaire 2 (EPAQ2), which has been developed and validated in England [34]. The Recent Physical Activity Questionnaire (RPAQ) developed from the EPAQ2 with a shorter time frame of 1 month instead of 1 year is currently under validation with promising results [35].

The Flemish Physical Activity Computerized Questionnaire (FPACQ) in employed/unemployed and retired people was developed in Belgium to assess detailed information on several dimensions of physical activity and sedentary behaviour over a usual week. A recent validation study concluded that the FPACQ is a reliable and reasonably valid questionnaire for assessing different dimensions of physical activity and sedentary behaviour [36]. Recently, a review of measures of television viewing time and other nonoccupational sedentary behaviour in adults concluded that this questionnaire has the strongest results for reliability and validity of any current measure of leisure-time sedentary behaviour [37].

The use of computerized questionnaires has several advantages compared with written surveys and can offer enormous possibilities in large-scale epidemiological studies [38]. An electronic survey can easily be standardized but at the same time is flexible, including explanatory material, prompts, error correction, menus, branches and skips. It is also cost and time saving because of the immediacy of data entry, elimination of coding errors, and offers the possibility of immediate scoring, reporting and interpreting of results. Moreover, because no written records exist, respondents also have a greater feeling of privacy and anonymity, giving rise to more honest reporting of sensitive information or reducing the amount of social desirability in the answer [39]. Finally, computer networks and the Internet allow large numbers of individuals to take the questionnaire at the same time [40]. Currently, apart from the FPACQ, the literature reveals only three studies in children or adolescents [41–43] and one study in adults [44] concerning the reliability and validity of computerized physical activity

questionnaires. As part of the ongoing InterAct study, (www.inter-act.eu) work is underway to assess the validity and reliability of a computerized RPAQ in 2000 adults from 10 different European countries using combined HR and movement sensing as the criterion method.

Self-reports for specific populations

Cognitive immaturity or degeneration makes self-report of physical activity difficult in the very young and elderly. Children's activity is unique, in that it is characterized by short bouts rather than more sustained periods of activity [45–47]. For this reason, specific recommendations of levels of desirable activity have been made for this age group [48]. Self-report is not viable in the young, [49] and previous day's recall has been suggested as the most appropriate method for children aged 10–11 years [30]. Decisions regarding the number of days, and which days of recall need to be made in the light of the study question [48]. It is necessary to rely on proxy reports for children (e.g. by parents or teachers), but the use of this technique is difficult as a child gets older and becomes more independent [47]. Activity diaries have been used successfully in adolescents [50,51].

The use of physical activity questionnaires, which have been designed and validated in younger populations, is inappropriate for the elderly [52]. Four questionnaires – the Modified Baecke Questionnaire, Zutphen Physical Activity Questionnaire, Yale Physical Activity Survey and Physical Activity Survey for the Elderly have been specifically designed for this segment of the population [53]. The elderly are a diverse population group in terms of physical and cognitive function and this is likely to be reflected in a wide range of activity levels and competence to self-report this activity.

Unlike objective measures of physical activity, self-reports are culturally very dependent. Validity results assessed in one population cannot be systematically extrapolated to other populations, ethnic groups or other geographical regions and limited questionnaires exist for nonwestern immigrants. Several validity studies for the use of questionnaires for specific populations have, however, recently been conducted. Most of these studies have addressed the validity of the IPAC and more research is required [53]:

- (1) Reliability and validity of the IPAQ-Chinese: the Guangzhou Biobank Cohort study [54];
- (2) The New Zealand Physical Activity Questionnaires: validation by heart-rate monitoring in a multiethnic population [55];
- (3) Concurrent validity of the International Physical Activity Questionnaire (IPAQ) in an Iiyiyiu Aschii (Cree) community [56].

Furthermore, information on psychometric properties for the use of physical activity questionnaires in populations with specific medical conditions is not always available. Specific questionnaires designed or validated in these populations need to be used to accurately evaluate daily physical activity [57–59].

Questionnaires should be clearly structured to guide the participant. They should preferably be comprised of closed questions and be ordered in a logical sequence. Questions must be unambiguous and explain the intent of the question clearly to the respondent; for example, the term 'exercise' may mean only activities which cause breathlessness to some, whereas a question about leisure-time walking or cycling will not capture active commuting to work. Leisure-time physical activity is a broad descriptor, and includes formal exercise programmes, such as walking, hiking, gardening, sport and dance [15]. Many questionnaires used in observational studies have focused on leisure-time physical activity but there is a danger in focusing on one aspect of physical activity [60]. This is particularly the case where the exact relationship between physical activity (e.g. EE or intensity) and health outcome (e.g. diabetes prevention) is not known. In addition, most of the physical activity questionnaires that focus on participation in sports have been developed for men [61].

Many questionnaires use the reported frequency and duration of activities to calculate EE of physical activity by ascribing MET values. It has been suggested that most questionnaires are unable to do this with accuracy [28,62]. However, questionnaires are able to give estimates of time spent in activities of various levels of intensity, and are able to rank people in levels of reported activity.

Despite the numerous validation studies already published, the validity of physical activity questionnaires for activity EE estimation remains unclear [63].

Considerations for researchers when using questionnaires

- (1) What exactly is the questionnaire designed to measure e.g. which dimension(s) and domain(s) of activity?
- (2) What is the time frame for the questionnaire?
- (3) Has the instrument been tested for reliability?
- (4) Has appropriate validation been undertaken, that is, against an objective measure?
- (5) Was the validation undertaken in a similar population?
- (6) What is the primary outcome of the questionnaire and does this fit with the research question?
- (7) How will the questionnaire be administered (face-to-face, by telephone, Internet, through post)?
- (8) Clear completion and return instructions must be provided.
- (9) Administration should follow a standard procedure.

- (10) How will data be cleaned, reduced and analysed?
- (11) What will constitute an outlier or an invalid recording?
- (12) What will be done with missing data, and in case of imputing data what will the basis of these decisions be?
- (13) For which population has the questionnaire been designed?
- (14) What is the responsiveness of the questionnaire?

