Assessment of Total Energy Expenditure and Physical Activity Using Activity Monitors

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Summary To assess total daily energy expenditure (TDEE) under daily living conditions, the doubly labelled water (DLW) technique is considered the gold standard. This technique is accurate but also costly and requires specific lab equipment and expertise. It also provides an average measure of TDEE over a period of one to two weeks and hence no information on physical activity (PA) patterns is available. To overcome these shortcomings, activity monitors can be used to assess activity patterns and an estimate of TDEE can be made, provided the activity monitor has been previously validated in daily life using DLW. Most activity monitors contain accelerometers, that measure the acceleration of the body and hence represent body movement. By definition, body movement leads to energy expenditure (EE) and hence the two always need to be related. Activity monitors that provide an estimate of EE need to be validated so that the contribution of the sensor output to the prediction of EE is known. Subject characteristics such as body mass, height, gender and age already explain most of the variation of TDEE; the accelerometer should then represent the physical activity component of TDEE and improve the explained variation. Many activity monitors also contain additional sensors measuring other (physiological) output parameters such as heart rate, skin temperature, galvanic skin response or gps positioning. Although promising, so far there is no compelling evidence that these additional sensors improve the prediction of EE, so careful consideration is needed whether or not these are worth the extra cost, and the extra battery power and storage capacity needed. Again, it is important to know the individual contribution of each outcome parameter to the prediction of TDEE. In conclusion, activity monitors are valuable tools in PA research but also in nutritional research when energy balance is studied.

Key Words accelerometry, doubly labelled water, total daily energy expenditure

Defining physical activity and energy expenditure

Physical activity can be defined as any body movement, produced by skeletal muscles, resulting in energy expenditure (*1*). Total daily energy expenditure (TDEE), also often referred to as average daily metabolic rate (ADMR), is the total amount of energy needed for the body to function (basal metabolic rate), digest food (diet-induced thermogenesis) and perform physical activity (physical activity-related energy expenditure). Basal metabolic rate (BMR) is measured in the morning, after a 12-h fast while lying on a bed, awake under thermoneutral conditions without external stimuli. Diet induced thermogenesis (DIT) is typically 10% of total TDEE when consuming an average mixed diet. When TDEE and BMR are measured, physical activity-related energy expenditure (PAEE) can then be calculated as 0.9 * TDEE−BMR.

When in energy balance, TDEE equals energy intake (EI). Therefore, accurately assessing TDEE could be an alternative for measuring EI, as the latter has been proven to be extremely difficult and prone to underreporting. As a matter of fact, in 2015, the Energy Balance Measurement Working Group published a statement to no longer use self-report to assess EI, as the use of decidedly inaccurate methods leads to false conclusions (*2*). As such, it was stated that the quote "something is better than nothing" must be changed to "something is worse than nothing" (*2*).

As said, one could study the other side of the energy balance equation, i.e., by measuring TDEE. When in energy balance, i.e., when no change in body mass or body composition occurs, TDEE will equal EI. Contrary to EI, TDEE can be measured accurately, under daily life conditions, using the doubly labelled water technique (DLW).

Assessing energy expenditure and physical activity
Doubly labelled water (DLW)

The doubly labelled water method uses the two stable isotopes deuterium (^{2}H) and oxygen-18 (^{18}O) to measure CO_2-production under daily living conditions. In short, after the collection of a baseline urine (or saliva or blood) sample, a dose of doubly labelled water with an exact known amount of both isotopes is ingested. Deuterium will equilibrate with the total body water pool whereas oxygen-18 will equilibrate with the water pool as well as the bicarbonate pool. Over the following days (up to 2–3 wk), deuterium will be lost as water and oxygen-18 will be lost as both water and CO_2. Hence, the difference in elimination rates is a measure of CO_2-production (*3*). In order to calculate EE, an RQ has to be assumed, which is generally 0.85, representing an average mixed diet. The DLW technique is accurate,

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non-invasive and can be used in daily life. On the other hand, the ^{18}O-isotope comes at a high cost and the analysis requires relatively expensive equipment (isotope-ratio mass spectrometry or laser spectroscopy) as well as expertise. Another disadvantage is time resolution, as average TDEE is typically calculated over one or two weeks. In subjects with a high to very high energy turnover, the TDEE could be calculated over time intervals of about 3 d or in extreme cases even 1 d, but with lower accuracy for one day measurements (4). To overcome these shortcomings, a vast amount of research has been conducted to predict EE using wearable sensors, especially accelerometers.

Activity monitors to assess physical activity and energy expenditure

A modern accelerometer is generally a small wearable sensor that measures accelerations in three planes (vertical, medio-lateral, antero-posterior) using a MEMS sensor (Micro Electro-Mechanical System). An accelerometer is typically only a few centimeters in size and weighs less than 30 g.

The purpose of an activity monitor in the first place is to accurately assess physical activity in order to capture habitual daily life activity patterns. The actual outcome measure of an activity monitor, in the case of accelerometers, is the acceleration signal, or basically every acceleration made by the human body. Or to be more exact, every acceleration of the body part the accelerometer is attached to. When a wearing position close to the center of mass is chosen, the acceleration signal best represents whole body movement, and by definition energy expenditure (5). An acceleration signal is often summarized as physical activity counts. To calculate the counts, the raw signal is first transformed to the absolute value (the positive number) and then all values can be added up over a chosen time interval by taking the integral. A count can hence be calculated for example as a count per minute or count per second. It should be realized that most accelerometers will also apply some filtering on the raw signal before activity counts are calculated. Filtering can be necessary for example to reduce noise, such as high frequency accelerations arising from transportation (e.g., a car) instead of body movement (6).

