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Physical activity assessment in the general population; instrumental methods and new technologies

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Abstract

The objective measurement of human movement and the quantification of energy expenditure due to physical activity is an identified need in both research and the clinical setting. Validated and well-defined reference methods (double labelled water, direct calorimetry, indirect calorimetry) are expensive and mostly limited to the laboratory setting. Therefore, in the last years, several objective measurement devices have been developed which are appropriate for field studies and clinical settings. There is no gold standard among them, as all have limitations. Pedometers are small, non-expensive, count the steps taken and give information on total physical activity, but not about physical activity patterns and behaviour. Accelerometers are expensive, save information about frequency and intensity of physical activity, but not about type of physical activity. Both pedometers and accelerometers only save information about lower body movement, but reliability about the estimation of energy expenditure is limited. Heart rate monitoring relates intensity to energy expenditure, but gives no information about physical activity. GPS watches are portable, relatively inexpensive, non-invasive and provide distance, speed, and elevation with exact time and location, but are maybe limited for the assessment of brief higher speed movement and energy expenditure. Combined motion sensors combine accelerometry with the measurement of physiological variables and share advantages of single devices and are more precise. Manufacturer software which applies activity-specific algorithms for the calculation of energy expenditure can affect energy expenditure results. Most of the devices estimate energy expenditure more accurately at light to moderate intensities; underestimation increases at very light and higher intensity activities.

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Key words: *physical activity, energy expenditure, accelerometer, pedometer, GPS.*

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ESTIMACIÓN DE LA ACTIVIDAD FÍSICA EN POBLACIÓN GENERAL; MÉTODOS INSTRUMENTALES Y NUEVAS TECNOLOGÍAS

Resumen

La medición objetiva del movimiento humano y la cuantificación del gasto energético debido a la actividad física es una necesidad identificada tanto en investigación como en clínica. Los métodos de referencia validados y bien definidos (el agua doblemente marcada, la calorimetría directa, la calorimetría indirecta) son caros y prácticamente se limitan a la investigación en el laboratorio. Por lo tanto, en los últimos años, se han desarrollado diferentes dispositivos de medición objetiva que son apropiados para los estudios de campo y clínicos. No hay ningún estándar de oro entre ellos, ya que todos tienen limitaciones. Los podómetros son ligeros, poco costosos, cuentan los pasos y aportan información sobre la actividad física total, pero no sobre el comportamiento y los patrones de actividad física. Los acelerómetros son caros, aportan información sobre patrón, frecuencia e intensidad de la actividad física, pero no sobre el tipo de actividad física. Los podómetros y acelerómetros únicamente recogen información sobre el movimiento del movimiento corporal, pero la validez en la estimación del gasto energético es limitada. La monitorización de la frecuencia cardíaca relaciona intensidad del ejercicio con gasto de energía, pero no aporta información sobre la actividad física. Los dispositivos GPS son portátiles, relativamente asequibles, no invasivos y recogen distancia, velocidad y elevación con hora y lugar exactos, pero quizás estén limitados para la evaluación de movimientos cortos de alta intensidad y elevado gasto energético. Los dispositivos de última generación combinan acelerometría con la medición de variables fisiológicas, comparten las ventajas de los dispositivos individuales y son más precisos. Para el cálculo del gasto energético se aplican algoritmos específicos de la actividad incluidos en el software del fabricante que pueden afectar a los resultados. La mayoría de los dispositivos estiman con mayor precisión el gasto energético a intensidades ligeras y moderadas, pero subestiman el gasto a intensidades muy ligeras y de mayor intensidad.

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Palabras clave: *Actividad física. Gasto energético. Acelerómetro. Podómetro. GPS.*

Background

Scientific evidence accumulating during the last decades has stated the benefits of regular physical activity on health and disease prevention[1]. Physical activity (PA) reduces both morbidity and mortality and can minimize the physiological effects of an otherwise sedentary lifestyle increasing the active lifespan[2]. Therefore, it is essential to provide reliable and valid methods to measure PA for population studies and the clinical setting.