Accelerometers

When a person moves, the body is accelerated in relation to muscular forces responsible for the acceleration of the body and, theoretically, to EE. Accelerometers measure acceleration of the body in one (vertical), two (vertical and medio-lateral) or three (vertical, medio-lateral and anterior-posterior) planes [64] by measuring the amplitude and frequency of acceleration [65]. Accelerometers do not always capture upper body movement or cycling, because the instrument is mostly positioned at the waist. The inability to measure all activities equally well is thus a limitation of accelerometry, but perhaps not a large one because activity monitors are reasonably accurate for measuring locomotor movement, which constitutes the bulk of daily activity (at least for adults) [66]. Accelerometers also underestimate the energy cost of walking on an incline or carrying heavy loads because the acceleration patterns remain essentially unchanged under these conditions, despite the increase in effort and subsequent energy cost required.

The device is enclosed in a case and typically attached to the hip (or lower back, ankle, wrist or thigh) by a strap; the wearing position is assumed not to be important, at least at a group level, but hip or lower back is probably preferable [67]. Not all monitors are waterproof and must therefore be removed before swimming and other water-based activities. A number of models are readily available, and studies have shown differences in results within and between models [68–71]. Regular mechanical calibration is recommended to overcome the former issue. The reader is referred to the following papers for the underlying scientific principles and technical specifications [64,72].

Accelerometry data are collected in 'real time' which means that patterns of activity can be determined [21]. There is a good relationship between counts and EE across many, but not all, activities. The strongest relationship is seen in walking and jogging activities, there is levelling off at higher intensities (i.e. running). Accelerometers are typically used to determine habitual activity, which necessitates measurement over multiple days; the actual number of days required is a subject of some debate [73]. There will be a range in day-to-day variation in different populations;

typically, it may be more variable in children requiring a longer wearing time, for example, 4–9 days, whereas 3–5 days is likely to be sufficient in many adult populations [67]. Depending on the anticipated compliance, consecutive days may be selected or two-three wearing occasions for a shorter period. It is important that the recording period allows for the measurement of activity during the week and also at weekends as activity levels may vary considerably between the two.

To correctly interpret the information from the recording period, it is important to account for the fact that the activity levels may also vary according to the season; activity levels have been shown to be higher during spring and summer compared with autumn and winter [74].

Detailed data are collected in a predetermined epoch; usually between 5 and 60 s. The raw data produced from many accelerometers are counts, which is the product of the amplitude and frequency of the vertical acceleration. Unfortunately, a count value is an arbitrary unit, which varies between monitor brands. Therefore, it is recommended to transform counts into units of acceleration (m/s^2) for between-monitors comparison. The output from activity monitors can be plotted against EE obtained during calibration activities and using cut-off values converted to time spent in different intensity levels (i.e. low intensity, moderately vigorous, vigorous) using regression equations. Estimates of PAEE from accelerometry can also be made using regression models derived from free-living measurements of PAEE by DLW but precision is low on an individual basis. However, calibration undertaken in a laboratory setting seems unsuitable for free-living populations [75], whereas free-living-derived equations may be able to predict PAEE at a group level [76].

The selection of a cut-off or intensity threshold can have an important bearing on the ascribing of intensity levels and is dependent on the activities performed when calibrating accelerometer output to EE [77,78]. Published data on cut point for sedentary activities from one of the most frequently used brands typically ranges from <100 to <800 counts per minute; for moderate intensity activities, the range is between 1900 and 8200 counts per minute. This variability means that time spent at different intensity levels will differ substantially in the same dataset dependent on the thresholds chosen. The reader is directed to useful papers on the issues surrounding calibration [73,78,79]. Recently, alternative methods, decision boundaries and receiver operating characteristic curves, have been proposed to determine cut points to reduce misclassification error [80]. More sophisticated approaches to data processing have been suggested to detect a multidimensional movement signature and assign a degree of membership to a (limited) set of activity types rather than the traditional

activity level which identifies activities of similar total acceleration but may have different energy costs [72].

The data produced from accelerometry are complex and lengthy but freely available programmes exist for data reduction and analysis, for example Mahuffe available from <http://www.mrc-epid.cam.ac.uk/Research/PA/Downloads.html>. One of the most challenging issues when working with accelerometry output data is managing missing data. The first decision is whether it is actually missing data rather than a sustained period of inactivity. Several studies use 10 min of 0 counts per minute as an indication of missing data, and remove such periods from analyses. Confusing inactivity and missing data would actually lead to a bias towards underestimating inactivity. There are two basic methods of data imputation: interpolation and average replacement [81]. Concurrent completion of an activity log can help identify reasons for non-wearing and help in ascribing appropriate values to these times. 'Decision rules' should be made at the planning stage of the study and reported in any subsequent publications. Such rules have been shown to have important bearing on outcome variables [82]. Recommendations of best practice in the use of accelerometers in the field and subsequent data handling are available [83].

Considerations for researchers when using accelerometers

- (1) One, two or three-dimensional accelerometry?
- (2) Decide the primary outcome of the study; total activity, type of activity, time spent at different intensity levels, or estimates of PAEE.
- (3) At the outset make a decision about the minimal wearing time to constitute a valid day.
- (4) What will constitute an outlier or an invalid recording?
- (5) What time interval will be selected?
- (6) What will be done with missing data, and if imputing data what will the basis of these decisions be?
- (7) How many days will be measured?
- (8) Is there going to be a time lag between initializing the monitor and participant wearing? If so, can the data analysis programme handle this delay?
- (9) How are accelerometers going to be distributed and returned, for example face-to-face or by mail?
- (10) Have sufficient instruction on placement, wearing and contact details been supplied?
- (11) Are participants going to be contacted by phone, SMS or email during the planned assessment to encourage compliance? Can incentives be used?
- (12) Are participants going to be asked to keep concurrent activity logs or detail wearing and non-wearing times?

Heart rate monitoring

There is a linear relationship between the increase in HR and the increase in EE during dynamic exercise involving

the large muscle groups. This relationship varies within and between individuals [84]; factors such as age, sex, weight and fitness level modulate this relationship [85] as do ambient temperature, body posture and emotional state such as anxiety or stress. Usually, PAEE is estimated from the linear relationship between HR and EE above a specific threshold, the flex HR point. This relationship is established during individual calibration while resting and for different intensities of physical activity (usually walking at different speeds on a treadmill). When HR drops below the flex point, resting EE is assumed. The flex HR method has been validated against free-living measurements of TEE and PAEE by DLW in children and adults and provides valid data at a group level [86,87]. However, one of the limitations of the method includes the lack of consensus on defining the flex HR point. To avoid the problems at low activity intensities, HR monitoring method should only be used to assess the time spent in moderate and vigorous activity. Numerous studies have shown that it is possible to estimate EE from HR using multivariate predictive equations derived from group data in adults [85,88–91] and children [92].