The raw acceleration signal or calculated physical activity counts are in principle the primary outcome parameter of an accelerometer, from which several secondary outcome parameters can be calculated, such as time spent in different intensity categories, sedentary behavior, energy expenditure or others. More information on activity patterns can be derived for example by determining cut-off points, meaning that depending on the amplitude of the acceleration signal an activity is classified as light, moderate or high intensity. This provides a more detailed activity pattern then just total PA, and moderate or vigorous intensity PA will have different physiological or health effects than light PA. Unfortunately, determining cut-offs to classify an activity as light, moderate or high is not that simple and hence different cut-offs have been published in literature, even for the same accelerometer. The consequence is that depending on the cut-off points chosen, there may be a large difference in time spent in for example moderate-to-vigorous PA (7, 8). Consequently, misclassification will occur for example about whether or not someone meets the PA recommendations or different associations with health outcomes will be found. Until consensus on cut-off points is reached, it is advised to use these outcomes as secondary outcome parameters and not the primary.

One of the advantages of accelerometry is the time resolution that can be achieved. Accelerometers these days often have a sampling frequency of 25 Hz (25 data points per sec) or higher. In contrast to DLW that assesses EE, accelerometers measure body movement, which could be considered a direct measure of physical activity. If an accelerometer measures body movement and DLW measures EE, both outcome parameters should by definition be related. This has led to a vast number of studies validating accelerometers against doubly labelled water (or indirect calorimetry equipment for lab-based validation studies) to assess the validity of the accelerometer to accurately capture physical activity. These studies are highly valuable, as the output of an accelerometer that does not relate to EE whatsoever, by definition doesn't measure physical activity but noise. In a validation study in 2005, it was shown that 83% of the variation in TDEE could be explained by the subject characteristics age, height and body mass, and the activity counts from the accelerometer with a standard error of estimate (SEE) of 1 MJ/d. When measured BMR or body composition was used instead of subject characteristics, the explained variation increased to 90% with a SEE of ~0.75 MJ/d. This means that with a tri-axial accelerometer, TDEE could be predicted fairly accurately, to within 1 MJ/d on the individual level or to 0.75 MJ/d when BMR or body composition is measured (9).

Several reviews were published on which activity monitors have been validated against doubly labelled water (10–12) and new validation studies are still being published (13–16). It's important to know that not all activity monitors show good validity and hence no good estimate of TDEE can be obtained. It should also be realized that validity is not only determined by the brand of an accelerometer but also by other variables such as the chosen output, analytical method and population (14). In addition, with the rapid technological advancements, it is hard to keep track of all new activity monitors or updates on existing ones, coming on the market, both research-based and commercial. This makes it impossible to validate every device and research on devices often suffers from "research lag," meaning that validation studies on a given device are not disseminated until after the devices have been replaced by new versions or models (17).

Additional sensors to accelerometry to improve the estimation of EE

Not all wearable sensors or activity monitors contain only accelerometers. Many activity monitors contain additional sensors to measure other physiological pa-

rameters such as heart rate, skin temperature, galvanic skin response or non-physiological parameters such as gps-location. It cannot be stated that adding more sensors by definition will improve the accuracy of the EE estimation. On the contrary, when adding the output of additional sensors to predict EE, the result may actually be worse than when using accelerometer output alone (*10, 18*). Activity monitors with multiple sensors should therefore always provide the raw signal of each sensor so that the individual contribution of each sensor to the explained variation of EE can be investigated.

As stated above, given the rapid developments in activity monitors, validating every device that comes on the market is not feasible nor a desirable way to move forward. In addition, adding multiple sensors and claiming superior validity without information on the individual contribution of each sensor is not accurate. Future studies would benefit from assessing EE using a gold standard reference technique (e.g., room calorimetry for simulated daily life studies and/or doubly labelled water for true daily life studies) and assess which output from an activity monitor is needed to improve the estimation of EE. Relevant output can come from accelerometry at different locations on the body, heart rate, heart rate variability, skin temperature, electric conductivity and others. Then the value or contribution of each signal to estimate EE can be investigated using a variety of different analysis techniques. Lab-based algorithms can be cross-validated in daily life and/or in different populations.

To conclude

The main advantages of using an activity monitor are that it is an objective method, it provides a high time resolution, it gives detailed information about activity patterns, it is generally small and unobtrusive, data can be stored for months and battery life is generally sufficient to observe over several weeks to months. When the outcome of interest is energy balance, an estimate of energy expenditure needs to be obtained. As explained above, some activity monitors will provide a good and objective estimate but validity of the monitor needs to be proven. When activity monitoring is combined with an accurate measure of BMR or body composition, the prediction of TDEE will become much stronger. Therefore, activity monitors can be a very valuable tool to study energy balance and health-related outcomes.

Disclosure of state of COI

No conflicts of interest to be declared.

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