Since Lavoisier performed his study introducing a dog in a metabolic chamber at the end of the 18^{th} Century, scientists know that PA is associated with an increase in oxygen consumption, carbon dioxide output and heat production when compared to rest. Even today, the methods linked to metabolism like direct and indirect calorimetry and doubly-labelled water (DLW) are considered as reference values for energy expenditure (EE) and PA and have been used to validate other methods and devices for assessing PA and EE. The doubly-labelled water method is considered the gold standard for measuring EE in free-living subjects[3]. It is ideal for free-living settings because it does not require any type of restrictive device and it yields accurate measurements of total energy expenditure (TEE) over periods of several days to a few weeks. However, DLW is limited as it does not provide information about frequency, intensity and duration of PA. Moreover, the high cost associated with the isotopes and sample analysis forbids widespread use of DLW in many clinical and research settings[3].

Direct calorimetry is accurate over time and adequate for resting metabolic measurements. But it is not practical for performing population studies, as it needs specific expensive equipment, only one person at a time can be measured and if PA is performed, sweat can create error measurements, among other limitations[4].

Indirect calorimetry estimates total body EE based on O_2 used and CO_2 produced. There are portable models which can be used in field studies. It is based on measures of respiratory gas concentrations, but it is only accurate for steady-state oxidative metabolism. The older methods of analysis are accurate but slow and the new methods are faster but expensive.

Observational methods are out of the scope of this review. Briefly, self-report is a common method used in assessing PA due to the fact that it is inexpensive, quick and a reliable alternative in a large sample size[5]. Self-reports can be carried out by interviewers (face to face or phone) or by the subject him/herself, and can be done in a prospective or retrospective way. But there is consensus in the literature that currently there is no questionnaire which can be considered optimal. Self-reports have the inconvenience of relying on the subjects memory and honesty. There are many PA questionnaires published in the literature. Several recent reviews[6,7] conclude that for children and adolescents, the most reliable are PDPAR (Previous Day Physical Activity Recall) and 3DPAR (3day PA recall, but filled in as a dairy or recalling maximal the previous day); for adults IPAQ (International Physical Activity Questionnaire) and FPACQ (Flemish PA computerized questionnaire in adults); and for elderly, the Standford Usual Activity Questionnaire. One can conclude that PA questionnaires must be adapted to the age group which is going to be studied, apart from socioeconomic, cultural and other aspects that should be considered as they can bias the information.

Interest

Since WHO started to include regular PA among the global recommendations related to health and non-communicable disease prevention, there has been a growing interest in assessing PA in an accurate way. Both researchers and policy makers identified the need to know how active subjects are in order to get deeper into scientific aspects and to launch public health policies. Interest on PA has grown also among nutrition experts, as EE has been given less attention over the years than energy intake when analysing the obesity epidemic. Energy balance is gaining in importance among the scientific community[8]. All in all, it is necessary in terms of health to know the accurate quantification of physical activity and to determine the effectiveness of physical activity intervention programmes[8]. All this has pushed the R&D of devices aiming at quantifying PA more objectively than when reporting PA by means of self-reports. Objective measures of PA quantify the level, and with some devices, the duration, intensity and patterning of daily PA in people from all ages in ways that are not influenced by recall ability, ethnicity, culture or socioeconomic status. As a result, objective measures can provide important insights into the true activity levels of people.

The aim of this review is to provide an overview of pros and cons of selected objective methods which can realistically be used to quantify PA in population studies. Specifically, we will analyse current state of the art of accelerometers, pedometers, heart rate monitoring, GPS technology, and some novel activity monitors combining several methods.

Controversy

When planning a study, the objective must be clearly stated in regard to monitoring PA and/or EE. PA is any bodily movement produced by skeletal muscles that results in caloric expenditure[9] and is commonly described by the following four dimensions: frequency, intensity, duration and types of activities[10]. There are different methods to quantify PA, often quantified by measuring EE. TEE is the energy spent, on average, in a 24 hour- period by an individual or a group of individuals. TEE comprises the resting metabolic rate (~ 60%), the thermic effect of food (~10 %) and EE due to PA (~30%).