Considerations for researchers when using heart rate

- (1) What level of calibration is required?
- (2) If individual calibration is to be undertaken using indirect calorimetry, decide on which activities most likely will be performed by the volunteers while free living.
- (3) How many days will the monitor be worn?
- (4) How to decide on the flex point?
- (5) In data analysis what is going to constitute an outlier?
- (6) Provide practical information on how to use the monitor.
- (7) How are monitors going to be distributed and returned e.g. face-to-face, by mail? Have sufficient instructions on placement and wearing and contact details been supplied?
- (8) Are participants going to be contacted by phone, SMS or email during the planned assessment to encourage compliance? Can incentives be used?

Combined accelerometer and heart rate monitors

An important development in the assessment of physical activity is the combined accelerometry and HR monitor, an early model was developed and piloted nearly 10 years ago [93]. In these devices, the pros of each method are combined, thereby negating some of the disadvantages of each method used alone; in addition, the measurement error from the two methods is not correlated. At lower levels of intensity, HR is less accurate at estimating EE; this is the level that accelerometers are most accurate at. It can be difficult to determine non-wearing times in accelerometers but this will be readily apparent in a

combined device because of the measurement of HR. An additional advantage of this method is that these new monitors are waterproof and the intention is that participants do not remove, except to replace pads that have perished. One study has studied the effect of monitor placement on physical activity estimates during treadmill and free-living activities [94]. The study found that placement (i.e. above or below the sternum) had minimal effect on movement counts and estimates of EE; placement of the monitor below the sternum may be marginally preferable for HR data [94].

More recently, the reliability and validity of a combined movement sensor has been shown [95]. The combined motion sensor is an accurate predictor of EE [96]. Combined sensors have been validated in adults and children [97,98]. Branched equation modelling has been suggested as a method of determining the weightings of reliance on the accelerometer data and/or HR data depending on the intensity of the activity [99,100]. A study investigating a range of calibration techniques with decreasing levels of complexity showed that simple calibration techniques (treadmill and step test) achieve acceptable levels of accuracy for this device to be considered as an objective measure in population studies. Although the monitors are relatively expensive, they are currently being used in semi large-scale population-based studies (> 5000 participants) suggesting that they are a feasible option in epidemiological research.

Considerations for researchers when using combined accelerometer and heart rate motion sensors

In addition to the considerations for using accelerometers the following points should be thought through:

- (1) What level of calibration is required? Will calibration methods used commonly for fitness testing be adequate?
- (2) Is the participant confident and competent at placing the device, that is, have sufficient explanation and written instructions been given?
- (3) Supply participants with additional pads to replace as required.

Pedometers

Pedometers are relatively simple and inexpensive devices, which measure the number of steps taken. Early models used a mechanical gear, whereas newer versions are electronic [101]. A systematic review of the validity of pedometers compared with accelerometers, observation, EE and self-report concluded that they are a valid method for assessing physical activity when compared with measurement through accelerometry with a reported median correlation of $r = 0.86$ [102]. Better accuracy has been reported at faster walking speeds but not running; good correlations to estimate EE have been shown

between step counts and oxygen uptake in children expressed as body mass scaled ($O_2/kg^{-0.75} \text{ min}$) ($r = 0.806$ for all activities) [103]. Valid assessments of physical activity have also been found in adolescents [104]. Comparisons of the most common pedometers have found wide variation between a couple of models and a smaller variation among the rest with greatest agreement at speeds between 4.8 and 6.4 km/h [105] and differences in computed steps when models were worn concurrently [106]. These differences are because of the variation in how steps are counted and therefore comparisons between studies may not be easily done [101]. Vast differences between research grade pedometers and some commercially available models have been found [107]. Most pedometers are accurate in the measurement of the number of accumulated steps during walking, and may be useful when monitoring the effect of an intervention aimed at increasing walking. One of the most promising uses of pedometers is as a motivational tool to achieve a predetermined target of daily accumulated steps (see for example <http://aom.americaonthemove.org>). An advantage of pedometers is that they can also be used in elementary school children and preschool children [108,109], although a closed box may be preferable to prevent tampering.

The considerations for researchers when using pedometers are similar to many of those listed already for the use of accelerometers in practice.

Considerations for researchers when using pedometers

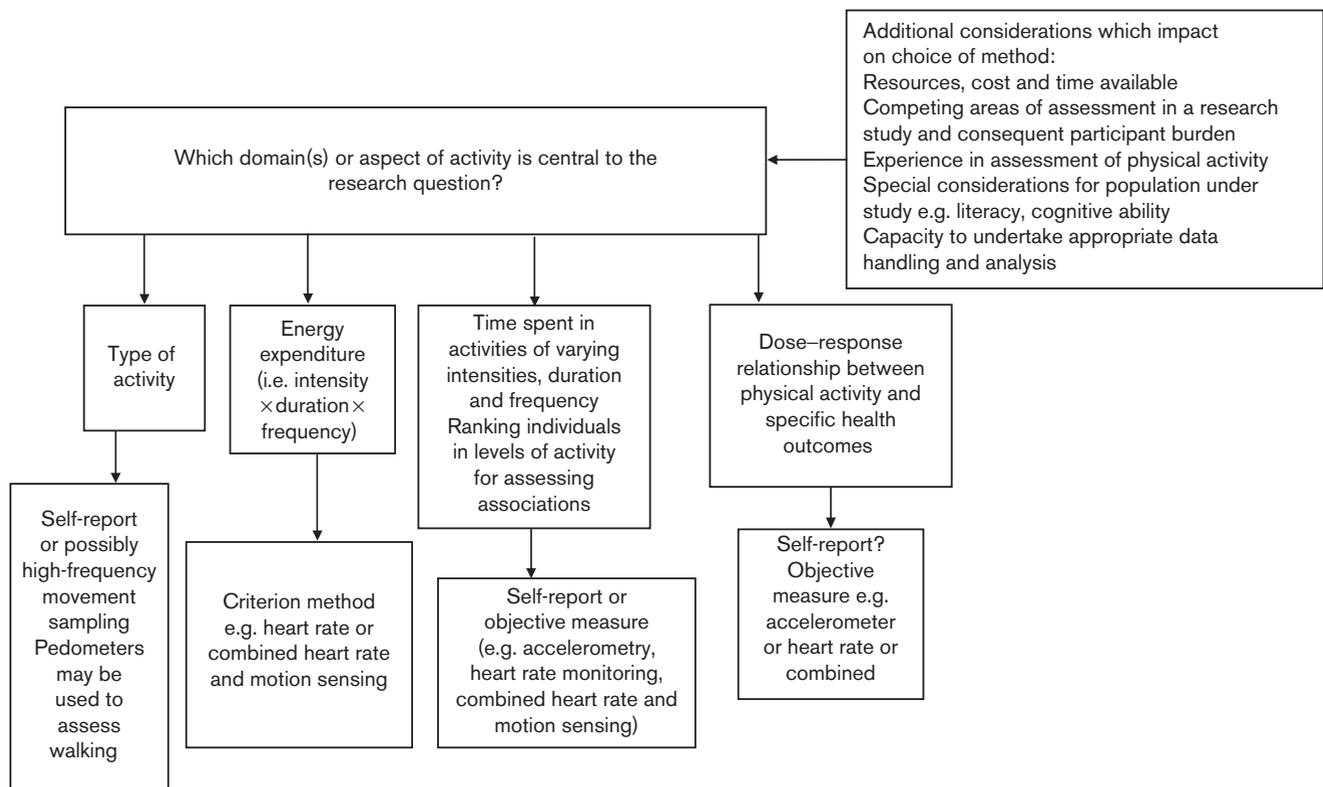
- (1) The aims and primary outcome of the study should be carefully considered to ascertain whether a pedometer would be an adequate measure of activity.
- (2) What type of activities is the population to be studied likely to engage in?
- (3) Similar to accelerometers, decisions should be made at the outset on the number of days and which days to be monitored and what will constitute valid wearing time.
- (4) Again, like other monitors, will incentives be offered to enhance compliance?
- (5) Higher quality and therefore more expensive models have been shown to be superior to cheaper models of pedometers.

Recommendations

Selection of an appropriate method

Selection of the method to assess physical activity is a crucial decision, yet it is often rushed and inadequately

Fig. 1



Guidance for the selection of an appropriate tool to assess physical activity.

throughout. Careful consideration must be given to the research question in the first place, and the dimension or domain of physical activity to be assessed. A thorough understanding of the pros and cons of each method is vital and these should be evaluated in the light of the practical aspects of the study (e.g. resources, participant numbers). Figure 1 provides a staged procedure for researchers faced with this selection issue.

The population under study merits a special mention. The choice of method must be appropriate to the age,

ethnicity and cognitive ability of the population. Attention should be paid to the practical considerations discussed above and thought must be given on how to maximize compliance with the measurement.

Influence of study type on methodology choice

The specific study type and design has an important bearing on the choice of method to measure physical activity. Table 2 summarizes appropriate methods for use in specific studies. A critical review of methods used in previous studies of a similar type is likely to be valuable to

Table 2 The assessment of physical activity with reference to study type

Study type	Study outcomes	Appropriate tool
Surveillance systems and surveys	Monitoring trends Comparisons within populations over time and between populations Walking specifically	Questionnaires which have demonstrated reliability and validity internationally i.e. IPAQ, GPAQ Pedometer
Observational large scale cohort studies (e.g. European Prospective Investigation into Cancer (EPIC) [111] Nurses Health Study [112] National Institute for Health-American Association of Retired Persons Diet and Health Study [113])	Association analyses between exposure(s) and outcome(s)	Self-report questionnaires that have been shown to be reliable and valid
Observational large-scale cohort studies in young people (e.g. European Youth Heart Study [114] Avon Longitudinal Study of Parents and Children [115])	Association analyses between exposure(s) and outcome(s)	Objective monitoring i.e. accelerometers or combined heart rate and motion sensing
Interventions and randomized controlled trials	Treatment and intervention effects	Objective monitoring i.e. accelerometers, heart rate monitoring and combined heart rate and motion sensing Doubly labelled water if investigating change in TEE or PAEE Pedometer if the intervention seeks to increase walking

GPAQ, Global Physical Activity Questionnaire; IPAQ, International Physical Activity Questionnaire.

Table 3 Advantages and disadvantages of methods used to assess physical activity

Method	Advantages	Disadvantages
Doubly labeled water	Suitable for all populations Moderate respondent burden Good precision of measure	Expensive Does not provide information about intensity, frequency or duration of physical activity
Accelerometry	Suitable for all populations Low respondent burden Objective indicator of body movement (acceleration) Provides information about intensity, frequency and duration Relatively easy data collection	Inaccurate assessment of a large range of activities Financial cost may prohibit assessment of large numbers of participants
Heart rate monitoring	Suitable for all populations Low respondent burden for short period Physiological parameter Provides information about intensity Good association with energy expenditure Easy and quick data collection Relatively cheap	Only useful for aerobic activities Conditions unrelated to physical activity can cause an increase in heart rate without a corresponding increase in VO ₂
Combined heart rate and accelerometer device	Suitable for all populations Low respondent burden Relative ease of data collection	Data analysis relatively complex Monitors relatively expensive
Pedometry	Suitable for all populations Low respondent burden Objective measure of common activity behaviour Easy data collection and analysis Cheap	Children may tamper or alter behaviour Are specifically designed to assess walking only Inability to record nonlocomotor movements Inability to examine the rate or intensity of movement
Direct observation	Mostly used in paediatric studies No respondent burden provides excellent quantitative and qualitative information	Expensive as labour intensive Observer presence may artificially alter normal physical activity patterns
Self-report	Suitable for all populations Low respondent burden captures quantitative and qualitative information Ease of data collection and analysis Cheap	Proxy reporters required for children and possibly elderly Reliability and validity problems associated with recall of activity

the researcher. Where comparisons between populations are required, replication of the same method should be evaluated. As discussed previously, several questionnaires have specifically been designed to enable cross-population comparisons (Table 2). The advent of technology means that objective measurement of physical activity is now affordable and feasible for large-scale studies and this has been incorporated in subsamples of national surveys (e.g. UK National Diet and Nutrition Survey, Health Survey England and the US National Health and Nutrition Examination Survey). When the remit of the study is to monitor trends, there may be a debate on whether to use the same tool for consistency or whether to move to a more accurate measure; a compromise may be possible. Ideally, the same instrument should be kept for temporal trend data and a new instrument, rigorously tested for its reliability and validity, must be introduced. In intervention studies, it is vital that the method chosen is sensitive to detect a treatment effect if present. Furthermore, the instrument should be able to capture changes in habitual physical activity because of possible compensation mechanisms, especially in older individuals [110].