Many authors agree that the method used to calculate the EE of aerobic and anaerobic activities significantly affects the EE estimates[11]. Most devices include manufacturer software which applies activity-specific algorithms for the calculation of EE based on analysis of the pattern of signals from the sensors. Most devices are continuously being improved and the software updated. Using one or the other algorithm can influence results.

PA intensity is usually classified into three categories: light, moderate and vigorous. One of the main difficulties is in establishing cut offs for these domains, mainly based on metabolic equivalents[12] (or METS). At which intensity does an activity not be moderate any more but vigorous? There is also quite a controversy regarding the *terminus* "moderate to vigorous PA" (MVPA). The cut points used have implications, not only for the time estimates of activity associated with accelerometer data *per se*, but also for self-report measures that may be validated using accelerometers as their criterion[13].

Limitations

Despite their potential benefits, modern activity monitors are not without limitations.

Most notably, they have a high cost compared with self-reports, which means they are generally not well suited to large population studies that would require the purchase of hundreds of devices. Compliance can be another limiting factor. Most of the devices, such as heart rate monitors, accelerometers and pedometers must be worn consistently and in a prescribed method to gather reliable data. Some study participants may view adhering to these requirements as inconvenient[7], mainly during rest or during specific activities.

Units of measurement vary between PA measuring instruments, i.e. beats per minute, counts, gas exchange, etc. For converting these values into PA assessment it is necessary to use several algorithm or equations. As stated above, the variety of devices currently on the market and the different algorithms used to calculate EE turns this controversy also into a limitation. Some devices even include the possibility to use diverse equations with the same recorded data, and therefore, the results can oscillate. Additionally, this variability limits comparability between results.

Potential tampering and influencing the results cannot be excluded. Once wearing the device, people could have a tendency to be more active or even to shake the monitor, among others. Specifically with pedometer, they can delete the step count displayed on the device's read-out screen by pushing an easily identified button. All these issues can affect reliability of data.

Another identified limitation is that several of the validation studies of the devices reviewed have been performed on a convenience sample of participants and/or on a relatively small sample size[14].

Current state and perspective

The methods of quantifying PA and EE can be summarized establishing a clear definition of the outcome variables with aims, characteristics, advantages and disadvantages (Table I). Using objective measures, PA can be assessed by registration of body movements or the physiological consequences of them. Some of the methods can be used for both aims, i.e accelerometers. Objective measures can provide important insights into the true activity levels of people as they are not influenced by recall ability, ethnicity, culture or socioeconomic status. Combination of methods generally increases accuracy.

Accelerometers are among the most commonly used methods to quantify PA objectively and have been used in all populations[15,16]. Acceleration is defined as the change in velocity over time. As accelerometers quantify movement over time, frequency, time and intensity of PA can be assessed, as well as PA patterns. During the past decade there has been a great increase in the number and variety of commercially available objective physical activity monitors on the market. Accelerometers are reasonably reliable and valid measures of PA. The small size makes it user-friendly. Several reviews agree that accelerometers can provide a rich, comprehensive profile of PA behavior that describes the total amount and intensity of PA, when and how PA is accumulated, and when periods of inactivity occur[7, 17]. But they do not provide information about the kind of activity and cannot estimate if people are walking with bags or with nothing. Moreover, the measurement can be influenced by the position of the accelerometer placed on the body (waist, wrist, ankle). Another inconvenient is that it does not capture upper body movement or cycling, and that it must be taken off for swimming, having a shower or bathing, unlike it is a waterproof device. Unfortunately, the costs linked to accelerometers make their utilization not always feasible in research, especially with a high sample size.

Accelerometers can be used to calculate EE (by introducing time, frequency and intensity on specific formula). Results seem to be more accurate for light and moderate than for vigorous activities. Accelerometers have been shown to underestimate EE at higher intensities due to a plateau around ten METs[18]. In addition, accelerometers were shown to inaccurately assess EE during incline walking. Massel L et al.[19] suggested that data processing of the accelerometer has a significant impact on the outcome depending on the rules employed in analysing the data. Additionally, analysis of accelerometer data is complex and time-consuming.