The selection of method to assess physical activity may be a trade-off between degree of validity and feasibility, but the method must be suitable for the aims of the study (Table 3). The choice of a crude or inappropriate method will lead to crude and misleading outcome data.

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Conflicts of interest: none.

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References

- 1 Ignarro LJ, Balestrieri ML. C. Napoli, Nutrition, physical activity, and cardiovascular disease: an update. *Cardio Res* 2007; **73**:326–340.
- 2 Thompson PD, Buchner D, Pina IL, Balady GJ, Williams MA, Marcus BH, *et al.* Exercise and physical activity in the prevention and treatment of atherosclerotic cardiovascular disease: a statement from the Council on Clinical Cardiology (Subcommittee on Exercise, Rehabilitation, and Prevention). *Circulation* 2003; **107**:3109–3116.
- 3 Haskell WL, Lee IM, Pate RR, Powell KE, Blair SN, Franklin BA, *et al.* Physical activity and public health: Updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Med Sci Sports Exerc* 2007; **39**:1423–1434.
- 4 Wareham NJ, Rennie KL. The assessment of physical activity in individuals and populations: why try to be more precise about how physical activity is assessed?. *Int J Obes* 1998; **22**:S30–S38.
- 5 Lagerros YT, Lagiou P. Assessment of physical activity and energy expenditure in epidemiological research of chronic diseases. *Eur J Epi* 2007; **22**:353–362.
- 6 Vanhees L, Lefevre J, Philippaerts R, Martens M, Huygens W, Troosters T, *et al.* How to assess physical activity? How to assess physical fitness? *Eur J Cardiovasc Prev Rehab* 2005; **12**:102–114.
- 7 Caspersen C, Powell K, Christenson G. Physical activity, exercise and physical fitness: definitions and distinctions for health-related research. *Public Health Reports* 1985; **100**:126–135.
- 8 Armstrong N, Welsman JR. The physical activity patterns of European youth with reference to methods of assessment. *Sports Med* 2006; **36**:1067–1086.
- 9 Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, *et al.* Compendium of Physical Activities: an update of activity codes and MET intensities. *Med Sci Sports Exerc* 2000; **32**:S498–S516.
- 10 Ridley K, Ainsworth BE, Olds TS. Development of a Compendium of Energy Expenditures for Youth. *Int J Behav Nutr Phys Act* 2008; **5**:45.
- 11 Harrell JS, McMurray RG, Baggett CD, Pennell ML, Pearce PF, Bangdiwala SI. Energy costs of physical activities in children and adolescents. *Med Sci Sports Exerc* 2005; **37**:329–336.
- 12 Saris WH, Blair SN, van Baak MA, Eaton SB, Davies PS, Di Pietro L, *et al.* How much physical activity is enough to prevent unhealthy weight gain? Outcome of the IASO 1st Stock Conference and consensus statement. *Obes Rev* 2003; **4**:101–114.
- 13 Kwan M, Woo J, Kwok T. The standard oxygen consumption value equivalent to one metabolic equivalent (3.5 ml/min/kg) is not appropriate for elderly people. *Int J Food Sci Nutr* 2004; **55**:79–82.
- 14 Byrne NM, Hills AP, Hunter GR, Weinsier RL, Schutz Y. Metabolic equivalent: one size does not fit all. *J Appl Physiol* 2005; **99**:1112–1119.
- 15 Howley ET. Type of activity: resistance, aerobic and leisure versus occupational physical activity. *Med Sci Sports Exerc* 2001; **33**:S364–S369.
- 16 Haskell WL, Kiernan M. Methodological issues in measuring physical activity and physical fitness when evaluating the role of dietary supplements for physically active people. *Am J Clin Nutr* 2000; **72**:S41S–S50S.
- 17 Bland JM, Altman DG. Measuring agreement in method comparison studies. *Stat Methods Med Res* 1999; **8**:135–160.
- 18 Schmidt ME, Steindorf K. Statistical methods for the validation of questionnaires—discrepancy between theory and practice. *Meth Info Med* 2006; **45**:409–413.
- 19 Montoye HJ. Introduction: evaluation of some measurements of physical activity and energy expenditure. *Med Sci Sports Exerc* 2000; **32**:S439–S441.
- 20 Shephard RJ. Assessment of occupational fitness in the context of human rights. *Can J Sports Sci* 1990; **15**:89–95.
- 21 Melanson EL Jr. and Freedson PS. Physical activity assessment: a review of methods. *Crit Rev Food Sci Nutr* 1996; **36**:385–396.
- 22 Schutz Y, Weinsier RL, Hunter GR. Assessment of free-living physical activity in humans: an overview of currently available and proposed new measures. *Obes Res* 2001; **9**:368–379.
- 23 Pols MA, Peeters PH, Kemper HC, Grobbee DE. Methodological aspects of physical activity assessment in epidemiological studies. *Eur J Epi* 1998; **14**:63–70.
- 24 Freedson PS and Miller K. Objective monitoring of physical activity using motion sensors and heart rate. *Res Q Exer Sport* 2000; **71**:S21–S29.
- 25 Sallis JF, Saelens BE. Assessment of physical activity by self-report: Status, limitations, and future directions. *Res Q Exer Sport* 2000; **71** (2 Suppl):S1–S14.
- 26 Baranowski T, Domel SB. A cognitive model of children's reporting of food intake. *Am J Clin Nutr* 1994; **59**:S212–S217.
- 27 Willis G, Royston P, Bercini D. The use of verbal report methods in the development and testing of survey questionnaires. *Appl Cog Psychol* 1991; **5**:251–267.
- 28 Shephard RJ. Limits to the measurement of habitual physical activity by questionnaires. *Br J Sports Med* 2003; **37**:197–206.
- 29 Kriska A, Caspersen C. A collection of physical activity questionnaires. *Med Sci Sports Exerc* 1997; **29**:1–205.
- 30 Sallis JF, Buono MJ, Roby JJ, Micala FG, Nelson JA. Seven-day recall and other physical activity self-reports in children and adolescents. *S Med Sci Sports Exerc* 1993; **25**:99–108.
- 31 Sallis JF, Haskell WL, Wood PD, Fortmann SP, Rogers T, Blair SN *et al.* Physical-Activity Assessment Methodology in the 5-City Project. *Amer J Epi* 1985; **121**:91–106.

- 32 Craig CL, Marshall AL, Sjoström M, Bauman AE, Booth ML, Ainsworth BE, *et al.* International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc* 2003; **35**:1381–1395.
- 33 Wendel-Vos GCW, Schuit AJ, Saris WHM, Kromhout D. Reproducibility and relative validity of the Short Questionnaire to Assess Health enhancing physical activity. *J Clin Epidemiol* 2003; **56**:1163–1169.
- 34 Wareham NJ, Jakes RW, Rennie KL, Mitchell J, Hennings S, Day NE. Validity and repeatability of the EPIC-Norfolk Physical Activity Questionnaire. *Int J Epidemiol* 2002; **31**:168–174.
- 35 Besson H, Brage S, Jakes R, Ekelund U, Wareham N. Validation of the Recent Physical Activity Questionnaire (RPAQ). in Objective Measurement of Physical Activity: satellite meeting of the ICDAM6 Conference. 2006. Odense, Denmark.
- 36 Matton L, Wijndaele K, Duvigneaud N, Duquet W, Philippaerts R, Thomis M, *et al.* Reliability and validity of the Flemish physical activity computerized questionnaire in adults. *Res Q Exerc Sport* 2007; **78**:293–306.
- 37 Clark BK, Sugiyama T, Healy GN, Salmon J, Dunstan DW, Owen N. Validity and reliability of measures of television viewing time and other non-occupational sedentary behaviour of adults: a review. *Obes Rev* 2009; **10**:7–16.
- 38 Vereecken CA, Maes L. Comparison of a computer-administered and paper-and-pencil-administered questionnaire on health and lifestyle behaviors. *J Adolesc Health* 2006; **38**:426–432.
- 39 Turner CF, Ku L, Rogers SM, Lindberg LD, Pleck JH, Sonenstein FL. Adolescent sexual behavior, drug use, and violence: increased reporting with computer survey technology. *Science* 1998; **280**:867–873.
- 40 Schmitz N, Hartkamp N, Brinshwicz C, Michalek S, Tress W. Comparison of the standard and the computerized versions of the Symptom Check List (SCL-90-R): a randomized trial. *Acta Psychiatr Scand* 2000; **102**:147–152.
- 41 Philippaerts RM, Matton L, Wijndaele K, Balduck AL, De Bourdeaudhuij I, Lefevre J. Validity of a physical activity computer questionnaire in 12-to 18-year-old boys and girls. *Int J Sports Med* 2006; **27**:131–136.
- 42 McMurray RG, Harrell JS, Bradley CB, Webb JP, Goodman EM. Comparison of a computerized physical activity recall with a triaxial motion sensor in middle-school youth. *Med Sci Sports Exerc* 1998; **30**:1238–1245.
- 43 Ridley K, Dollman J, Olds T. Development and Validation of a Computer Delivered Physical Activity Questionnaire (CDPAQ) for Children. *Ped Exerc Sci* 2001; **13**:35–46.
- 44 Vandelanotte C, De Bourdeaudhuij I, Sallis JF, Spittaels H, Brug J. Efficacy of sequential or simultaneous interactive computer-tailored interventions for increasing physical activity and decreasing fat intake. *Ann Behav Med* 2005; **29**:138–146.
- 45 Kohl HW, Fulton JE, Caspersen CJ. Assessment of physical activity among children and adolescents: a review and synthesis. *Prev Med* 2000; **31**:S54-S76.
- 46 Sirard JR, Pate RR. Physical activity assessment in children and adolescents. *Sports Med* 2001; **31**:439–454.
- 47 Pate RR. Physical activity assessment in children and adolescents. *Crit Rev Food Sci Nutr* 1993; **33**:321–326.
- 48 Welk GJ, Corbin CB, Dale D. Measurement issues in the assessment of physical activity in children. *Res Q Exerc Sport* 2000; **71**:S59–S73.
- 49 Sallis JF. Self-report measures of children's physical activity. *J Sch Health* 1991; **61**:215–219.
- 50 Ekelund U, Yngve A, Sjoström M. Total daily energy expenditure and patterns of physical activity in adolescents assessed by two different methods. *Scand J Med Sci Sports* 1999; **9**:257–264.
- 51 Bratteby LE, Sandhagen B, Fan H, Samuelson G. A 7-day activity diary for assessment of daily energy expenditure validated by the doubly labeled water method in adolescents. *Eur J Clin Nutr* 1997; **51**:585–591.
- 52 Washburn RA. Assessment of physical activity in older adults. *Res Q Exerc Sport* 2000; **71**:79–88.
- 53 Wolin KY, Heil DP, Askew S, Matthews CE, Bennett GG. Validation of the International Physical Activity Questionnaire-Short among Blacks. *J Phys Act Health* 2008; **5**:746–760.
- 54 Deng HB, Macfarlane DJ, Thomas GN, Lao XQ, Jiang CQ, Cheng KK, *et al.* Reliability and validity of the IPAQ-Chinese: the Guangzhou Biobank Cohort study. *Med Sci Sports Exerc* 2008; **40**:303–307.
- 55 Moy KL, Scragg RK, Mclean G, Carr H. The New Zealand Physical Activity Questionnaires: validation by heart-rate monitoring in a multiethnic population. *J Phys Act Health* 2008; **5** (Suppl 1):S45–61.
- 56 Egelund GM, Denomme D, Lejeune P, Pereg D. Concurrent validity of the International Physical Activity Questionnaire (IPAQ) in an liyiyi Aschii (Cree) community. *Can J Public Health* 2008; **99**:307–310.