Table I
An overview to quantify physical activity assessment

	Methods	*Aim*	*Characteristics*	*Advantages*	*Disadvantages*
Objective methods	*Accelerometer*	– Measure of acceleration of the body or segments of the body in one or more directions. – Monitoring of frequency, intensity and duration of physical activity.	– Relationship between movement and time. – 3 types: uniaxial (vertical movement), biaxial and triaxial (several planes).	– An objective method to assess levels of physical activity. – Extensively validated. – Small size. – Suitable for use across all age groups.	– Cost. – No information about type of physical activity.
	Pedometer	– Provides data on the total ambulatory activity.	– Should be placed on the hip.	– Inexpensive. – Suitable for all age population including children.	– Cannot measure intensity, frequency and duration. – Cannot calculate energy expenditure, need an extrapolation formula. – No information about type of physical activity. – Unreliability in different situations as non-impact activity, abdominal fat and slow walking.
Subjective methods	*Self-report*	– To collect information provided by subjects.	– Subjective methods of quantifying physical activity.	– Patterns of activity can be identified. – Inexpensive.	– Not adequate for children. – Participants may be do not complete the diary.
	Behavioural observational	– Data about physical activity behaviour.	– Contextual information. – The observer collects the information.	– Observers can be evaluates different behaviours.	– Expensive. – Trained observer needed.
Reference methods	*Doubly labelled water*	– Measures total energy expenditure across CO_2 production.	– Beverage is marked to differentiate it from metabolic water.	– Suitable for all population. – Moderate response burden. – Valid estimation for energy expenditure.	– Expensive. – Cannot be provide information about frequency, duration and intensity.
	Direct calorimeter	– Direct measures energy expenditure.	– Measures total heat produced by the body in a time frame.	– Accurate over time. – Good for resting metabolic energy measurement.	– Expensive – Slow. – Exercise equipment adds extra heat. – Sweat creates errors in measurements. – Not practical or accurate for exercise. – Cannot provide information about metabolites.
	Indirect calorimeter	– Provides estimation of energy expenditure.	– Objective measure.	– Accurate and reliable measure of energy expenditure. – Valid estimation in laboratory and field in short periods of times.	– Expensive – Difficult to use long time in free living conditions.

Table I (cont.)
An overview to quantify physical activity assessment

	Methods	*Aim*	*Characteristics*	*Advantages*	*Disadvantages*
Physiological variables	*Heart rate*	– Direct measure of energy expenditure.	– Estimation of energy expenditure from monitoring heart rate.	– Information about frequency, intensity and duration. – Suitable for the majority of populations. – Can use in waterproof. – Relatively inexpensive. – Easy and quick data and analysis.	– Only measures aerobic activities. – It is necessary calibration. – Can be affected by: temperature, contamination, gender, genetic, body composition, metabolism, medicine, age, time of the day.

In reference to types of accelerometers, triaxial accelerometer perceives acceleration in several planes. As human movement is multidimensional, it has been suggested by some authors that results in three dimensions are better methods to evaluate acceleration and EE than in uniaxial and biaxial models[20]. If additionally to PA we also want to analyse sedentary and/or sleeping behaviour, a triaxial accelerometer would be more indicated as it differentiates if the subject is sitting or lying. One of the debates going on in scientific literature is regarding the number of days subjects must wear the accelerometer in order to obtain reliable data. Ideally, the accelerometer should be worn for seven days, in order to record a whole week including the week-end, as subjects do not follow the same PA pattern each day. Other author indicates that the accelerometer should be worn for at least for 5 days[21]. In order to analyse compliance, most authors agree that subjects should filled in an "Incidences sheet" in order to record any incidence like wearing off the accelerometer during some activities, etc. Compliance in the wearing of accelerometers has turned out to be a critical issue. In the HELENA study, a representative study on nutritional status and PA behaviour, among others, carried out in European adolescents, subjects were asked to wear the accelerometer for 7 days. After a thoughtful review of recorded data, subjects were considered as valid if they had worn the accelerometer at least for 3 days during 8 consecutive hours[15]. This is in line with current recommendations. The accelerometer should be worn the number of days which guarantee reliable data for at least three days. One of these days should be a week-end day.