- 57 Verbunt JA, Huijnen IP, Koke A. Assessment of physical activity in daily life in patients with musculoskeletal pain. *Eur J Pain* 2008; **13**:231–242 [Epub ahead of print 10 July 2008]
- 58 Liang H, Tomey K, Chen D, Savar NL, Rimmer JH, Braunschweig CL. Objective measures of neighborhood environment and self-reported physical activity in spinal cord injured men. *Arch Phys Med Rehabil* 2008; **89**:1468–1473.
- 59 Le Grande MR, Elliott PC, Worcester MU, Murphy BM, Goble AJ. An Evaluation of Self-report Physical Activity Instruments Used in Studies Involving Cardiac Patients. *J Cardiopulm Rehabil Prev* 2008; **28**:358–369.
- 60 Wareham NJ. Epidemiological studies of physical activity and diabetes risk, and implications for diabetes prevention. *Appl Physiol Nutr Metab* 2007; **32**:778–782.
- 61 Oguma Y, Shinoda-Tagawa T. Physical activity decreases cardiovascular disease risk in women: review and meta-analysis. *Am J Prev Med* 2004; **26**:407–418.
- 62 Macfarlane DJ, Lee CC, Ho EY, Chan KL, Chan D. Convergent validity of six methods to assess physical activity in daily life. *J Appl Phys* 2006; **101**:1328–1334.
- 63 Neilson HK, Robson PJ, Friedenreich CM, Cszimadi I. Estimating activity energy expenditure: how valid are physical activity questionnaires? *Am J Clin Nutr* 2008; **87**:279–291.
- 64 Chen KY, Bassett DR. The technology of accelerometry-based activity monitors: current and future. *Med Sci Sports Exerc* 2005; **37**:S490–S500.
- 65 Trost SG, Ward DS, Moorehead SM, Watson PD, Riner W, Burke JR. Validity of the computer science and applications (CSA) activity monitor in children. *Med Sci Sports Exerc* 1998; **30**:629–633.
- 66 Welk GJ. *Physical activity assessments for health-related research*. Champaign IL: Human Kinetics; 2002.
- 67 Trost SG, Mciver KL, Pate RR. Conducting accelerometer-based activity assessments in field-based research. *Med Sci Sports Exerc* 2005; **37**:S531–S543.
- 68 Eslinger DW, Tremblay MS. Technical reliability assessment of three accelerometer models in a mechanical setup. *Med Sci Sports Exerc* 2006; **38**:2173–2181.
- 69 Plasqui G, Westerterp KR. Physical activity assessment with accelerometers: an evaluation against doubly labeled water. *Obesity* 2007; **15**:2371–2379.
- 70 Welk GJ, Blair SN, Wood K, Jones S, Thompson RW. A comparative evaluation of three accelerometry-based physical activity monitors. *Med Sci Sports Exerc* 2000; **32**:S489–S497.
- 71 Welk GJ, Schaben JA, Morrow JR. Reliability of accelerometry-based activity monitors: a generalizability study. *Med Sci Sports Exerc* 2004; **36**:1637–1645.
- 72 Pober DM, Staudenmayer J, Raphael C, Freedson PS. Development of novel techniques to classify physical activity mode using accelerometers. *Med Sci Sports Exerc* 2006; **38**:1626–1634.
- 73 Reilly JJ, Penpraze V, Hislop J, Davies G, Grant S, Paton JY. Objective measurement of physical activity and sedentary behaviour: review with new data. *Arch Dis Child* 2008; **93**:614–619.
- 74 Kristensen PL, Korsholm L, Moller NC, Wedderkopp N, Andersen LB, Froberg K. Sources of variation in habitual physical activity of children and adolescents: the European youth heart study. *Scand J Med Sci Sports* 2008; **18**:298–308.
- 75 Nilsson A, Andersson SA, Andersen LB, Froberg K, Riddoch C, Sardinha LB. Between- and within-day variability in physical activity and inactivity in 9- and 15-year-old European children. *Scand J Med Sci Sports* 2008; **19**:1–9.
- 76 Ekelund U, Sjoström M, Yngve A, Poortvliet E, Nilsson A, Froberg K, *et al.* Physical activity assessed by activity monitor and doubly labeled water in children. *Med Sci Sports Exerc* 2001; **33**:275–281.
- 77 Freedson P, Pober D, Janz KF. Calibration of accelerometer output for children. *Med Sci Sports Exerc* 2005; **37**:S523–S530.
- 78 Matthews CE. Calibration of accelerometer output for adults. *Med Sci Sports Exerc* 2005; **37**:S512–S522.
- 79 Welk GJ. Principles of design and analyses for the calibration of accelerometry-based activity monitors. *Med Sci Sports Exerc* 2005; **37**:S501–S511.
- 80 Jago R, Zakeri I, Baranowski T, Watson K. Decision boundaries and receiver operating characteristic curves: new methods for determining accelerometer cutpoints. *J Sports Sci* 2007; **25**:937–944.
- 81 Catellier DJ, Hannan PJ, Murray DM, Addy CL, Conway TL, Yang S, *et al.* Imputation of missing data when measuring physical activity by accelerometry. *Med Sci Sports Exerc* 2005; **37**:S555–S562.
- 82 Masse LC, Fuemmeler BF, Anderson CB, Matthews CE, Trost SG, Catellier DJ, *et al.* Accelerometer data reduction: A comparison of four

- reduction algorithms on select outcome variables. *Med Sci Sports Exerc* 2005; **37**:S544–S554.
- 83 Ward DS, Evenson KR, Vaughn A, Rodgers AB, Troiano RP. Accelerometer use in physical activity: best practices and research recommendations. *Med Sci Sports Exerc* 2005; **37**:S582–S588.
- 84 Li R, Deurenberg P, Hautvast JG. A critical evaluation of heart rate monitoring to assess energy expenditure in individuals. *Am J Clin Nutr* 1993; **58**:602–607.
- 85 Dugas LR, Van Der Merwe L, Odendaal H, Noakes TD, Lambert EV. A novel energy expenditure prediction equation for intermittent physical activity. *Med Sci Sports Exerc* 2005; **37**:2154–2161.
- 86 Ceesay SM, Prentice AM, Day KC, Murgatroyd PR, Goldberg GR, Scott W, *et al.* The use of heart-rate monitoring in the estimation of energy-expenditure—a validation-study using indirect whole-body calorimetry. *Br J Nutr* 1989; **61**:175–186.
- 87 Livingstone MBE, Prentice AM, Coward WA, Ceesay SM, Strain JJ, McKenna PG, *et al.* Simultaneous Measurement of Free-Living Energy-Expenditure by the Doubly Labeled Water Method and Heart-Rate Monitoring. *Am J Clin Nutr* 1990; **52**:59–65.
- 88 Hilloskorpi HK, Pasanen ME, Fogelholm MG, Laukkanen RM, Manttari AT. Use of heart rate to predict energy expenditure from low to high activity levels. *Int J Sports Med* 2003; **24**:332–336.
- 89 Rennie KL, Hennings SJ, Mitchell J, Wareham NJ. Estimating energy expenditure by heart-rate monitoring without individual calibration. *Med Sci Sports Exerc* 2001; **33**:939–945.
- 90 Strath SJ, Swartz AM, Bassett DR, O'Brien WL, King GA, Ainsworth BE. Evaluation of heart rate as a method for assessing moderate intensity physical activity. *Med Sci Sports Exerc* 2000; **32**:S465–S470.
- 91 Keytel LR, Goedecke JH, Noakes TD, Hilloskorpi H, Laukkanen R, Van Der Merwe L, *et al.* Prediction of energy expenditure from heart rate monitoring during submaximal exercise. *J Sports Sci* 2005; **23**:289–297.
- 92 Livingstone MBE, Robson PJ, Toton M. Energy expenditure by heart rate in children: an evaluation of calibration techniques. *Med Sci Sports Exerc* 2000; **32**:1513–1519.
- 93 Rennie K, Rowsell T, Jebb SA, Holburn D, Wareham NJ. A combined heart rate and movement sensor: proof of concept and preliminary testing study. *Eu J Clin Nutr* 2000; **54**:409–414.
- 94 Brage S, Brage N, Ekelund U, Luan J, Franks PW, Froberg K, *et al.* Effect of combined movement and heart rate monitor placement on physical activity estimates during treadmill locomotion and free-living. *Eur J Appl Physiol* 2006; **96**:517–524.
- 95 Brage S, Brage N, Franks PW, Ekelund U, Wareham NJ. Reliability and validity of the combined heart rate and movement sensor Actiheart. *Eur J Clin Nutr* 2005; **59**:561–570.
- 96 Strath SJ, Bassett DR, Swartz AM, Thompson DL. Simultaneous heart rate-motion sensor technique to estimate energy expenditure. *Med Sci Sports Exerc* 2001; **33**:2118–2123.
- 97 Crouter SE, Churilla JR, Bassett DR. Accuracy of the Actiheart for the assessment of energy expenditure in adults. *Eur J Clin Nutr* 2007; **62**:704–711.
- 98 Corder K, Brage S, Wareham NJ, Ekelund U. Comparison of PAEE from combined and separate heart rate and movement models in children. *Med Sci Sports Exerc* 2005; **37**:1761–1767.
- 99 Brage S, Brage N, Franks PW, Ekelund U, Wong MY, Andersen LB, *et al.* Branched equation modeling of simultaneous accelerometry and heart rate monitoring improves estimate of directly measured physical activity energy expenditure. *J Appl Physiol* 2004; **96**:343–351.
- 100 Thompson D, Batterham AM, Bock S, Robson C, Stokes K. Assessment of low-to-moderate intensity physical activity thermogenesis in young adults using synchronized heart rate and accelerometry with branched-equation modeling. *J Nutr* 2006; **136**:1037–1042.
- 101 Melanson EL, Knoll JR, Bell ML, Donahoo WT, Hill JO, Nysse LJ, *et al.* Commercially available pedometers: considerations for accurate step counting. *Prev Med* 2004; **39**:361–368.
- 102 Tudor-Locke C, Williams JE, Reis JP, Pluto D. Utility of pedometers for assessing physical activity: convergent validity. *Sports Med* 2002; **32**:795–808.
- 103 Eston RG, Rowlands AV, Ingledew DK. Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. *J Appl Physiol* 1998; **84**:362–371.
- 104 Jago R, Watson K, Baranowski T, Zakeri I, Sunmi YM, Baranowski J, *et al.* Pedometer reliability, validity and daily activity targets among 10-to 15-year-old boys. *J Sports Sci* 2006; **24**:241–251.
- 105 Crouter SE, Schneider PL, Karabulut M, Bassett DR. Validity of 10 electronic pedometers for measuring steps, distance, and energy cost. *Med Sci Sports Exerc* 2003; **35**:1455–1460.
- 106 Schneider PL, Crouter SE, Bassett DR. Pedometer measures of free-living physical activity: comparison of 13 models. *Med Sci Sports Exerc* 2004; **36**:331–335.
- 107 Tudor-Locke C, Sisson SB, Lee SM, Craig CL, Plotnikoff RC, Bauman A. Evaluation of quality of commercial pedometers. *Can J Public Health. Revue Canadienne de Sante Publique* 2006; **97**:S10–S15.
- 108 Cardon G, De Bourdeaudhuij I. A pilot study comparing pedometer counts with reported physical activity in elementary schoolchildren. *Pediatr Exerc Sci* 2004; **16**:355–367.
- 109 Cardon G, De Bourdeaudhuij I. Comparison of pedometer and accelerometer measures of physical activity in preschool children. *Pediatr Exerc Sci* 2007; **19**:205–214.
- 110 Westterterp KR. Physical activity as determinant of daily energy expenditure. *Physiol Behav* 2008; **93**:1039–1043.
- 111 Khaw KT, Jakes R, Bingham S, Welch A, Luben R, Day N, *et al.* Work and leisure time physical activity assessed using a simple, pragmatic, validated questionnaire and incident cardiovascular disease and all-cause mortality in men and women: the European Prospective Investigation into Cancer in Norfolk prospective population study. *Int J Epi* 2006; **35**:1034–1043.
- 112 Colditz GA, Hankinson SE. The Nurses' Health Study: lifestyle and health among women. *Nat Rev Cancer* 2005; **5**:388–396.
- 113 Schatzkin A, Subar AF, Thompson FE, Harlan LC, Tangrea J, Hollenbeck AR, *et al.* Design and serendipity in establishing a large cohort with wide dietary intake distributions—The National Institutes of Health-American Association of Retired Persons Diet and Health Study. *Am J Epi* 2001; **154**:1119–1125.
- 114 Riddoch C, Edwards D, Page A, Froberg K, Anderssen SA, Wedderkopp N, *et al.* The European Youth Heart Study—cardiovascular disease risk factors in children: rationale, aims, study design, and validation of methods. *J Phys Act Health* 2005; **2**:115–129.
- 115 Golding J, Pembrey M, Jones R, ALSPAC Team. ALSPAC—The Avon Longitudinal Study of Parents and Children—I. Study methodology. *Paediatr Perinatal Epidemiol* 2001; **15**:74–87.