A pedometer is a much simpler device which counts steps. It must be placed on the hips, because it counts the times the legs move up and down during ambulation. This information is recorded and displayed as steps are taken during walking or running. Pedometers have also been widely used during the last years and have a good reliability both in children and adults and can be used to establish PA guidelines. Step count is a simply way to quantify the amount of PA. Currently, user-friendly PA guidelines do not only include recommendations on type and time spent performing PA and exercise, but also the number of steps per day that should be taken to be considered active (at least 6000 steps/day), to prevent obesity (10000 steps/day) or to lose weight (12000 steps/day)[22]. For children and adolescents, 9000 steps/day are recommended[23]. Unlike accelerometers, pedometers do not give information about intensity, frequency and duration of PA. A low reliability has been observed when participants walk slowly (less than 60m/min), perform upper body movement, have high body fat mass or perform non-impact activities (like bicycling). Pedometers cannot be worn in water and, this fact combined with their measurement solely of ambulation results in a lack of capacity to assess activities such as swimming, diving or water play[7]. They may not be able to reliably detect

Table II
New technologies to quantify physical activity

	Methods	*Aim*	*Characteristics*	*Advantages*	*Disadvantages*
Future developments	*GPS*	– Provides objective data about location, domain of activity, speed and training burden.	– Provide distance, speed, and elevation with exact time and location.	– Information about frequency, intensity and duration. – Heart rate. – Distance. – Altitude. – Can obtain information on real-time.	– Expensive. – Qualified staff.
	Combined motion sensors	– To measure direct energy expenditure and body movement (frequency, intensity and duration).	– Combined heart rate and body movement by accelerometer.	– Direct measure (combined physiological measure of heart rate and body movement, i.e. frequency, duration and intensity).	– Price. – Data processing is time consuming.

steps in individuals with gait abnormalities. PA assessment using accelerometers is more accurate than with pedometers when people walk slowly[24]. For getting data on EE, a formula must be used considering age, height and weight, distance walked and the length of the stride.

Heart rate monitors register the heart rate response to the intensity of the PA. However, they may not be able to accurately estimate energy expenditure and physical activity levels because heart rate is influenced by a wide range of factors that are unrelated to PA[5]. Heart rate is dynamic and known to be influenced by a number of different factors. Body temperature, food intake, body posture, medications, individual cardio-respiratory fitness level, genetics and PA can all influence heart rate and, as a result, can confound estimates of PA and EE derived through heart rate monitoring[8]. In addition, the ability of heart rate monitors to accurately estimate EE and assess PA patterns during low intensity and extremely high intensity activity has been questioned. Most of authors agree that combining accelerometry with heart rate monitoring increases accuracy in assessing PA[25].

Over the years, techniques for the study of human movement have improved in complexity and precision. New technologies as GPS (Table II), high frequency methods and combined motion sensors give a new perspective and should be taken into account when measuring PA or EE.

GPS technology has been used in athletes to quantify movement in training. However, commercial GPS watches maybe limited for the assessment of brief higher speed movement. The results of this main study's suggested that the GPS watches tested provide less reliable estimates of EE during walking, especially at higher speeds (7 km/h). Nevertheless, GPS watches are portable, relatively inexpensive, non-invasive and provide distance, speed, and elevation with exact time and location. The measurement error should be considered when comparing results from individuals wearing different GPS watches and other devices measuring EE, such as an accelerometer. Currently, heart rate monitors are used for short periods of time (training bouts), currently the GPS does not improve the accuracy of this type of PA; however, they are very useful for activities where there is displacement[26].

A new generation of monitors that either combine multiple accelerometers on different body segments or that combines accelerometry with other physiological signals in a single device has contributed to a progress in the PA assessment field.

One of these new devices is the SenseWear Armband (SWA) (BodyMedia, Inc.,Pittsburgh, PA). SWA, an extremely simple and inexpensive apparatus, provides quite accurate measurements of energy expenditure in humans and in baboons. It is worn on the back of the upper arm and combines five different sensors. Data are collected from a skin temperature sensor, near body temperature sensor, heat flux sensor, galvanic skin response sensor, and a biaxial accelerometer. The biaxial accelerometer registers the movement of the upper arm and provides information about body position. The information from the sensors, together with gender, age, height, and weight, are incorporated into proprietary algorithms to estimate EE. These algorithms are activity specific and are automatically applied on the basis of an analysis of the pattern of signals from the sensors.

The SWA has been shown to accurately assess EE at rest and during low to- moderate intensity PA in adults[27] and children[28] using either indirect calorimetry or doubly labelled water. The SWA did not provide accurate estimates of energy expenditure at high intensity levels (above ten METs or a running speed of 6 mph (161 m/min)) in young adults. In this study, in addition, the measurement error increased with increasing exercise intensity due to the plateau or ceiling effect in energy estimations of the SWA. In the validation study of performed by Arvidsson et al.[16] in 11 to 13 year aged children, the SenseWear Pro2 Armband underestimated energy cost of most activities, an underestimation that increased with increased physical activity intensity. These findings have important implications for monitoring total daily energy expenditure and activity energy expenditure in humans engaging in high intensity physical activity.

In a recent study comparing several of the available activity monitors (SenseWear Pro3 Armband (SWA, v.6.1), the SenseWear Mini, the Actiheart, ActiGraph, and ActivPAL), the difficulty in estimating accurately EE during light to moderate intensity was observed[28]. The SWA and AH multi-sensor monitors provided accurate group estimates of EE during light and moderate semi-structured intensity activities, but showed larger individual estimation error. On the other hand, the accelerometry-based activity monitors showed larger error for estimation of lower intensity activities of daily living. Only the SenseWear Mini assessed low intensity activities in an accurate manner. The authors recommend that future research should focus on assessing lower intensity activities using the newly developed techniques to improve MET estimates of accelerometry-based activity monitors (i.e., artificial neural networking and Hidden Markov Modeling), making direct comparisons to multi-sensor activity monitors.

Danneker et al.[29] analysed a shoe-based PA monitor, which incorporates insole pressure sensors and triaxial accelerometry to classify major postures/activities and estimate EE and compared it with other PA monitors (Actical, ActiGraph, IDEEA, DirectLife, and Fitbit). Estimated EE using the shoe-based device was not significantly different than measured EE. The IDEEA and the DirectLlife estimates of EE were not significantly different than the measured EE, but the ActiGraph and the Fitbit devices significantly underestimated EE. The authors proposed that estimating EE based on classification of PA can be more accurate and precise than estimating EE based on total physical activity

Fitbit One (Fitbit Inc., San Francisco, CA), another novel activity monitor, is a stepcounter and distance monitor. In their recent validation study, Tacaks et al.[30] concluded that these kind of devices are valid and reliable for measuring step count at multiple speeds, but that they are inaccurate at measuring distance travelled. Placement of the Fitbit One activity monitor (whether in a pocket or on the hip) did not affect the accuracy of the step counts reported. The variability in underestimation of EE for the different activities may be problematic for weight loss management applications.

Conclusions

The objective measurement of human movement and the quantification of energy expenditure due to physical activity is an identified need in both research and the clinical setting. Validated and well-defined reference methods are expensive and mostly limited to the laboratory setting. Newly objective measurement devices have been developed which are appropriate for field studies and clinical settings, but all have limitations. Pedometers count the steps taken and give information on total physical activity, but not about PA patterns and behaviour. Accelerometers save information about frequency and intensity of PA, but not about type of PA. Both pedometers and accelerometers only save information about lower body movement and reliability about the estimation of energy expenditure is limited. Heart rate monitoring relates intensity to EE, but gives no information about PA. GPS watches are maybe limited for the assessment of brief higher speed movement and EE. Combined motion sensors share advantages of single devices and are more precise, but activity-specific algorithms for the calculation of EE can affect EE results. Most of the devices estimate EE more accurately at light to moderate intensities; underestimation increases at very light and higher intensity activities.

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